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THE CLASSICAL STRUCTURE MODEL OF SINGLE PHOTON AND CLASSICAL POINT OF VIEW WITH REGARD TO WAVE-PARTICLE DUALITY OF PHOTON

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Abstract—The enigma of the wave-particle duality of photon has remained unimpressively explained for a century since Einstein presents the concept of the photon in 1905. This article establishes a classical geometric structure model of a single photon based on field matter, educes a formula for the size of a photon; assumes that there only are two kinds of photon of right hand and left hand circular polarized, and suggests the frequency ω of photon polarization rotated to be its spin frequency. It ascribes the wavelike of photon to its spin motion and the particle-like to its translation motion. From the point of photon particle instead of wave view to re-analyze Young's double-slit interference and polarizer experiments, gives reasonable mechanism. It defines the phase velocity and the group velocity of a photon. It gives a unified and consistent understanding of quantum particle of light and classical electromagnetic waves field. Evidently, such a precisely defined conceptual model is reasonable, objective and easy to accept for classical physicists.

1. INTRODUCTION

The puzzle [1] of the wave-particle duality of light has remained unsatisfactorily explained nearly a century since Albert Einstein first proposed the photon, the quantum unit of light ($E = \hbar\omega,\ \vec{p} = \hbar\vec{k}$) in 1905. This concept led to the revelation that light could be particle and wave at the same time, in some unimaginable way. Light interacted with matter according to mechanical principle, it had come full circle from Newton's corpuscles to Maxwell's waves to Einstein's photons. But there remained a problem deep and stubborn, unavoidable and inexplicable, the basic paradox: How could particles of light display the

inherent wave property of interference? How could they cancel each other to give darkness? How could a photon change its polarization direction when passing through a polaroid? Nothing in Einstein's hypothesis explained this. In 1917, he ever said: "For the rest of my life I will reflect on what light is" [1]. As he wrote a friend, he felt his struggle with the enigma might drive him to the madhouse. He explored the paradox in a Gedanken experiment, imagining an interference experiment of an extremely weak light source that emits one photon at a time. In 1909 Taylor [2] conducted such an experiment for three months, at most only a few photons at a time. It resulted in an ordinary wavelike interference fringe. Somehow, each single photon travels through both slits to interfere with itself. It seems that appearance of wave or particle is determined by the experimental arrangement. In 1986 Grangier et al. [3] reported a modern version of Taylor's experiment based on laser, it showed that a lone photon indeed interfere with itself. So far, the nearly widespread consensus among the quantum physics community all over the world is that light is a particle and also a wave — depending on the experiment. It takes wave and particles as two different faces of reality. When you measure the properties of light, you see one aspect or the other depending on the experiment, but never both. As a cost the foundation of quantum mechanics (QM) is to sacrifice the objective process to physical phenomena. Even single-photon interference passing through a double slit is deemed [4] to be one of the defining experiments of quantum mechanics, and without other simple experiment that demonstrates the wave-particle duality so well. This led to Richard Feynman describe the double-slit interference for particles as "a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains only mystery" [5]. In frequent discussions about quantum theory, however, the double-slit interference acts as a classic gedanken experiment for its clarity in expressing the central puzzles of quantum mechanics.

In quantum electrodynamics (QED), after quantization of the electromagnetic (E&M) field, we obtained the photon field [6, 7]. The "Schrödinger's equation" for the photon is represented by Maxwell equation. Photons are bosons, so the number of photons that can be in any one state must be unrestricted. The polarization vector $\mathbf{e}$ acts for photon as the "spin part" of the wave function. The rest mass of the photon is zero, there is no rest frame, since it moves with the velocity of light in every frame of reference. There is always a distinctive direction in space, the direction of the momentum vector $\mathbf{k}$ (say the z-axis). In such a case there is clearly no symmetry with respect to whole

group of rotation in three dimensions but only axial symmetry about the preferred axis, so the component of photon's angular momentum along the z-axis, is conserved. This quantity is called the helicity. For massless particle there is no rest frame and the helicity can take only two values $\Lambda = \pm s$. The state of a photon having a definite momentum in fact is twofold degenerate. It is described by a "spin" wave function which is a vector $\mathbf{e}$ in x-y plane. Vector $\mathbf{e}$ with only the component $\mathbf{e}_x + i\mathbf{e}_y$ or $\mathbf{e}_x - i\mathbf{e}_y$ non-zero correspond to the components $\Lambda = +1$ or -1 respectively; these are $\mathbf{e} = \mathbf{e}^{(+)}$ and $\mathbf{e} = \mathbf{e}^{(-)}$. In other words, the values $\Lambda = +1$ and -1 correspond to right-hand and left-hand circular polarization of the photon. Thus the component of the photon angular momentum along the direction of its motion can have only the two values of ± 1.

