Interpretation of Quantum Mechanics in Terms of Discrete Time I

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From the discretization of time, the nonlocality of matter and electromagnetic waves can be inferred. These nonlocal waves provide a new perspective on the nonlocality of quantum phenomena, such as wave collapse and entanglement, and the wave-particle duality. Interactions can be divided into bound states and scattering, which are all described by the modified Dirac equation. From the modified Dirac equation, the quantum condition of the bound state can be obtained. Regarding scattering, elastic scattering is related to wave nature, and inelastic scattering is related to particle nature. The wave nature is expressed in all bound states and elastic scattering, and the particle nature corresponds to the case of inelastic scattering. And, in the case of inelastic scattering, a model for wave collapse is presented.

1 Introduction

The significance of this paper is to newly understand quantum mechanics from the point of view of discrete time. Quantum mechanics is a system established by experiment, but its interpretation is diverse. However, it is rare to have a perspective that integrates and coherently interprets the various phenomena of quantum mechanics. The perspective of discrete time is very different from existing interpretations, but it provides an interesting perspective. Since the new perspective is very unfamiliar, I will briefly summarize the contents presented in the previous papers [1–3].

The analysis of the dynamical system from the perspective of discrete time has opened a new way to see things that have not been understood in the existing quantum mechanics or existing results from a completely different perspective. In the first paper [1], from the point of view of discrete time, matter is divided into two types with completely different dynamic principles. Type 1 is an ordinary matter that satisfies the Dirac equation, and type 2 is completely new. Type 2 does not interact with the gauge fields and is only affected by gravity. And considering its energy density, it can be interpreted as dark matter.

Since existing relativistic quantum mechanics cannot explain anomalies during interactions, it has no choice but to lead to quantum field theory that assumes second quantization and vacuum energy. This theory is based on the ontological basis of the statistical mechanical analogy that a field is a collection of independent infinite harmonic oscillators. On the other hand, the type 1 field does not make such an ontological assumption. If type 1 is a free particle, it can be interpreted as an ordinary matter that satisfies the Dirac equation, but the concept of the field is quite different from the existing one. In the type 1 field, the current harmonic oscillation is determined by contributions from the past and future of discrete time Δt. From this point of view, it was shown that the mass and charge of elementary particles during interactions must be corrected by causal delay, and this correction showed that it can explain anomalies such as anomalous magnetic moment and Lamb shift [2,3].

2 The meaning of discrete time

Discrete time means that there is a minimum value of time change, which is a unit of time that cannot be further divided. In other words, it can be said that "time does not pass" from one click of time to the next, and if we consider the hypothetical events on this unit of time, we can infer that they all occurred at the same time. Thus, a discrete unit of time is a collection of simultaneous events.

By the way, this collection of simultaneous events has a special character. Before discussing that, consider the following thought experiment. Observer A is in a car moving at speed v. There is a light source in the middle of the car and light detectors on the front and rear walls of the car. The events in which light reaches both detectors are simultaneous for observer A. However, for B, a stationary observer outside the car, the two events are not simultaneous. Because the car is moving, the light reaching the rear becomes an event that occurs earlier than the light reaching the front. This relativity of simultaneity is a natural result of the special theory of relativity based on the concept of continuous space-time.

However, in discrete time, the relativity of simultaneity is limited. Under the same circumstances, if a car moves by Δl in discrete time Δt, what happens to observer B during which simultaneous events to observer A occur? For observer B, Δt is a situation in which time does not pass from one click to the next click, so the events until the movement by Δl are simultaneous. Thus, within the range of time Δt, simultaneous events for observer A are also simultaneous events for observer B. In other words, in discrete time, local absolute simultaneity is established. Such a discussion holds within Δt. Of course, the relativity of simultaneity is established as time passes beyond the click of Δt. Hypothetical events in Δt do not hold the Lorentz transformation and cannot be expressed in Minkowski space-time, which is based on the concept of continuous space-time. However, since the theory of relativity is established beyond the Δt click, for example, the time Δt for observer B is $\Delta t' = \Delta t/\gamma$ for observer A. In summary, discrete time can be said to be a collection of events in which local absolute simultaneity is established.

