Nature of Light: What Hidden Behind Young's Double-Slit Experiment?

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We experimentally prove that the famous single- and double-slit experiments are merely the scattered-light phase transition by slit edges rather than the conventional view of the transmitted-light effect by slits. The nature of the wave-particle duality of light quanta can be well understood with the help of the hypothesis of the quantized chiral photons having an intrinsic dual-energy cyclic exchange property. With the suggested theoretical framework, the experimental diffraction pattern of a single slit is analytically determined and numerically confirmed.

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The physical nature of light has been studied for centuries and a rich picture of the photon has been established (interference, diffraction, reflection, refraction, wavelength, frequency, speed, polarization, wave-particle duality, etc.). These findings seem to indicate that physicists have thoroughly mastered the secrets of light, unfortunately, this is not the case. From Newton and Huygens conflict about whether the light is a particle [1–4] or a wave [5] to the wave-particle duality in the quantum age [6], the debate about the nature of light has never stopped. In 1951, Einstein wrote to one of his friends, "All the fifty years of conscious brooding have brought me no closer to the answer to the question: What are light quanta?".

One might have expected that with the latest developments in modern physics [7–11], the debate will eventually be resolved and a clear picture of the nature of light achieved ultimately. Over the past decades, although significant research efforts have been devoted to uncovering the features of light and photon, but the confusion status of the duality of light today is similar to or worse than that of Einstein's era. Photon, as the simplest and most elementary particle of the universe, we have to accept two contradictory pictures of wave and particle, and must use sometimes the wave picture and sometimes the particle picture, while at times we may use either. So, is the photon really as we think? Frankly speaking, it is time for us to reconsider one fundamental question: What is the wave-particle duality of light?

In this Letter, we first experimentally study the well-known single-slit diffraction and double-slit interference and obtain some very interesting results, which suggest that the patterns both for single and double slits are generated by the scattered light from the edges of the slits. Furthermore, the slit-edge-scattering (SES) mechanism implies that photons should follow determinate trajectories and the double-slit 'which-way' experiments are not physical reality. Obviously, these conclusions will directly challenge the authoritative interpretations established by the mainstream physics community. Secondly, we propose a dual-energy cyclic-exchange hypothesis of chiral photons, which possess the intrinsic wave-particle duality. Under the new theoretical framework, the nature of the wave and particle property of light is unified and the formation mechanism of the single-slit diffraction and double-slit interference fringes is no longer mysterious.

Despite Young's double-slit experiment [5] (see Fig.1) has been widely regarded as providing conclusive evidence that light is a wave and was even considered by Feynman to be the heart of quantum mechanics. But it must be pointed out that what the experiment really reveals has been completely misunderstood, which may be one of the main reasons for the difficult situation of physics today. Our primary aim is to obtain some convincing experimental evidence that the diffraction and interference patterns are the built-up effect of the scattered light from the edges of the slits instead of the coherent effect of the transmitted light through the slits. For this purpose, we have prepared a series of single and double-slit samples on 304 stainless steel plates by photochemical etching technology.

The first experiment was carried out without placing the aquarium in the light path and the distance between the slit and the screen $L = 10m$ (see Fig. 1). Figure 2 shows the schematic of four samples (A, B, C and D) and corresponding experimental patterns (the right subgraphs), respectively. It is noteworthy that the four samples were intentionally prepared in pairs of complementary structures (Yin and Yang in Chinese), which mean that if we stack samples A and B or samples C and D together, they will be completely opaque. From the right of Fig. 2, it is not difficult to find that the experimental patterns [Figs. 2(a) and 2(b), Figs. 2(c) and 2(d)] of Yin-Yang pairs are identical except for the random scattered light around the center. These experiment provide powerful evidence that the so-called interference and diffraction

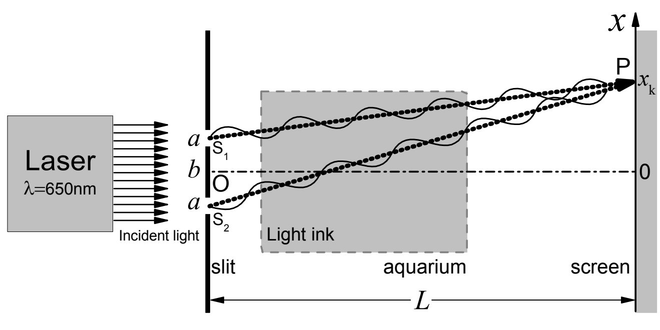

Figure 1: Schematic of improved Young's double-slit experiment.

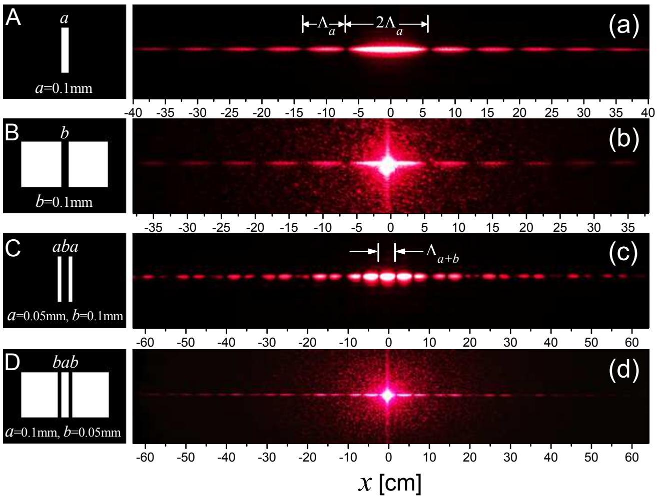

Figure 2: Comparison of diffraction and interference patterns between slits (Yin) and filaments (Yang), (a) single slit, (b) single filament, (c) double slit, and (d) double filament.