So far although having some knowledge about photon mentioned above, we do not yet have unified understanding of photon and light. The wave picture is described by Maxwell's equations. Photons are invoked when light interacts with matter, as if a wave of light were breaking on the material to become a spray of quanta. But how does one become the other? How do separate photons correlate their actions to make a single wave? What is the meaning of a single, distinct photon? Until these puzzles are resolved, our comprehension of light remains incomplete.

Based on classical and quantum electrodynamics and electromagnetic engineering practices, this paper presents a distinct picture of the wave-particle duality of photon, to give a basic concept of the geometry, the size and the behavior way of photon. The aim is to establish a photon model imaginable. Using this model to re-analyze Young's double slit interference, and polarizer experiments. We can apprehend light and other frequency band of electromagnetic (E&M) wave in a purely objective way, have favored sensory knowledge or spiritual awareness.

2. THE BASIC HYPOTHESES

As usual the model appears as a few hypotheses below:

(A) Since photon is the minimum unit of the classical electromagnetic field energy it is reasonable to assume that a photon consists of electric field vector matter $\mathbf{E}_p$ and magnetic field vector matter $\mathbf{H}_p$ with $\mathbf{H}_p \perp \mathbf{E}_p$, $\mathbf{E}_p$ and $\mathbf{H}_p$ overlapping at the same spherule space. We denote the orientations of the electric and magnetic field vector matter by a red and green arrow respectively as shown in Fig. 1. The wave vector $\mathbf{k}$ can also be ascribed to individual photon, thus the energy flow of a photon $\mathbf{S}_p = \mathbf{E}_p \times \mathbf{H}_p$ along the k direction. This case is identical with the typical one of a classical E&M plane-wave. This way, a photon is

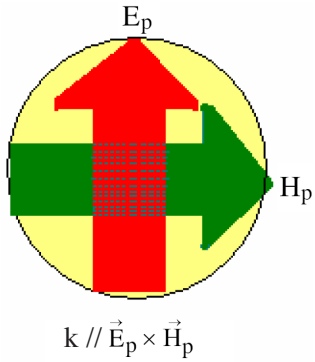

Figure 1. Classical structure of single photon.

very a cell of a plane E&M wave. In other words a classical plane E&M wave consists of overlapping and disposing of a lot of photons described above. Simply we can also say that a photon is very a minimum plane E&M wave. A photon has no rest mass, but motional mass. According to Einstein mass-energy relation

$$E = mc^2 = pc = \hbar\omega \tag{1}$$

the motional mass of photon is

$$m = \hbar\omega/c^2 \tag{2}$$

The momentum of the photon is $\vec{p} = \hbar\vec{k}$, here $(2\pi\hbar)$ is Plank constant. The m comes of the $\mathbf{E}_p$ and $\mathbf{H}_p$, a kind of field matter defined by Maxwell' field equations. The "field matter", a kind of "vectorial, enterable, massless matter", differs from "scalar, impenetrable, material mass" as usual. The motional mass of a photon is very made up from such field matter.

(B) Since the spin angular momentum of photon is $J = \pm\hbar$, this suggests that there are neither unpolarized photon nor linear polarized (LP) photon in our realistic world, so only exist right-hand circular polarized (RCP) and left-hand circular polarized (LCP) photons corresponding respectively to the helicity values $\Lambda = +1$ and -1. The right (left)-hand CP light consists of right (left)-rotating photons, while the LP light is synchronously synthesized from coherent left-rotating and right-rotating photon pairs (Fig. 2).