In the previous paper [2], Δt was defined as the time for light to pass through the Compton wavelength of a matter, $\Delta t \overset{\text{def}}{=} \frac{\hbar}{mc^2}$. If the Compton wavelength is regarded as the "spatial domain" of a matter, Δt can be regarded as the "temporal domain" of the matter. Therefore, what the above discussion means is that the relativity of simultaneity is established outside matter, and the absoluteness of simultaneity dominates inside matter. Discrete time is not a concept of objective reality that clicks regardless of matter, like Newton's concept of absolute time, but a unique click inherent in matter.

Let's find out the characteristics of the field defined in discrete time. Since the field defined in continuous spacetime holds the local principle, the local parts of the field can change independently. However, if the field defined in discrete time can change locally and independently, the basic premise of discrete time is violated because time must also change as a variable in response to the change of field. Therefore, a field defined in discrete time cannot be changed locally, and all parts of the field must act simultaneously. That is, a field defined in discrete time cannot be divided.

3 Formation of nonlocal waves

In discrete time, the spinor $\Psi(x^\mu)$ at any point x^μ of type 1 is given by the sum of Δt future and past contributions to x^μ, so that $\Psi(x^\mu)$ evolves into $e^{-i\Delta x^\alpha p_\alpha}\Psi(x^\mu)$ [1]. Eq. (1) and Fig. 1 show this as a formula and figure, respectively.

$$(x^\mu + \Delta x^\mu)\Psi(x^\mu) - x^\mu\Psi(x^\mu + \Delta x^\mu) = \Delta x^\mu e^{-i\Delta x^\alpha P_\alpha}\Psi(x^\mu) \,. \quad (1)$$

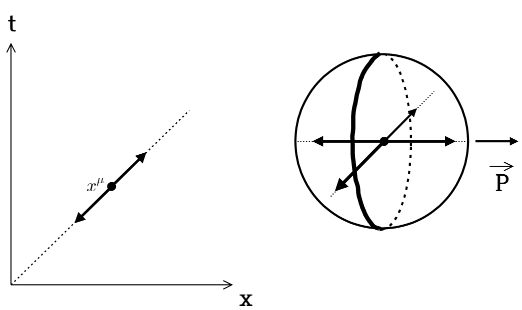

Fig. 1: Contributions of spinors at x^μ.

The left side of Fig. 1 shows spinors contributing from Δt future and past at x^μ, in the 1+1 dimension, and the right side shows them in 3-dimensional real space. All points on the right hemisphere are Δt future and all points on the left hemisphere are past. At the center point, all spinors contributing from the future appear to the left, and all spinors contributing from the past appear to the right. As discussed in the previous section, all events in the right hemisphere are simultaneous events, and all events in the left hemisphere are also simultaneous events.

Furthermore, spinors at every point on the right hemisphere can also be represented as contributions from future and past spinors. Then, the same sphere can be drawn at every point on the right hemisphere, and this process can be repeated over and over again. As a result, a wavefront with the same phase can be represented as the left side of Fig. 2.

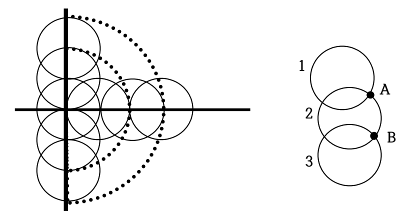

Fig. 2: Formation of simultaneous wavefronts.

By the way, the wavefront formed in this way has special properties. On the right side of Fig. 2, A is the common point of 1 and 2. Point A is simultaneous with all points on hemisphere 1 and also with all points on hemisphere 2. Therefore, all points on hemispheres 1 and 2 are simultaneous with each other. This is established only when hemispheres 1 and 2 overlap. Since this process can continue to expand, all the points on the wavefront shown on the left in Fig. 2 are simultaneous.

