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Heuristic Solution to the Conundrum of the *Zitterbewegung*

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Abstract

Assuming the Dirac wavefunction describes the state of a single particle. We propose that the relation derived by Schrödinger, which contains the *Zitterbewegung* term, is a position equation for an amplitude modulated wave. Namely, the elementary constituents are amplitude modulated waves. Indeed, we surmise that a second wave is associated with the particle, which corresponds to a signal. At the same time, we interpret that Broglie's wave corresponds to a carrier. Furthermore, the quantum object is a recording medium and, like in a hologram, information encoded on its surface. We suggest a description and the cause of the *Zitterbewegung* heretofore never considered regarding the previous assertions. Hereunder, we shall also apply the quantum amplitude modulation interpretation to the single-photon wave function by Bialynicki-Birula. The predictions are testable, thence providing evidence for the proposed hypothesis.

Keywords

Zitterbewegung, Electron, Photon, Photon Wave Function, Maxwell's Equations, Measurement Problem

1. Introduction

Per the analysis by Schrödinger of the position operator regarding Dirac's relativistic formalism [1], the free particle, along with its translational motion, ought to exhibit an oscillatory activity that he called the *Zitterbewegung* [2]. The prediction is a high-frequency oscillation at the speed of light in a vacuum with amplitude half the reduced Compton wavelength. The *Zitterbewegung* has been the subject of many studies and discussed in detail in numerous books and papers [3]-[10]. However, after almost a hundred years, it remains an elusive enigma, because there is no consensus on or knowledge of its cause or description and technological constraints. Its comprehension is paramount, because it is a consequence of the theory at the foundations of quantum electrodynamics.

Some researchers have proposed models that eliminate the "problem" of the *Zitterbewegung*. In contrast, other researchers allege they have observed the *Zitterbewegung* indirectly, simulated by trapped-ion experiments [11] and in a Bose-Einstein condensate [12]. However, the accepted interpretation explains that the *Zitterbewegung* is due to the interference of positive and negative energy plane waves. For the reason that when applying the Foldy-Wouthuysen [13] transformation to wave packets of entirely positive or negative plane waves, there is no *Zitterbewegung* term. Moreover, in quantum electrodynamics, the Dirac wave function does not describe just the state of an electron, but it also contains a part relating to the positron. Indeed, the positive and negative plane waves are interpreted or replaced by a particle-antiparticle annihilating pair, and when the function describing the electron is separated, the *Zitterbewegung* disappears.

Nonetheless, with a fundamental relation between sine and exponential functions, manipulating the *Zitterbewegung* term in the position equation resembles the mathematical representation of amplitude-modulated waves. Therefore, suggesting quantum objects described by Dirac's relativistic formalism are amplitude modulated waves and, the Dirac wave function represents a single entity. There is amplitude modulation interference among the wave packet's positive and negative waves. The positive and negative waves are analogous to a signal and carrier wave. The elementary constituent is a system of two interfering undulations, and the particle is an emergent phenomenon.

A novel interpretation of the quantum theory follows naturally from the Dirac theory, the amplitude modulation hypothesis. At our present technological height, we modulate waves to convey information. Consequently, the quantum object is an information carrier encrypted on its surface. The amount of data is one bit, reminding us of John Archibald Wheeler's famous phrase "it from bit". The mechanism that encrypts information on the surface is the *Zitterbewegung*, an epiphenomenon interpreted here as the expansion and contraction of the elementary constituent [14]. Therefore, regarding the formalism of the Dirac equation, it is our impression that it describes the encoding and transfer of information through a communication channel. This channel is the vacuum or any other medium.

The *Zitterbewegung* for massless quantum objects like photons defers from those with rest mass. Nevertheless, we interpret the proposed wave function for the photon by Bialynicki-Birula amongst others [15] [16] regarding the amplitude modulation interpretation. Consequently, we suggest testable predictions about the photon, illustrating the photon's *Zitterbewegung* and introducing the correct matrices that encode Maxwell's equations in a Dirac-Schrödinger type equation.