(C) In QED [6, 7], the ω is regarded as the photon oscillation frequency, the $\pm\hbar$ is the spin angular momentum of photon. We suppose that photon never oscillates though the EM fields do, ω is the polarization-rotation angular frequency of photon, i.e., spin frequency. The wave

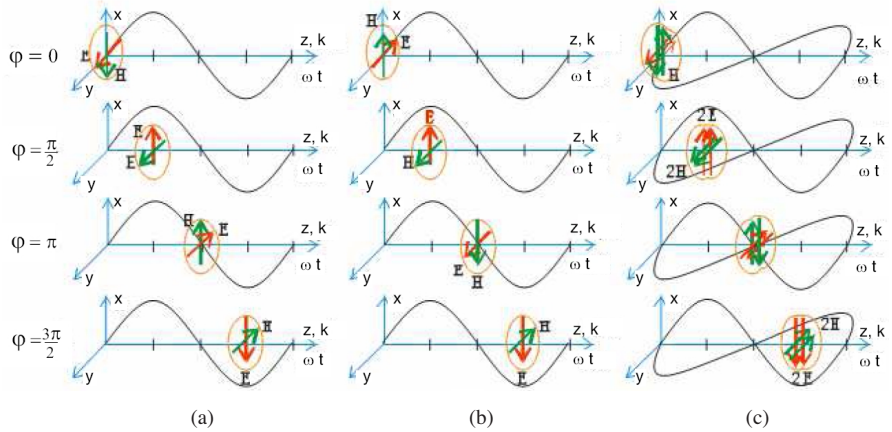

Figure 2. Classical picture of wave-particle duality of a single-photon: (a) left-rotating photon; (b) right-rotating photon; (c) linear polarized photon pair. At $\varphi = 0,\ \pi$, the photon pair is in "instant hidden state", at $\varphi = \pi/2,\ 3\pi/2$, the photon pair is in "apparent state". Here only shows four phase point. Here $\varphi = kz - \omega t$.

number k is the number of its rotating periods per unit length along the motional direction. For the plane wave photons in vacuum, there is disperse relations $\vec{\omega} = c\vec{k}$ for right-hand spin, $\vec{\omega} = -c\vec{k}$ for left-hand spin. The time spent for a photon to travel a distance of a wavelength (λ) along its k direction exactly equals to that for it to rotates a full circle (2π radian) in the free space, as shown in Fig. 2. The orientations of $\mathbf{E}_p$, $\mathbf{H}_p$ define the rotating phase of photon (see Fig. 2). Here we define the translating speed of a photon as the group velocity v_g,

$$v_g = \frac{p}{m} = \frac{\hbar k}{m} \tag{3}$$

The phase speed of a photon is defined as the moving velocity of its rotating phase

$$v_p = \frac{\omega}{k} = f\lambda \tag{4}$$

The fact of $v_g = v_p = c$ in the free space means that the photon translation motion and its spin rotating one are fully synchronous. Obviously, the energy of a photon can be rewritten as

$$E = mc^2 = mv_g v_p = pv_p \tag{5}$$

In the unbounded vacuum space, a photon behaves helically, i.e., to translation at light speed c and spin at ω. At any instant moment its energy, momentum and spin angular momentum keep conservation. Its wavelike property originates from the periodicity of its helically rotating motion, instead of its wave spreading all over the place. In fact, According to our model the centroid of photon behaves beeline motion while its $\mathbf{E}_p$ and $\mathbf{H}_p$ behave helically motion. This is a necessary consequence of conservation of energy, momentum and spin angular momentum of photon.

(D) When the same frequency photons interfere each other, two typical cases occur. When the $\mathbf{E}_p(\mathbf{H}_p)$ of two coherent photons is in the same direction, the synthesized electric (magnetic) vector equals to $2\mathbf{E}_p(2\mathbf{H}_p)$, the "apparent energy" is four times single-photon energy. This is called "apparent state" of photons. It is equivalent to four photons to present. Likewise, when the $\mathbf{E}_p(\mathbf{H}_p)$ of two coherent photons is opposite, the synthesized electric (magnetic) vector is null. It is equivalent to no photons to present. This is called "hidden state" of photons. Actually the $\mathbf{E}_p(\mathbf{H}_p)$ of two coherent photons can intersect at any angle within 0°–360°.

In a sense, a LP light is formed by the RCP light and the LCP light synchronously interfere each other. There two knots during a period. The knot points of the wave indicate the field energy being zero, however the energy flow of each photon still proceed forward (refer to Fig. 2). We call the knots as "instant hidden states". Obviously the combined energy flow or power flow does not equal to the sum of the energy flows of two photons, whereas depends on their rotating phases. Therefore for a LP light, its instant energy flow varies versus time, only the average energy flow keeps constant.