This simultaneous wavefront is not local. If we consider the field defined on this wavefront, as discussed in the previous section, it cannot change locally. Interactions occurring at one point on the wavefront occur simultaneously at all points on the wavefront. A wavefront is nonlocal, but the local principle still applies between one wavefront and another. This non-locality of type 1 waves is fundamentally different from the wave concept explained only by the existing local principle.

So far, we have discussed the nonlocality of a type 1 wave, that is, a matter field wave. We will now discuss the nonlocality of electromagnetic waves. The electric and magnetic fields individually obviously apply the local principle. But what about electromagnetic waves? In judging the nonlocality of electromagnetic waves, I will refer again to the proposition discussed earlier. In discrete time, the collection of simultaneous events establishes local absolute simultaneity. Therefore, if a wavefront composed of certain simultaneous events has local absolute simultaneity, it can be judged that the wavefront is a nonlocal wave.

Electromagnetic waves are produced by accelerating electric charge. Around the accelerating charge, there are kinks of the field, and these kinks are what form the wave. The kinks depend on the motion of the charge, and the motion of the charge is performed in units of discrete time Δt . Then, the kinks formed between Δt can also be said to be simultaneous events to the observer fixed on the charge, which, according to the above discussion, can also be said to be simultaneous events to the stationary observer. Therefore, electromagnetic waves can be said to have local absolute simultaneity, so they can be said to be nonlocal waves like matter field waves.

Until now, we have had a somewhat unfamiliar discussion that matter field waves and electromagnetic waves are nonlocal waves. However, in my opinion, the fact that these are nonlocal waves is already included in the existing quantum mechanics. In quantum mechanics, the energy of light is $E = h\nu$. What does this equation mean? If we try to understand it as a wave, there is no local nature of a wave at all. So, it should be understood as a particle, but what does the frequency of a particle mean? The fact that the energy of light does not depend on the local properties of the wave means that the wave is nonlocal. Light is created by kinks, the magnitude of which determines the frequency, and the total kinks form a nonlocal wavefront. An interaction at one point of the wavefront acts simultaneously on all parts of the wavefront. Therefore, the energy of light does not depend on the local properties of the wave, but is proportional only to its frequency.

4 Wave collapse and wave-particle duality

Quantum mechanics has various interpretations depending on the meaning of the wave function and measurement. In this paper, these meanings are as follows. The wavefunction is not a probability concept, but an objective real field, and the measurement is merely the interaction between elementary particles.

Based on the discussion in the previous section, let's infer the wave collapse, which is an intrinsic property of nonlocal waves, and the particle nature of matter and light.

When an electron interacts with an electromagnetic wave, the wavefront of the electron and the wavefront of the electromagnetic wave meet. If one part of the wavefront of an electron is affected by an electromagnetic wave, all parts of the wavefront of an electron are simultaneously affected because of the intrinsic property of nonlocal waves. It is as if all the information of the electron wavefront is concentrated at the point of contact and interacts with the electromagnetic wave. This can be seen as a kind of wave collapse, and it can be said to be the definition of the particle nature of electrons. This discussion can be equally applied to electromagnetic waves interacting with electrons. Electromagnetic waves are also nonlocal waves, and when interacting with electrons, the entire wave is concentrated in a local area, which is the particle nature of light, that is, the definition of a photon. The electrons and photons concentrated in this local area exchange energy and momentum as particles. In other words, the interaction—which we will discuss in the next section, corresponds to inelastic scattering—occurs on a "quantum" unit. After the interaction, they move as new free waves, each with new energy and momentum. In the next section I will present a mathematical model for the collapse of matter waves.

The wave-particle duality is one of the most important phenomena that reveals the essence of quantum mechanics, and contains a deep mystery about the existence of matter. However, current understanding of this remains superficial. It is difficult to understand that matter or photons choose one state among particle or wave depending on the situation*. If there is a correct theory, there must be a clear reason for having a particular state in a particular situation. The reality of quantum mechanical existence presented in this paper is as follows. A nonlocal wave causes a wave collapse at a specific interaction to acquire particle properties, and when the interaction disappears, the wave properties are restored. This process is repeated.

