

The alternate interpretation of the Quantum theory utilizing indefinite metric

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(Dated: 23 April 2021)

In this paper, we propose an alternate interpretation of the quantum theory using objective physical reality that does not depend on the conventional probability interpretation.

As typical physical phenomena for the probability interpretation, we consider the single-photon interference, single-electron interference, and EPR correlation experiments using photon polarization. For the calculation using the alternate interpretation, the minus sign derived from the covariant quantization of Maxwell's equations, which is associated with the scalar potential of time axis component of four-vector, is taken as it is as an inevitable request from the theory. We show that both conventional and alternate interpretation derive the identical calculation results for these single photon, single electron interference, and EPR correlation.

These alternate calculation processes describe that there is the scalar potential in whole space-time and when there is some geometrical arrangement in the space, the scalar potential forms the oscillatory field of the potential according to the arrangement. It reveals the objective physical reality that the single-photon, single-electron interference, and EPR correlation are generated by the movement of the photons and electrons in the oscillatory field with interference.

In addition, we show that the oscillatory field formation of the scalar potential depending on the geometrical arrangement causes energy fluctuation in the space, which enables removal of infinite zero-point energy and causes spontaneous symmetry breaking and Casimir effect. By recognizing the electromagnetic field as an unitary $U(1)$ gauge field and generalizing it to a special unitary $SU(2)$, we also show the uncharged particle, e.g. neutron, interferences are generated by the geometrical arrangement of the $SU(2)$ gauge field. Furthermore, we discuss the origin of the scalar potential by distinguishing the space where the substance exists and the vacuum.

Finally, by introducing the extended Lorentz gauge, we propose the alternate solution without physical state and subsidiary condition for the contradiction between Lorentz gauge as an operator equation and the commutation relation in the covariant canonical quantization of Maxwell's equations with the conventional Lorentz gauge.

This paper contains the compilation of published author's papers^{1,2} in addition to featured discussions such as the physical reality, uncharged particle interference and alternate proposal for the contradiction between Lorentz gauge as an operator

equation and commutation relation³.

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I. INTRODUCTION

The standard quantum theory has been constructed based on probability interpretation. An arbitrary state of a microscopic physical system such as an atom or elementary particle is represented by a state vector equate with a vector in Hilbert space. An expected value of a physical quantity is obtained from the eigenvalue equation of an operator representing a physical quantity. That is the outline of the calculation technique of the standard quantum theory based on probability interpretation.

According to the idea of equating this physical state with a vector in Hilbert space, the inner product of the vectors is interpreted as representing the probability that the state of the system exists in the space-time. Calculations using this basic concept are in agreement with experimental results. Without this concept, single photon and electron interference are difficult to explain. In addition, an entangled state exhibiting long-range correlation that seem to contradict relativity has been discussed by probability interpretation.

However, as long as follow this concept, it is difficult to solve the paradoxes associate with a wave packet reduction typified by "Schrödinger's cat" and "Einstein, Podolsky and Rosen (EPR)".^{4,5}

To interpret quantum theory without these paradoxes, de Broglie and Bohm proposed the so-called "hidden variable" theory.^{6,7} However it is considered "hidden variable" has been rejected by violation of Bell's inequality. The rejection of "hidden variables" due to the violation of Bell's inequality is inconsistent with relativity that relies on the locality of physical laws.

Although the improvement has not been completed so far, some researchers have been trying to improve the quantum theory based on probability interpretation to fit relativity.⁸⁻¹²

Various discussions and experiments have been conducted associate with the correctness of the basic concept of quantum theory that requires description of physical phenomena beyond relativity and common sense. For examples, quantum mechanical superpositions by some experiments have been reviewed.¹³ The atom interference by using Bose-Einstein condensates (BECs) has been reported experimentally and theoretically.^{14,15} The coherence length of an electron or electron-electron interference by using Aharonov-Bohm oscillations in an electronic MZI has been discussed theoretically.^{16,17} A plasmonic modulator utilizing an interference of coherent electron waves through Aharonov-Bohm effect has been stud-

ied by the author.¹⁸ The entangle states have been widely discussed experimentally and theoretically.^{19–24} The photon interference by using nested MZIs and vibrate mirrors has been measured and analyzed.^{25,26} The double-slit electron diffraction has been experimentally demonstrated.²⁷

These reports associated with quantum phenomena have convinced the validity of the basic concept of the probability interpretation, and the reliability of the standard quantum theory based on the probability interpretation has come to be considered unwavering.

However, these reports just confirmed the agreement between the measurement results and the calculation results based on the basic concept of the probability interpretation, and examined the application of the interference derived from the probability interpretation. They have considered no possibility other than the probability interpretation of quantum theory.

In this paper, we propose an alternate interpretation of the quantum theory without probability interpretation and show the identical calculation results are obtained for single photon interference, single electron interference, and EPR correlation utilizing both conventional and alternate interpretation. Then we also show the alternate interpretation describes objective physical reality that photons and electrons are actually moving in space-time instead of probability interpretation.

According to the alternate interpretation, the concept of pure state of which probabilities are fundamental sense does not need in nature. Only the concept of mixed states of which probabilities are statistical sense is physically valid as a natural law. Although the probability interpretation of the standard quantum theory using the mixed state is useful for calculations, it is shown that quantum theory will be deterministic physics without probability interpretation as in classical physics.

In addition, we show that the removal of infinite zero-point energy without artificial subtraction, Casimir effect and spontaneous symmetry breaking can be spontaneously obtained. Furthermore, by generalizing the electromagnetic field of unitary gauge field to special unitary gauge field, we also show uncharged particle interference can be explained as the same mechanism, i, e., by the geometrical arrangement of the $SU(2)$ gauge field.

The structure of this paper is as follows.

In chapter II, we summarize the covariant quantization of Maxwell's equation that requires an indefinite metric, which is the essence of this paper, and discuss that the indefinite

metric obtained by the quantization should take precedence over the probability interpretation.

In chapter III, we indicate the difference in calculation and interpretation for single-photon interference, single-electron interference and EPR correlation between using the conventional probability interpretation and alternate interpretation. Despite the differences, except for the interpretation, the identical results can be obtained as the observable physical phenomena. In addition, we show a convenient format for calculation named “simple calculation method”, which simplifies the calculation of the alternate interpretation. From the calculation results by the alternate interpretation, it becomes clear that the scalar potential is a physical reality with a minus sign of indefinite metric.

In chapter IV, as applications of the alternate interpretation, we show that the removal of infinite zero-point energy, Casimir effect, spontaneous symmetry breaking can be spontaneously obtained utilizing the generalization of the geometrical arrangement in the space discussed in chapter III. We also refer to the general approach for single particle interference include uncharged particle.

In chapter V, the origin of the indefinite metric potential and Maxwell’s equations in vacuum, which is the core of the alternate interpretation examined in this paper, is discussed.

In chapter VI, we discuss the contradiction between Lorentz condition as an operator and commutation relation in covariant canonical quantization of Maxwell’s equations. Then we propose the alternate method introducing the extended Lorentz gauge that can avoid the contradiction without physical state and subsidiary condition.

In chapter VII, we summarize the alternate interpretation.

II. COVARIANT QUANTIZATION OF MAXWELL'S EQUATIONS

In order to revise the basic concept of the conventional standard quantum theory based on probability interpretation to the alternate interpretation using objective physical reality, covariant quantization of Maxwell's equations using Lorentz gauge is indispensable instead of using Coulomb gauge. That will be shown together with concrete calculations in the following chapters.

The purpose of the quantization described in this chapter is to clarify the introduction of the minus sign required by the indefinite metric, which is necessary for the discussion in the following chapters.

For that purpose, quantization is performed using Fourier transform without going into the details of canonical quantization, namely, the four-vector satisfying the covariant form of Maxwell's equations is expressed by the Fourier transform of plane wave expansion and then those Fourier coefficients are replaced with operators along with setting commutation relations.

The canonical covariant quantization of Maxwell's equations in Lorentz gauge requires the discussions other than the purpose of this chapter, i.e., associate with the selection of Lagrangian density and the setting of commutation relations. Therefore the canonical quantization will be dealt with independently and discussed in Chapter VI.

However, there is no difference in calculations and discussions in the following chapters, whether the quantization in this chapter or the canonical quantization is adopted.

A. Quantization using Lorentz gauge

The subject of the discussion is Maxwell's equations below.

$$\begin{aligned} \left(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \mathbf{A} - \nabla \left(\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} \right) &= -\mu_0 \mathbf{i} \\ \left(\Delta - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \phi + \frac{\partial}{\partial t} \left(\nabla \cdot \mathbf{A} + \frac{1}{c^2} \frac{\partial \phi}{\partial t} \right) &= -\frac{\rho}{\varepsilon_0} \end{aligned} \quad (1)$$

where μ_0 and ε_0 are the permeability and permittivity of a vacuum respectively.

In the Maxwell's equations (1), the electromagnetic potentials ϕ and \mathbf{A} are expressed as following four-vector in Minkowski space.

$$A^\mu = (A^0, A^1, A^2, A^3) = (\phi/c, \mathbf{A}) \quad (2)$$

The charge density ρ and space currents \mathbf{i} are also expressed as following four-currents.

$$j^\mu = (j^0, j^1, j^2, j^3) = (c\rho, \mathbf{i}) \quad (3)$$

Hence, by setting the axes of Minkowski space as $x^0 = ct$, $x^1 = x$, $x^2 = y$, $x^3 = z$, Maxwell's equations in the Lorenz gauge are expressed as following covariant form

$$\square A^\mu = \mu_0 j^\mu, \quad \partial_\mu A^\mu = 0 \quad (4)$$

In addition, the conservation of charge

$$\text{div } \mathbf{i} + \partial\rho/\partial t = 0 \quad (5)$$

is expressed as following covariant form.

$$\partial_\mu j^\mu = 0 \quad (6)$$

where,

$$\partial_\mu = (1/c\partial t, 1/\partial x, 1/\partial y, 1/\partial z) = (1/\partial x^0, 1/\partial x^1, 1/\partial x^2, 1/\partial x^3) \quad (7)$$

and \square is the d'Alembertian : $\square \equiv \partial_\mu \partial^\mu \equiv \partial^2/c^2 \partial t^2 - \Delta$.

The covariant and contravariant vectors can be transformed to each other using the simplest Minkowski metric tensor $\mathbf{g}_{\mu\nu}$ as follows.

$$\mathbf{g}_{\mu\nu} = \mathbf{g}^{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \quad (8)$$

$$A_\mu = \mathbf{g}_{\mu\nu} A^\nu, \quad A^\mu = \mathbf{g}^{\mu\nu} A_\nu \quad (9)$$

The following quadratic form of a four-vector is invariant under a Lorentz transformation.

$$(x^0)^2 - (x^1)^2 - (x^2)^2 - (x^3)^2 \quad (10)$$

The wave front equation can be expressed by applying a minus sign to the above quadratic form and can be described by using metric tensor as follows.

$$-\mathbf{g}_{\mu\nu} x^\mu x^\nu = -x^\mu x_\mu = x^2 + y^2 + z^2 - c^2 t^2 = 0 \quad (11)$$

This quadratic form, including the minus sign, is also introduced into the inner product of arbitrarily vector and commutation relations in Minkowski space.

Maxwell's equations that satisfy the four-vectors with no four-current in free space can be expressed as the following Fourier transform by plane wave expansion.²⁸

$$A_\mu(x) = \int d\tilde{k} \sum_{\lambda=0}^3 [a^{(\lambda)}(k) \epsilon_\mu^{(\lambda)}(k) e^{-ik \cdot x} + a^{(\lambda)\dagger}(k) \epsilon_\mu^{(\lambda)*}(k) e^{ik \cdot x}] \quad (12)$$

$$\tilde{k} = \frac{d^3k}{2k_0(2\pi)^3} \quad k_0 = |\mathbf{k}| \quad (13)$$

where the unit vector of time-axis direction n and polarization vectors $\epsilon_\mu^{(\lambda)}(k)$ are introduced as $n^2 = 1$, $n^0 > 0$ and $\epsilon^{(0)} = n$, $\epsilon^{(1)}$ and $\epsilon^{(2)}$ are in the plane orthogonal to k and n

$$\epsilon^{(\lambda)}(k) \cdot \epsilon^{(\lambda')}(k) = -\delta_{\lambda,\lambda'} \quad \lambda, \lambda' = 1, 2 \quad (14)$$

$\epsilon^{(3)}$ is in the plane (k, n) orthogonal to n and normalized

$$\epsilon^{(3)}(k) \cdot n = 0, \quad \epsilon^{(3)}(k) \cdot \epsilon^{(3)}(k) = -1 \quad (15)$$

Hence $\epsilon^{(0)}$, $\epsilon^{(1)}$ (and $\epsilon^{(2)}$) and $\epsilon^{(3)}$ can be recognized as a polarization vector of scalar wave, transversal waves and a longitudinal wave respectively. Here we take the following the easiest forms as these vectors.

$$\epsilon^{(0)} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad \epsilon^{(1)} = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad \epsilon^{(2)} = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad \epsilon^{(3)} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad (16)$$

The quantization is performed by replacing the Fourier coefficients of the four-vector with operators $\hat{A}_\mu \equiv \sum_{\lambda=0}^3 \hat{a}^{(\lambda)}(k) \epsilon_\mu^{(\lambda)}(k)$ and setting the commutation relations as follows.

$$[\hat{A}_\mu(k), \hat{A}_\nu^\dagger(k')] = -\mathbf{g}_{\mu\nu} \delta(k - k') \quad (17)$$

The time-axis component has the opposite sign of the space axes. Because $\langle 0 | \hat{A}_0(k) \hat{A}_0^\dagger(k') | 0 \rangle = -\delta(k - k')$,

$$\langle 1 | 1 \rangle = -\langle 0 | 0 \rangle \int d\tilde{k} |f(k)|^2 \quad (18)$$

where $|1\rangle = \int d\tilde{k} f(k) \hat{A}_0^\dagger(k) |0\rangle$. Therefore, the time-axis component is the source of indefinite metric.

Here, when we identify $|1\rangle$ as the single photon state by the probability interpretation, the probability that there is one photon in space is negative. Therefore the probability interpretation is inapplicable for the covariant quantization.

Mathematically, the negative sign of the inner product of vectors is contrary to the definition of the inner product of vectors in Hilbert space.

In the first place, equating of the physical state vectors $|x\rangle$ and those inner product $\langle x|x\rangle$ with the vectors and those inner product in Hilbert space such as $|x\rangle \geq 0 \quad \langle x|x\rangle = 0 \Leftrightarrow |x\rangle = 0$ was not derived from theory, but estimated and artificially introduced.

The reliability of the identification has been established as a result of accumulating agreement between the calculation results obtained from the probability interpretation and various experimental results.

In addition to the reliability, the mathematical procedures which can reconcile the probability interpretation with the indefinite metric has been developed for example so-called Gupta-Bleuler formalism^{29,30} and Nakanishi-Lautrup formalism³¹ as will be mentioned in chapter VI. However, such a procedures are not necessarily required theoretically, and can be understood as mathematical techniques to be consistent with the probability interpretation by introducing artificial manipulation such as physical states and subsidiary conditions.

On the other hand, the minus sign is necessarily introduced from Maxwell's equations and the theory of relativity. In the first place, the physical space of the natural world is expressed as Minkowski space even if gravity is ignored or Riemann space if gravity is included, and the metric is not limited to a positive definite value.

In this paper, we accept the introduction of the minus sign as an inevitable request from the theory, and propose an alternate interpretation of the quantum theory without probability interpretation. In the following chapters we show the calculation results of single-photon interference, single-electron interference and EPR correlation using probability interpretation can be faithfully reproduced by introducing the minus sign. Then we also show these phenomena will be clear the image of objective physical reality.

If Coulomb gauge is adopted, the scalar potential of the time axis component, which is the source of the indefinite metric, will be ignored. Therefore the discussion in the next chapter becomes difficult. In addition, the explicit covariance of Maxwell's equations is also lost, hence Lorentz gauge should be adopted to construct the basic concept of physical law independent of the coordinate system.

III. SINGLE PHOTON, SINGLE ELECTRON INTERFERENCE AND EPR CORRELATION

In this chapter, we show the calculation methods for the single photon interference, single electron interference, EPR correlation by using both probability and alternate interpretation. We emphasize that the calculation of single-photon and single-electron interference by using probability interpretation imposes the description that a single particle that cannot be further divided must be considered as if it were divided into separate paths on us.

On the other hand, the calculation of single-photon and single-electron interference by using the alternate interpretation reveals that the scalar potential, which is the source of the indefinite metric, forms an oscillatory field due to the geometrical arrangement of the experimental setups. Then we can obtain the image of objective physical reality which describes the inseparable single photon or electron moves in the oscillatory field while interfering with each other.

For EPR correlation, the calculation utilizing polarized photons will be discussed. On the calculation of EPR correlation by using probability interpretation, two photons having polarizations orthogonal to each other must be considered as a correlated photon pair state (Entanglement), which simultaneously splits into different paths and only probabilistically exists in whole space-time. This kind of explanation requires not only the probability interpretation but also the "denial of locality" which contradicts the relativity such that the polarization of the photon of the other path is determined at the very moment when the polarization is found by the polarization measurement of the photon of the other path.