In the free space, each photon like material point, moves forward at light speed c by virtue of its inertia. The plane wave solution could describe not only a light beam, but also a single-photon.

$$\begin{aligned}\vec{E}(0,0,z,t) &= E_p(\vec{e}_x + i\vec{e}_y)\exp[i(kz-\omega t)],\\ \vec{H}(0,0,z,t) &= H_p(\vec{e}_x + i\vec{e}_y)\exp[i(kz-\omega t)]\end{aligned} \tag{6}$$

$$\begin{aligned}\vec{E}(0,0,z,t) &= E_p(\vec{e}_x - i\vec{e}_y)\exp[i(kz-\omega t)],\\ \vec{H}(0,0,z,t) &= H_p(\vec{e}_x - i\vec{e}_y)\exp[i(kz-\omega t)]\end{aligned} \tag{7}$$

$$\begin{aligned}\vec{E}(0,0,z,t) &= E_p\vec{e}_x\exp[i(kz-\omega t)],\\ \vec{H}(0,0,z,t) &= H_p\vec{e}_y\exp[i(kz-\omega t)]\end{aligned} \tag{8}$$

here $\vec{e}_x$ and $\vec{e}_y$ is unit vector along x and y axis respectively. Eqs. (6), (7) and (8) describe the left-rotating, the right-rotating photon and the LP photon pair, as shown in Figs. 2(a), (b) and (c) respectively. It is easy to see that a LP photon pair can be decomposed into two CP photons, and vice versa according to equations (6), (7) and (8). An elliptic-polarized light is composed of two orthogonal LP lights with different number of photon-pairs.

(E) That light-line bends in a gravity field indicates that photon follows mechanical laws. According to equivalence principle in general relativity, the motional mass of photon has the physical significance of inertia too. We suppose that a photon is a spherical particle with radius as $\mathbf{r}_p$. According to Newton mechanics [8] the moment of inertia of the photon is

$$I = \frac{2}{5} m r_p^2 \tag{9}$$

Thus the angular momentum of the photon

$$I\omega = \hbar \tag{10}$$

Substituting Eq. (9) in (10), we obtain the radius of photon

$$r_p = \sqrt{\frac{5}{2}}\frac{c}{\omega} = \sqrt{\frac{5}{2}}\frac{1}{k} = \sqrt{\frac{5}{2}}\lambda\!\!\!^{-} \approx \frac{\lambda}{4} \tag{11}$$

Obviously it is reasonable that the photon size is inverse proportional to its frequency. The higher the frequency the clearer the nature of the particle-like for the photon. According to the current point of view, any elementary particle should be geometrical point without size which demanded by relativity. However, photon without rest mass has no Lorentz shrinkage in its motional direction, so its size is not restricted by special relativity. In order to construct a concept of magnitude of order, we enumerate the size of a gamma-ray photon with energy 0.511 MeV below.

$$r_p = \sqrt{\frac{5}{2}}\frac{1}{k} = \sqrt{\frac{5}{2}}\frac{\hbar c}{E} \approx 6.12 \times 10^{-13}(\mathrm{m})$$

In order to obtain the estimation of the field matter intensity of the photon, let

$$\left(\frac{\mu_0}{2}H_p^2 + \frac{\varepsilon_0}{2}E_p^2\right)\frac{4}{3}\pi r_p^3 = mc^2 = h\nu \tag{12}$$

where μ_0 is vacuum permeability, ε_0 the vacuum permittivity. Due to the electric energy equals to the magnetic energy, Eq. (12) can be substituted as

$$\varepsilon_0 E_p^2 \left(\frac{4}{3}\pi r_p^3\right) = h\nu \tag{13}$$

Substituting Eq. (11) in (13), we obtain

$$E_p = \left(\frac{3}{2\sqrt{10}}\right)^{3/2} \sqrt{\frac{\hbar\mu_0}{\pi^3 c}}\omega^2, \quad H_p = \left(\frac{3}{2\sqrt{10}}\right)^{3/2} \sqrt{\frac{\hbar\varepsilon_0}{\pi^3 c}}\omega^2 \tag{14}$$

For the gamma-ray photon with energy 0.511 MeV, $E_p = 9.28 \times 10^{16}$ (V/m); $H_p = 2.46 \times 10^{14}$ (A/m). Next we will use the theoretic model proposed above to explain two optical phenomena.