2. Quantum Amplitude Modulation

Dirac was not content regarding the Klein-Gordon equation. He sought to obtain a Schrödinger type relativistic wave equation that was first order in time and always gave a positive probabilistic density compared to the Klein-Gordon equation. To achieve his quest, he needed the square root of the relativistic energy-momentum expression. In the subsequent, p represents the momentum, c is the speed of light in a vacuum, $\mathcal{E}$ the energy, m is the relativistic mass, and m_0 the invariant mass.

$$\mathcal{E}^2 = p^2c^2 + m_0^2c^4 \tag{1}$$

Indeed, Dirac factored the equation above with original ineffable insight and obtained his relativistic Hamiltonian H.

$$H = c\boldsymbol{\alpha}\cdot\boldsymbol{p} + m_0c^2\beta. \tag{2}$$

Thus, as a consequence of the Hamiltonian, the time dependence of the position operator of the free particle, calculated in the Heisenberg representation, is the following velocity, where $\hbar$ is the reduced Planck constant, x the position, t time, and i the imaginary unit.

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{i}{\hbar}\left[\boldsymbol{x}, H\right] = c\boldsymbol{\alpha} = \boldsymbol{u} \tag{3}$$

The above, an element of the Dirac Hamiltonian, is the Dirac velocity $\boldsymbol{u}$, and its constituents are 4×4 matrices that, along with β, are known as the gamma matrices. This result is unorthodox since the matrices' eigenvalues are ±1, implying that the absolute value of the particle's velocity in each spatial direction is c. Furthermore, the velocity is not a constant of motion, and its components do not commute with each other or with the Hamiltonian and the momentum; therefore, they cannot be measured simultaneously [17] [18] [19]. Since the velocity is not a constant of motion, Schrödinger found the acceleration that follows where $\omega = H/\hbar$ is an angular frequency.

$$\dot{\boldsymbol{u}} = -2c\omega i\left(\boldsymbol{\alpha}(0) - cH^{-1}\boldsymbol{p}\right)\mathrm{e}^{-2i\omega t}. \tag{4}$$

Since we interpret the Dirac wavefunction describes the state of a single particle. Notice that in the previous equation, there is a dimensionless operator. We will treat it as a unit vector, thus denoting it by $\boldsymbol{\zeta}$. That is, we shall commence the heuristic analysis by assuming that the *Zitterbewegung* has a coordinate system.

$$\boldsymbol{\zeta} = \left(\boldsymbol{\alpha}(0) - cH^{-1}\boldsymbol{p}\right) \tag{5}$$

From this perspective, expanding the exponential term in Equation (4) illustrates the classical equation of acceleration in simple harmonic motion.

$$\dot{\boldsymbol{u}} = -a\left(\sin(2\omega t) + i\cos(2\omega t)\right)\boldsymbol{\zeta} \tag{6}$$

Because it is a free particle, and again, from the perspective of the coordinate system, the acceleration ($a = 2c\omega$) must be internal, suggesting that it has a substructure, subject to two hook-type forces. These forces are out of phase, opposite, and equal magnitude.

Integrating the acceleration, Schrödinger obtained another equation for Dirac's velocity.

$$\boldsymbol{u} = c^2 H^{-1} \boldsymbol{p} + c\mathrm{e}^{-2i\omega t} \boldsymbol{\zeta} \tag{7}$$

The first term in the previous equation is the velocity of a free particle, and, undeniably, it is a group velocity.

$$\boldsymbol{v} = c^2 H^{-1} \boldsymbol{p}. \tag{8}$$

The expression allows the interpretation of Dirac's velocity as phase velocity since rearranging Equation (7) provides a case of Rayleigh's formula, which relates the phase velocity and the group velocity of a wave packet. Furthermore, Pauli's covariant equation is an alternate way to reach the previous conclusion. Pauli formulated Dirac's Hamiltonian in the following covariant form, where γ^μ is a four-vector, in which the space-part is $c\beta\boldsymbol{\alpha}$, and the time-part is $c\beta$.

$$m_0 c^2 = \gamma^\mu p_\mu \tag{9}$$

By comparing the Pauli covariant equation to the phase velocity definition, we deduce that the four-vector, γ^μ is a phase velocity. Therefore, the dilemma that arises from the eigenvalues of the components of Dirac's velocity, found to be troubling because a particle with mass cannot move at light speed, is resolved since we are dealing with a phase velocity, the interference displaces at the rate of the group velocity, rather than that of the phase velocity. We obtain the harmonic oscillator's speed equation by expanding the second term of Equation (7).

$$\boldsymbol{u} = c\left(\cos(2\omega t) - i\sin(2\omega t)\right)\boldsymbol{\zeta} \tag{10}$$

While the interference displaces at the group velocity rate, there is a superimposed oscillation at the speed of light in the vacuum.