On the other hand, according to the alternate interpretation, the correlated photon pair has the designated polarization that is determined when it generates, and when the polarization direction is measured, those photons are interfered with the scalar potential that forms an oscillatory field due to the geometrical arrangement of the experimental setup. We clarify that there seems to be a non-local long-range correlation beyond the causality due to the interference with the potential.

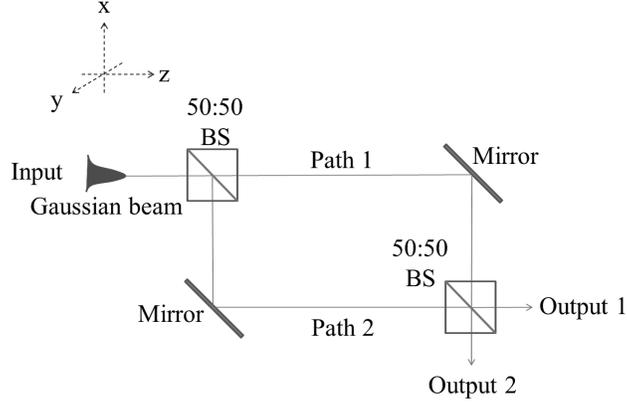


FIG. 1. Schematic view of Mach-Zehnder Interferometer (MZI). BS:Beam Splitter.

A. Single photon interference

1. Calculation using probability interpretation

Figure 1 shows a schematic view of the Mach-Zehnder Interferometer (MZI) and coordinate system.¹

On the probability interpretation, the calculation of the single photon interference by using Maxwell's equations (1) in free space ($\mathbf{i} = 0, \rho = 0$) in Coulomb gauge eliminates the scalar potential ϕ and only uses the quantized vector potentials \hat{a} and \hat{a}^\dagger as the photon annihilation and creation operator respectively.

According to the reference³², the following electric field operator of which square $\hat{E}^\dagger \hat{E}$ is used as an electric field intensity operator proportional to the photon number, and number state $|n\rangle$ are introduced to calculate the single photon interference of the MZI.

$$\hat{E} = \frac{1}{\sqrt{2}}\hat{a}_1 \exp(i\theta) + \frac{1}{\sqrt{2}}\hat{a}_2 \quad (19)$$

where \hat{a}_{1or2} is the photon annihilation operator corresponding to an optical mode passing through path 1 or 2, respectively, θ is a phase difference corresponding to the difference in length between the two paths.

\hat{a}_{1or2} and \hat{a}_{1or2}^\dagger are defined along with the expected photon number from the photon creation and annihilation operators \hat{a} and \hat{a}^\dagger in free space (MZI input) before the photons are split into two paths as follows.

$$\langle n|\hat{a}_1^\dagger \hat{a}_1|n\rangle = \langle n|\hat{a}_2^\dagger \hat{a}_2|n\rangle = \langle n|\hat{a}_1^\dagger \hat{a}_2|n\rangle = \frac{1}{2}n \quad (20)$$

$$\hat{a} = \frac{\hat{a}_1 + \hat{a}_2}{\sqrt{2}}, \quad \hat{a}^\dagger = \frac{\hat{a}_1^\dagger + \hat{a}_2^\dagger}{\sqrt{2}} \quad (21)$$

The photon number at the MZI output is calculated as follows by using the squared operator and the number state.³²

$$\langle \hat{I} \rangle \propto \langle n | \hat{E}^\dagger \hat{E} | n \rangle = \frac{1}{2} \langle n | \hat{a}_1^\dagger \hat{a}_1 | n \rangle + \frac{1}{2} \langle n | \hat{a}_2^\dagger \hat{a}_2 | n \rangle + \cos \theta \langle n | \hat{a}_1^\dagger \hat{a}_2 | n \rangle \quad (22)$$

where $\langle \hat{I} \rangle$ is the expected field intensity proportional to the photon number.

Substituting 1 ($n = 1$) for the photon number as a single photon, the above expected value is calculated to be as follows.

$$\langle \hat{I} \rangle \propto \frac{1}{4} + \frac{1}{4} + \frac{1}{2} \cos \theta = \frac{1}{2} + \frac{1}{2} \cos \theta \quad (23)$$

The above calculations can be interpreted that the photon incident from the MZI is passing through both path 1 and 2 simultaneously with probability 1/2 along with the phase difference corresponding to the optical length between the two paths, as is clear from the form of the electric field operator introduced in (19), the expected photon number (20) on each path, the division of the photon creation and annihilation operator (21).

This interpretation is valid as statistical physics that when the intensity of light incident on the MZI is high and the photon number n is large, approximately $n/2$ photons are on one side and $n/2$ photons are on the other side.

This kind of statistical state has been introduced as a mixed state which is multiplied by a density matrix proportional to the probability including the pure state having a fundamental probability. The probability interpretation using the mixed state is considered statistically valid.

However, even if the intensity of light incident on the MZI is very low and it is considered to be a single photon that cannot be split any more, the single photon is considered as a pure state with fundamental probability and passes through both path 1 and 2 simultaneously with probability 1/2.

2. Calculation using alternate interpretation

In order to revise the probability interpretation to alternate interpretation with objective physical reality, we examine again the electromagnetic field of the incident photon beam on the MZI in Figure 1.

First, assume that a light beam having an angular frequency ω and a propagation constant β polarized in the x-axis direction propagates in the z-axis direction, and the electric field of the light beam forms, for example, a Gaussian distribution of which cross-sectional shape is well localized in free space. Then, the electric field of the input light beam can be expressed as follows.

$$\mathbf{E} = \mathbf{e}_x \cdot C_E \cdot \exp\left(-\frac{x^2 + y^2}{w_0^2}\right) \cdot \cos(\omega t - \beta z) \quad (24)$$

where, \mathbf{e}_x is unit vector parallel to the x-axis. C_E is an arbitrary constant which is proportional to the magnitude of the electric field. w_0 is the radius of the optical beam. \mathbf{E} and \mathbf{B} are expressed by vector and scalar potentials as follows.

$$\begin{aligned} \mathbf{E} &= -\frac{\partial}{\partial t}\mathbf{A} - \nabla\phi \\ \mathbf{B} &= \nabla \times \mathbf{A} \end{aligned} \quad (25)$$

By introducing a vector function \mathbf{C} , \mathbf{A} is calculated from (24) and (25) as follows.

$$\begin{aligned} \mathbf{A} &= -\frac{1}{\omega}\mathbf{e}_x \cdot C_E \cdot \exp\left(-\frac{x^2 + y^2}{w_0^2}\right) \cdot \sin(\omega t - \beta z) + \mathbf{C} \\ \frac{\partial}{\partial t}\mathbf{C} &= -\nabla\phi \end{aligned} \quad (26)$$

To localize \mathbf{B} to space, we can take \mathbf{C} as an irrotational vector function $\nabla \times \mathbf{C} = 0$. For example, \mathbf{C} and ϕ can be expressed by introducing an arbitrary scalar function λ which satisfies $\mathbf{C} = \nabla\lambda$ and $\nabla\left(\frac{\partial}{\partial t}\lambda + \phi\right) = 0$.

Then \mathbf{B} is expressed as follows

$$\begin{aligned} \mathbf{B} &= \nabla \times \mathbf{A} \\ &= \frac{\beta}{\omega}\mathbf{e}_y \cdot C_E \cdot \exp\left(-\frac{x^2 + y^2}{w_0^2}\right) \cdot \cos(\omega t - \beta z) \\ &\quad - \frac{2y}{\omega \cdot w_0^2}\mathbf{e}_z \cdot C_E \cdot \exp\left(-\frac{x^2 + y^2}{w_0^2}\right) \cdot \sin(\omega t - \beta z) \end{aligned} \quad (27)$$

Therefore, \mathbf{E} and \mathbf{B} are localized in the free space in the input. In contrast, the vector and scalar potentials are not necessarily localized. The above localized form (24) is one example, other forms which satisfy the Maxwell's equations (1) in free space $\mathbf{i} = 0$ and $\rho = 0$ can be adopted.

Note that, the free space propagation will expand the radius of the Gaussian beam. However, that of the propagated beam $w(z)$ will be approximately 10.5mm when the beam

of which launched radius $w_0 = 10\text{mm}$ propagates $z = 100\text{m}$ in free space. This value can be calculated using $w(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}$ in the case of wavelength $\lambda = 1\mu\text{m}$. Hence the spatially expansion of the beam will be negligible small in the case of the paths of the MZI are less than several tens meters.

As described above, even if the photon is localized, the potentials are not always localized. In particular, the scalar potential can exist in whole space-time. The alternate interpretation is shown below by utilizing the existence of the scalar potential as the objective physical reality.

First, note that vector potentials and scalar potential are mixed by Lorentz transformation. Therefore from the Lorentz invariance, vector potentials and scalar potential should be equally treated as $\langle 1|\hat{A}_0^\dagger\hat{A}_0|1\rangle = \langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle = \langle 1|\hat{A}_2^\dagger\hat{A}_2|1\rangle = \langle 1|\hat{A}_3^\dagger\hat{A}_3|1\rangle$.

For simplicity of calculation, the incident beam in the figure 1 is assumed to be perfectly polarized on the x-axis, and the longitudinal wave that is considered to be unphysical presence is ignored, i.e., $A_2 = 0$, $A_3 = 0$. However, as mentioned above, the scalar potential can exist in the whole space-time. Therefore, the four-vector at the input of the MZI is expressed as follows.

$$A_\mu = (A_0, A_1, 0, 0) \quad (28)$$

It is reasonable for physically phenomenon taht the scalar potential is split when there are two paths of the MZI. Here, we examine that a single photon represented by a transverse wave polarized in the x-axis passes through path 1 and the scalar potential A_0 is divided into both paths 1 and 2 with a phase difference θ between the two paths. In this case, the four-vector ($\equiv A_{\mu:(\text{path1})}$) along path 1 and four-vector ($\equiv A_{\mu:(\text{path2})}$) along path 2 of MZI can be expressed as follows.

$$\begin{aligned} A_{\mu:(\text{path1})} &= \left(\frac{1}{2}e^{i\theta/2}A_0, A_1, 0, 0\right) \\ A_{\mu:(\text{path2})} &= \left(\frac{1}{2}e^{-i\theta/2}A_0, 0, 0, 0\right) \end{aligned} \quad (29)$$

By replacing Fourier coefficients of the four-vector with operators $\hat{A}_\mu \equiv \sum_{\lambda=0}^3 \hat{a}^{(\lambda)}(k)\epsilon_\mu^{(\lambda)}(k)$ and setting the commutation relations, the single photon interference can be calculated using the potentials as an operator. According to the quantization, photon annihilation operators corresponding to optical modes passing through MZI paths 1 and 2 are defined as $\hat{A}_{\mu:(\text{path1})}$ and $\hat{A}_{\mu:(\text{path2})}$ respectively. Here we must introduce the indefinite metric into the product of

the operator as follows.

$$\hat{A}^\dagger \hat{A} = -\mathbf{g}_{\mu\nu} \hat{A}^{\mu\dagger} \hat{A}^\nu = -\mathbf{g}^{\mu\nu} \hat{A}_\mu^\dagger \hat{A}_\nu \quad (30)$$

Hence the photon number operator at the output of MZI can be obtained as following expression by using the photon annihilation operator at the point $\hat{A}_{\mu:(\text{path1})} + \hat{A}_{\mu:(\text{path2})}$.

$$-\mathbf{g}^{\mu\nu} \{ \hat{A}_{\mu:(\text{path1})} + \hat{A}_{\mu:(\text{path2})} \}^\dagger \{ \hat{A}_{\nu:(\text{path1})} + \hat{A}_{\nu:(\text{path2})} \} = -\frac{1}{2} \hat{A}_0^\dagger \hat{A}_0 + \hat{A}_1^\dagger \hat{A}_1 - \frac{1}{2} \hat{A}_0^\dagger \hat{A}_0 \cos \theta \quad (31)$$

where, the following relations are used.

$$\begin{aligned} -\mathbf{g}^{\mu\nu} \hat{A}_{\mu:(\text{path1})}^\dagger \hat{A}_{\nu:(\text{path1})} &= -\frac{1}{4} \hat{A}_0^\dagger \hat{A}_0 + \hat{A}_1^\dagger \hat{A}_1 \\ -\mathbf{g}^{\mu\nu} \hat{A}_{\mu:(\text{path1})}^\dagger \hat{A}_{\nu:(\text{path2})} &= -\frac{1}{4} e^{-i\theta} \hat{A}_0^\dagger \hat{A}_0 \\ -\mathbf{g}^{\mu\nu} \hat{A}_{\mu:(\text{path2})}^\dagger \hat{A}_{\nu:(\text{path1})} &= -\frac{1}{4} e^{i\theta} \hat{A}_0^\dagger \hat{A}_0 \\ -\mathbf{g}^{\mu\nu} \hat{A}_{\mu:(\text{path2})}^\dagger \hat{A}_{\nu:(\text{path2})} &= -\frac{1}{4} \hat{A}_0^\dagger \hat{A}_0 \end{aligned}$$

From (31) and |1) with the Lorentz invariance, $\langle \hat{I} \rangle \propto \frac{1}{2} - \frac{1}{2} \cos \theta$ can be calculated. By selecting the proper reference point of the phase difference, (23) is reproduced.

$$\langle \hat{I} \rangle \propto \frac{1}{2} + \frac{1}{2} \cos \theta \quad (32)$$

Here, in order to clarify the motion of the scalar potential and the single photon as an objective physical reality, we further study the setup of the single photon MZI experiment. Since the electromagnetic field has time reversal invariance, there is no particular reason to distinguish the input and output of the MZI. Therefore, the photon annihilation operator at the confluence of the input of the MZI should be represented as the output of the MZI. Then

$$\hat{A}_\mu = \hat{A}_{\mu:(\text{path1})} + \hat{A}_{\mu:(\text{path2})} = \left(\cos \frac{\theta}{2} \hat{A}_0, \hat{A}_1, 0, 0 \right) \quad (33)$$

It is physically reasonable to assume that there is clearly single photon at the input of the MZI. If (28) is used to calculate the photon number with the single photon state at the input of the MZI, the result is calculated to be $\langle 1 | (-\hat{A}_0^\dagger \hat{A}_0 + \hat{A}_1^\dagger \hat{A}_1) | 1 \rangle = 0$. Therefore if we erase the scalar potential as $\hat{A}_0 = 0$, we can not obtain the interference. On the other hand, the photon number is 1 when $\theta = \pm N\pi$ (N : odd number) in (33). Therefore, we should recognize the scalar potential at the input of the MZI is nonzero (not empty, i.e., $\hat{A}_0 \neq 0$) but rather cancels each other out with opposite phase waves, i.e., $\cos(\theta/2) = 0$. From this study, it is possible to obtain a picture that the scalar potential generates an oscillatory field like $f(\theta) \cdot \hat{A}_0$ when there is a division (geometrical arrangement) in the space. Where $f(\theta)$

is an oscillatory function of θ . The formation of the oscillatory field can be recognized as a "hidden variable" associate with the EPR correlation, which will be dealt with in the next section. It is possible to interpret that a substantial photon moves in the oscillatory field, which interferes with each other. Therefore, the expected value of the field intensity at any spatial position is calculated as $\langle \hat{I} \rangle \propto \frac{1}{2} + \frac{1}{2} \cos \theta$ using (33). From the discussion, no matter where the substantial photon moves in the space, no photon can be observed at the position where $\theta = \pm N\pi$ (N : odd number) in the space.

In this way, if we accept the indefinite metric required from the covariant quantization without probability interpretation, a clear image of objective physical reality is obtained. That is to say, there is a scalar potential on both paths of the MZI, which forms an oscillatory field caused by the path division of the MZI, and a single photon incident from one path passes through while interfering with the oscillatory field. The formation of the oscillatory field caused by the path division examined here corresponds to the fact that the phase term depending on the potentials introduced on the electron wave function cannot be eliminated in the spatially multiple-connected region in Aharonov-Bohm effect.^{33,34}

We can replace the above calculation and picture by an analogy of electronic circuits that the scalar potential corresponds to the bias current (voltage) and the vector potential, which represents a single photon, corresponds to a signal current (voltage) added to the bias current (voltage). However, in this case, the bias current (voltage) is not direct current (DC) (or voltage), but an alternating bias current (AC) (or voltage) that interferes with the signal current (voltage), which causes output fluctuations. In summary, an observed signal fluctuates when the signal is added on a fluctuating reference. In addition, if we use the analogy of homodyne detection wireless communication or optical communication, the scalar potential corresponds to a continuously oscillating local oscillator placed at the receiving end and a single photon corresponds to a signal. This corresponds to extracting the signal information by the interference between the continuous wave of the local oscillator and the signal at the receiving end, and the image shows that each point in whole space-time has a local oscillator.

