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Photon Wave-particle Hybrid Structure and Wheeler's Single Photon Double-slit Delayed Choice Experiment

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

The interpretation of single-photon double slit Wheeler's delayed choice experiment leads to a weird inference: "what observer does now can change what happened in the past". It subverts our cognitions. Other interpretations are also in dispute. I try to find another possible way that can better explain the experiments. For this purpose, we try to reacquaint what is a photon; what structure it possesses, and how the structure influences photon behavior. In 1905 Einstein supposed that the photon is a quantum of EM radiation; according to the quantum interpretation, the probability density of a coherent state undergoes a sinusoidal vibration with time; it will also excite a quantized EM wave. So we start our research from an axially symmetric EM wave beam. We discovered and proved that under the Quantification Law of Charge, there is a kind of axially symmetric EM-wave beam which is a quantum of circularly polarized light. Its energy is concentrated in a very small packet; this energy packet will be proven to have photon properties, like $\in = h\nu$, $p = h/\lambda$, spin $\pm\hbar$, obeying B-E statistics, etc. On the other hand, the width of the sodium spectral lines identifies that the energy packet carries a long EM wave beam. They form a wave-particle hybrid structure. It exhibits both wave property and particle property all the time in the experiments. Its interpretation for the single photon double slits Wheeler's delayed choice experiment does not lead to the above strange inference.

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1. INTRODUCTION

What is a photon? Does a photon have structure? How does the structure influence photon's properties? Can it avoid the weird inference from the single-photon double slit Wheeler's delayed choice experiment? As to my knowledge, no one had down similar research.

In chapter II, we discovered and proved that under the Quantification Law of Charge, there is a kind of axially symmetric EM-wave beam, it is quantized. Its energy concentrates on a very small cylindrical packet (quantum); this energy packet has photon properties: $\in = h\nu$, $p = h/\lambda$, spin $\pm\hbar$, obeying B-E statistics [1].

In chapter III, we study the width of the sodium's bright yellow spectrum lines in the experiment, it identifies that there must be a long EM beam closely following the energy packet [2-4. They construct a wave-particle hybrid structure. In chapter IV, it is a different explanation of Wheeler's single-photon double slit delayed choice experiment [5-7]. Chapter V is conclusion.

2. THERE IS A KIND OF AXIAL SYMMETRIC EM-BEAM IT HAS THE BASIC PROPERTIES OF PHOTONS

Far away from the vibrating electric dipole at point O, the field intensities E , H are [8].

$$E(\rho,\vartheta,\nu,t) = \sqrt{\frac{\mu_0}{\varepsilon_0}}H = \frac{\pi M_0 \nu^2}{c^2 \varepsilon_0 \rho}\sin\vartheta\cos\omega(t - \frac{\rho}{c}) \qquad (1)$$

Let us study an axial symmetric EM wave beam and its properties. For any axial symmetric EM wave beam from point O (abbreviated as wave-beam in the following if not mentioned), symmetry requires the beam conical (then its wave surfaces circular) and $d\vartheta$ small enough. The wave-beam has $E = H = 0$ at the tangent points if their side boundary is tangent to the line $\vartheta = 0$. Due to axial symmetry, all these wave-beams from point O must have $E = H = 0$ on their whole side boundary; other wave-beams from point O must have the same property if their boundary is tangent to the former, and so on. Then we can affirm that any wave-beam from point O, all have $E = H = 0$ on the side boundary. This is the first important property of the axial symmetry EM beams.

From now on, we use the coordinates system $x, y, z (= \rho)$. The rectangular coordinates on the wave surfaces are x, y and the radius vector of the beam from point O is $z = \rho$. Then a wave-beam from point O along the z -direction can be generally written as

$$E(r,\nu,z,t) = E_0 \cos 2\pi(\frac{t}{T} - \frac{z}{\lambda}) \quad (E_0 = A(\frac{r}{R})\frac{\nu^2}{z} \succ 0,\ |r| = \sqrt{x^2 + y^2} \prec R) \qquad (2)$$

We do not presuppose the wave-beam has a relation with the photon and quantization.

Let us name the geometrical plane that is perpendicular to the EM beam as "observation plane (O-plane)". Of course, if the beam is spherical, the "O-plane" implies a series of concentric spherical surfaces.