Schrödinger continued the examination by integrating the velocity and obtained the following position equation:

$$\boldsymbol{x}(t) = \boldsymbol{x}(0) + c^2 H^{-1} \boldsymbol{p}t + \frac{1}{2} i\hbar c H^{-1}\left(\mathrm{e}^{-2i\omega t} - 1\right)\boldsymbol{\zeta} \tag{11}$$

The first two terms are the position of a particle moving at the group velocity, and the third term is the *Zitterbewegung*, $\boldsymbol{x}_z(t)$. The maximum amplitude of this harmonic oscillation is half the reduced Compton wavelength ($\lambda_r = c\hbar H^{-1}$). The amplitude is equivalent to the fundamental harmonic of a standing wave. The Compton wavelength is considered a particle property relevant to all material particles [20]. Although obtained by applying energy and momentum principles to photons' scattering by electrons, this length appears in quantum phenomena that do not do with scattering. The accepted significance of the Compton wavelength of a particle is the wavelength of a photon whose energy is identical to that particle's invariant mass. However, it is impossible to understand its role in the *Zitterbewegung* and other quantum phenomena with this definition. We interpret that the *Zitterbewegung* relates with the Compton wavelength regarding the amplitude of the elementary constituent's surface oscillations.

$$\boldsymbol{x}_z(t) = \frac{\lambda_r}{2}\left(\sin(2\omega t) + i\cos(2\omega t)\right)\boldsymbol{\zeta} - i\frac{\lambda_r}{2}\boldsymbol{\zeta}. \tag{12}$$

Equation (12), the expansion of the *Zitterbewegung* term, describes a harmonic motion, or pulsation, which occurs around the "stable" kernel of the particle, represented by the second term, which has the same magnitude as the oscillation. The reduced Compton wavelength represents the maximum radius of the free particle. Hence, the relativistic reduced Compton wavelength is the radius of the particle. From this point of view, this length's persistent occurrence, in quantum results, is comprehensible.

$$\lambda_r \to \frac{\hbar c}{\mathcal{E}} = \frac{\hbar}{m_0 c}\sqrt{1-\frac{v^2}{c^2}} \tag{13}$$

The relativistic reduced Compton wavelength is speed-dependent. Therefore a change in the internal structure accounts for results obtained for electrons in scattering experiments. The outcomes from these experiments, conducted at energies around 29 GeV, restricted the particle size to 10^{-18} m or smaller [21]. Thus, researchers interpreted the observation as indicating that the electron is a point particle. However, the reduced relativistic Compton wavelength at the energy range of the experiment is in that order providing evidence for this hypothesis. Technically the elementary constituent resembles a resonating cavity, whose surface has the behavior of a harmonic oscillator. The previous analysis does not reveal the nature of the interference phenomena we are dealing with; however, with the following relation between exponential functions and sine:

$$\sin(\omega t) = \frac{1}{2i}\left(\mathrm{e}^{i\omega t} - \mathrm{e}^{-i\omega t}\right). \tag{14}$$

The *Zitterbewegung* term takes the form of the mathematical representation of an amplitude-modulated wave.

$$\boldsymbol{x}_z(t) = \lambda_r \sin(\omega t)\mathrm{e}^{-i\omega t}\boldsymbol{\zeta} \tag{15}$$

That suggests that the interference that generates the wave packet is an amplitude modulation. Hence, the particle is the interference of two waves, one equivalent to a signal and the other to a carrier, and the bandwidth frequency is the *Zitterbewegung* frequency. These waves' functions are possible to obtain by rewriting the *Zitterbewegung* term as follows, since, wherein the most straightforward amplitude modulation scheme, the modulating signal is usually a sine function. In the following, the amplitude of the signal and carrier, represented by λ_s and λ_c, respectively, and κ is a proportionality constant such that $\kappa\lambda_s\lambda_c = \lambda_r$.

$$\boldsymbol{x}_z(t) = \kappa\left(\lambda_s \sin(\omega t)\right)\left(\lambda_c \mathrm{e}^{-i\omega t}\right)\boldsymbol{\zeta} \tag{16}$$

The velocity associated with the signal is the group velocity in wave packets. Therefore, the carrier is de Broglie's wave. Since the waves are coherent, the wave parameter equations that associate the wavelength to the speed and frequency f are the following.

$$\lambda_s f = v, \quad \lambda_c f = u \tag{17}$$

The following are the functions where h is Planck's constant, and the value of the proportionality constant is, $\kappa = 1/\left(4\pi^2\lambda_r\right)$, given that $\lambda_s\lambda_c = 4\pi^2\lambda_r^2$.

$$y_s(t) = \frac{h}{mu}\sin(\omega t) = \lambda_s \sin(\omega t), \quad y_c(t) = \frac{h}{mv}\mathrm{e}^{-i\omega t} = \lambda_c \mathrm{e}^{-i\omega t} \tag{18}$$

The signal's quotient is the momentum connected to the phase velocity [22]: subsequently, the quantum object has two linear momentums.