It is convenient to calculate the single photon interference by introducing the following operator \hat{A}'_0 instead of \hat{A}_0 using the above operator \hat{A}_1 .

$$\begin{aligned}
\hat{A}'_0 &= \frac{1}{2}\gamma e^{i\theta/2}\hat{A}_1 - \frac{1}{2}\gamma e^{-i\theta/2}\hat{A}_1 \\
\hat{A}'_0^\dagger &= \frac{1}{2}\gamma e^{-i\theta/2}\hat{A}_1^\dagger - \frac{1}{2}\gamma e^{i\theta/2}\hat{A}_1^\dagger
\end{aligned} \tag{34}$$

where $\gamma^2 = -1$ (i.e., γ corresponds to the square root of the determinant of Minkowski metric tensor $\sqrt{|\mathbf{g}_{\mu\nu}|} \equiv \sqrt{\mathbf{g}} \equiv \sqrt{-1} = \gamma$)

By using the operator, the expected field intensity $\langle \hat{I} \rangle \propto \langle 1 | (\hat{A}'_0 + \hat{A}_1)^\dagger (\hat{A}'_0 + \hat{A}_1) | 1 \rangle$ can be calculated as follows.

$$\begin{aligned}
\hat{A}_0^\dagger \hat{A}'_0 &= -\frac{1}{4}\hat{A}_1^\dagger \hat{A}_1 - \frac{1}{4}\hat{A}_1^\dagger \hat{A}_1 + \frac{1}{4}e^{i\theta}\hat{A}_1^\dagger \hat{A}_1 + \frac{1}{4}e^{-i\theta}\hat{A}_1^\dagger \hat{A}_1 \\
&= -\frac{1}{2}\hat{A}_1^\dagger \hat{A}_1 + \frac{1}{2}\hat{A}_1^\dagger \hat{A}_1 \cos \theta \\
\hat{A}_1^\dagger \hat{A}'_0 &= \frac{1}{2}\gamma e^{i\theta/2}\hat{A}_1^\dagger \hat{A}_1 - \frac{1}{2}\gamma e^{-i\theta/2}\hat{A}_1^\dagger \hat{A}_1 \\
\hat{A}_0^\dagger \hat{A}_1 &= \frac{1}{2}\gamma e^{-i\theta/2}\hat{A}_1^\dagger \hat{A}_1 - \frac{1}{2}\gamma e^{i\theta/2}\hat{A}_1^\dagger \hat{A}_1
\end{aligned} \tag{35}$$

Finally, we can obtain the following result.

$$\begin{aligned}
\langle 1 | \hat{A}_1^\dagger \hat{A}_1 | 1 \rangle &= 1 \\
\langle 1 | \hat{A}'_0^\dagger \hat{A}'_0 | 1 \rangle &= -\frac{1}{2} + \frac{1}{2} \cos \theta \\
\langle 1 | \hat{A}_1^\dagger \hat{A}'_0 | 1 \rangle &= \frac{1}{2}\gamma e^{i\theta/2} - \frac{1}{2}\gamma e^{-i\theta/2} \\
\langle 1 | \hat{A}'_0^\dagger \hat{A}_1 | 1 \rangle &= \frac{1}{2}\gamma e^{-i\theta/2} - \frac{1}{2}\gamma e^{i\theta/2} \\
\langle 1 | \hat{A}_1^\dagger \hat{A}_1 | 1 \rangle + \langle 1 | \hat{A}'_0^\dagger \hat{A}'_0 | 1 \rangle + \langle 1 | \hat{A}_1^\dagger \hat{A}'_0 | 1 \rangle + \langle 1 | \hat{A}'_0^\dagger \hat{A}_1 | 1 \rangle &= \frac{1}{2} + \frac{1}{2} \cos \theta
\end{aligned} \tag{36}$$

This form is equivalent to using the following four-vector instead of (29).

$$\begin{aligned}
\hat{A}_{\mu:(\text{path1})} &\equiv (0, \hat{A}_1, 0, 0) \\
\hat{A}_{\mu:(\text{path2})} &\equiv \left(\frac{1}{2}ie^{i\theta/2}\hat{A}_0 - \frac{1}{2}ie^{-i\theta/2}\hat{A}_0, 0, 0, 0 \right)
\end{aligned} \tag{37}$$

We call this expression ‘‘simple calculation method’’ in this paper. When this simple calculation method is interpreted by physical reality, the single photon passes through only path 1 and the oscillatory field caused by scalar potential exists only on path 2. Although the picture of oscillatory field formation by the scalar potential remains, we lost the natural picture discussed based on the Gaussian light beam that the scalar potential exists in whole

space-time. Furthermore, as will be described later, it obscures the generalized picture of the oscillatory field formation by arbitrary number paths. Therefore, we should understand that it does not faithfully describe the objective physical reality, though this simple calculation method is a convenient format for reproducing the calculation results.

In the above calculations, the scalar potential that requires the indefinite metric was treated as an operator as a physical reality. Following the standard quantum theory, we call the form Heisenberg picture in which the indefinite metric of the scalar potential is imposed on an operator. Then, we can call the form Schrödinger picture in which the indefinite metric of the scalar potential is imposed on a state vector.

In Schrödinger picture, the expected field intensity can be calculated using the state $|1\rangle_S + |\zeta\rangle$ at output 1 (or 2: $\frac{\pi}{2}$ phase difference) and the photon annihilation operator in Schrödinger picture \hat{A}_S , which is proportional to the electric field operator $\hat{E} \propto \hat{A}_S$ at output 1 (or 2). Where, $|1\rangle_S$ and $|\zeta\rangle$ are the states which indicate the single photon passes through only path 1 and the scalar potentials passes through (or exist) only path 2.

Nothing is observed on path 2, hence $\langle\zeta|\zeta\rangle = 0$ is required.

For a more detailed definition is as follows. The operators \hat{A}_1 , \hat{A}_S and state $|1\rangle$, $|1\rangle_S$ can be translated by using the Hamiltonian $\hat{\mathcal{H}}$ as $\hat{A}_1 = e^{i\hat{\mathcal{H}}t/\hbar}\hat{A}_S e^{-i\hat{\mathcal{H}}t/\hbar}$ and $|1\rangle_S = e^{-i\hat{\mathcal{H}}t/\hbar}|1\rangle$ respectively. Then $\hat{A}'_0|1\rangle$ can be expressed by using simple calculation method (34) as follows.

$$\begin{aligned}\hat{A}'_0|1\rangle &= e^{i\hat{\mathcal{H}}t/\hbar}\hat{A}_S \left(\frac{1}{2}\gamma e^{i\theta/2} e^{-i\hat{\mathcal{H}}t/\hbar} - \frac{1}{2}\gamma e^{-i\theta/2} e^{-i\hat{\mathcal{H}}t/\hbar} \right) |1\rangle \\ &= e^{i\hat{\mathcal{H}}t/\hbar}\hat{A}_S \left(\frac{1}{2}\gamma e^{i\theta/2} - \frac{1}{2}\gamma e^{-i\theta/2} \right) |1\rangle_S\end{aligned}\quad (38)$$

Here we define

$$|\zeta\rangle \equiv \left(\frac{1}{2}\gamma e^{i\theta/2} - \frac{1}{2}\gamma e^{-i\theta/2} \right) |1\rangle_S\quad (39)$$

Hence $\langle 1|\hat{A}'_0\dagger\hat{A}'_0|1\rangle = \langle\zeta|\hat{A}'_0\dagger\hat{A}'_0|\zeta\rangle$. When $\theta = 0$, $|\zeta\rangle = 0$, i.e., $\langle\zeta|\zeta\rangle = 0$. Nothing is observed in this phase. The expected value of the field intensity using the probability interpretation is also reproduced by using Schrödinger picture of the simple calculation method.

$$\begin{aligned}\langle\hat{I}\rangle &\propto (\langle 1|_S + \langle\zeta|) \hat{A}'_0\dagger\hat{A}'_0 (|1\rangle_S + |\zeta\rangle) \\ &= 1 + \langle\zeta|\hat{A}'_0\dagger\hat{A}'_0|\zeta\rangle + \langle 1|\zeta\rangle_S + \langle\zeta|1\rangle_S = 1 - \frac{1}{2} + \frac{1}{2}\cos\theta = \frac{1}{2} + \frac{1}{2}\cos\theta\end{aligned}\quad (40)$$

Because $\langle\zeta|\zeta\rangle = -\frac{1}{2} + \frac{1}{2}\cos\theta$ and $\langle\zeta|\zeta\rangle \leq 0$ when $\theta \neq \pm N\pi$ (N : even number), $|\zeta\rangle$ is an indefinite metric vector. Therefore we can understand that the above calculation represents

Schrödinger picture in which the indefinite metric of the scalar potential is imposed on a state vector.

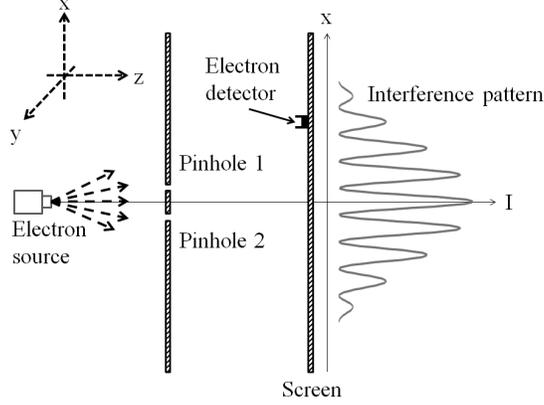


FIG. 2. Schematic view of a typical setup for the single electron interference experiment. : The electron emitted from the electron source passes through the two pinholes and is detected by the electron detector on the screen, and the detection frequency is recorded as an interference pattern on the screen.

B. Single electron interference

1. Calculation using probability interpretation

Figure 2 shows the schematic view of a typical setup for the single electron interference experiment.^{1,35} This experimental setup is also the equivalent setup for single photon interference which has the divided path.

In the quantum mechanical description using probability interpretation, the single-electron interference in the figure 2 is calculated using the following probability amplitude

$$\phi_1 = \langle x|1\rangle\langle 1|s\rangle, \quad \phi_2 = \langle x|2\rangle\langle 2|s\rangle \quad (41)$$

and probability (density) of finding the electron on the screen.³⁵

$$P_{12} = |\phi_1 + \phi_2|^2 \quad (42)$$

Where $\phi_1 = \langle x|1\rangle\langle 1|s\rangle$ and $\phi_2 = \langle x|2\rangle\langle 2|s\rangle$ are composed of probability amplitudes as follows.

$$\langle 1_{\text{or}}2|s\rangle \equiv \langle \text{electron arrives at pinhole 1 or 2} \mid \text{electron leaves } s \text{ (electron source)} \rangle$$

$$\langle x|1_{\text{or}}2\rangle \equiv \langle \text{electron arrives at screen } x \mid \text{electron leaves pinhole 1 or 2} \rangle$$

When either pinhole 1 or 2 is closed, the each and total probabilities are calculated to be $P_1 = |\phi_1|^2$, $P_2 = |\phi_2|^2$ and $P = P_1 + P_2 \neq P_{12}$. In this case, the interference when both pinholes

open at the same time will not be reproduced. Therefore the probability interpretation that a single electron passes through both pinholes simultaneously has been introduced, though it cannot be further divided.

This single electron interference also gives the same interference of the single photon interference described in section III A.

In probability interpretation, the charge operator is defined instead of the photon number operator defined in the calculation of the single photon interference, and the states of the single electron passing through path 1 and path 2 are introduced. The single electron interference can be calculated by using the charge operator and the above two states.

Specifically, we replace the n -photon number state with the electron-number state $|n\rangle$ where n electrons are present, and the photon number operator $\mathbf{n} = \hat{a}^\dagger \hat{a}$ composed of the operator \hat{a} of the expression (21) is replaced by defining the charge operator $\mathbf{Q} \equiv \int d^3x j_0(x)$.

Where $j_0(x)$ is the 0-th component of four-current $j_\mu = (q, \mathbf{i})$, $\partial^\mu j_\mu = \frac{\partial q}{\partial t} + \nabla \cdot \mathbf{i} = 0$. Because the charge operator satisfies $\mathbf{Q}|n\rangle = nq|n\rangle$, n electronic states are eigenstates of \mathbf{Q} .^{28,36}

Here the state $|1\rangle_{1\&2}$ that a single electron simultaneously passes through both path 1 and 2 with probability 1/2 can be expressed as follows.

$$|1\rangle_{1\&2} = \frac{1}{\sqrt{2}}|1\rangle \exp i\theta + \frac{1}{\sqrt{2}}|1\rangle \quad (43)$$

where, θ is the phase corresponding to the difference of the path length. Then expected charge intensity $\langle \hat{I} \rangle$ can be calculated as follows.

$$\langle \hat{I} \rangle \propto \langle 1|_{1\&2} \mathbf{Q} |1\rangle_{1\&2} = q(1 + \cos \theta) \propto q \left(\frac{1}{2} + \frac{1}{2} \cos \theta \right) \quad (44)$$

This is the same expression as the single photon interference in the previous section.

2. Calculation using alternate interpretation

In order to revise the probability interpretation to alternate interpretation with objective physical reality, we start by reexamining the experimental setup in figure 2 with classical electromagnetism. In figure 2, the propagating electron will correspond to an electron beam of which spatial current density is $j = Nqv$ in classical electromagnetism. Where N is the number of electron per unit volume, q is the electron charge and v is the electron velocity.

In the case of the radius of the electron beam is w_0 , the current I can be expressed as $I = \pi w_0^2 j$. In accordance with Biot-Savart Law, the propagation generates magnetic fields and potentials around the propagation path. Assuming that the electron propagates parallel to z-axis (from $z = -L$ to $z = L$) at a constant velocity, the vector potentials around the propagation path are expressed as follows.³⁷

$$\begin{aligned} A_x &= A_y = 0 \\ A_z &= \frac{I}{2\pi\epsilon_0 c^2} \ln \frac{2L}{r} \end{aligned} \quad (45)$$

where $r = \sqrt{x^2 + y^2}$, assuming $L \gg r$, ϵ_0 is the permittivity and c is the speed of light.

Therefore the vector potential definitely passes through not only the pinhole the electron passes through but also the opposite pinhole.

Thus, similar to the single photon interference described in the previous section, we can obtain the picture that the electron as an objective physical reality propagates through the pinhole on one side and the potentials exist on both side. The potentials are composed of both existing potentials in whole space-time and generated potentials by the movement of the electron.

Hence, the electron wave functions should be expressed as follows in such a case.

$$\begin{aligned} \psi'_1 &= \psi_1 \cdot \exp \left[i \frac{q}{\hbar} \int_{s \rightarrow \text{Pinhole1} \rightarrow \text{screen}} (\phi dt - \mathbf{A} \cdot d\mathbf{x}) \right] \\ \psi'_2 &= \psi_2 \cdot \exp \left[i \frac{q}{\hbar} \int_{s \rightarrow \text{Pinhole2} \rightarrow \text{screen}} (\phi dt - \mathbf{A} \cdot d\mathbf{x}) \right] \end{aligned} \quad (46)$$

where ψ'_1 and ψ'_2 are the electron wave functions on the screen passing through pinhole 1 and 2 with the potentials respectively. ψ_1 and ψ_2 are the electron wave functions heading to pinhole 1 and 2 at the electron source without the effects of the potentials.

The following expression is the probability of finding an electron on the screen by using probability interpretation.

$$P_{12} \propto |\psi'|^2 = |\psi'_1 + \psi'_2|^2 = |\psi_1|^2 + |\psi_2|^2 - 2\text{Re} \left(\exp \left[i \frac{q}{\hbar} \oint_{s \rightarrow 1 \rightarrow \text{screen} \rightarrow 2 \rightarrow s} (\phi dt - \mathbf{A} \cdot d\mathbf{x}) \right] \psi_1^* \psi_2 \right) \quad (47)$$

where 1 and 2 of the integration path denote pinhole 1 and 2 respectively.

Although the probability interpretation insists the single electron passes through pinholes 1 and 2 simultaneously, the expression (47) is derived from the picture that the single electron

passes through a pinhole on one side assuming that there are potentials on both sides as mentioned above. Hence this is considered to be the expected value of the charge intensity observed on the screen.

However, (47) uses the wave function. We need to shift from the wave function to the state vector to clarify the picture. Note that (47) is a formula equivalent to Aharonov-Bohm effect.³³ The phase term can be eliminated in a single connected region where the spatial region can contract to a single point but cannot be eliminated in multiple-connected region where the spatial region can not contract to a single point.

As generalize and discuss in Chapter IV, the spatial structure of the multiple-connected region is the cause of single photon or electron interference in the presence of geometrical arrangement such as two slits or two pinholes described in the previous section.

Here, we extend the electron wave function to the state vector, and introduce the state $|\psi_1\rangle$ where a single electron passes through the pinhole 1 and the state $|\psi_2\rangle$ where the potential passes through (exists) the pinhole 2 by using simple calculation method.

In Schrödinger picture of standard quantum theory, the state that electrons exist in a space without an electromagnetic field is expressed by direct product $|\psi\rangle|0\rangle \equiv |\psi, 0\rangle$, where $|\psi\rangle$ is the electron state and $|0\rangle$ is the 0-photon number state which considered as vacuum state. This direct product state can be recognized as a state $|\psi_1\rangle$ that the single electron passes through the pinhole 1.

On the other hand, the state that there exists only scalar potential without the single photon as an objective physical reality can be expressed as $|0\rangle + |\zeta\rangle$, i.e., the superposition of the 0-photon state $|0\rangle$ and $|\zeta\rangle$, by using the simple calculation method of Schrödinger picture.