Eq. (2) will excite a standing wave on the O-plane z . Let $z = \rho$ and $t = t' - \frac{z}{c}$, the standing wave function is

$$E(r,\nu,z,t) = A(\frac{r}{R})\frac{\nu^2}{z}\cos 2\pi\frac{t}{T} \quad (0 \prec r \prec R \prec \infty,\ 0 \le t \prec \infty)$$

$$A(\frac{r}{R})_{r=R} = 0 \quad (r = R) \text{ (According to the first important property)} \qquad (3)$$

Because $A(\frac{r}{R}) \succ 0$, when $r \to \pm R$, it has the same limit $\lim_{r\to\pm R} A(\frac{r}{R})$ which is not zero. So $A(\frac{r}{R})$ is an even function; and equals to 0 when $r = \pm R$, therefore its Fourier series is

$$A(\frac{r}{R}) = \sum_{j=1}^{\infty} b_{2j-1} \cos 2\pi(2j-1)\frac{r}{4R} \overset{let}{=} \sum_{j=1}^{\infty} b_{2j-1} \cos 2\pi(2j-1)\frac{r}{\Lambda} \qquad (\Lambda = 4R \ , \ |r| \le R \ ) \tag{4}$$

If we substitute Eq. (4) into Eq. (3), then we have

$$E(r,\nu,z,t) = \frac{\nu^2}{z}\sum_{j=1}^{\infty} b_{2j-1}\cos 2\pi(2j-1)\frac{r}{4R}\cos 2\pi\frac{t}{T}$$

$$= \frac{\nu^2}{2z}\sum_{j=1}^{\infty}[b_{2j-1}\cos 2\pi(\frac{r}{\Lambda_{2j-1}} - \frac{t}{T}) + b_{2j-1}\cos(\frac{r}{\Lambda_{2j-1}} + \frac{t}{T})] \overset{let}{=} E_+(r - \nabla t) + E_-(r + \nabla t)$$

$$(\Lambda_{2j-1} = \frac{\Lambda}{2j-1}, \Lambda = 4R, \nabla = \frac{\Lambda}{T}) \tag{5}$$

The functions $E_+(r - \nabla t)$, and $E_-(r - \nabla t)$ are two compounds traveling waves on the O-plane. They move toward each other along the diameter. It gives us three inferences: (A), (B), (C):

(A). Axial symmetry requires all b_{2j-1} and Eq. (4), (5) independent of the direction r. But the EM theory shows that the radiation of vibrating $\vec{E}$ on the O-plane is anisotropic 8]. It means that if the beam is linearly polarized, the coefficients b_{2j-1} will be different in the different directions r. It contradicts the symmetry requirement for the amplitude $A(\frac{r}{R})$. So the EM wave beam must be circularly polarized. It makes the time average of any coefficient b_{2j-1} and $A(\frac{r}{R})$ to have rotational symmetry on the O-planes. This is the second important property of the wave beam.

The wave function of the axial symmetry EM wave-beam can be written as

$$E(r,z,\nu,t) = E_0 e^{\mp 2\pi i(\frac{t}{T} - \frac{z}{\lambda})} \qquad (\nu\lambda = c, |r| \prec R, \ E_0 = A(\frac{r}{R})\frac{\nu^2}{z} \succ 0)$$

$$E(r,z,\nu,t) = 0 \qquad (r = R, E_0 = 0) \tag{6}$$

Negative exponent and positive exponent represent the right circular polarized and left circular polarized EM-wave beam respectively.

(B). The compound traveling waves $E_+(r - \nabla t)$, and $E_-(r - \nabla t)$ are tangent to the O-plane and along the radial direction, so the energy flow that passes through all cross sections in the same sector is equal

$$S_{\pm}(r_i,z,t)\,r_i\,\delta\theta\,\delta z = S_{\pm}(r_k,z,t)\,r_k\,\delta\theta\,\delta z \qquad (-R \prec r_i \prec r_k \prec R) \qquad (7)$$

The Poynting Vectors along any radial direction on the O-plane are

$$S_+ = S_- = \sqrt{\frac{\varepsilon_0}{\mu_0}}E_+^2 = \sqrt{\frac{\varepsilon_0}{\mu_0}}E_-^2 = \sqrt{\frac{\varepsilon_0}{\mu_0}}\frac{A^2(\frac{r}{R})}{z^2}\nu^4\sin^2\vartheta \succ 0 \qquad (8)$$