Researchers have proposed that the *Zitterbewegung* is a circulatory motion that generates the spin and other related phenomena. The *Zitterbewegung*, according to Hestenes and Rivas [23] [24], is a helical motion. That is, the displacement of the particle is a helix. Indeed Hestenes suggest that the helical motion causes a rotating electric dipole moment and argues that the observed resonance in electron channeling experiments conducted by Gouanère *et al.* is due to the interaction of the dipole field with the crystal lattice [25]. The dissection of the *Zitterbewegung* term illustrates that it is the combination of four oscillatory movements. The following are the position terms of the oscillatory motions, which, we propose, represent a nutation, precession, self-orbital angular momentum, and the spin in that order.

$$\frac{1}{2}i\hbar c^2 H^{-2}\boldsymbol{p}, \ -\frac{1}{2}i\hbar c^2 H^{-2}\mathrm{e}^{-2i\omega t}\boldsymbol{p}, \ \frac{1}{2}i\hbar c H^{-1}\mathrm{e}^{-2i\omega t}\boldsymbol{\alpha}(0), \ -\frac{1}{2}i\hbar c H^{-1}\boldsymbol{\alpha}(0) \tag{19}$$

There are two angular momentums for each linear momentum associated with the elementary constituent. The nutation and precession are related to the signal and, the others, to the carrier. The vibrations of these intrinsic angular momentum states are synchronized periodic motions like a clock. Because of frequency differences, particles, such as electrons, do not return to their initial phase after a 360˚ rotation. Indeed, the nutation coupled to the precession and the spin coupled to the self-orbital momentum. The nutation and spin complete a cycle at the particle frequency. The precession and orbital motion at the *Zitterbewegung* frequency explain why the electron returns to its original state only after a 720˚ rotation. The nutation and self-orbital momentum generate oscillating electric dipoles, while the precession, like the spin, should cause another magnetic dipole moment for the electron. One of the electric dipoles is proportional to the de Broglie wavelength and vibrates at the *Zitterbewegung* frequency. At the same time, the other is proportional to the signal wavelength vibrating at the particle frequency. The intrinsic electric dipoles differ from those predicted by some versions of the Standard Model since these do not violate the principle of time-reversal symmetry.

3. Single-Particle Entropy

The modulation of waves accomplishes the transmission of information. In amplitude modulation, the instantaneous fluctuation of the signal amplitude induces modifications in the carrier's amplitude, which in the case at hand, causes the surface of the wave packet to expand and contract. Therefore since the Dirac velocity components are not equal, the oscillation is not in phase in all spatial directions, creating distortions on the surface membrane while maintaining a constant area. Accordingly, analogous to holograms, information encoded on a surface, in the fluctuation patterns, the maximums, and minimums generated by the *Zitterbewegung*. There is a connection between entropy and the information capacity of a system. With the precise mathematical partition function, it is possible to obtain the entropy S of the system. There is a proposed entropy function for the single-particle [26]. However, applying statistical mechanics to systems with few elements determined by quantum rules is unclear for some researchers. In principle, it might not apply to a single particle [27]. Once more, we shall assume the single-particle has entropy and estimate the information it conveys through a heuristic approach. Thus, we will treat the two-wave system as a classical system since it has the behavior of the harmonic oscillator, subject to two forces with the following magnitude: k represents the surface membrane's stiffness.

$$F = \frac{1}{2}\lambda_r k \tag{20}$$

Because the system's natural frequency is the *Zitterbewegung* frequency, the k constant has the following value:

$$k = \frac{4\hbar c}{\lambda_r^3}. \tag{21}$$

Each wave contributes to the energy of the system; therefore, the maximum potential energy is:

$$\mathcal{E} = \frac{1}{4}k\lambda_r^2. \tag{22}$$

We are dealing with the quantum object's inner workings, of which there is no knowledge. Therefore, suppose the equipartition theorem applies to the system and equates to its energy. We obtain the following relation where κ_B is Boltzmann constant, and T is the absolute temperature on the wave packet membrane;

$$\kappa_B T = \frac{1}{4}k\lambda_r^2. \tag{23}$$

The previous equation associates the temperature and acceleration of the surface and resembles the Fulling-Unruh-Davis effect equation by a π factor.