Speaking of electromagnetism, fields with local properties are real, and their waves (as nonlocal waves) are real, and photons formed by the collapse of waves are real. We discussed earlier that the quantum of a photon energy should depend only on its frequency, but there is one more thing to consider here. When an electromagnetic wave is generated by kinks caused by the acceleration of an electric charge, the amount of the charge becomes a variable of the photon energy. The quantum concept of photon energy is established only when the charge amount of all free elementary particles is the same. In reality it is. That is, quantization of photon energy is established by quantization of charge.

5 Bound state and scattering

In terms of discrete time, interacting particles satisfy the modified Dirac equation [2].

$$\mathrm{D_m}\Psi = \left(i\gamma^\mu\partial_\mu - f_{1r}\gamma^\mu p_\mu - f_{2r}\gamma^\mu\Delta p_\mu\right)\Psi = 0\,. \qquad (2)$$

where

$$\begin{aligned} f_{1r} &= \mathrm{Re}(f_1) = \frac{1}{3}\,\mathrm{Re}\left(\frac{\mathrm{e}^{-ix^\alpha p_\alpha}}{\mathrm{e}^{-ix^\alpha p_\alpha} + 2\left(\mathrm{e}^{-ix^\alpha \Delta p_\alpha} - 1\right)}\right) \\ f_{2r} &= \mathrm{Re}(f_2) = \frac{1}{3}\,\mathrm{Re}\left(\frac{2\mathrm{e}^{-ix^\alpha \Delta p_\alpha}}{\mathrm{e}^{-ix^\alpha p_\alpha} + 2\left(\mathrm{e}^{-ix^\alpha \Delta p_\alpha} - 1\right)}\right). \end{aligned} \qquad (3)$$

Eq. (2) is a first-order linear differential equation, and the way it is applied differs depending on the type of interaction

*Wheeler's delayed choice experiment clearly shows the contradiction of the existing quantum mechanical view of duality. And the Elitzur–Vaidman bomb tester claims that interaction-free measurements are possible based on the existing viewpoint. In my next paper, I will present a new interpretation of these experiments from the new perspective presented above.

– scattering and bound state. In the case of the scattering process, for example, the scattering of electron and photon interacts in an extremely limited space-time region, so the modified Dirac equation is also applied only in such a limited space-time region. On the other hand, in the case of ceaseless interaction, such as in the bound state, the modified Dirac equation holds without limitation because the interaction occurs in a relatively wide space-time region.

5.1 Bound state

5.1.1 $\Delta \mathbf{p}_\mu \ll \mathbf{p}_\mu$

In this case, that is, when the interaction is very small, f_{1r}, f_{2r}, and the modified Dirac equation is as follows

$$\begin{aligned} & f_{1r} \cong \frac{1}{3}, \quad f_{2r} \cong \frac{2}{3}\cos\left(x^\alpha p_\alpha\right) \\ & \left(i\gamma^\mu \partial_\mu - \frac{1}{3}\gamma^\mu p_\mu - \frac{2}{3}\cos\left(x^\alpha p_\alpha\right)\gamma^\mu \Delta p_\mu\right)\Psi = 0\,. \end{aligned} \tag{4}$$

The solution of (4) satisfies the following equation

$$\partial_\mu \Psi = -\frac{i}{3}\left(p_\mu + 2\cos\left(x^\alpha p_\alpha\right)\Delta p_\mu\right)\Psi. \tag{5}$$

And the solution of (5) is as follows

$$\begin{aligned} \Psi &= c\,\exp\left[-\frac{i}{3}\int^{x^\mu}\left(p_\mu + 2\cos\left(x'^\alpha p_\alpha\right)\Delta p_\mu\right)dx'^\mu\right] \\ &= c\,\exp\left[-\frac{i}{3}p_\mu x^\mu - \frac{2i}{3}\int^{x^\mu}\cos\left(x'^\alpha p_\alpha\right)\Delta p_\mu dx'^\mu\right]. \end{aligned} \tag{6}$$