Let $r_i \to r$, $r_k \to R$ in Eq. (7) and $\lim_{r\to R} A(\frac{r}{R}) = +const. \overset{let}{=} A_R$ in Eq. (8) be the limit at the side boundary; then we have

$$A(\frac{r}{R}) = A_R\sqrt{\frac{R}{r}} \quad (0 \prec r \prec R\,,\, A_R = \lim_{r\to R} A(\frac{r}{R}))$$

$$A(\frac{r}{R})_{r=R} = 0 \quad (r = R) \qquad (9)$$

Because $\lim_{r\to 0} A_R\sqrt{\frac{R}{r}} \to \infty$ when $r \to 0$ it means that the beam's interaction probability with other particles at the center of the wave surfaces is far greater than other parts of the surface. It gives a definite result while the beam's position is measured. The wave beam acts as a particle; it exhibits particle property. It is the third important property of the wave beam.

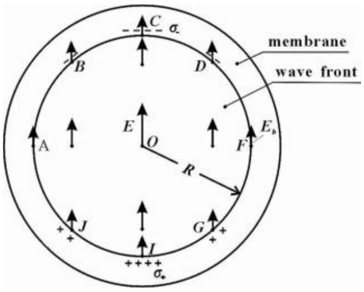

Fig. 1. Sketch map of the central symmetry of the field $\vec{E}(E_x, E_y)$ on wave bean's surfaces [9-11] (where vector $\vec{H}(\perp \vec{E})$ to be omitted)

(C). because the Poynting Vectors, Eq. (8) are the same when $r \to \pm R$, so when $r \to \pm R$, $E_+(r)$ equals to $E_-(r)$ and not zero. But due to all $\left|\cos 2\pi(2j-1)(\pm\frac{r}{4R})\right|_{r=\pm R} = 0 \quad (j = 1,2,...)$, Eq. (5) gives us a very important result

$$\left|E_-(r+\nabla t) + E_+(r-\nabla t)\right|_{r=\pm R} \equiv 0 \qquad (10)$$

Any compound traveling wave $E_-(r+\nabla t)$ (and $E_+(r-\nabla t)$) tangent to the O-plane, it reflects at the boundary with 180^0 phase loss to become $E_+(r-\nabla t)$ (and $E_-(r+\nabla t)$). It indicates that for the compound travelling wave $E_-(r+\nabla t)$ (and $E_+(r-\nabla t)$), the wave-beam's whole lateral boundary is a surface of perfect reflection. The reflection of the electromagnetic waves does not occur between the vacuum and the field itself; reflection can only happen at the interface between two different media. For the circumstance where the only possibility is that there must have a massless (because of speed c) media differed from the vacuum, named membrane always around the lateral boundary of the wave-beam to make a perfect reflection and keeps the EM energy inside the lateral boundary, not to diverge. This is the fourth important property of the wave-beam**.**

The existence of the lateral membrane brings us four inferences (C_1), (C_2), (C_3), (C_4): [12,13].

(C_1) The EM momentum rate of change perpendicular to the arc ds on the lateral boundary is $\frac{2S(R,z,\theta)}{c}ds$. It causes a pair of circular tension $T(R,z,\theta)$ at two ends of the ds . According to the mechanical equilibrium condition, we have $2T\,d\phi = 2T\frac{ds}{2R} = \frac{2S}{c}ds$. $d\phi$ Is the angle between the tangent and the circular tension T ; R is the radius of the wave surface. The integration gives

$$T(R,z,\theta) = \frac{2R}{c}S(R,z,\theta) = \frac{2R}{cz^2}\sqrt{\frac{\varepsilon_0}{\mu_0}}A_R^2\nu^4\sin^2\theta \qquad (11)$$

The tension $T(R,z,\theta)$ distributes double helically along the side boundary. The maximum tension $T_{\max}(R,z,\theta)$ and maximum stress $\Sigma_{\max}$ on the cross sections of the membrane both happen at points A and F (where $\theta = \pm 90^0$), Fig. 1. So

$$\Sigma_A = \Sigma_F = \Sigma_{\max} \propto \frac{R}{z^2} A_R^2 \nu^4 \quad (12)$$

They also form a double helix. This is the fifth important property of the wave-beams.