The direct product of the state and the electron state is $|\psi\rangle(|0\rangle + |\zeta\rangle) = |\psi\rangle|0\rangle + |\psi\rangle|\zeta\rangle = |\psi_1\rangle + |\psi\rangle|\zeta\rangle$. We can recognize the state $|\psi\rangle|\zeta\rangle$ as the same state as pinhole 2 with no electrons and only scalar potential exist. Therefore $|\psi\rangle|\zeta\rangle = |\psi_2\rangle$ will be reasonable.

Finally, the charge intensity on the screen of the single electron interference is obtained

by using (39) as follows.

$$\begin{aligned}
\langle \hat{I} \rangle &\propto (\langle \psi_1 | + \langle \psi_2 |) \mathbf{Q} (|\psi_1\rangle + |\psi_2\rangle) \\
&= \langle \psi_1 | \left(1 + \frac{1}{2} \gamma e^{-i\theta/2} - \frac{1}{2} \gamma e^{i\theta/2} \right) \mathbf{Q} \left(1 + \frac{1}{2} \gamma e^{i\theta/2} - \frac{1}{2} \gamma e^{-i\theta/2} \right) |\psi_1\rangle \\
&= q \left(\frac{1}{2} + \frac{1}{2} \cos \theta \right)
\end{aligned} \tag{48}$$

As described in the case of simple calculation method, the oscillatory field of the scalar potential existing on both pinholes is represented by the pinhole on one side. Therefore, by returning from the simple calculation method to the original method, we can obtain the picture that the scalar potential is divided by two pinholes to form an oscillatory field, and a single electron entering from one pinhole in the oscillatory field passes through while interfering with the oscillatory field and reaches the screen.

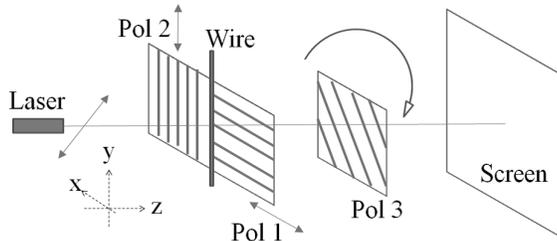


FIG. 3. Typical setup for the Quantum Eraser. Pol1 and Pol2 are fixed linear polarizers with polarizing axes perpendicular (x and y). Pol3 is a revolvable linear polarizer.^{2,38}

C. EPR correlation

1. Calculation using probability interpretation

For the calculation of EPR correlation using photon polarization by probability interpretation, it is helpful to first examine an experimental setup using polarizers called Quantum Eraser shown in figure 3.^{2,38}

The phenomenon of the Quantum Eraser is outlined below.

In case of no polarizers, we can observe an interference pattern composed of dark and bright fringes on the screen because light passing on the left of the wire is combining, or “interfering,” with light passing on the right-hand side. This means “we have no information about which path each photon went”.

In case of polarizers 1 and 2, which are called “which-path markers”, are positioned right behind the wire as shown in Figure 3, the launched light polarized in 45° direction from the laser is polarized in perpendicular (x-polarized and y-polarized) by these polarizers. This means “which-path markers” have made available the information about which path each photon went. Therefore we can observe no interference pattern on the screen .

When polarizer 3 with the polarization angle $+45^\circ$ or -45° is subsequently inserted in front of the screen in addition to the “which-path markers”, the interference pattern reappears due to the invalidation of the information of “which-path markers” by Polarizer 3.

The mathematical description of the erasure and reappearance of the interference pattern is as follows. The x- and y-polarized photon passing through polarizer 1 and 2 can be

expressed by following quantum-superposition state.

$$|x\rangle = \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle \quad (49)$$

and

$$|y\rangle = \frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle \quad (50)$$

where “+” and “-” stand for polarizations $+45^\circ$ and -45° with respect to x .

As seen in the left-hand side of equations. (49) and (50), the photons passing through polarizers 1 and 2 are polarized at right angles to each other. This prevent the interference pattern. In other words, “which-path makers” have enabled information about which path each photon went. The right side of equations (49) and (50) have the same polarization states, but the interference patterns created by the polarizer states of $+45^\circ$ and -45° are inverse fringes and annihilate each other. Therefore, there are no interference patterns in the sum total of the images.

The subsequent insertion of the polarizer 3 with the polarization angle $+45^\circ$ or -45° can allow only $|+\rangle$ or $|-\rangle$ to pass through polarizer 3. Therefore, either $|+\rangle$ or $|-\rangle$ of both equations (49) and (50) can create the interference pattern again, which means that we can not identify which-path the photons had passed through, i.e., polarizer 3 has disabled the information of “which-path makers”.

As is clear from (49) and (50), enable/disable information about which side of the wire each photon passed through is interpreted by the states that contains $+45^\circ$ and -45° polarized single photon with a probability of $1/2$ even if the laser light intensity becomes extremely low and it becomes an indivisible single photon.

In order to calculate the single photon interference by probability interpretation, we replace the side of the polarizer 1 with path 1 and the side of polarizer 2 with path 2 of MZI in the calculation of single photon interference in the previous section. In addition, the ratio of photon passage by polarizers 1, 2 and 3 are replaced with those rotation angles. We examine both x-polarized and y-polarized photon emitted from the laser in the calculation. These calculations give the same results as the EPR correlation described later.

In the calculation, all angles of the polarizers are based on the x axis. The x-polarized light beam emitted from the laser should not be able to pass through polarizer 2, which allows only y-polarization to pass. However, probability interpretation asserts that x-polarized light is a superposition of polarization states different from x-polarized light like (49). Therefore,

the calculation is possible by replacing the probability that a photon can pass with a phase that is proportional to the difference between the polarization angle of the photon and the angle of the polarizer.

The probability that an x-polarized photon can pass through the side of the polarizer 1 is described as the angle of the polarizer 1. In this case, since it is originally polarized on the x axis, the phase can be selected as 0. The photon polarized in the x-axis after passing through the polarizer 1 is described by introducing the rotation angle $|\phi|$ of the polarizer 3 corresponding to the probability that the photon can pass through the polarizer 3 into the phase.

On the other hand, the x-polarized photon passing through the polarizer 2 is described as a rotation angle $\pi/2$ corresponding to the probability that the photon can pass through the polarizer 2.

The rotation angle $\frac{\pi}{2} - |\phi|$ by the polarizer 3 is further introduced into the photon passing through the polarizer 2. In addition, the phase difference θ between the polarizer 1 and 2 is introduced on the x-polarized photon. Now we can define the following electric field operator.

$$\begin{aligned}\hat{E} &= \frac{1}{\sqrt{2}}\hat{a}_1 \exp(i|\phi| + \theta) + \frac{1}{\sqrt{2}}\hat{a}_2 \exp\left(i\frac{\pi}{2}\right) \exp\left\{i\left(\frac{\pi}{2} - |\phi|\right)\right\} \\ &= \frac{1}{\sqrt{2}}\hat{a}_1 \exp(i|\phi| + \theta) + \frac{1}{\sqrt{2}}\hat{a}_2 \exp\{i(\pi - |\phi|)\}\end{aligned}\quad (51)$$

The interference on the screen is calculated as same as in the previous section.

$$\langle \hat{I} \rangle \propto \langle n | \hat{E}^\dagger \hat{E} | n \rangle = \frac{1}{2} \langle n | \hat{a}_1^\dagger \hat{a}_1 | n \rangle + \frac{1}{2} \langle n | \hat{a}_2^\dagger \hat{a}_2 | n \rangle - \cos(\theta + 2|\phi|) \langle n | \hat{a}_1^\dagger \hat{a}_2 | n \rangle \quad (52)$$

$\langle \hat{I} \rangle$ is the expected field intensity, which is proportional to the number of photons, as in the previous section. In the probability interpretation, the above expected value is calculated as follows, including the case of a single photon of which photon number is 1 ($n = 1$).

$$\langle \hat{I} \rangle \propto \frac{1}{2} - \frac{1}{2} \cos(2|\phi| + \theta) \quad (53)$$

In the case of the y-polarized light beam emitted from the laser, we transpose the phase θ to the y-polarized side and introduce the phases of the polarizers in the same way as for the x-polarized light. Then the electric field operator can be calculated as follows,

$$\hat{E} = \frac{1}{\sqrt{2}}\hat{a}_1 \exp\left\{i\left(\frac{\pi}{2} + |\phi|\right)\right\} + \frac{1}{\sqrt{2}}\hat{a}_2 \exp\left\{i\left(\frac{\pi}{2} - |\phi| + \theta\right)\right\} \quad (54)$$

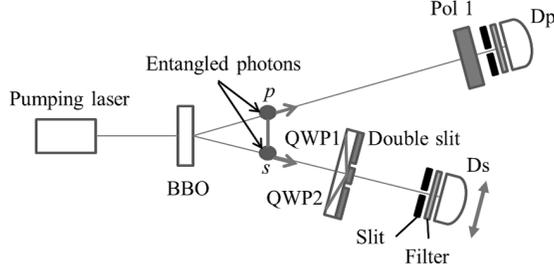


FIG. 4. Typical setup for the Delayed Choice Quantum Eraser. QWP1 and QWP2 are quarter-wave plates aligned in front of the double slit with fast axes perpendicular. Pol1 is a linear polarizer. BBO (β -BaB₂O₄) crystal generates entangled photons by spontaneous parametric down-conversion²²..

Finally, we can obtain as follows.

$$\langle \hat{I} \rangle \propto \frac{1}{2} + \frac{1}{2} \cos(2|\phi| - \theta) \quad (55)$$

Here, if the laser beam contains one or more x-polarized and y-polarized photons each with a probability of 1/2, the intensity of the interference is given by the sum of (53) and (55) as follows.

$$\langle \hat{I} \rangle \propto 1 - \frac{1}{2} \cos(2|\phi| + \theta) + \frac{1}{2} \cos(2|\phi| - \theta) \quad (56)$$

In the expression, when $\phi = \pm\pi$, $\pm\frac{1}{2}\pi$, it becomes $\langle I \rangle \propto 1$ and the interference fringes are erased, $\phi = \pm\frac{1}{4}\pi$ becomes $\langle I \rangle \propto 1 \pm \sin\theta$ and the interference fringe is reproduced.

Even if the laser intensity is very weak and consists of an x-polarized single photon and a y-polarized single photon, (56) is satisfied.

The delayed-choice Quantum Eraser for examining the EPR correlation below corresponds to the case that the emitted photon from the laser is an x-polarized single photon and a y-polarized single photon of this Quantum Eraser. The intensity of the photon interference obtained in the experiment is the same as (53) and (55).

Figure 4 shows the typical setup for the Delayed Choice Quantum Eraser for examining EPR correlation. This experimental setup is similar setup where the polarizer 1 plays the role of the polarizer 3 in figure 3 of Quantum Eraser. In this setup, the BBO is excited by the light emitted from the laser to create p and s photons of which polarizations are orthogonal to each other. These photons propagate in different paths, and p is scanned by the polarizer 1 and measured by the detector Dp. The photon s is measured by Ds through

the quarter-wave plates 1 and 2 of which fast axes are orthogonal to each other and the double slit on the back surface thereof, and further through the slit and the filter.

In this experiment, the setup is arranged according to the following order, and the result in each arrangements is obtained.

1. When polarizer 1, QWP1 and QWP2 are removed, the coincidence counts of D_s versus D_p shows an intensity fluctuation of the photon which indicates the interference by the double slit.
2. When QWP1 and QWP2 are installed, the intensity fluctuation of the coincidence counts is erased.
3. The polarizer 1 is additionally installed in the direction that matches the fast axis of QWP1. Then, the intensity fluctuation of the coincidence counts reappears as the interference.
4. Subsequently, the angle of the polarizer 1 is rotated by 90 degrees. Then, the intensity fluctuation of the coincidence counts shows the interference of which the bright and dark reversed.

From this procedure, the polarizer 1 corresponds to the polarizer 3 of Quantum Eraser described above and looks like erases or reappears the information about which path (QWP1 or QWP2) each photon went. That is a phenomenon similar to the above-mentioned Quantum Eraser. Moreover, although the polarization direction setting of the photon p and the observation of the interference by the photon s are performed at spatially separated positions, the polarization of these photons is completely correlated with one side being x-polarized and the other side being y-polarized. Here the interferences in the opposite phase obtained in steps 3 and 4 are given by (53) and (55) calculated by the Quantum Eraser described above.

When the distance from BBO to D_p is arranged longer than the distance from BBO to the double slit, such arrangement becomes a delayed choice because the choice of the polarization direction of the photon p by the polarizer 1 is performed after the observation of the interference by the photon s . In this arrangement, the presence or absence of the interference can also be observed by the same procedure as above. This seems that the erasing or reproduction of the information of “which-path marker” by the polarizer 1 was

determined after the observation. Note 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, as discussed in the reference²².

When s and p are single photons, the probability interpretation asserts that the photon s and p do not have a state of x polarization (or y polarization) that is fixed from the beginning such as $|x\rangle_s$ or $|y\rangle_s$ and $|x\rangle_p$ or $|y\rangle_p$. Instead they are in the superposition states of those polarizations as follows.

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|x\rangle_s|y\rangle_p + |y\rangle_s|x\rangle_p) \quad (57)$$

Such perfect correlated state existing in a spatially separated region is called correlated photon pair state (Entanglement). According to the probability interpretation for the entanglement, both photon s and p propagate each path as superposition of x-polarized and y-polarized state (57).

This postulates the existence of long-range correlation beyond the causality that contradicts the locality of physical laws, i.e., theory of relativity, because even if the photons are far apart from each other, when the state of one photon (s or p) is observed and determined to be $|x\rangle$ then that of the other photon (p or s) suddenly changes from the quantum-superposition state into $|y\rangle$. Historically, EPR paper⁵ written by “Einstein, Podolsky and Rosen (EPR)” first pointed out the imperfections of the standard quantum theory by taking up such non-local correlation states. At present, the correlated photon pair state (Entanglement) is also called the EPR state.

2. Calculation using alternate interpretation

Here we revise the incomprehensible probability interpretation such as correlated photon pair state to alternate interpretation using objective physical reality.

The results of the interference (53) and (55) are obtained in both setups in figure 3 and figure 4 as mentioned above. These results has been thought to be peculiar to quantum theory, which cannot be obtained by classical calculation assuming that a single photon has a fixed polarization. The violation of Bell’s inequality supports the calculation results of the quantum theory.^{39,40}

However, the obtaining the identical calculation results both probability and alternate

interpretation using objective physical reality with locality means that Bell's inequality violates in both cases.

In the following, the results of the interference (53) and (55) are reproduced with a picture of the objective physical reality by replacing the side of the polarizer 1 as the photon path s and the side of the polarizer 2 as the photon path p in the setup of figure 4 respectively.

As a picture of objective physical reality, we assume the laser creates either fixed x- or y-polarized single photon, or two photons with fixed x- and y-polarized single photon. Since there is a scalar potential in whole space-time as described in the calculation of single photon interference, the four-vector in the space from the laser output to immediately before passing through the polarizer 1 and 2 is expressed as follows.

$$A_\mu = (A_0, A_1, A_2, 0) \quad (58)$$

Where, in order to simplify the calculation, the non-physical longitudinal wave was ignored as $A_3 = 0$.

First, we calculate in the case of there exists an x-polarized single photon and scalar potential. This case corresponds to the calculated situation for (53). When the x-polarized single photon and the scalar potential pass through both polarizers, the x-polarized photon can only pass through polarizer 1 but not polarizer 2. When the scalar potential is divided on each side, a phase difference is introduced associated with the division. Therefore the following expressions are appropriate for the four-vectors after passing through each polarizer.

$$A_{(x \text{ pol } 1) \mu} = \left(\frac{1}{2} e^{i\theta_x/2} A_{(x)0}, A_{(x)1}, 0, 0 \right), A_{(x \text{ pol } 2) \mu} = \left(\frac{1}{2} e^{-i(\theta_x/2+\pi/2)} A_{(x)0}, 0, 0, 0 \right) \quad (59)$$

Here, a phase shift $\pi/2$ based on x-polarized photon is introduced into the scalar potential passing through the polarizer 2. Where, the phase difference due to the division of the scalar potential is divided into both sides for the symmetrical description as θ_x .

When the x-polarized photon polarized by the polarizer 1 that represent the physical reality of real x-polarized photon among this four-vector is trying to pass through the polarizer 3, it can not pass through the polarizer 3 of which rotation angle is not x axis. However, because the scalar potential passes through with obtaining $|\phi|$ phase shift, which corresponds to the rotation angle of the polarizer 3, the phase term becomes $i(|\phi| + \theta_x/2)$.

On the other hand, the scalar potential that has passed through the polarizer 2 is polarized in y-direction. Therefore in the case of the rotation angle of the polarizer 3 is measured from the x-axis ($x=0$), $\pi/2$ is added to the rotation angle of the polarizer 3, then the phase becomes $-i(|\phi| + \theta_x/2 + \pi)$.