Δp_μ means interaction, so it is determined according to the specific situation. If it is an electrostatic potential like the potential in a hydrogen atom, Δp_μ is independent of the integral variable in (6) because there is only a scalar potential energy component that is independent of time. Thus

$$\Psi = c\,\exp\left[-\frac{i}{3}\left(p_\mu x^\mu + 2\epsilon\left(\Delta p_\mu\right)\sin\left(x^\mu p_\mu\right)\right)\right]. \tag{7}$$

$\epsilon\left(\Delta p_\mu\right)$ is a small quantity linear to Δp_μ. In (7), for Ψ to be a free wave, i.e. harmonic oscillation, $\sin\left(x^\mu p_\mu\right) = 0$, so the following quantum condition is derived

$$x^\mu p_\mu = n\pi \;\; (n = 0, \pm 1, \pm 2, \cdots)\,. \tag{8}$$

For any given p_μ, x^μ that satisfies (8) has as its solution a certain region in space-time. Harmonic oscillations that exist in this region can be referred to as standing waves. As a simple example, consider the case where the electron in a hydrogen atom is in uniform circular motion. In this case, the phase value is as follows

$$\begin{aligned} \oint\left(E dt - \vec{P}\cdot d\vec{x}\right) &= E\oint dt - \vec{P}\cdot\oint d\vec{x} \\ &= -mvr\pi = n\pi \\ \therefore L = mvr = n\,. \end{aligned} \tag{9}$$

Eq. (9) agrees with the well-known Bohr's quantum condition for the hydrogen atom.

In (7), when $\epsilon \to 0$, the 4-momentum appearing in the phase part is not p_μ but $p_\mu/3$. This result is questionable because the system we are dealing with is a system in which a free particle with 4-momentum p_μ becomes $p_\mu + \Delta p_\mu$ by interaction. However, as we will see later, this does not violate the law of conservation of energy at all.

In the case of $\Delta p_\mu \to 0$, if $\gamma^\mu p_\mu = m$ is used, (4) can be expressed as follows

$$i\frac{\partial \Psi}{\partial t} = \left(\vec{\alpha}\cdot\hat{P} + \frac{1}{3}\beta m\right)\Psi\,. \tag{10}$$

In (7), the free wave solution is as follows for $\epsilon \to 0$

$$\Psi = \begin{pmatrix}\varphi \\ \chi\end{pmatrix}\exp\left(-\frac{i}{3}x^\mu p_\mu\right). \tag{11}$$

In (11), φ and χ are two-component spinors. Using (12), (10) becomes (13)

$$\frac{\partial \Psi}{\partial t} = \frac{1}{3}E\Psi, \;\; \hat{P}\Psi = \frac{1}{3}\vec{P}\Psi\,. \tag{12}$$

$$E\Psi = \left(\vec{\alpha}\cdot\vec{P} + \beta m\right)\Psi\,. \tag{13}$$

In (13), the energy of Ψ is $\pm\sqrt{\vec{P}^2 + m^2}$, which is equal to the energy of the free particle before interaction. So, as expected, energy is conserved.

5.1.2 $\Delta \mathbf{p}_\mu = \mathbf{p}_\mu$

In this case, the modified Dirac equation is:

$$\left\{i\gamma^\mu\partial_\mu - \left(f_{1r} + f_{2r}\right)m\right\}\Psi = 0\,. \tag{14}$$

$$\begin{aligned} G\left(x^\mu\right) &\overset{\text{def}}{=} f_{1r} + f_{2r} = \mathrm{Re}\left(\frac{1}{3 - 2e^{ix^\mu p_\mu}}\right) \\ &= \frac{3\cos\left(x^\mu p_\mu\right) - 2}{13 - 12\cos\left(x^\mu p_\mu\right)}\,. \end{aligned} \tag{15}$$

In (14), the condition for Ψ to become a plane wave in a specific space-time region is that G must be constant, which means that G has an extreme value in that region. Therefore, the following condition must be satisfied

$$\partial_\lambda G\left(x^\mu\right) = -\frac{15\;p_\lambda\sin\left(x^\mu p_\mu\right)}{\left(13 - 12\cos\left(x^\mu p_\mu\right)\right)^2} = 0\,. \tag{16}$$

Eq. (16) is the same quantum condition as in $\Delta p_\mu \ll p_\mu$.