(C$_2$) According to the Maxwell EM theory, the surface charge density σ on the inner side of the membrane is $\sigma_\theta = D_n = \varepsilon_0 E_n$. Because $E_n = \frac{A_R}{z}\nu^2 \cos\theta$, so on the lower half helix, Fig 1, the positive charge density σ_θ is

$$\sigma_\theta = \left| \varepsilon_0 \frac{A_R}{z} \nu^2 \cos\theta \right| \quad (0 \le \theta \prec \pi) \quad (13)$$

The points of the same σ_θ (+ and -) on the inner side of the membrane form an equal σ_θ-double helix. It means that the charges also distribute helically along the z-axis (the sixth important property of the wave-beam).

The total positive charge in the lower half helix of the membrane, Fig. 1 is

$$q = \int_z^{z+\delta} dz \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sigma_\theta R d\theta = 2\varepsilon_0 \Phi A_R \nu^2 \delta \quad (\Phi = \frac{R}{z}) \quad (14)$$

The upper half has the same amount of $-q$. δ Is the length of the charged membrane. Finite q makes the length δ finite. The wave-beam is an axial symmetric EM train.

According to the Quantification Law of Charge, the axial symmetric wave-beam $q = \pm e$ is the lowest energy train that can exist independently in reality. The others are $\pm ke \ \ (k = 2,3,...)$. We name the one with $q = \pm e$ as elementary train (The quark theory does not involve in this paper). An elementary train possesses charge $+e$ or $-e$, shortest charged membrane length δ and relative lowest energy $\in$ (the seventh important property of the axial symmetry wave-beams).

(C$_3$) When the conical elementary train moves forward, the circumferences of the membrane become longer and longer. The maximum radius $R_{\max}$ of the conical membrane must exist otherwise the EM-train will diverge unceasingly; no information that the train carries from far we can receive. It contradicts the observation and experimental evidences.

So, when the elementary train is emitted, its energy $\in$ distributes all over the conical train. After its radius get big the $R_{\max}$; its energy concentrates into a cylindrical lateral membrane with the radius $R_{\max}$ and length δ . Let's call it $\in$-energy packet of the elementary train. Include the above properties; this is the eighth important property of the elementary train.

However, we have noticed that there may be a possible opposing opinion on the existence of $R_{\max}$: "The conical wave beam and its energy can go far need not gathering to the $\in$-(energy) packet because the energy of a conical wave beam can collapse to a point when it is measured". Indeed, this opinion may be available for the phenomena on earth; but it can not explain the phenomena from the universe. For the light beam from a star in the deep universe, if it is a conical wave, it will cover any big celestial body, such as the sun; how to calculate the deflection angle through the sun? So this opposing opinion is not available in general.

The $\in$-packet is a circular polarized EM field wrapped by a cylindrical membrane with helical distribution $\pm e$, Fig. (1). The helical distribution $\pm e$, the tension T in the cylindrical membrane, and the circular polarized EM field inside construct a very steady structure. Mechanical equilibrium among them keeps the integrity, shape, and size of the structure. The membrane is also an EM shield it can prevent the external EM influences in the process of propagation.

Is the length of the elementary train L equal to the length δ of $\in$-(energy) packet? If the length $L = \delta$, the elementary train is like a bullet; if the length $L \succ \delta$, then, according to the formation process of the $\in$-packet, the elementary train is consists of an energy packet and a conical residual EM wave with far smaller energy; it closely follows the packet. In other words, the elementary train possesses a wave-particle hybrid structure.

We will prove that such helical structure of E, H plus speed c will make the $\in$ - packet having $\in = h\nu$, spin $\hbar$ and basic properties of the photon in the following.

(C$_4$) Calculation and proof of the $\in$-packet:

Let $d\sigma_r \approx 2\pi r dr$ be the ring area on the wave surface, then according to the EM theory, the average field energy $\in$ of the $\in$-packet can be written as

$$\in = \frac{1}{2}\int_{z_0-\delta}^{z_0} dz \int_0^R \varepsilon_0 \frac{A^2(\frac{r}{R})}{z^2} \nu^4 2\pi r\, dr \tag{15}$$

Here we suppose that the energy of the membrane can be neglected in comparison to the $\in$-packet's. Eq. (15) and Eq. (9) give us

$$\in \overset{(9)}{=} \frac{1}{2}\int_{z_0-\delta}^{z_0} dz \int_0^{\Phi} 2\pi\varepsilon_0 A_R^2 \Phi \nu^4\, d\phi = \pi\varepsilon_0 A_R^2 \Phi^2 \nu^4 \delta \qquad (\Phi = \frac{R}{z} = \frac{R_{\max}}{z_0}) \tag{16}$$