Hence the four-vector at the polarizer 3 is expressed as follows.

$$\begin{aligned} A_{(x \text{ pol } 1, 2 \rightarrow 3) \mu} &\equiv A_{(x \text{ pol } 1 \rightarrow 3) \mu} + A_{(x \text{ pol } 2 \rightarrow 3) \mu} \\ &= \left(\frac{1}{2} e^{i(|\phi| + \theta_x/2)} A_{(x)0} + \frac{1}{2} e^{-i(|\phi| + \theta_x/2 + \pi)} A_{(x)0}, A_{(x)1}, 0, 0 \right) \end{aligned} \quad (60)$$

Here from Lorentz invariance, $\langle 1|A_0^\dagger A_0|1\rangle = \langle 1|A_1^\dagger A_1|1\rangle = \langle 1|A_2^\dagger A_2|1\rangle = 1$ is required as in single photon interference. Then the following interference can be obtained.

$$\langle I_s \rangle \propto \langle 1|A_{(x \text{ pol } 1, 2 \rightarrow 3)}^\dagger A_{(x \text{ pol } 1, 2 \rightarrow 3)}|1\rangle = \frac{1}{2} + \frac{1}{2} \cos(2|\phi| + \theta_x) \quad (61)$$

Note that $A^\dagger A \equiv -g_{\mu\nu} A^{\mu\dagger} A^\nu = -A_0^\dagger A_0 + A_1^\dagger A_1 + A_2^\dagger A_2 + A_3^\dagger A_3$.

This can be interpreted that the interference between the oscillatory field caused by the scalar potential and x-polarized photon determines the photon intensity that can pass through the polarizer 3.

Similarly, in the case of there exists y-polarized single photon and scalar potential, the phase difference of the divided scalar potential can be θ_y as follows.

$$A_{(y \text{ pol } 1) \mu} = \left(\frac{1}{2} e^{i(\theta_y/2 + \pi/2)} A_{(y)0}, 0, 0, 0 \right), A_{(y \text{ pol } 2) \mu} = \left(\frac{1}{2} e^{-i\theta_y/2} A_{(y)0}, 0, A_{(y)2}, 0 \right) \quad (62)$$

$$\begin{aligned} A_{(y \text{ pol } 1, 2 \rightarrow 3) \mu} &\equiv A_{(y \text{ pol } 1 \rightarrow 3) \mu} + A_{(y \text{ pol } 2 \rightarrow 3) \mu} \\ &= \left(\frac{1}{2} e^{i(|\phi| + \theta_y/2 + \pi/2)} A_{(y)0} + \frac{1}{2} e^{-i(|\phi| + \theta_y/2 + \pi/2)} A_{(y)0}, 0, A_{(y)2}, 0 \right) \end{aligned} \quad (63)$$

Then the following interference can be obtained.

$$\langle I_p \rangle \propto \langle 1|A_{(y \text{ pol } 1, 2 \rightarrow 3)}^\dagger A_{(y \text{ pol } 1, 2 \rightarrow 3)}|1\rangle = \frac{1}{2} + \frac{1}{2} \cos(2|\phi| + \theta_y) \quad (64)$$

Choosing the phase difference due to the division of the scalar potential as $\theta \equiv \theta_x - \pi = -\theta_y$, the identical interferences (53) and (55) are calculated as follows..

$$\langle I_s \rangle \propto \frac{1}{2} - \frac{1}{2} \cos(2|\phi| + \theta), \quad \langle I_p \rangle \propto \frac{1}{2} + \frac{1}{2} \cos(2|\phi| - \theta) \quad (65)$$

Furthermore, when there are x-polarized single photon, y-polarized single photon and scalar potential, the four-vector at polarizer 3 is the sum of (60) and (63), we can reproduce (56) by simple calculation as follows.

$$\langle 1|A_{(x, y \text{ pol } 1, 2 \rightarrow 3)}^\dagger A_{(x, y \text{ pol } 1, 2 \rightarrow 3)}|1\rangle = 1 - \frac{1}{2} \cos(2|\phi| + \theta) + \frac{1}{2} \cos(2|\phi| - \theta) \quad (66)$$

Now, we have shown that the identical results (53), (55) and (56) can be obtained by using the indefinite metric as it is. In addition, we show that the identical results can be obtained by the simple calculation method.

In the simple calculation method, we consider the state that only the scalar potential exists without real photon and forms the oscillatory field. This state is represented by $|\zeta\rangle$ as shown in the single photon calculation. Therefore, in this experimental setup, the state of x-polarized single photon in the space should be replaced by $|x\rangle + |\zeta\rangle$ instead of $|x\rangle$. However, when the scalar potential exists in a space without division, the phase difference due to the path difference is $\theta = 0$, and the oscillatory field due to the interference of the scalar potential is not formed, so $\langle \zeta|\zeta\rangle = 0$.

Here we note the above and choose the states of the x-polarized single photon and the y-polarized single photon as follows.

$$\begin{aligned} |x\rangle + |\zeta_{\phi,x}\rangle &= |x\rangle + \frac{1}{2}\gamma e^{i|\phi|} e^{-i\theta/2}|x\rangle - \frac{1}{2}\gamma e^{-i|\phi|} e^{i\theta/2}|x\rangle \\ |y\rangle + |\zeta_{\phi+\frac{1}{2}\pi,y}\rangle &= |y\rangle + \frac{1}{2}\gamma e^{i(|\phi|+\frac{1}{2}\pi)} e^{i\theta/2}|y\rangle - \frac{1}{2}\gamma e^{-i(|\phi|+\frac{1}{2}\pi)} e^{-i\theta/2}|y\rangle \end{aligned} \quad (67)$$

By using the states we can calculate the interference in the presence of the x-polarized single photon as follows.

$$\begin{aligned} \langle I\rangle &\propto (\langle x| + \langle \zeta_{\phi,x}|) (|x\rangle + |\zeta_{\phi,x}\rangle) = \langle x|x\rangle - \frac{1}{2}\langle x|x\rangle - \frac{1}{2}\langle x|x\rangle \cos(2|\phi| + \theta) \\ &= \frac{1}{2} - \frac{1}{2} \cos(2|\phi| + \theta) \end{aligned} \quad (68)$$

This is identical with (53). Similarly, we can calculate the identical interference (55) in the presence of the y-polarized single photon.

Finally, we can calculate the interference in the presence of both x-polarized and y-polarized photons as follows,

$$\langle I\rangle \propto \left(\langle x| + \langle \zeta_{\phi,x}| + \langle y| + \langle \zeta_{\phi+\frac{1}{2}\pi,y}| \right) \left(|x\rangle + |\zeta_{\phi,x}\rangle + |y\rangle + |\zeta_{\phi+\frac{1}{2}\pi,y}\rangle \right) \quad (69)$$

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

$$\langle I\rangle \propto (\langle x| + \langle \zeta_{\phi,x}|) (|x\rangle + |\zeta_{\phi,x}\rangle) + \left(\langle y| + \langle \zeta_{\phi+\frac{1}{2}\pi,y}| \right) \left(|y\rangle + |\zeta_{\phi+\frac{1}{2}\pi,y}\rangle \right) \quad (70)$$

This is the sum of the result (53) when only x-polarized photon exists and the result (55) when only y-polarized photon exists. Therefore (56) is reproduced.

$$\langle I\rangle \propto 1 - \frac{1}{2} \cos(2|\phi| + \theta) + \frac{1}{2} \cos(2|\phi| - \theta) \quad (71)$$

This simple calculation method is the Schrödinger picture in which the calculation of an indefinite metric is imposed on the state vector. As in the case of single-photon interference, we can calculate the interference using Heisenberg picture in which the calculation of an indefinite metric is imposed on the operator. In Heisenberg picture, the photon number operator is replaced with $\mathbf{n} = (\hat{A}_1^\dagger + \hat{A}_p^\dagger)(\hat{A}_1 + \hat{A}_p)$. Where, \hat{A}_1 and \hat{A}_p (p : polarization = x, y, \dots , etc.) are the photon annihilation operator that represents a real photon and a photon annihilation operator that represents a scalar potential polarized in the p direction. These operators can be defined as follows.

$$\hat{A}_x = \frac{1}{2} \gamma e^{i|\phi|} e^{-i\theta/2} \hat{A}_1 - \frac{1}{2} \gamma e^{-i|\phi|} e^{i\theta/2} \hat{A}_1, \hat{A}_x^\dagger = \frac{1}{2} \gamma e^{-i|\phi|} e^{i\theta/2} \hat{A}_1^\dagger - \frac{1}{2} \gamma e^{i|\phi|} e^{-i\theta/2} \hat{A}_1^\dagger \quad (72)$$

We can reproduce (68) by using the above operators of Heisenberg picture.

$$\langle I\rangle = \langle n | (\hat{A}_1^\dagger + \hat{A}_x^\dagger) (\hat{A}_1 + \hat{A}_x) | n \rangle = \langle n | \mathbf{n}_1 | n \rangle + \langle n | \hat{A}_x^\dagger \hat{A}_x | n \rangle \propto \frac{1}{2} - \frac{1}{2} \cos(2|\phi| + \theta) \quad (73)$$

Note that the Heisenberg picture imposes the indefinite metric calculation on the operator, so we should replace the ordinary photon annihilation operator for x-polarization \hat{A}_1 with $\hat{A}_1 + \hat{A}_x$, where \hat{A}_x is the photon annihilation operator derived from the scalar potential \hat{A}_x . Therefore, the photon number operator in the presence of x-polarized and y-polarized photons is $(\hat{A}_1 + \hat{A}_x) + (\hat{A}_2 + \hat{A}_y)$. We can reproduce (71) as follows by choosing the appropriate phase of these replacements.

$$\begin{aligned} \langle I\rangle &= \langle n | (\hat{A}_1^\dagger + \hat{A}_x^\dagger + \hat{A}_2^\dagger + \hat{A}_y^\dagger) (\hat{A}_1 + \hat{A}_x + \hat{A}_2 + \hat{A}_y) | n \rangle \\ &= \langle n | \mathbf{n}_1 | n \rangle + \langle n | \hat{A}_x^\dagger \hat{A}_x | n \rangle + \langle n | \mathbf{n}_2 | n \rangle + \langle n | \hat{A}_y^\dagger \hat{A}_y | n \rangle \\ &\propto 1 - \frac{1}{2} \cos(2|\phi| + \theta) + \frac{1}{2} \cos(2|\phi| - \theta) \end{aligned} \quad (74)$$

Where, we assume that there are the same number of x-polarized and y-polarized photons.

$$\langle n|\mathbf{n}_1|n\rangle \equiv \langle n|\hat{A}_1^\dagger\hat{A}_1|n\rangle = \langle n|\mathbf{n}_2|n\rangle \equiv \langle n|\hat{A}_2^\dagger\hat{A}_2|n\rangle = n$$

Under the condition $|n\rangle \equiv |n\rangle_x + |n\rangle_y$, we can calculate equivalent relations to those in conventional quantum theory such as $\hat{A}_1|n\rangle = \hat{A}_1|n\rangle_x + \hat{A}_1|n\rangle_y = \sqrt{n}|n-1\rangle_x$, $\hat{A}_2|n\rangle = \hat{A}_2|n\rangle_x + \hat{A}_2|n\rangle_y = \sqrt{n}|n-1\rangle_y$ and $\langle n|\hat{A}_1^\dagger\hat{A}_2|n\rangle = \langle n|\hat{A}_2^\dagger\hat{A}_1|n\rangle = 0$. Where $|n\rangle_x, |n\rangle_y$ is the n photon number state of the x- and y-polarized photon respectively.

Using the alternate interpretation, it is also possible that the polarization direction of the photon pair created in BBO in figure 4 is controlled by the scalar potential as describe below.

The scalar potential exists in whole space-time even if there is no photons. Therefore when the angle of the polarizer 1 is set to $|\phi|$, the scalar potential is affected by the setting. This state can be expressed as the sum of $|0\rangle$ where no photon exists and $|\zeta_{|\phi}\rangle$ where the scalar potential is oriented by the rotation of the polarizer 1. This state can be expressed as follows by a simple calculation method.

$$|0\rangle + |\zeta_{|\phi}\rangle = |0\rangle + \frac{1}{2}\gamma e^{i(|\phi|-|\psi|)} e^{i\theta/2}|0\rangle - \frac{1}{2}\gamma e^{-i(|\phi|-|\psi|)} e^{-i\theta/2}|0\rangle \quad (75)$$

Where, ψ is the polarization angle of the photon s that would be created by the BBO and propagates to the direction of the polarizer 1. The propagation speed of the scalar potential is equal to the speed of light because it is an electromagnetic potential. Therefore, the state that BBO creates photon $|\psi\rangle$ with polarization angle $|\psi|$ is calculated to be the product of state which represents the scalar potential arrived at BBO and photon creation operator $\hat{A}_{|\psi|}^\dagger$ of which polarization angle is $|\psi|$ as follows.

$$\hat{A}_{|\psi|}^\dagger|0\rangle + \hat{A}_{|\psi|}^\dagger|\zeta_{|\phi}\rangle = |\psi\rangle + \frac{1}{2}\gamma e^{i(|\phi|-|\psi|)} e^{i\theta/2}|\psi\rangle - \frac{1}{2}\gamma e^{-i(|\phi|-|\psi|)} e^{-i\theta/2}|\psi\rangle \quad (76)$$

Note that the scalar potential propagates along a single path to BBO in this setup, hence the phase is $\theta = 0$. Therefore

$$\langle I\rangle \propto \frac{1}{2} + \frac{1}{2} \cos(2|\phi| - 2|\psi|) \quad (77)$$

Because a single photon is created, $\langle I\rangle = 1$ is required and $\psi = \phi$ is obtained. That is to say, photons are created at the setting angle of the polarizer 1.

Where, even if the photon pair is created with random polarization from BBO regardless of the setting angle of the polarizer 1, the polarizations of the photon pair are orthogonal

to each other. Hence, (65) is observed due to the interference between the classical local perfect correlation determined when the photon pair is created and the oscillatory field of the scalar potential.

Here, the alternate interpretation of the EPR correlation can be explained using the objective physical reality, which the real photons move in the oscillatory field of the scalar potential that causes interference. Then, at the polarizer, it is possible to interpret that the photon of the polarization different from that before the interference is created by the interference between the real photon and the scalar potential, and the photon before the interference is annihilated. The alternate interpretation is consistent with the quantum field theory that particles are created and annihilated by the excitation of vacuum. In addition, it has been said that the conventional quantum theory based on probability interpretation was proved to be correct due to the violation of Bell's inequality by various experimental setups of EPR correlation devised so as not to have a loophole.⁴¹ However even if we use the alternate interpretation based on objective physical reality, we can obtain the identical results as conventional quantum theory, therefore the violation of Bell's inequality does not show the denial of locality of physical laws and physical reality, nor does it support the validity of conventional quantum theory based on probability interpretation.

Note that, in the above calculation of the alternate interpretation for EPR correlation, the two phases are introduced, one is from the space division θ and the other is from the rotation angle of the polarizer ϕ . The former is obviously a geometrical phase on real space such as Aharonov-Bohm effect³³ and the later can be identified as so-called Pancharatnam's phase⁴² which is a geometrical phase on Poincaré sphere. Therefore we can understand that EPR correlation is caused by two types of the geometrical phases. The detailed study of the relation between various physical phenomena and the geometrical phases must be needed but it is the future work.

IV. APPLICATION

We revealed that by examining photons, electrons, and scalar potentials as objective physical reality without using probability interpretation, the calculation results of single-photon interference, single-electron interference, and EPR correlation agree with those obtained by probability interpretation in the preceding chapters. Here, we will discuss some phenomena peculiar to quantum theory that can be explained by alternate interpretation using the objective physical reality.

For the discussion, it is first necessary to generalize the formation of the oscillatory field by the scalar potential discussed in the preceding chapters. The discussions in the preceding chapters are all setups where there is two paths that divides the space into two. We will generalize the above setups and examine what kind of oscillatory field is formed when the whole space-time is divided into three or four to any number (arbitrary geometrical arrangement), and what kinds of physical phenomena are caused by that oscillatory field. As a result of the examination, it is shown that the fluctuation of zero-point energy of the electromagnetic field, Casimir effect, and the spontaneous symmetry breaking are naturally derived with the image of objective physical reality.

We also present a general approach for single particle interference associated with the generalization.