$$T = \left(\frac{\hbar}{2c\kappa_B}\right)a \tag{24}$$

The temperature fluctuates at the *Zitterbewegung* frequency. The relation above also reveals that surface regions reach temperatures higher than the closest star's interior for a particle like an electron. From introductory thermodynamics, if a surface has a temperature, it radiates; it emits photons; that is, the system loses energy. Nonetheless, the energy of a free particle is a constant of motion. Therefore, the electron has come to equilibrium by emitting and absorbing photons; it has a fluctuating gas of photons surrounding it, thereby illustrating another enigmatic result of the Dirac theory:

$$\frac{\mathrm{d}H}{\mathrm{d}t} = -q\boldsymbol{u} \cdot \boldsymbol{E}. \tag{25}$$

The prior is a power equation, where q represents charge, and $\boldsymbol{E}$ is the electric field strength, indicating the electron's energy and electric field fluctuates. Regarding Equation (23), we obtain the magnitude of a force, which is equivalent to that in relation (20).

$$F = \frac{2}{\lambda_r}\kappa_B T \tag{26}$$

This active force is proportional to the temperature; therefore, it is an entropic force, which is phenomenological and not fundamental. The system's statistical tendency to maximize its entropy generates them. This force is perpendicular to the particle surface, where entropy increases [28].

$$T\mathrm{d}S = F\mathrm{d}x \tag{27}$$

The system's entropy equals Boltzmann's constant by substituting Equation (26) and the *Zitterbewegung* amplitude as the integration limit in this version of the second law of thermodynamics.

$$S = \int \frac{F}{T}\mathrm{d}x = \kappa_B \tag{28}$$

Hence, regarding entropy as information, it is equivalent to one bit; each elementary constituent carries or can encode a binary unit of information.

4. Riemann-Silberstein (R-S) Vectors

The previous analysis corresponds to particles with rest mass. For a massless particle like the photon, the phase velocity equals the group velocity; therefore, Equation (5) equals zero. However, as we shall see, the photon also has a particular "trembling motion" and conveys a binary unit of information. We reach this conclusion by interpreting the consequences of applying the amplitude modulation hypothesis to the single-photon wave function Bialynicki-Birula and other researchers proposed. The following equations represent the (R-S) vectors $\boldsymbol{\Gamma}_1$ and its complex conjugate $\boldsymbol{\Gamma}_1^*$ [29], where $\boldsymbol{B}$ is the magnetic field strength and ε_0 the vacuum permittivity.

$$\boldsymbol{\Gamma}_1 = \sqrt{\frac{\varepsilon_0}{2}}\left(\boldsymbol{E} + ic\boldsymbol{B}\right),\ \boldsymbol{\Gamma}_1^* = \sqrt{\frac{\varepsilon_0}{2}}\left(\boldsymbol{E} - ic\boldsymbol{B}\right) \tag{29}$$

According to Bialynicki-Birula, the functions expressed in monochromatic plane waves reveal that each R-S vector represents the photon in a specific helicity and polarization state. Also, they each have equal energy with opposite signs, and each component evolves independently in the vacuum. Therefore, it is necessary to have both vectors to have a complete description of the photon, forming a six-component wave function $\boldsymbol{I}$.

$$\boldsymbol{I} = \begin{pmatrix} \boldsymbol{\Gamma}_1 \\ \boldsymbol{\Gamma}_1^* \end{pmatrix} \tag{30}$$

where the product is the energy per unit volume stored in a photon,

$$\boldsymbol{I}\cdot\boldsymbol{I}^{\dagger}=\frac{\varepsilon_0}{2}\left(E^2+c^2B^2\right)\begin{pmatrix}1\\1\end{pmatrix}. \tag{31}$$

Namely, the proposed wave function is a superposition of quantum states that propagate independently. We commence the analysis by introducing other complex vectors that, with the previous pair, complete a set of eight elements.