Where z_0 is the distance between the point source O and the end of the elementary train when it just becomes totally cylindrical. After the $\in$-packet totally becomes cylindrical, we have $A^2(\frac{r}{R}) = A_R^2 \frac{R_{\max}}{r}$, and its energy is

$$\in = \frac{1}{2}\int_{z_0}^{z_0+\delta} dz \int_0^{R_{\max}} 2\pi\varepsilon_0 A_R^2 R_{\max} \nu^4\, dr = \pi\varepsilon_0 A_R^2 R_{\max}^2 \nu^4 \delta \tag{17}$$

According to the conservation law of energy, Eq. (16) and (17) are equal, so $z_0 = 1m$ for any ν. All elementary train of different frequency spends the same time t_0 to become cylindrical (the ninth important property of the elementary train):

$$t_0 = \frac{z_0}{c} = \frac{1}{c}\sec \tag{18}$$

Let $q = e$ and eliminate δ in the Eq. (14), (17), it gives us a very important relation

$$\in = h\nu \qquad (h = \frac{\sqrt{3}}{4} ceA_R) \tag{19}$$

h Is a proportionality factor independent of frequency ν. The energy in the $\in$-packet is proportional to the frequency ν (the tenth important property of the elementary train) [14,15].

Compare to the Max Plank postulate in 1900, the proportionality factor h is just the Planck constant [16,17]. Einstein's postulate $\in = h\nu$ is a logical result of the Quantification Law of Charge.

According to special relativity $\in = mc^2$ and the definition of inertia moment, $\in$-packet's moment of inertia about the z-axis on the O-plane is

$$I = \frac{\delta}{2}\int_0^{R_{\max}} r^2 \frac{\varepsilon_0}{c^2} A_R^2 R_{\max} \nu^4 2\pi\, dr = \pi\varepsilon_0 A_R^2 R_{\max}^4 \nu^4 \frac{\delta}{3c^2} = \frac{\in R_{\max}^2}{3c^2} \qquad (d\in = c^2 dm) \tag{20}$$

On the other hand, when a beam of circularly polarized light is incident at an absorbing surface, classical EM theory predicts that the surface must experience a torque. Calculation gives the torque T per unit area as [18,19]

$$\mathrm{T} = \frac{\mathrm{I}}{2\pi\nu} \tag{21}$$

Irradiance I of the beam is the rotational power per unit area that the unit surface absorbs.

Since EM energy is quantized that is proved in (C), if we let N be the number of $\in$-packets per unit area that hit the surface every second. Then, N is the number of the $\in$-packets in the cube of the beam having a magnitude $1(m^2)\times c(m)$ that the surface absorbs in a second, so the total spin and total energy of the $\in$-packets in the cube that the unit surface absorbs every second are $\mathrm{T} = N\Sigma$ and $\mathrm{I} = N\in$. Where Σ and $\in$ are the spin and energy of the $\in$-packet. So

$$\Sigma = \frac{\in}{2\pi\nu} \tag{22}$$

According to the definition of angular momentum $\Sigma = 2\pi\nu I$, plus the Eq. (17) and (20) we have

$$R_{\max} = \frac{\sqrt{3}c}{2\pi\nu} \tag{23}$$

For visible light, if we take it $\lambda = 6\times10^{-7}\,m$, then $R_{\max}$ is almost $1.7\times10^{-7}m$. The $\in$-packet is small.

From Eq. (19) and (22), we have the angular momentum of the $\in$-packet: [20]

$$\Sigma = \frac{h}{2\pi} \overset{let}{=} \hbar \tag{24}$$

Because ν, λ in Eq. (6) should satisfy the condition $\nu\lambda = c$, so it is the translation motion of the helical structure of vectors E, H plus intrinsic speed c that makes the $\in$-packet definite spin $\hbar$. [21-23].

If the elementary train is left circular polarized, its spin $-\hbar$ is in the opposite rotation direction on the O-planes. The $\in$-packet's spin $\pm$, right or left is decided by the direction of its double helix E,H structure plus speed c, not other factors. Any elementary train can take only one fixed spin $\hbar$ or $-\hbar$ (the eleventh important property of the elementary train).

According to the fact that the spin of the photon equals to $\pm\frac{1}{2\pi}$ Planck constant, it identifies again that the constant h in the equation (19), (20) is the Planck constant.