A. Generalization of the geometrical arrangement

The division into two paths dealt with in the preceding chapters divides the scalar potential into two, and the divided coefficient was set to $1/2$ and the phase difference was set to θ . In order to extend that into an arbitrary number of divided paths, we introduce divided coefficients r_j and phases θ_j of the scalar potential. Then, the scalar potential can be expressed as follows, where M is the number of divided paths.

$$\sum_{j=1}^M r_j e^{i\theta_j} A_0 \quad (78)$$

where $\sum_{j=1}^M r_j = 1$. The case of the preceding chapters correspond to $M = 2$, $r_1 = r_2 = 1/2$ and $\theta_1 = -\theta_2 = \theta/2$ etc. Therefore, the expected value of the number of photons can be calculated by the following photon annihilation operator when there is an x-polarize single photon in arbitrary number of divided paths.

$$\hat{A}_\mu = \left(\sum_{j=1}^M r_j e^{i\theta_j} \hat{A}_0, \hat{A}_1, 0, 0 \right) \quad (79)$$

Then

$$\begin{aligned} \langle \hat{I} \rangle &\propto \langle 1 | -\mathbf{g}^{\mu\nu} \hat{A}_\mu^\dagger \hat{A}_\nu | 1 \rangle \\ &= - \left\{ \sum_{j=1, k=1}^M r_j r_k e^{i(\theta_j - \theta_k)} \right\} \langle 1 | \hat{A}_0^\dagger \hat{A}_0 | 1 \rangle + \langle 1 | \hat{A}_1^\dagger \hat{A}_1 | 1 \rangle \\ &= - \left\{ (r_1^2 + r_2^2 + \dots + r_M^2) + \sum_{j \neq k}^M r_j r_k e^{i(\theta_j - \theta_k)} \right\} + 1 \end{aligned} \quad (80)$$

Because $0 \leq r_j \leq 1$, then $0 \leq \langle 1 | -\mathbf{g}^{\mu\nu} \hat{A}_\mu^\dagger \hat{A}_\nu | 1 \rangle \leq 1$. When $M \rightarrow \infty$ and the phases are completely random, $\sum_{j=1}^{\infty} r_j e^{i\theta_j}$ converges with 0. The division of the path is caused by the existence of matter in space-time, and $M \rightarrow \infty$ can be regarded as the actual physical space where there are many innumerable matter. We call this “real vacuum” in this paper.

On the other hand, $M = 1$ in (78) can be regarded as a space-time without any substance in space such as an empty container. We call this “ideal vacuum” in this paper.

Expressing the generalization by a simple calculation method, the following operators and states can be applied to arbitrary geometrical arrangement instead of (34) and (39).

$$\begin{aligned}
\hat{A}'_0 &= \gamma \sum_{j=1}^{\infty} r_j e^{i\theta_j} \hat{A}_1 - \gamma \sum_{j=1}^{\infty} r_j e^{-i\theta_j} \hat{A}_1 \\
\hat{A}'_0{}^\dagger &= \gamma \sum_{j=1}^{\infty} r_j e^{-i\theta_j} \hat{A}_1^\dagger - \gamma \sum_{j=1}^{\infty} r_j e^{i\theta_j} \hat{A}_1^\dagger
\end{aligned} \tag{81}$$

$$|\zeta\rangle \equiv \left(\gamma \sum_{j=1}^{\infty} r_j e^{i\theta_j} - \gamma \sum_{j=1}^{\infty} r_j e^{-i\theta_j} \right) |1\rangle_S \tag{82}$$

From the generalization of the divided path, it can be seen that when some geometrical arrangement is brought into the “ideal vacuum” and the path is divided, the expected value fluctuates depending on the oscillatory field.

B. Zero point energy of the electromagnetic fields

The photon creation and annihilation operators obtained from traditional quantization procedure for quantum optics in Coulomb gauge have relationships with harmonic oscillator as follows. (We examine only x-polarized photon for simplicity.)

$$\begin{aligned}\hat{A}_1 &= \frac{1}{\sqrt{2\hbar\omega}} (\omega\hat{q} + i\hat{p}) \\ \hat{A}_1^\dagger &= \frac{1}{\sqrt{2\hbar\omega}} (\omega\hat{q} - i\hat{p})\end{aligned}\quad (83)$$

where \hat{q} and \hat{p} are position and momentum operators obeying the commutation relation $[\hat{q}, \hat{p}] = i\hbar$. Hamiltonian of harmonic oscillator is expressed as follows.

$$\hat{\mathcal{H}} = \frac{1}{2} (\hat{p}^2 + \omega^2\hat{q}^2) \quad (84)$$

Then following relations are obtained.

$$\begin{aligned}\hat{A}_1^\dagger\hat{A}_1 &= \frac{1}{2\hbar\omega} (\hat{p}^2 + \omega^2\hat{q}^2 + i\omega\hat{q}\hat{p} - i\omega\hat{p}\hat{q}) \\ &= \frac{1}{\hbar\omega} \left(\hat{\mathcal{H}} - \frac{1}{2}\hbar\omega \right) \\ \hat{A}_1\hat{A}_1^\dagger &= \frac{1}{\hbar\omega} \left(\hat{\mathcal{H}} + \frac{1}{2}\hbar\omega \right)\end{aligned}\quad (85)$$

From (85) and $\langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle = 0$, zero-point energy conventionally has been recognized as $\langle 0|\hat{\mathcal{H}}|0\rangle = \frac{1}{2}\hbar\omega$, i.e.,

$$\langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle = \frac{1}{\hbar\omega} \langle 0| \left(\hat{\mathcal{H}} - \frac{1}{2}\hbar\omega \right) |0\rangle = \frac{1}{\hbar\omega} \left(\langle 0|\hat{\mathcal{H}}|0\rangle - \frac{1}{2}\hbar\omega \right) = 0 \quad (86)$$

This conventional fixed zero-point energy originates from the definition of the photon creation and annihilation operators in (83) without the scalar potentials. However we have obtained the idea that there exists the potentials in whole space-time. Then we should replace (83) with followings by using the operators in (34).

$$\begin{aligned}\hat{A}'_0 + \hat{A}_1 &= \frac{1}{\sqrt{2\hbar\omega}} (\omega\hat{q} + i\hat{p}) \\ \hat{A}'_0 + \hat{A}_1^\dagger &= \frac{1}{\sqrt{2\hbar\omega}} (\omega\hat{q} - i\hat{p})\end{aligned}\quad (87)$$

Therefore Hamiltonian will be the same expression of the interference as follows.

$$\hat{\mathcal{H}} = \hbar\omega \left(-g^{\mu\nu} \hat{A}'_\mu \hat{A}_\nu \right) + \frac{1}{2}\hbar\omega \quad (88)$$

Hence the energy of single photon state also fluctuates.

$$\langle 1|\hat{\mathcal{H}}|1\rangle = -\frac{1}{2}\hbar\omega\langle 1|\hat{A}_0^\dagger\hat{A}_0|1\rangle \cos\theta + \frac{1}{2}\hbar\omega\langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle + \frac{1}{2}\hbar\omega \quad (89)$$

The single photon can be observed at some point with $\theta = \pm N\pi$, (N : oddnumber). By using Lorentz invariance $\langle 1|\hat{A}_0^\dagger\hat{A}_0|1\rangle = \langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle$

$$\begin{aligned} \langle 1|\hat{\mathcal{H}}|1\rangle &= \frac{1}{2}\hbar\omega\langle 1|\hat{A}_0^\dagger\hat{A}_0|1\rangle + \frac{1}{2}\hbar\omega\langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle + \frac{1}{2}\hbar\omega \\ &= \langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle\hbar\omega + \frac{1}{2}\hbar\omega = \hbar\omega \end{aligned} \quad (90)$$

Therefore, $\langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle = \frac{1}{2}$. This leads to the replacement of the expected photon number as follows.

$$\langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle = -\frac{1}{2}, \quad \langle 1|\hat{A}_1^\dagger\hat{A}_1|1\rangle = \frac{1}{2}, \quad \langle 2|\hat{A}_1^\dagger\hat{A}_1|2\rangle = \frac{3}{2}, \quad \dots \quad (91)$$

Generally, $\langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle$ is considered to be 0. However, we should accept $\langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle = -\frac{1}{2}$ which requires indefinite metric. We will revise this calculation later in this section. Even with the revision, the conclusion that the zero-point energy fluctuates remains unchanged.

Then absolute value of the single photon interference moves depending on the selection of $\langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle$. However $\langle \hat{I} \rangle \propto \frac{1}{2} \pm \frac{1}{2} \cos\theta$ remains unchanged.

By using the expectation value, zero-point energy is calculated to be as follows.

$$\begin{aligned} \langle 0|\hat{\mathcal{H}}|0\rangle &= -\hbar\omega \left\{ (r_1^2 + r_2^2 + \dots + r_M^2) + \sum_{j \neq k}^M r_j r_k e^{i(\theta_j - \theta_k)} \right\} \langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle \\ &\quad + \hbar\omega \langle 0|\hat{A}_1^\dagger\hat{A}_1|0\rangle + \frac{1}{2}\hbar\omega \\ &= \frac{1}{2}\hbar\omega \left\{ (r_1^2 + r_2^2 + \dots + r_M^2) + \sum_{j \neq k}^M r_j r_k e^{i(\theta_j - \theta_k)} \right\} \end{aligned} \quad (92)$$

This shows that the zero-point energy fluctuates such that $0 \leq \langle 0|\hat{\mathcal{H}}|0\rangle \leq \frac{1}{2}\hbar\omega$ depending on the path division. This also explains the spontaneous symmetry breaking. From this, infinite zero-point energy due to infinite degrees of freedom is removed when the phase is completely random with $M \rightarrow \infty$ in (92).

In the above discussion, we replaced the operator (83) with (87). However, if the operator \hat{A}_0 is introduced, we should replace the commutation relation of the position and momentum

operators $[\hat{q}, \hat{p}] = i\hbar$ with $[\hat{q}_\mu, \hat{p}_\nu] = -g_{\mu\nu}i\hbar$ and examine the time axis component as follows.

$$\begin{aligned}\hat{A}_0^\dagger \hat{A}_0 &= \frac{1}{2\hbar\omega} (\hat{p}_0^2 + \omega^2 \hat{q}_0^2 + i\omega \hat{q}_0 \hat{p}_0 - i\omega \hat{p}_0 \hat{q}_0) \\ &= \frac{1}{\hbar\omega} \left(\hat{\mathcal{H}}_0 + \frac{1}{2} i\omega [\hat{q}_0, \hat{p}_0] \right) = \frac{1}{\hbar\omega} \left(\hat{\mathcal{H}}_0 + \frac{1}{2} \hbar\omega \right) \\ \hat{A}_0 \hat{A}_0^\dagger &= \frac{1}{\hbar\omega} \left(\hat{\mathcal{H}}_0 - \frac{1}{2} \hbar\omega \right)\end{aligned}\quad (93)$$

where $\hat{\mathcal{H}}_0$ is the Hamiltonian corresponds to the energy of time axis. Hence, the total Hamiltonian $\hat{\mathcal{H}}$ can be calculated as follows using $\hat{\mathcal{H}}_1$ (Hamiltonian of the spatial component of (85))

$$\hat{\mathcal{H}} \equiv \hat{\mathcal{H}}_1 - \hat{\mathcal{H}}_0 = \hbar\omega \left(-g^{\mu\nu} \hat{A}_\mu^\dagger \hat{A}_\nu \right) + \frac{1}{2} \hbar\omega + \frac{1}{2} \hbar\omega \quad (94)$$

Here we note that similar to the discussion the above, the last term obtained from the commutation relation between the position and momentum operator of the time axis component should include a mathematical expression that incorporates the phase by the path division, similar to $\{ \}$ in (80). We set the mathematical expression to f , then the zero-point energy can be expressed as follows.

$$\begin{aligned}\langle 0 | \hat{\mathcal{H}} | 0 \rangle &= \hbar\omega \langle 0 | \left(-g^{\mu\nu} \hat{A}_\mu^\dagger \hat{A}_\nu \right) | 0 \rangle + \frac{1}{2} \hbar\omega \langle 0 | 0 \rangle + \frac{1}{2} \hbar\omega \langle 0 | f | 0 \rangle \\ &= \frac{1}{2} \hbar\omega + \frac{1}{2} \hbar\omega f\end{aligned}\quad (95)$$

In order to determine f , we calculate the energy of 1-photon state with the help of (80). Finally, the following zero-point energy is obtained.

$$\begin{aligned}\langle 1 | \hat{\mathcal{H}} | 1 \rangle &= \hbar\omega \langle 1 | \left(-g^{\mu\nu} \hat{A}_\mu^\dagger \hat{A}_\nu \right) | 1 \rangle + \frac{1}{2} \hbar\omega \langle 1 | 1 \rangle + \frac{1}{2} \hbar\omega \langle 1 | f | 1 \rangle \\ &= \hbar\omega - \hbar\omega \left\{ (r_1^2 + r_2^2 + \dots + r_M^2) + \sum_{j \neq k}^M r_j r_k e^{i(\theta_j - \theta_k)} \right\} + \frac{1}{2} \hbar\omega + \frac{1}{2} \hbar\omega f\end{aligned}\quad (96)$$

This is always single photon energy $\hbar\omega$ in whole space-time. Therefore, in the case of the ideal vacuum with $M = 1$ split path, $\{ \}$ will be 1, i.e., $f = 1$. In the case of the actual vacuum with $M \rightarrow \infty$ split paths, $\{ \}$ will be 0, i.e., the value will be $f = -1$. Otherwise, the value fluctuates such as $-1 < f < 1$ depending on $\{ \}$. Therefore, the zero-point energy fluctuates as follows depending on the geometrical arrangement existing in the space.

$$0 \leq \langle 0 | \hat{\mathcal{H}} | 0 \rangle = \frac{1}{2} \hbar\omega + \frac{1}{2} \hbar\omega f \leq \hbar\omega \quad (97)$$

C. Casimir effect

The zero-point energy has been measured through Casimir effect.⁴³⁻⁴⁷ The following circumstance can be identified as a typical setup for the measurement of Casimir effect. From the discussion in the zero-point energy, if a certain space that is not “real vacuum” but “ideal vacuum” is prepared and a certain geometrical arrangement, e.g. two parallel plates, is placed in the space, then the zero-point energy of the space and geometrical arrangement are calculated to be $\frac{1}{2}\hbar\omega$ and $0 \leq \langle 0|\hat{\mathcal{H}}|0\rangle \leq \frac{1}{2}\hbar\omega$ using (92) respectively or $\hbar\omega$ and $0 \leq \langle 0|\hat{\mathcal{H}}|0\rangle \leq \hbar\omega$ using (97) respectively. Because the energy of the geometrical arrangement is not exceed that of the space, the geometrical arrangement is subjected to a compressive stress from the space in both calculations.

This kind of attractive force derived from the energy difference between the geometrical arrangements is identical with the basic concept of Van der Waals force which will be the origin of Casimir effect.⁴⁸

D. Spontaneous symmetry breaking

Traditional approach of the spontaneous symmetry breaking, which explores the possibility of $\mathbf{Q}|0\rangle \neq 0$ or $|0\rangle$ is not an eigenstate of \mathbf{Q} , has been discussed using Goldstone boson or Higgs boson.^{28,49} Where $|0\rangle$ is vacuum state.

However, the scalar potential exists on the whole space-time as mentioned in this paper, and there are no electron at pinhole 2. Therefore, the state of pinhole 2, i.e., $|\psi_2\rangle$, can be identified as vacuum instead of $|0\rangle$. We have shown that the identical calculation result with the probability interpretation is obtained by using the identification. From the relation of $\langle\psi_2|\psi_2\rangle = 0$, if $|\psi_2\rangle$ is an eigenstate of \mathbf{Q} , i.e., $\mathbf{Q}|\psi_2\rangle = \alpha|\psi_2\rangle$, then $\langle\psi_2|\mathbf{Q}|\psi_2\rangle = \alpha\langle\psi_2|\psi_2\rangle = 0$, where α is an eigenvalue.

However from (48) and the generalization of the geometrical arrangement in section IV A, $\langle\psi_2|\mathbf{Q}|\psi_2\rangle$ fluctuates between $-q$ and 0 depending on the phase of the scalar potentials. Hence, the vacuum $|\psi_2\rangle$ is not an eigenstate of \mathbf{Q} , which expresses the spontaneous symmetry breaking.

There is no fluctuation in the real space with completely random phases as shown in section IV A. That is to say, there is symmetry. We can identify such space as “real vacuum”. However the fluctuation gains entrance into the real vacuum when the geometrical arrangement in the space changes, and eventually the symmetry is broken towards “ideal vacuum” where has no geometrical arrangement.

This idea holds even if the origin is vice versa, i.e., “ideal vacuum” instead of “real vacuum”. The space gains symmetry when $M = 1$ or $M \rightarrow \infty$.

The above discussion that the real vacuum is filled with potentials of which state exists under (or above) the original ground state is identical with the spontaneous symmetry breaking using the analogy of superconductivity when we replace \mathbf{Q} or $\hat{\mathcal{H}}$ with energy level reported by Y. Nambu and G. Jona-Lasinio.^{50,51} When the phase difference is fixed, the one vacuum is selected and the selection breaks the symmetry of vacuum.

In addition, as described in section IV B, the fluctuation of the zero-point energy of electromagnetic fields $0 \leq \langle 0|\hat{\mathcal{H}}|0\rangle \leq \frac{1}{2}\hbar\omega$ (or $\hbar\omega$) also shows that the vacuum is not the eigenstate of the photon number. That is the spontaneous symmetry breaking. Eventually, the spontaneous symmetry breaking is caused by the geometrical arrangement of space-time, which produces the oscillatory field of the scalar potential (time-axis component of a vector

field). This argument derived from the oscillatory field might seem like peculiar but it is consistent with the conventional idea of spontaneous symmetry breaking that the vacuum is degenerate.