$$\boldsymbol{\Gamma}_2=\sqrt{\frac{\varepsilon_0}{2}}\left(i\boldsymbol{E}-c\boldsymbol{B}\right),\ \boldsymbol{\Gamma}_2^*=\sqrt{\frac{\varepsilon_0}{2}}\left(-i\boldsymbol{E}-c\boldsymbol{B}\right)$$

$$\boldsymbol{\Gamma}_3=\sqrt{\frac{\varepsilon_0}{2}}\left(-\boldsymbol{E}-ic\boldsymbol{B}\right),\ \boldsymbol{\Gamma}_3^*=\sqrt{\frac{\varepsilon_0}{2}}\left(-\boldsymbol{E}+ic\boldsymbol{B}\right)$$

$$\boldsymbol{\Gamma}_4=\sqrt{\frac{\varepsilon_0}{2}}\left(-i\boldsymbol{E}+c\boldsymbol{B}\right),\ \boldsymbol{\Gamma}_4^*=\sqrt{\frac{\varepsilon_0}{2}}\left(i\boldsymbol{E}+c\boldsymbol{B}\right)$$

These complex vectors are associated; thereby, knowing one of them, generating the rest is straightforward.

$$\boldsymbol{\Gamma}_1=i\boldsymbol{\Gamma}_4,\ \boldsymbol{\Gamma}_4=i\boldsymbol{\Gamma}_3,\ \boldsymbol{\Gamma}_3=i\boldsymbol{\Gamma}_2,\ \boldsymbol{\Gamma}_2=i\boldsymbol{\Gamma}_1 \tag{32}$$

$$\boldsymbol{\Gamma}_4^*=i\boldsymbol{\Gamma}_1^*,\ \boldsymbol{\Gamma}_3^*=i\boldsymbol{\Gamma}_4^*,\ \boldsymbol{\Gamma}_2^*=i\boldsymbol{\Gamma}_3^*,\ \boldsymbol{\Gamma}_1^*=i\boldsymbol{\Gamma}_2^* \tag{33}$$

$$\boldsymbol{\Gamma}_1=-\boldsymbol{\Gamma}_3,\ \boldsymbol{\Gamma}_2=-\boldsymbol{\Gamma}_4,\ \boldsymbol{\Gamma}_1^*=-\boldsymbol{\Gamma}_3^*,\ \boldsymbol{\Gamma}_2^*=-\boldsymbol{\Gamma}_4^* \tag{34}$$

$$\boldsymbol{\Gamma}_1+\boldsymbol{\Gamma}_2+\boldsymbol{\Gamma}_3+\boldsymbol{\Gamma}_4=0,\ \boldsymbol{\Gamma}_1^*+\boldsymbol{\Gamma}_2^*+\boldsymbol{\Gamma}_3^*+\boldsymbol{\Gamma}_4^*=0 \tag{35}$$

$$\boldsymbol{\Gamma}_n\cdot\boldsymbol{\Gamma}_n^*=\boldsymbol{\Gamma}_1\cdot\boldsymbol{\Gamma}_1^*=\boldsymbol{\Gamma}_2\cdot\boldsymbol{\Gamma}_2^*=\boldsymbol{\Gamma}_3\cdot\boldsymbol{\Gamma}_3^*=\boldsymbol{\Gamma}_4\cdot\boldsymbol{\Gamma}_4^*=\frac{\varepsilon_0}{2}\left(E^2+c^2B^2\right) \tag{36}$$

Moreover, writing the electric and magnetic field strength regarding the R-S vectors is similar to some quantum mechanics equations.

$$\boldsymbol{E}=\frac{\boldsymbol{\Gamma}_1+\boldsymbol{\Gamma}_1^*}{2}=-\frac{\boldsymbol{\Gamma}_3+\boldsymbol{\Gamma}_3^*}{2},\ \boldsymbol{B}=\frac{\boldsymbol{\Gamma}_2+\boldsymbol{\Gamma}_2^*}{2ic}=-\frac{\boldsymbol{\Gamma}_4+\boldsymbol{\Gamma}_4^*}{2ic}$$

As mentioned before, Bialynicki-Birula, by expressing the first R-S vectors in terms of the orthogonal relations regarding monochromatic electromagnetic plane waves, revealed that each vector represents a photon in a specific polarization and helicity state. Hence, following the same procedure with the new R-S vectors indicates that each represents a photon's particular polarization and helicity state; the formalism predicts eight polarization states. Therefore, four possible wave functions suggest four possible types of photons, where each is in two specific polarization modes. In the following, we introduce other helpful relations among the R-S vectors connected with the orthogonal equations, written in a more general and convenient form, where $\boldsymbol{u}'$ represents the photon's phase velocity.