On the other hand $\Phi = \frac{R_{\max}}{z_0} = R_{\max}$, let $q = e$, then Eq. (14) and (17) give

$$\delta = \frac{\pi e^2}{4\varepsilon_0 h\nu} \tag{25}$$

$$\frac{\delta}{R_{\max}} = \frac{\sqrt{3}\pi^2 e^2}{6c\varepsilon_0 h} \approx 0.04 \tag{26}$$

It holds for any frequency ν. The $\in$-packets of different ν have different surface radii $R_{\max}$ and length δ; but have the same shape and the same ratio $\delta / R_{\max} \approx 0.04$ as like a round coin (The twelfth important property of the elementary train).

The $\in$-packet possesses energy $\in = h\nu$, definite shape, definite volume and particle-like property, it is really a particle. According to Einstein's relations $\in^2 = p^2c^2 + m_0^2c^4$ for the relativistic particle, and let $m_0 = 0$, then the $\in$-packet's momentum is [24,25].

$$p = \frac{h}{\lambda} \tag{27}$$

This is the thirteenth important property of the elementary train.

Owing to the helical structure of $\pm e$, and extremely small of dimension, the electric fields of $\pm e$ in the distance will offset each other, *so the $\in$- packet is "charge free",* in fact**.** On the other hand, when the $\in$-packet moves forward, $\pm e$ rotating on the O-planes will produce different directions of magnetic fields. They will also offset each other no matter the EM-trains' helical structure right or left. So $\in$-packet are magnetic-free at the same time. Since the EM effect is the main interaction in the microscopic world, elementary trains with different spin directions are difficult to distinguish. They are rigorously identical and then obey B-E statistics (the fourteenth important property of the elementary train) [26].

The elementary train possesses the same basic properties of the photon: energy $\in = h\nu$, momentum $p = h/\lambda$, spin $+\hbar$ or $-\hbar$, and obeys B-E statistics; besides, the $\in$-packet as a particle with speed c of course can play the role of force carrier for EM force. Therefore, put aside duality for a moment, we can say that the elementary EM-train is Einstein's photon, or vice versa. At least they are equivalent.

Classical formula of total power P emitted from a vibrating electric dipole $\mathrm{M} = \mathrm{M}_0 \cos 2\pi\nu t$ is [8]

$$\mathrm{P} = \frac{16\pi^3 \mathrm{M}_0^2 \nu^4}{3\varepsilon_0 c^3} \overset{(20)}{=} \left(\frac{64\sqrt{3}\pi^3 \mathrm{M}_0^2}{9\varepsilon_0 c^4 e A_R}\nu^3\right) h\nu \overset{let}{=} N h\nu \quad (28)$$

The source radiates $N \propto \nu^3$ photons per second and every photon has energy $\in = h\nu$, so its radiative power is $\mathrm{P} \propto \nu^4$.

Rewrites Eq. (16) as

$$\frac{\in}{\delta} = \pi\varepsilon_0 \nu^4 A_R^2 R_{\max}^2 = \varsigma(\nu)$$
(29)

For definite ν, ratio $\in/\delta$ is constant. If a ν-train has more energy $n\in = nh\nu$, then $\in$ *-($nh\nu$) energy packet* must have a longer length $n\delta$ (the fifteen important properties of the elementary train).

Let us take the derivatives from the Eq. (6), $E(r,z,\nu,t) = E_0 e^{\mp 2\pi i\left(\frac{t}{T}-\frac{z}{\lambda}\right)}$, we have

$$\frac{\partial^2 E}{c^2 \partial t^2} = (\mp 2\pi\nu i)^2 \frac{E}{c^2} = -\frac{4\pi^2}{c^2 h^2} \in^2 E = -\frac{\in^2}{c^2 \hbar^2} E \quad (30)$$

$$\frac{\partial^2 E}{\partial z^2} = E\left(\pm\frac{2\pi i}{\lambda}\right)^2 = -\frac{4\pi^2}{\lambda^2} E = -\frac{1}{\hbar^2 c^2} p^2 c^2 E \quad (31)$$

Substitute above $\in$ and pc into the relativistic energy-momentum relation. $\in^2 = (pc)^2 + (m_0 c^2)^2$, we have

$$\frac{\partial^2 E}{c^2 \partial t^2} - \frac{\partial^2 E}{\partial z^2} + \frac{m_0^2 c^2}{\hbar^2} = 0 \quad (32)$$

This is the Klein–Gordon equation; the Schrödinger equation for the relativistic particle. As a relativistic particle, the photon rest mass $m_0 = 0$, it satisfies this type of the Schrödinger equation (the sixteenth important property of the elementary train).