E. General approach for single particle interference

By generalizing (40) and (48), single particle interference can be described as follow.

$$\begin{aligned}\langle I \rangle &= (\langle \phi | + \langle \zeta |) \mathbf{F} (|\phi\rangle + |\zeta\rangle) \\ &= f + \langle \zeta | \mathbf{F} | \zeta \rangle + f \langle \phi | \zeta \rangle + f \langle \zeta | \phi \rangle\end{aligned}\quad (98)$$

When $\langle \zeta | \mathbf{F} | \zeta \rangle + f \langle \phi | \zeta \rangle + f \langle \zeta | \phi \rangle = -\frac{1}{2}f + \frac{1}{2}f \cos \theta$, single particle interferences of \mathbf{F} by 2-path geometrical arrangement, i.e., $\langle I \rangle = f \left\{ \frac{1}{2} + \frac{1}{2} \cos \theta \right\}$ is generated. Where \mathbf{F} is an arbitrary observable operator of the particle, $|\phi\rangle$ is an eigenstate of \mathbf{F} , f is the eigenvalue of \mathbf{F} under state $|\phi\rangle$ and $|\zeta\rangle$ is an indefinite metric vector expressing the oscillatory field of the scalar potential.

When \mathbf{F} is number operator of the particle \mathbf{n} , and $|\phi\rangle$ is the single particle state of (98), the expected number of the particle fluctuates as follows.

$$\begin{aligned}(\langle 1 | + \langle \zeta |) \mathbf{n} (|1\rangle + |\zeta\rangle) &= 1 + \langle \zeta | \mathbf{n} | \zeta \rangle + \langle 1 | \zeta \rangle + \langle \zeta | 1 \rangle \\ &= \frac{1}{2} + \frac{1}{2} \cos \theta\end{aligned}\quad (99)$$

In the case of arbitrary geometrical arrangement, the expected number of the particle can be calculated as follows using similar expression (81), (82) and (80).

$$\langle \hat{I} \rangle \propto - \left\{ (r_1^2 + r_2^2 + \dots + r_M^2) + \sum_{j \neq k}^M r_j r_k e^{i(\theta_j - \theta_k)} \right\} + 1 \quad (100)$$

The above generalization is based on the electromagnetic field, which is a commutative (Abelian) gauge field, i.e., U(1) gauge field : unitary group of dimension 1, in the preceding chapters. The above discussion can be generalized to the non-commutative (non-Abelian) gauge field as follows.

The existence of the electromagnetic field can be derived, so called gauge transformation of the second kind, as a gauge field by gauge invariance of the phase transformation of the electron wave function ψ with conservation of charge Q as follows.

$$\psi' = U \psi \quad (101)$$

where $U = e^{i\chi Q}$ is a unitary transformation, χ is an arbitrary function of space-time point $(x) \equiv (\mathbf{x}, t)$.

Note that the conservation of charge Q means as follows. We can express the wave function Ψ in the initial state composed of elementary particles a, b, \dots with charges Q_a, Q_b, \dots as the product of the wave functions of each elementary particle ψ_a, ψ_b, \dots . Even if the initial state changes to the final state composed of elementary particles a', b', \dots , the law of conservation of charge holds, i.e., $Q_a + Q_b + \dots = Q_{a'} + Q_{b'} + \dots$.

When the phase factors $e^{i\chi Q_a}, e^{i\chi Q_b}, \dots$ are multiplied to the wave functions, the phase factor $e^{i\chi(Q_a+Q_b+\dots)} = e^{i\chi Q}$ is multiplied to the initial wave function, where Q is the total charge of the initial state. From the law of conservation of charge, the same phase factor $e^{i\chi(Q_a+Q_b+\dots)} = e^{i\chi(Q_{a'}+Q_{b'}+\dots)} = e^{i\chi Q}$ is applied to the final state.

However, the derivative operation by ∂_μ to the above transformation $U\psi$ is calculated to be as follows.

$$\partial_\mu \psi' = e^{i\chi Q} \{ \partial_\mu + iQ\partial_\mu \chi \} \psi \quad (102)$$

While the kinetic term which includes derivative operators such as momentum changes, the gauge transformation of the second kind should be the phase transformation that does not change in physical quantities because of the local causality.

Therefore the derivative operator ∂_μ is replaced with covariant derivative $D_\mu = \partial_\mu - iQA_\mu$ to recover the invariance of the physical quantities, where A_μ is a four-vector. By using this replacement with the following gauge transformations,

$$\begin{aligned} \psi' &= e^{i\chi Q} \psi \\ A'_\mu &= A_\mu + \partial_\mu \chi \end{aligned} \quad (103)$$

we can calculate as follows.

$$\begin{aligned} (D_\mu \psi)' &= \{ \partial_\mu - iQA'_\mu \} e^{i\chi Q} \psi \\ &= e^{i\chi Q} \{ (\partial_\mu + iQ\partial_\mu \chi) - i(QA_\mu + Q\partial_\mu \chi) \} \psi \\ &= e^{i\chi Q} \{ \partial_\mu - iQA_\mu \} \psi = e^{i\chi Q} D_\mu \psi \end{aligned} \quad (104)$$

Hence, the invariance of the physical quantities, e.g., momentum $p_\mu = (E/c, \mathbf{p}) = i\hbar\partial_\mu$, is obtained.

$$\langle \psi', P'_\mu \psi' \rangle = \langle e^{i\lambda Q} \psi, e^{i\lambda Q} P_\mu \psi \rangle = \langle \psi, P_\mu \psi \rangle \quad (105)$$

where $P_\mu = i\hbar D_\mu = i\hbar(\partial_\mu - iQA_\mu)$.

The gauge field A_μ , as described above, is introduced because of the existence of the gauge transformation associate with the conservation of charge Q and the local causality. In quantum electrodynamics, the gauge field A_μ is equated with the electromagnetic potential A_μ . Because $U = e^{i\chi Q}$ is a unitary transformation of dimension 1, the gauge field A_μ is called U(1) gauge field.

Extending the above procedure to a multicomponent wave function such as nucleon with isotopic spin conservation, the non-commutative (non-Abelian) gauge field B_μ is introduced.

For example, the wave function of nucleon ψ can be described by two-component composed of proton p and neutron n which are spin 1/2 fermions with z-axis isotopic spin $I_3 = 1/2$ and $I_3 = -1/2$ respectively. The subscript 3 of the isotopic spin \mathbf{I} is used because it is not the rotation of real three-dimensional space x, y, z , but the rotation of the three-dimensional isotopic space. The invariance under local isotopic spin rotations leads to formulating a principle of isotopic gauge invariance and the existence of a vector field B_μ ($= 2\mathbf{b}_\mu \cdot \mathbf{I}$) which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge as discussed above. The specific expression is as follows.

$$\psi' = S\psi \quad (106)$$

where $S = e^{i\boldsymbol{\theta} \cdot \mathbf{I}}$ is a 2×2 special unitary (SU(2)) matrix, $\boldsymbol{\theta}$ is the vector that specifies the axis and angle of the rotation in isotopic space. The isotopic spin \mathbf{I} is described as $\mathbf{I} = \frac{\boldsymbol{\tau}}{2}$ using following Pauli matrix $\boldsymbol{\tau}$.

$$\tau_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \quad \tau_2 = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, \quad \tau_3 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \quad (107)$$

The subscripts 1, 2, 3 are used accordance with those of \mathbf{I} .

When $\boldsymbol{\theta}$ is extended as an arbitrary function of space-time point $(x) \equiv (\mathbf{x}, t)$, the derivative operator ∂_μ is replaced with the following covariant derivative D_μ by introducing the vector fields B_μ not to change in physical quantities, as same in the case of U(1) gauge transformation.⁵²

$$D_\mu = (\partial_\mu - i\epsilon B_\mu)\psi \quad (108)$$

with the following gauge transformation.

$$B'_\mu = SB_\mu S^{-1} + \frac{i}{\epsilon} S \partial_\mu S^{-1} \quad (109)$$

where ϵ is an arbitrary constant called coupling constant and $B_\mu = 2\mathbf{b}_\mu \cdot \mathbf{I}$ respectively. (Bold-face letters denote three-component vectors in isotopic space.)

Because $S = e^{i\theta \cdot \mathbf{I}}$ is a special unitary transformation of dimension 2, the vector field B_μ (\mathbf{b}_μ) is called SU(2) gauge field. The generalized Aharonov-Bohm effect by the SU(2) gauge field had been discussed by Wu and Yang.³⁴

Therefore the vacuum is filled with the gauge fields which interact with the particle (e.g., nucleon) as same as in the discussion of subsection III B.

We can obtain the similar discussion and calculation of the uncharged particle such as neutron interference⁵³ originating from B_μ field by replacing the four-vector potential A_μ in subsection III B with B_μ .

Hence, the single particle interference, whether charged or not, can be caused by the geometrical arrangement of the gauge fields.

In the same discussion above, some single-particle self-fluctuation include neutrino oscillation^{54,55} can be explained.

V. ORIGIN OF THE INDEFINITE METRIC POTENTIAL

In this paper, we have revised the quantum theory using the oscillatory field of the scalar potential, which is the source of the indefinite metric. Although this scalar potential is a well-known quantity in classical electromagnetism, we examine this scalar potential again and extract the meaning of the alternate interpretation of this paper and future issues.

In quantum optics, we can usually use Coulomb gauge to divide the electric field and current density as follows.³²

$$\begin{aligned}\mathbf{E} &= \mathbf{E}_T + \mathbf{E}_L, & \nabla \cdot \mathbf{E}_T &= 0, & \nabla \times \mathbf{E}_L &= 0 \\ \mathbf{i} &= \mathbf{i}_T + \mathbf{i}_L, & \nabla \cdot \mathbf{i}_T &= 0, & \nabla \times \mathbf{i}_L &= 0\end{aligned}\quad (110)$$

where the indexes ‘‘T’’ and ‘‘L’’ stand for ‘‘Transverse’’ and ‘‘Longitudinal’’, respectively. ‘‘Transverse’’ components of Maxwell’s equations using electromagnetic potentials can be expressed as follows.

$$\begin{aligned}\nabla \times \mathbf{E}_T &= -\frac{\partial \mathbf{B}}{\partial t}, & \nabla \times \mathbf{B} &= \frac{1}{c^2} \frac{\partial \mathbf{E}_T}{\partial t} + \mu_0 \mathbf{i}_T \\ \mathbf{E}_T &= -\frac{\partial \mathbf{A}}{\partial t}, & \nabla \cdot \mathbf{B} &= 0\end{aligned}\quad (111)$$

where \mathbf{B} is the magnetic field. In addition, ‘‘Longitudinal’’ components can be expressed as follows.

$$\begin{aligned}\mathbf{E}_L &= -\nabla \phi, & \nabla \cdot \mathbf{E}_L &= \frac{\rho}{\epsilon_0} \\ \mathbf{i}_L &= \epsilon_0 \nabla \frac{\partial \phi}{\partial t} = -\epsilon_0 \frac{\partial \mathbf{E}_L}{\partial t}\end{aligned}\quad (112)$$

Therefore the transverse and longitudinal components seem associated with the magnetic field variation and with charges as the regular scalar potential, respectively.

However, these associations depend on coordinate systems. ‘‘Transverse’’ and ‘‘Longitudinal’’ components are mixed by Lorentz transformation. Then the associations lost meaning, which is the important assertion of relativity.⁵⁶

This relative association justifies the identification of scalar potentials and vector potentials, i.e., identify the number operators as $\langle 1|A_0^\dagger A_0|1\rangle = \langle 1|A_1^\dagger A_1|1\rangle = \langle 1|A_2^\dagger A_2|1\rangle = 1$ by Lorentz invariance. Hence we would better use Maxwell’s equations (4) in Lorentz gauge, because Coulomb gauge removes the explicit covariance of Maxwell’s equations.

Maxwell's equations in Lorentz gauge can be express as follows by utilizing the linearity of the equation (4).

$$\begin{aligned}\square A^\mu &= \square(A^\mu_{(\text{mat})} + A^\mu_{(\text{vac})}) = \mu_0 j^\mu \\ \partial_\mu A^\mu &= \partial_\mu(A^\mu_{(\text{mat})} + A^\mu_{(\text{vac})}) = 0\end{aligned}\tag{113}$$

where index “mat” and “vac” mean “matter” associated with four-current and “vacuum”, respectively. Because we can naturally assume that there are no four-current in vacuum, $A^\mu_{(\text{mat})}$ and $A^\mu_{(\text{vac})}$ obey the following Maxwell's equations respectively.

$$\square A^\mu_{(\text{mat})} = \mu_0 j^\mu, \quad \partial_\mu A^\mu_{(\text{mat})} = 0\tag{114}$$

$$\square A^\mu_{(\text{vac})} = 0, \quad \partial_\mu A^\mu_{(\text{vac})} = 0\tag{115}$$

The substantial photon excited by the four-current will be expressed by equation (114). Note that equation (115) replaced $A^\mu_{(\text{vac})}$ with $A^\mu_{(\text{mat})}$ can express the motion of the potentials associated with the four-current in the spatial domain where is far from and does not contain the four-current.

In contrast, equation (115) expresses the motion of the potentials that have nothing to do with “matter” in vacuum. This evokes us the concept of an ether such that vacuum is the sea filled with the potentials. The special relativity⁵⁶ has negated the static ether, but the above filling potentials propagate at the speed of light rather than static entities. Aharonov-Bohm effect clearly indicates that not only electromagnetic fields but also the potentials can make electron interference.^{33,57,58} Similarly, the filling potentials in equation (115) can make interference with substantial photon. This is similar to the concept of the non-integrable phase factor associated with the multiple-connected region of the space, which was also noted in Aharonov-Bohm effect.³⁴ As the space is divided, a phase term associated with the division is introduced and cause interference.

We generally use A^μ in equation (113) to calculate photon related phenomena unconsciously, i.e., without separating them into “matter” and “vacuum”. Unfortunately, we will not be able to distinguish between $A^\mu_{(\text{mat})}$ and $A^\mu_{(\text{vac})}$. This is very similar to distinguishing between sea spray and seawater. In fact, no separation is necessary, as both are ever-changing potentials derived from the same Maxwell's equations (113). Hence the filling potentials in vacuum can expel and incorporate the potentials associated with “matter”, which gives us the description that vacuum creates and annihilates substantial photon.

The source of the indefinite metric scalar potential examined in this paper seems to be the time-axis component of the potential (115) in vacuum though it is difficult to distinguish.

On the other hand, Maxwell's equations, which has been formulated as a compilation of classical electromagnetism based on experimental facts of electric and magnetic phenomena from the Faraday era, can be considered as (114).

Here we recognize that (114) is derived from experimental facts, and (115) is derived as a gauge field under the local commutative gauge transformation regardless of experimental facts. Then the recognition emphasize the similarity between the introduction of the gauge field due to the invariance of the local phase transformation on the space-time structure and the phenomenon of vacuum fluctuation due to the geometrical arrangement of the space examined in this paper.

In the analogy of the electronic circuit or the communication using homodyne detection mentioned in the preceding chapter, (115) corresponds to the bias current (voltage) or the continuous wave generated from the local oscillator, and (114) corresponds to the signal wave. If the bias is a stable DC current (voltage), there is no problem in extracting only the AC current (voltage) as a signal. However when the DC current (voltage) fluctuates, the signal as the AC current (voltage) also fluctuates.

It is useful for engineering applications to examine the actual physical phenomenon as the circuit or communication in which the DC current (voltage) fluctuates.

VI. CONTRADICTION OF THE COVARIANT CANONICAL QUANTIZATION

In this chapter, we examine the contradiction between Lorentz gauge and commutation relations in covariant canonical quantization of Maxwell's equations on conventional method, and propose alternate method.