Eq. (14) is related to pair production. If Δp_μ is the 4-momentum of the incident photon and $p_\mu = p_\mu^{elctron} + p_\mu^{positron}$, that is, the sum of the 4-momentum of the electron and the positron, Ψ in (14) becomes the wave function for the entire electron and positron. This plane wave will persist until a new interaction occurs. If an interaction occurs on one side (electron) of this free wave, the whole system will be affected at the same time due to the characteristics of nonlocal waves, so the other side (positron) will also "experience the same interaction at the same time". This can be said to be the mechanism of entanglement.

5.2 Scattering

In the case of elastic scattering, there is no change in the energy of the incident particle. That is, since $\Delta p_0 = 0$ and $|\vec{P'}| = |\vec{P}|$ hold, the incident wave and the reflected wave have the same wavelength, so it is predicted that wave collapse will not occur when they interact. Assuming that the interaction occurs within the range of Δt during elastic scattering, $\Delta p_\mu = 0$ and $f_{1r} = 1/3$ just before and after the interaction, so the following free wave equation is established

$$\left(i\gamma^\mu \partial_\mu - \frac{1}{3}m\right)\Psi = 0\,. \qquad (17)$$

On the other hand, in inelastic scattering, there is a change in the energy of the incident particle and the target particle. This means that the properties of the wave before and after the interaction are different. The mechanism that enables this process is the concept of wave collapse discussed in section 4. During inelastic scattering, a nonlocal wave instantly collapses and becomes a particle state. In this particle state, energy and momentum are exchanged, and as a result, a new wave corresponding to new energy and momentum is formed. We will now present a model for this wave collapse.

When an interaction occurs in a local region in space-time, the modified Dirac equation is also applied only in a local region. In this case, f_{1r} and f_{2r} must, of course, be quantities defined in a local region. Therefore, f_{1r} and f_{2r} must be corrected to converge to 0 at large x^μ. In this case, the collapse of the wave inevitably occurs.

In order to model the wave collapse during inelastic scattering, we introduce a damping factor ϵ_μ that satisfies the following condition

$$\begin{aligned} &x^\mu = \left(t, \left|\vec{x}\right| \hat{n}_{\vec{x}}\right), \quad \epsilon_\mu = \left(\epsilon_0, \left|\vec{\epsilon}\right| \hat{n}_{\vec{\epsilon}}\right) \\ &\mathrm{e}^{-\epsilon_\mu x^\mu} \to 0, \;\text{ as }\; x^\mu \to \infty, \;\text{ for }\; \hat{n}_{\vec{x}} \cdot \hat{n}_{\vec{\epsilon}} = -1\,. \end{aligned} \qquad (18)$$

And if the new 4-momentum p'_μ is defined as follows, the modified Dirac equation and f'_{1r}, f'_{2r} are as follows. For simplicity, we will discuss wave collapse for the special case $\Delta p_\mu = a p_\mu$ (a is a real number)

$$\begin{aligned} &p'_\mu = p_\mu - i\epsilon_\mu \\ &\left\{i\gamma^\mu \partial_\mu - \left(f'_{1r} + a f'_{2r}\right)\gamma^\mu p'_\mu\right\}\Psi = 0\,. \end{aligned} \qquad (19)$$

where

$$\begin{aligned} f'_{1r} &= \frac{1}{3}\,\mathrm{Re}\left(\frac{\mathrm{e}^{-ix\cdot p'}}{\mathrm{e}^{-ix\cdot p'} + 2\left(\mathrm{e}^{-iax\cdot p'} - 1\right)}\right) \\ &= \frac{1}{3}\,\mathrm{Re}\left(\frac{\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-ix\cdot p}}{\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-ix\cdot p} + 2\left(\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-iax\cdot p} - 1\right)}\right) \\ f'_{2r} &= \frac{2}{3}\,\mathrm{Re}\left(\frac{\mathrm{e}^{-iax\cdot p'}}{\mathrm{e}^{-ix\cdot p'}\mathrm{e}^{-ix\cdot p} + 2\left(\mathrm{e}^{-iax\cdot p'} - 1\right)}\right) \\ &= \frac{2}{3}\,\mathrm{Re}\left(\frac{\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-iax\cdot p}}{\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-ix\cdot p} + 2\left(\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-iax\cdot p} - 1\right)}\right). \end{aligned} \qquad (20)$$