Because Eq. (6) can be satisfied the relativistic Schrödinger-equation, it is proved that the equation of motion of the $\in$-packet is being proved to satisfy the Schrödinger equation.

The Eq. (32) becomes Maxwell EM wave equation when $m_0 = 0$. In other words, the Maxwell EM wave equation is also the Schrödinger-equation for the photon.

3. EXISTENCE OF A LONG ψ-WAVE AND WAVE-PARTICLE HYBRID STRUCTURE OF PHOTONS

For visible light, let us take $\lambda = 6\times 10^{-7} m$, then $R_{\max}$ is about $1.7\times 10^{-7} m$. The $\in$-packet's length is about $\delta \approx 0.04 R_{\max} \approx 7\times 10^{-9} m$.

To radiate a photon is a result of quasi-periodic vibration (Δt finite). According to the Fourier analysis, the intrinsic line width m_0 of the spectral line is due to the finite length $c\Delta t$ of the elementary train (photon), where $\Delta\nu\Delta t \geq 1$. [27,28].

As well known, there are two bright yellow spectrum lines from the sodium lamp in the experiment. Their wavelengths are 5895.92×10^{-10}m ($\nu \approx 5.088\times 10^{14}\, 1/\sec$) and 5889.95×10^{-10}m ($\nu \approx 5.093\times 10^{14}\, 1/\sec$) respectively. The frequency difference between the two yellow spectrum lines is about $\Delta\nu_{Na} \approx 5\times 10^{11}\, 1/\sec$.

If we suppose the elementary train length $c\Delta t$ equals the length of the $\nu = \frac{1}{T} = \frac{c}{\lambda}$ -packet $\delta \approx 7\times10^{-9} m$, then $\Delta\nu \geq \frac{c}{c\,\Delta t} = \frac{c}{\delta} \approx 4.3\times10^{16} \succ\succ \Delta\nu_{Na}$; so the intrinsic line width $\Delta\nu$ of a sodium yellow spectrum line will be far greater than $\Delta\nu_{Na} \approx 5\times10^{11}\ 1/\sec$; it will cover the second sodium yellow spectrum line; it will even cover other elements' spectrum lines. In other words, if the elementary train length is equal to the length of the $\nu = \frac{1}{T} = \frac{c}{\lambda}$ -packet, there is only one very broad yellow spectrum line that appeared in the experiment, not two! This is a very strong experimental evidence to identify that the length L of elementary train is far longer than the length δ of the $\nu = \frac{1}{T} = \frac{c}{\lambda}$ -packet. So, back to the process of forming the $\nu = \frac{1}{T} = \frac{c}{\lambda}$ -packet, we can confirm that there must be a long EM beam following the $\nu = \frac{1}{T} = \frac{c}{\lambda}$ -energy packet. The elementary train is an $h\nu$ (energy)-packet floating in front of a conical circularly polarized EM wave of length $L(\succ\succ \delta)$. Let us name the following conical EM beam in the elementary train as ψ -wave. The elementary train is consists of an $h\nu$ (energy)-packet and a conical ψ -wave. It forms "a very small and slim $h\nu$ energy packet floating in front of a long ψ -wave" wave-particle hybrid structure. The length L is the coherence length of the $h\nu$ photon (the seventeenth important property) [5].

4. WHEELER'S SINGLE PHOTON DOUBLE SLITS DELAYED CHOICE EXPERIMEN

In the ordinary single photon double-slits experiment, the light spot on the screen is one-to-one correspondence with the photons radiated by the light source. No evidence from the spot shows it has been split. So, one-to-one light spot ($\in$ - packet spot) on the screen exhibits the particle property of the photon. Over time, an interference patterns developed; the spots on the screen gradually becomes a distribution of interference patterns. It exhibits both the wave property and particle property of the particle in the same experiment.

In this experiment, because the photon itself (the $\in$ - packet) is a particle it cannot split into two parts to pass two slits, the only possibility is that when the $\in$ - packet and ψ -wave arrive at the two slits, it is the ψ -wave who splits into two wave beams to pass two slits and form the distribution of phase differences, the probability distribution pattern on the screen. As for the photon itself ($\in$ - packet), owing to the momentum $\pm\Delta p$ of the Heisenberg uncertainty principle $\Delta x \Delta p \geq \frac{\hbar}{2}$ at the slit Δx , it will deflect in general and locates randomly at a point on the screen.