A. Canonical quantization and contradiction of commutation relations

First, an overview of canonical quantization and conventional method are outlined below. The subject is Maxwell's equations in free space with zero four-current as follows again.

$$\square A^\nu - \partial_\mu \partial^\nu A^\mu = 0 \quad (116)$$

In order to adopt canonical quantization, the following classical lagrangian density has been introduced.

$$\begin{aligned} \mathcal{L}_{class} &= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \equiv -\frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu) (\partial^\mu A^\nu - \partial^\nu A^\mu) \\ &= -\frac{1}{2} \partial_\mu A_\nu \partial^\mu A^\nu + \frac{1}{2} \partial_\mu A_\nu \partial^\nu A^\mu \end{aligned} \quad (117)$$

Indeed the following Euler-Lagrange equation gives Maxwell's equations (116).

$$\partial_\mu \frac{\partial \mathcal{L}_{class}}{\partial (\partial_\mu A_\nu)} - \frac{\partial \mathcal{L}_{class}}{\partial A_\nu} = 0 \quad (118)$$

By using this lagrangian density, the canonically conjugate variables π^i , $i = (1, 2, 3)$ can be defined as follows.

$$\begin{aligned} \pi^i &= \frac{\partial \mathcal{L}_{class}}{\partial \dot{A}_i} = -\frac{1}{4} \frac{\partial}{\partial \dot{A}_i} (F_{0i} F^{0i}) \\ &= -\frac{1}{4} \frac{\partial}{\partial \dot{A}_i} ((\partial_0 A_i - \partial_i A_0) (\partial^0 A^i - \partial^i A^0) + (\partial_i A_0 - \partial_0 A_i) (\partial^i A^0 - \partial^0 A^i)) \\ &= \partial^i A^0 - \partial^0 A^i \end{aligned} \quad (119)$$

However the conjugate variable π^0 can not be defined as follows.

$$\pi^0 = \frac{\partial \mathcal{L}_{class}}{\partial \dot{A}_0} = 0 \quad (120)$$

Therefore a number of fixing gauge conditions have been proposed. Well-known gauges are Coulomb gauge $\nabla \cdot \mathbf{A} = 0$ and Lorentz gauge $\partial_\mu A^\mu = 0$. Because Coulomb gauge spoils the explicit covariance due to the separation of A_0 from the four-vector, fixing Lorentz gauge has been examined by using following lagrangian density.

$$\mathcal{L}_0 = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}(\partial_\rho A^\rho)^2 \quad (121)$$

When we use the lagrangian density (121), Maxwell's equations in Lorentz gauge can be obtained from Euler-Lagrange equation (118).

$$\square A^\nu = 0 \quad (122)$$

Here the action integral of (117) is as follows.

$$\begin{aligned} S &\equiv \int d^4x \mathcal{L}_{class} \\ &= \int d^4x \left(-\frac{1}{2} \partial_\mu A_\nu \partial^\mu A^\nu + \frac{1}{2} \partial_\mu A_\nu \partial^\nu A^\mu \right) \end{aligned} \quad (123)$$

The second term of the above integral is calculated to be $\frac{1}{2}(\partial_\mu A^\mu)^2$ by partial integration. Then the lagrangian density (121) which derives Maxwell's equations (122) can be calculated to be following lagrangian density.

$$\mathcal{L}'_0 = -\frac{1}{2} \partial_\mu A_\nu \partial^\mu A^\nu \quad (124)$$

The canonically conjugate variables can be obtained by using this lagrangian density as follows .

$$\pi^\mu = \frac{\partial \mathcal{L}'_0}{\partial \dot{A}_\mu} = -\dot{A}^\mu \quad (125)$$

Here quantization is performed by replacing the fields with operators and set the following equal-time commutation relations.

$$\begin{aligned} [A^\mu(\mathbf{x}, t), \pi^\nu(\mathbf{x}', t)] &= -[A^\mu(\mathbf{x}, t), \dot{A}^\nu(\mathbf{x}', t)] \\ &= i g^{\mu\nu} \delta^3(\mathbf{x} - \mathbf{x}') \end{aligned} \quad (126)$$

$$[A^\mu(\mathbf{x}, t), A^\nu(\mathbf{x}', t)] = [\pi^\mu(\mathbf{x}, t), \pi^\nu(\mathbf{x}', t)] = 0 \quad (127)$$

However (126) and (127) derive the following relations.

$$[\partial_\mu A^\mu(\mathbf{x}, t), A^\nu(\mathbf{x}', t)] = i g^{0\nu} \delta^3(\mathbf{x} - \mathbf{x}') \neq 0 \quad (128)$$

Hence (128) is inconsistent with Lorentz gauge $\partial_\mu A^\mu = 0$ as an operator.

Therefore some other lagrangian densities have been proposed. The following lagrangian with auxiliary scalar field B , which is called Nakanishi-Lautrup formalism, will be the most comprehensive form³¹.

$$\mathcal{L}_{NL} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + B\partial^\mu A_\mu + \frac{1}{2}\alpha B^2 \quad (129)$$

Where α is an arbitrarily real parameter. The inconsistency between Lorentz gauge $\partial_\mu A^\mu = 0$ and (128) can be avoided by using the lagrangian (129), introduction of physical states $|\text{phys}\rangle$ and a restriction of Lorentz gauge in terms of the physical states defined by a subsidiary condition, i.e., $\langle \text{phys} | \partial_\mu A^\mu | \text{phys} \rangle = 0$.

B. Extended Lorentz gauge

The approach using (129) seems to be an artificially imposed mathematical technique by introducing an unreal physical field B and unphysical man-made mathematical formality called “subsidiary condition”. That is to say, there is a tendency to describe by artificial mathematical techniques to be consistent with probability interpretation and seem to deviate from the mathematical description of natural laws. In addition, the approach has been introduced for avoidance of negative norm as premises for “probability interpretation”. However, as mentioned in this paper, the indefinite metric can express the physical reality that is inevitably required by theory, which is indispensable to the law of nature. Just because it violates the probability interpretation, it might be fatal fault to remove the indefinite metric by making full use of mathematical techniques according to the artificially introduced hypothesis and conditions.

Hence, we examine the lagrangian density (124) and Maxwell’s equations in Lorentz gauge (122) again. It is to be noted that Lorentz gauge is dispensable for deriving (122). Indeed (122) is derived from lagrangian density (121) or (124) independently of Lorentz gauge. Alternatively the following condition is indispensable from (116).

$$\partial_\mu \partial^\nu A^\mu = 0 \quad (130)$$

Hence from Lorentz invariance

$$\partial_\mu A^\mu = \epsilon(\text{scaler}) \quad (131)$$

This condition (we call this “extended Lorentz gauge”) also has the following gauge invariance of (116) by introducing an arbitrary scalar function χ .

$$A'^{\mu} = A^{\mu} + \partial^{\mu}\chi \quad (132)$$

Although this replacement has been well known, we can imagine that four-vector A^{μ} move on the bias vector $\partial^{\mu}\chi$ such as AC signal and bias current (voltage) of an electric circuit or communication using homodyne detection.

By choosing $\square\chi = 0$, (131) can be obtained repeatedly as follows.

$$\partial_{\mu}A'^{\mu} = \partial_{\mu}A^{\mu} + \square\chi = \partial_{\mu}A^{\mu} = \epsilon \quad (133)$$

Hence

$$A^{\mu} = A_L^{\mu} + f^{\mu} \quad (134)$$

where A_L^{μ} and $f^{\mu} = f^{\mu}(\mathbf{x}, t)$ are a general solution of Lorentz gauge, i.e., $\partial_{\mu}A_L^{\mu} = 0$, and a linear formula as a function of \mathbf{x}, t with $\partial_{\mu}f^{\mu} = \epsilon$ respectively. The most common linear formula f^{μ} is the same as a coordinate transformation in form described as follows.

$$f^{\mu} = \beta(a_{\nu}^{\mu}x^{\nu} + b^{\mu}) \quad (135)$$

where β is a constant for fixing the appropriate dimension. Therefore

$$\epsilon = \beta(a_0^0 + a_1^1 + a_2^2 + a_3^3) = \text{Tr}(\varepsilon) \quad (136)$$

Where, ε is 4×4 matrix with matrix elements a_{ν}^{μ} multiplied by β . Here we replace ϵ with operator $\hat{\epsilon}$ and substitute for (128)

$$[\partial_{\mu}A^{\mu}(\mathbf{x}, t), A^{\nu}(\mathbf{x}', t)] = [\hat{\epsilon}, A^{\nu}(\mathbf{x}', t)] = i\mathbf{g}^{0\nu}\delta^3(\mathbf{x} - \mathbf{x}') \neq 0 \quad (137)$$

C. Discussion

We examine the commutation relation $[\partial_{\mu}A^{\mu}, A] = [\hat{\epsilon}, A] \equiv \hat{\epsilon}A - A\hat{\epsilon} \neq 0$ by using matrix representation of the operator. The matrix representation of the photon creation and annihilation operators, A^{\dagger} and A , and photon number state vectors $|\mathbf{n}\rangle$ are expressed as follows.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & \cdots \\ 0 & 0 & \sqrt{2} & 0 & \cdots \\ 0 & 0 & 0 & \sqrt{3} & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}, \quad A^\dagger = \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots \\ 1 & 0 & 0 & 0 & \cdots \\ 0 & \sqrt{2} & 0 & 0 & \cdots \\ 0 & 0 & \sqrt{3} & 0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad (138)$$

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ \vdots \end{bmatrix}, \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ \vdots \end{bmatrix}, \quad |2\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ \vdots \end{bmatrix}, \quad |3\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ \vdots \end{bmatrix}, \cdots \quad (139)$$

When $\hat{\epsilon} = \epsilon I$, where I is an identity matrix or operator, the operator $\hat{\epsilon}$ just serves as the constant scalar $[\hat{\epsilon}, A] = \epsilon[I, A] = \epsilon(IA - AI) = 0$, then (137) can not be obtained. From (136), we should adopt the operator $\hat{\epsilon}$ that satisfies $\text{Tr}(\hat{\epsilon}) = \sum \epsilon^{ii} = \epsilon$ when we replace ϵ with the operator $\hat{\epsilon}$. Hence, the following matrix representation can be adopted as $\hat{\epsilon}$, where we set all diagonal elements to 0 for simplicity. Even if the diagonal element is not 0, the same result as below can be obtained.

$$\hat{\epsilon} = \begin{bmatrix} \epsilon^{00} & 0 & 0 & 0 & \cdots \\ 0 & \epsilon^{11} & 0 & 0 & \cdots \\ 0 & 0 & \epsilon^{22} & 0 & \cdots \\ 0 & 0 & 0 & \epsilon^{33} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad (140)$$

Here we can calculate as follows.

$$\begin{aligned}
[\hat{\epsilon}, A] &\equiv \hat{\epsilon}A - A\hat{\epsilon} \\
&= \begin{bmatrix} 0 & \varepsilon^{00} & 0 & 0 & \dots \\ 0 & 0 & \sqrt{2}\varepsilon^{11} & 0 & \dots \\ 0 & 0 & 0 & \sqrt{3}\varepsilon^{22} & \dots \\ 0 & 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} - \begin{bmatrix} 0 & \varepsilon^{11} & 0 & 0 & \dots \\ 0 & 0 & \sqrt{2}\varepsilon^{22} & 0 & \dots \\ 0 & 0 & 0 & \sqrt{3}\varepsilon^{33} & \dots \\ 0 & 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \\
&= \begin{bmatrix} 0 & \varepsilon^{00} - \varepsilon^{11} & 0 & 0 & \dots \\ 0 & 0 & \sqrt{2}(\varepsilon^{11} - \varepsilon^{22}) & 0 & \dots \\ 0 & 0 & 0 & \sqrt{3}(\varepsilon^{22} - \varepsilon^{33}) & \dots \\ 0 & 0 & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \ddots & \end{bmatrix}
\end{aligned} \tag{141}$$

Hence if at least one $\varepsilon^{ii}(i > 0)$ is $\varepsilon^{ii} \neq \varepsilon^{i\pm 1i\pm 1}$ then $[\hat{\epsilon}, A] \neq 0$ will be satisfied.

By utilizing the relationship (136), we can define the operator $\hat{O} \equiv \hat{\epsilon}$ that satisfies $\text{Tr}(\hat{\epsilon}) = \Sigma\varepsilon^{ii} = 0$ because $\hat{\epsilon}$ satisfies $\text{Tr}(\hat{\epsilon}) = \Sigma\varepsilon^{ii} = \epsilon$ like (140). Therefore $\hat{O} \equiv \partial_\mu A^\mu(\mathbf{x}, t)$ satisfies (128) as the conventional Lorentz gauge

As described in single photon calculation, even if the number of photon becomes 0 due to interference, the invisible photons are there at the space-time due to the interference of the opposite phase waves.

Even if the photon number becomes 0 due to interference, there is the invisible photons at the space-time point due to the interference of waves with opposite phases. It is necessary to identify that space with a space-time of the phase state such that $f(\theta) = 0$, and it cannot be set to 0 as an empty space-time.

Similarly, considering the right side of the Lorentz condition $\partial_\mu A^\mu = 0$ as empty 0 and quantizing it as 0 will ignore the space-time that has some geometrical arrangement.

Since classical Lagrangian density (117) assumes free space which is an ideal vacuum with no geometrical arrangement, the same approach will be applicable by introducing a phase into A_0 that includes the existence of the geometrical arrangement.

VII. SUMMARY

Probability interpretation, which is the basic concept of quantum theory, has been considered essential in order to match the observation results of quantum phenomena with theory. However, the probability interpretation had not been able to provide the picture of objective physical reality like classical physics and gave rise to the famous paradox that an indivisible particle is in a quantum superposition state divided into two or more paths instead of objective physical reality.

In addition, the probability interpretation asserts that the divided two particle in EPR state have a correlation even if they are far apart, and one of pair is suddenly changed from probability existence to a particle as an objective physical reality at the very moment when the other of pair is observed. This correlation leads to a physical phenomenon that exceeded the speed of light that contrary to relativity. However, a technology called quantum teleportation has been tried to develop by applying the physical phenomena that exceed the speed of light.

In this paper, we have discarded the probability interpretation that conflicts with common sense and proposed an alternate interpretation of the quantum theory using objective physical reality, which reproduces the same observation results as the conventional standard quantum theory.

For the alternate interpretation, we have used an indefinite metric associate with covariant quantization of Maxwell's equations. Although some mathematical procedures have been developed to remove it because the indefinite metric contradicts the probability interpretation, in this paper, we pay attention to the fact that the indefinite metric is inevitably required from the theory, and have approved that the probability interpretation should be removed instead. Therefore we have incorporated the indefinite metric into the calculations of single photon, single electron interference and EPR correlation as it is. Then by using covariant description and simple calculation method, we have shown when the space is divided into two paths, the scalar potential, which is the source of the indefinite metric, forms an oscillatory field by the division. We have clarified the objective physical realities that the single photon, single electron and photon pair having opposite polarizations move in the oscillatory field which occurs the interferences and correlations, and shown that the calculation results agree with the conventional standard quantum theory.

For EPR correlation, various reports have been made that suggest there exists a long-range correlation beyond the causality.^{19–21,41,59–61} We believe that these reports can be explained by the oscillatory field of the scalar potential caused as the result of path division and the indefinite metric in this paper.

We have also shown that the number of space division in the ideal vacuum or real vacuum corresponds to 1 (no division) or ∞ respectively by generalizing the number of the division of the space from two into an arbitrary number, and clarified that the oscillatory field due to the scalar potential is formed when some geometrical arrangement come into in the ideal space.

Furthermore, we have shown that the zero-point energy fluctuates due to the oscillatory field of the scalar potential, the removal of the infinite zero-point energy which was difficult for conventional quantum theory and the Casimir effect originating from zero-point energy can be calculated.

Conventionally, there is an argument that the zero-point energy is simply subtracted to erase in engineering applications. By using an analogy from an electric circuit, we have discussed that this kind of approach corresponds to the signal of AC coupling which subtract DC bias voltage (current). And a real physical phenomenon corresponds to the electric circuit of which bias voltage (current) is not DC component but AC component, which causes interference with the AC component of the signal.

In addition, we have clarified that the space has symmetry when the number of division of the space is 1 (no division) or ∞ and at other number of division the oscillatory field of the scalar potential is generated which breaks the symmetry.

Moreover, We have discussed the generalization of a single particle interference and suggested that the neutrino oscillation may be caused by the self-interference fluctuation due to the oscillatory field of the physical quantity corresponding to the indefinite metric. In this generalization, we showed that the approach for a commutative gauge field such as an electromagnetic field in this paper could be applied to a non-commutative gauge field such as uncharged particle. However there will be a future works in non-commutative gauge field to complete the foundation of the law of physics. In future work, the introduction of indefinite metric will be a theoretical requirement that should be introduced in any fields.

We have discussed the origin of the scalar potential, which is the essence of this paper, by separating Maxwell's equations into two equations associate with matter and vacuum

and shown the picture that vacuum create and annihilate photons as the objective physical reality.

Finally, we have discussed the contradiction between Lorentz condition as an operator and commutation relation in covariant canonical quantization of Maxwell's equations, and proposed the alternate method that can avoid the contradiction by introducing the extended Lorentz gauge.

Despite the different interpretation and calculation methods, both the conventional probability and the alternate interpretation in this paper give the same calculation results. This can be regarded as a one-to-one correspondence of the inverse problem. The conventional standard quantum theory is not a systematic representation of physical observations (outcome) by mathematical expression using objective physical reality, but the assumption replaced by non-physical state (pseudo-reality) called probability interpretation, because it was initially difficult to explain the observation result (outcome) by objective physical reality. For example, we can estimate the sound (outcome) from the shape and state of the musical instrument (reality). On the contrary, from the sound (outcome), we can estimate some of sound sources, for example, an electric sound devices (pseudo-reality), in addition to the musical instrument (reality) that actually makes the sound. Even if the observations (sounds or outcomes) are identical, the true reality must be unique.

The alternate interpretation seems to be superior to probability interpretation because intuitively reasonable and exactly follows from Maxwell's equations, relativity and the indefinite metric derived from covariant quantization and gives the same result as the conventional standard quantum theory that reproduces the experimental results.

Despite the reproduction of such identical results and the theoretical derivation, no new concept has been introduced. The conventional concepts such as state vectors, operators as physical quantities, commutation relations and gauge transform remain unchanged. This seems to be evidence that such concepts of conventional quantum theory is in the theoretically correct direction. However the probability interpretation and applications based on it seems to result in pseudoscience, in addition, mathematical procedures associated with it might be extra things for physics.

From the alternate interpretation, the incompleteness of quantum theory, which has been alerted by A. Einstein, might originate from lack of introduction of indefinite metric as an objective physical reality.

As A. Einstein continued to insist⁵, we also insist that quantum theory should be debated and reconstructed using an objective physical reality without probability interpretation.

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