In (20), both f'_{1r} and f'_{2r} converge to 0 at large x^μ by $\mathrm{e}^{-\epsilon_\mu x^\mu}$ factor. Now let's find the solution of (19)

$$\begin{aligned} &\partial_\mu \Psi = -\frac{i}{3} p'_\mu \left(1 + S'\right)\Psi \\ &\text{where }\; S'(x) = \mathrm{Re}\left(\frac{2\,(a-1)\,\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-iax\cdot p} + 2}{\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-ix\cdot p} + 2\left(\mathrm{e}^{-\epsilon\cdot x}\mathrm{e}^{-iax\cdot p} - 1\right)}\right). \end{aligned} \qquad (21)$$

$$\begin{aligned} \Psi &= c\,\exp\left\{-\frac{i}{3}\,p'_\mu \int^{x^\mu} \left(1 + S'\right) dx'^\mu\right\} \\ &= c\,\exp\left\{-\frac{i}{3}\left(x^\mu p_\mu + p_\mu \int^{x^\mu} S' dx'^\mu\right)\right\} \times \\ &\times \exp\left(-\frac{1}{3}\,\epsilon_\mu x^\mu - \frac{1}{3}\,\epsilon_\mu \int^{x^\mu} S' dx'^\mu\right). \end{aligned} \qquad (22)$$

As expected, since the factor $\mathrm{e}^{-\frac{1}{3}\epsilon_\mu x^\mu}$ exists in Ψ, it converges to 0 at large t. This means the collapse of the wave.

Of course, these results are different from the concept of simultaneous wave collapse of nonlocal waves discussed above. The reason is the fundamental limitation of the modified Dirac equation. Since the modified Dirac equation does not accurately represent the behavior of non-local waves, but approximates it to the behavior of local waves in continuous space-time, it cannot describe concepts such as simultaneous collapse of waves. But, it can be said that it has value as a model of wave collapse. On the other hand, in the interaction such as the bound state, there is no phenomenon such as wave collapse, but a standing wave is formed, so the modified Dirac equation representing the behavior of a local wave represents the exact behavior of the wave.

6 Conclusions

One of the most important concepts inferred from the discretization of time is the nonlocality of matter and electromagnetic waves. The nonlocality of waves can naturally cause wave collapse when interacting. This state of wave collapse means particle nature and also corresponds to the quantum state. What this paper concludes about the wave-particle duality is that particle and wave properties are not selected by matter according to circumstances, but are determined only by the way of interaction. It is done by analysis of the modified Dirac equation.

Interactions can be divided into bound states and scattering, which are all described by the modified Dirac equation. Quantum conditions can be obtained in a bound state, which is expected to be the same as in conventional quantum mechanics. Scattering can be divided into elastic scattering and inelastic scattering, both of which are forms of interaction. Elastic scattering is related to wave nature and inelastic scattering is related to particle nature. According to the analysis of the modified Dirac equation, the wave nature is expressed in all bound states and elastic scattering. An example is the Davisson–Germer experiment which demonstrates the wave nature of electrons. The particle nature correspond to the case of inelastic scattering. Examples include the photoelectric effect and Compton scattering.

The particle nature resulting from the collapse of nonlocal waves encompasses the quantum concept of the existing quantum mechanics, and the nonlocal wave concept encompasses the existing classical field. For matter (nonlocal waves, and particle nature due to wave collapse), and for electromagnetics (classical fields, nonlocal waves, and particle nature due to wave collapse), each stage of existence participates in interaction as a physical reality.

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