3. YOUNG'S INTERFERENCE EXPERIMENT

For Thomas Young's double-slit interference experiment, in spite of the probability result calculated by QM wave function theory consistent with that by classical E&M wave theory, QM by no means gives the idiographic physical mechanism occurred. From the view point of classical photon particle, the origin of this interference pattern is very difficult to understand. In order to do so Bohm introduce quantum mechanic potentials [9] in his hidden variables theory. According to the hypotheses proposed above it is easy to explain Young's experiment. The mechanism of the interference pattern formation is the same as that of classical wave. In the bright fringe of the interference pattern, two photons from two slits respectively add in phase, resulting in $2\mathbf{E}_p(2\mathbf{H}_p)$. As if the energy is four times single-photon energy, but it does not mean four photons to appear. Here we call the two as in "apparent state" of photons. In the dark fringe, two photons from two slits respectively are 180° out of phase, causing destructive interference and the synthetic field quantity $\mathbf{E}_p - \mathbf{E}_p = 0$, $\mathbf{H}_p - \mathbf{H}_p = 0$. Here we call the two in "hidden state" of photons which only do not cause light-chemical reactions or photoelectric effect. The true meaning of the interference pattern only indicates the phase message of photons in the detection plane, instead of re-distribution of photons themselves.

4. INTERFERENCE WITH POLAROID SHEET

Consider a beam of LP light incident normally on a polarizer with polarization plane and the orientation of optic axes made an angle of

45°. How do the photons cross through the polarizer? How do they change their polarization direction? Existing QM textbooks [10, 11] can by no means answer what the physical mechanism is. And the popular point of view deems that QM needs not answer this sort of problems. According to the hypothesis (A), (B), (C), (D) above in the model, an objective mechanism can be given.

In fact, LP light is composed of RCP and LCP-rotating photon pairs. There exists no LP single-photon. For a light beam, there always are many photon pairs impinging on the polarizer simultaneously at a time. These photon pairs possess different phase each other generally. As shown in Fig. 3 photon pairs aa' and bb' are LP photon pairs with respect to yz plane. When they meet with the polarizer, photon a' and b combine a new LP photon pair parallel to the optical axes of polarizer, so they pass through it. While photon a and b' combine another LP photon pair perpendicular to the optical axes of polarizer, thus they is obstructed. This way the light after the polarizer, as a macroscopic effect changes its polarized plane parallel to the optic axis of polarizer. For a relative intense light beam, the phase distribution of a great number of LP photon pairs substantially is random. When they reach the polarizer, almost every photon can find a new partner to make a new pair either parallel to or perpendicular to the optic axis. Therefore the probability of the passing through to the obstructed is 50 to 50.

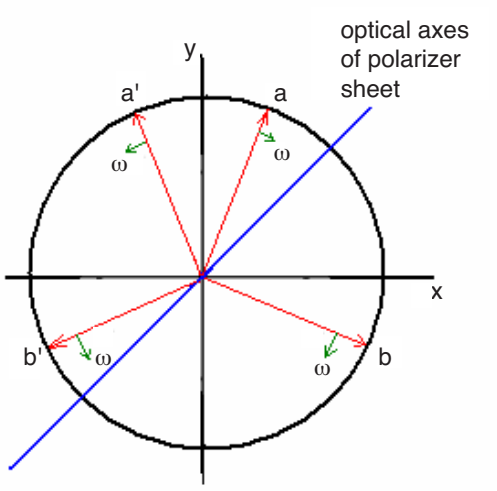

Figure 3. The polarization plane(yz) of LP light makes 45 angle with the optic axis of polarizer.

5. SUMMARY

A photon is characterized by its $\mathbf{E}_p$, $\mathbf{H}_p$ and $\mathbf{k}$. Because each photon consists of vector field matter, the combined field depends on their rotating phase. Like particle else the photon also follows the conservation laws of energy, momentum and angular momentum. The model presented here describes the physical mechanism of the wave-particle duality of a single photon. It can objectively illustrate the physical reality. This model gives a new and rational interpretation to Young's interference and polarizer experiments. It need not to give up the objective process to physical phenomena. According this model we may have a unified understanding between the classical electromagnetic field and the quantum particle of light.

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