For all $\in$ - packets, they one by one pass through the slit Δx and will be deflected symmetrically. Behind the slit is free space, photon moves straight here, so, logically speaking, the one by one $\pm\Delta p_x$ -packets (photons) must also distribute symmetrically and continuously on the screen. But what appear on the screen are bright and dark interference fringes, not continuous bright patterns. It means that the degree of brightness and darkness on the screen is not only decided by the number of $\in$ -packets that arrived at the point but also decided, even mainly decided by the phase difference between the $\in$ -packet and the coherent ψ -wave from another slit [5].

Due to the quantization of $\in$ -packet, so the energy left in the ψ -wave must be far smaller than $h\nu$, the ψ -wave cannot have ability to influence $\in$ -packet's energy. How can the ψ -wave infect the brightness of the $\in$ -packets (photons) even become dark? The only possibility for the ψ -wave to influence the photon, we guess, is to restrict the activity of the $\in$ -packet (photon) that is to restrict a photon's probability to interact with matter.

It reminds us that we can arrange the phase of the coherent ψ -wave to control the brightness of the $\in$ -packet(s) (photon(s)) for technical purposes like to forcing the $\in$ -packet(s) (photon(s)) becomes dark, or to be a light switch, or to write or draw a picture on the shiny background, etc.

The ψ -wave of the photon is just the de Broglie wave; its wave function, Eq. (6) is just the state function in quantum mechanics; it completely specifies the states of the photon [12,29].

How does the particle-wave hybrid structure explain the single photon Wheeler's delayed choice experiment?

When a single photon was emitted from a light source, the ψ -wave and $\in$ - packet arrives at the first half-silvered mirror simultaneously, the ψ -wave beam will be evenly divided into two beams to transmit (A→) and reflect (B→) respectively. When they arrive at two-photon detectors (C), because of only one (A→ or B→) of the beams carries a photon and the photon detector can not detect the wave, so only one detector can have a react. It can determine which path the photon takes (A→C or B→C). It exhibits particle properties

If we suddenly put a half-silvered mirror in front of the two detectors, it can make the wave beam with a photon and the second wave beam with no photon to interfere (the interference happens between two ψ -wave beams, not two $\in$ - packets). If the optical path difference is properly adjusted, the interference wave beams can be canceled in one direction (A→C or B→C), the detector in this direction will not be able to be brightening no matter whether an $\in$ - packet or no $\in$ - packet reaches there. The situation of an $\in$ - packet arriving, but dark is like the situation of a photon arriving at the dark fringe in the interference pattern, it becomes dark. The detector in the other direction will definitely brighten as long as it receives a photon. So, owing to the wave-particle hybrid structure that the strange statement: "The present behavior of the observer can determine what happened in the past" doesn't appear.

In the ordinary single photon double slit experiment, once a photon ($\in$ - packet) is detected (being absorbed or disturbed) by a detector, the ψ -wave beam must also disappear or disturbed, because the ψ -wave and $\in$ - packet are co-existing, they exist or disappear or disturbed at the same time. If one of the ψ -wave beams in the experiment is disturbed to disable by certain reasons, only another beam of ψ - wave with its $\in$ - packet can reach the screen, then total particles that one by one passes through the same slit Δx will be deflected symmetrically. As long as the experiment time is long enough, it will not only form a symmetrical pattern on the screen but also form a single-slit diffraction pattern. We believe that this assertion will be confirmed in the experiments.

5. CONCLUSION

In order to avoid the weird inference "What the observer does now can determine what happened in the past" in Wheeler's delayed choice experiments, we give up a current explanation and study an axial symmetric EM-wave beam. We discover and prove that under the Quantification Law of Charge, there exists a kind of axial symmetric EM-wave beam it is a quantum of circularly polarized light. It is being proven possesses photon properties: $\in = h\nu$, $p = h/\lambda$, spin $\pm\hbar$, wave-particle duality, obeying B-E statistics and so on; Besides, the study on the width of the sodium spectral lines identifies that the energy packet carries a long conical EM wave beam. The $\in$ - packet and ψ – wave form a wave-particle hybrid structures. It exhibits wave property and particle property all the time in any experiment. It explains single photon Wheeler delayed choice experiments without the above weird conclusion.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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