$$\boldsymbol{E}=-\boldsymbol{u}'\times\boldsymbol{B},\ \boldsymbol{B}=\frac{1}{c^2}\boldsymbol{u}'\times\boldsymbol{E},\ \left\|\boldsymbol{u}'\right\|=c \tag{37}$$

$$\boldsymbol{\Gamma}_1^*=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_2^*,\ \boldsymbol{\Gamma}_2^*=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_3^*,\ \boldsymbol{\Gamma}_3^*=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_4^*,\ \boldsymbol{\Gamma}_4^*=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_1^* \tag{38}$$

$$\boldsymbol{\Gamma}_1=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_2,\ \boldsymbol{\Gamma}_2=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_3,\ \boldsymbol{\Gamma}_3=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_4,\ \boldsymbol{\Gamma}_4=\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_1 \tag{39}$$

Quantum theory asserts that the wave function contains all information about a system, and this state function evolves according to the Schrödinger equation. Therefore, if the R-S vectors are the photon's wave function, it contains all the information. We thereby have laid the foundation for obtaining information about the photon from the proposed wave function with the previous identities.

5. Photon Energy

The corresponding operator is applied to the wave function to extract the desired physical quantity following the quantum mechanics rules. The same results are obtained, starting with whichever of the R-S vectors. Thus the first R-S vector will serve as the example to derive the photon's energy equations.

$$i\hbar\frac{\partial}{\partial t}\boldsymbol{\Gamma}_n = H\boldsymbol{\Gamma}_n \tag{40}$$

with Maxwell's equations in the vacuum, the relations among the R-S vector and the momentum operator p we obtain:

$$\begin{aligned} i\hbar\frac{\partial}{\partial t}\boldsymbol{\Gamma}_1 &= i\hbar\sqrt{\frac{\varepsilon_0}{2}}\left(\frac{\partial \boldsymbol{E}}{\partial t} + ic\frac{\partial \boldsymbol{B}}{\partial t}\right) \\ &= i\hbar\sqrt{\frac{\varepsilon_0}{2}}\left(c^2\nabla\times\boldsymbol{B} - ic\nabla\times\boldsymbol{E}\right) \\ &= i\hbar c\nabla\times\boldsymbol{\Gamma}_4 \\ &= -c\boldsymbol{p}\times\left(\frac{\boldsymbol{u}'}{c}\times\boldsymbol{\Gamma}_1\right) \\ &= \left(\boldsymbol{p}\cdot\boldsymbol{u}'\right)\boldsymbol{\Gamma}_1 - \left(\boldsymbol{p}\cdot\boldsymbol{\Gamma}_1\right)\boldsymbol{u}' \end{aligned} \tag{41}$$

The second term in the previous equation is the transversality condition, therefore is equal to zero. The first term is the Dirac Hamiltonian for a massless particle.

$$H = \boldsymbol{u}'\cdot\boldsymbol{p} \tag{42}$$

The phase velocity is a Dirac-type velocity, $u_i' = c\alpha_i'$; its components are the subsequent matrices that comply with the Dirac matrices' algebra.

$$\alpha_i'^2 = 1,\ \alpha_i'\alpha_j' + \alpha_j'\alpha_i' = 0 \tag{43}$$

$$\alpha_1' = \begin{pmatrix} 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \\ 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \end{pmatrix},\ \alpha_2' = \begin{pmatrix} 0 & 0 & i & 0 \\ 0 & 0 & 0 & i \\ -i & 0 & 0 & 0 \\ 0 & -i & 0 & 0 \end{pmatrix},\ \alpha_3' = \begin{pmatrix} 0 & 0 & 0 & i \\ 0 & 0 & -i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix}$$

with the previous matrices, the Dirac-type Hamiltonian (42), when squared, reduces to the photon's energy-momentum equation.

$$\mathcal{E} = cp \tag{44}$$

Furthermore, by following the same procedure for the wave function, however, expressed in terms of plane waves, Planck's energy expression results.

$$\mathcal{E} = \omega\hbar \tag{45}$$

6. Photon *Zitterbewegung*

Following the previous analysis, an elementary constituent whose energy equation is a Dirac type Hamiltonian is amplitude modulated wave. Thus since the phase velocity matrices are 4 × 4, we propose the quantum system is a pair of coupled waves, or two interfering sub-systems, described by a single eight-component wave function.

$$\boldsymbol{\Psi}_n = \begin{pmatrix} \boldsymbol{\psi}_n \\ \boldsymbol{\psi}_n^* \end{pmatrix}. \tag{46}$$

Each wave has four components; the R-S vectors are three of these.

$$\boldsymbol{\psi}_n = \begin{pmatrix} 0 \\ \boldsymbol{\Gamma}_n \end{pmatrix},\ \boldsymbol{\psi}_n^* = \begin{pmatrix} 0 \\ \boldsymbol{\Gamma}_n^* \end{pmatrix}. \tag{47}$$

Furthermore, Maxwell's equations in free space take the form of a Schrödinger-Dirac-type equation; this is not new, however, written with the correct matrices.

$$i\hbar \frac{\partial \boldsymbol{\psi}_n}{\partial t} = \boldsymbol{u}' \cdot \boldsymbol{p}\boldsymbol{\psi}_n,\ i\hbar \frac{\partial \boldsymbol{\psi}_n^*}{\partial t} = \boldsymbol{u}' \cdot \boldsymbol{p}\boldsymbol{\psi}_n^* \tag{48}$$

Regarding the proposed wave function, since it is a coupled system and the complex conjugate is not a mere mathematical tool to calculate the probability, we predict that the photon's polarization and helicity oscillate: the possible quantum states alternate. Namely, the quantum system is not in a superposition of states in this interpretation. It is a reversible flipping of polarization caused by a continuous fluctuation of the helicity, continuously oscillating from one polarization to another and constantly oscillating. The vibration is the "trembling motion" or *Zitterbewegung* of the photon. The oscillation frequency between states is the photon's frequency, taking twice this frequency to complete a cycle. This alternation of states is the quintessence of a binary code, reversibility from one to zero—the Dzhanibekov Effect aids in the visualization of the fluctuation.

7. Conclusions

Even though the quantum theory is exceptionally successful, this theory has lingering difficulties which have caused the proposal of numerous interpretations. We suggest a new insight that resolves the controversies. With the Dirac formalism, we build a description of the elementary constituents we interpret, which are amplitude modulated waves. It is astonishing to find a particular modulation type in an equation that results from special relativity. The paradigm is a system of two waves analogous to a carrier and signal; the de Broglie wave corresponds to the carrier. Therefore, the Dirac wave function represents a single particle. Namely, the equation providing the phenomenological description of the modulation process is Dirac's quantum relativistic wave equation, where the interference among the undulations generates a discrete entity. Hence, the particle is an emergent phenomenon, and this assertion clarifies the wave-particle duality.

Half of the quantum object has been absent from the theory or analysis, given the possibility of a second wave associated with the quantum object. This omission is the source of the bizarre paradoxes and counterintuitive results.

Following our analysis concerning the possible objective reality of the *Zitterbewegung*, we propose it is a surface effect for material particles as a consequence of amplitude modulation. The quantum entity is a "stable" configuration whose surface, as mentioned before, has the behavior of a harmonic oscillator. There is no dispersion of the wave packet; it expands and contracts. The oscillation encrypts a binary unit of data on the particle's surface. The surface also has a temperature; this is understandable when considering electromagnetic interactions in the Heisenberg formalism. With the time dependence of the Hamiltonian, we interpret the system's energy as fluctuating; it is emitting and absorbing energy in the form of real photons. Indeed, the link between the power and the electron's electric field suggests a way to manipulate inertia, addressed in a forthcoming paper. The amplitude modulation interpretation has testable consequences for the electron with current technologies: an additional magnetic dipole moment and two electric dipole moments.

We introduced matrices that follow the anticomutation relations of the Gamma matrices, and with these, correctly encode Maxwell's equations in a Schrodinger-Dirac type equation. The matrices are the components of the phase velocity for the photon. We also obtained the photon's energy by introducing new R-S vectors and identities. Regarding the proposed eight-component wave function for the single-photon, under this interpretation of the photon's quantum mechanics, the wave function's modulus is not a probability density but an energy density.

Moreover, we hypothesize that the photon's polarization and helicity states are oscillating. Above all, there is no superposition of quantum states in this interpretation of the quantum theory. There is an oscillation amongst the possible quantum states. It can be seen that this settles the measurement problem, and it is the likely cause of the difference in the correlation factor predictions between classical and quantum theory in the entanglement phenomenon. The Entanglement phenomenon is a form of synchronicity; there are no mysterious connections between quantum particles.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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