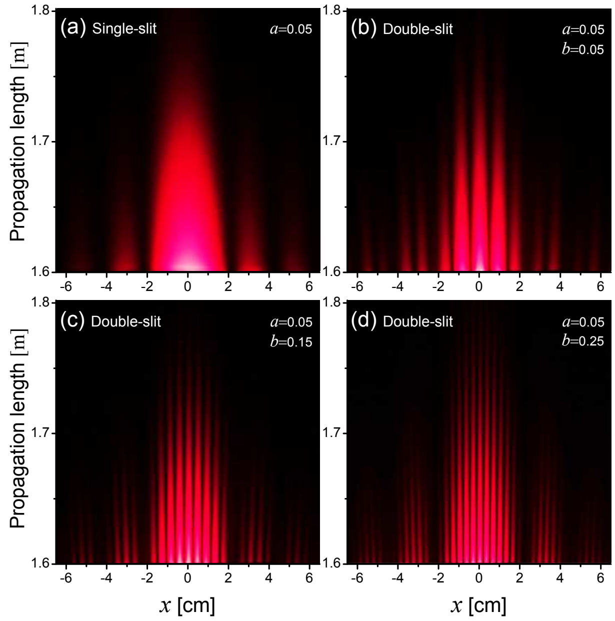

Figure 3: 3D diffraction and interference patterns of aquarium experiments, (a) single-slit of $a = 0.05mm$, (b)-(d) double-slit of $a = 0.05mm$, $b = 0.05mm$, $0.15mm$ and $0.25mm$, respectively.

phenomena are actually the "edge-effect" (photon has a well-defined trajectory) rather than the "slit-effect" (photon propagation without trajectory) described by various authoritative textbooks. Furthermore, the SES mechanism is sufficient to support that the "which-way" question does not exist at all.

From Figs. 2(a) and 2(b) , apart from the brightest center of width $2\Lambda_a = 2L\lambda/a \approx 13.0cm$, the stripes are changed by the period $\Lambda_a = L\lambda/a \approx 6.5cm$. Why only the width of the brightest center is doubled? At the end of the Letter, we will show that this particularity is associated with the transmitted light passing directly through the slit. Furthermore, the SES mechanism implies that the single slit and the double slit share the same physical mechanism. Then, the main difference between them is that the former has only two scattering edges while the latter has four, correspondingly, the pattern of the double slit has one more fringe spacing parameter $\Lambda_{a+b} = L\lambda/(a + b) \approx 4.3cm$, as indicated in Fig. 2 (c).

In order to gain physical insight into interference and diffraction phenomena, we designed the second experiment as shown in Fig. 1, where an aquarium filled with light-ink was placed at a distance of $L = 1.6m$ from the slit. Four experimental samples and corresponding slit parameters are illustrated in Fig. 3 which intuitively and vividly show the fringes and the corresponding intensity of different stripes. Incredibly, the patterns look like they were frozen in the water. According to the experimental results, we can draw the following conclusions: 1) the envelope of the double slit pattern is determined by the single slit, and the most direct effect of the double slit is the "splitting" of the single slit pattern of Fig. 3(a). From Figs. 3(b)-(d), the splitting rules are $2(a+b)/a+1$ and $(a + b)/a$ for the central brightest stripe and the other bright stripes, respectively; 2) the red (bright) and dark stripes are 3D spatial distribution from the edges of the slits to the distant space along the direction of light propagation, instead of what we have once thought were only on the 2D screen; 3) both single- and double-slit experiments reveal a same collective phase transition of photons: the unstriped phase before the slits to the striped phase behind the slits. So, what kind of physical mechanism can ensure that the patterns like the multiple streams of red and dark water "flow" never disturbing each other?

To begin the theoretical study, it must be emphasized that Planck's quantum hypothesis ($E = h\nu$) [4] is incomplete as it can only describe the particle nature but ignores the wave nature of light, and what quantum mechanics has attempted to let the photon possess a wave property by means of the wave function is a failure. As an intuition, whether the photons are particles or waves or both, the photon's self-energy may be the most critical factor. In fact, the strict periodic wave behavior is a very common physical phenomenon, such as spring oscillator, LC oscillator, which are both dual-energy systems and satisfy the energy relationships: $E_p(t) = E_m \sin^2(\omega t + \varphi_0)$ and $E_k(t) = E_m \cos^2(\omega t + \varphi_0)$, where $E_p(t)$ is potential energy, $E_k(t)$ is kinetic energy and $E_m(t)$ is the total energy of the oscillators, they obey the law of energy conversion and conservation (or energy complementarity principle): $E_p(t) + E_k(t) = E_m = constant$. For spring oscillator, $E_m = m\omega^2 A^2/2$ (where m, ω and A are the mass, the frequency, and the amplitude, respectively), while for LC oscillator, $E_m = CU^2/2$ (where C is the capacitance and U is the maximum voltage on the capacitance).

Since the wave characteristics of light have been experimentally confirmed, it is natural to consider whether Maxwell's electromagnetic field theory can be applied to describe the wave nature of light. In 1922, Oseen claimed that the approximate solutions of the quanta can be solved from

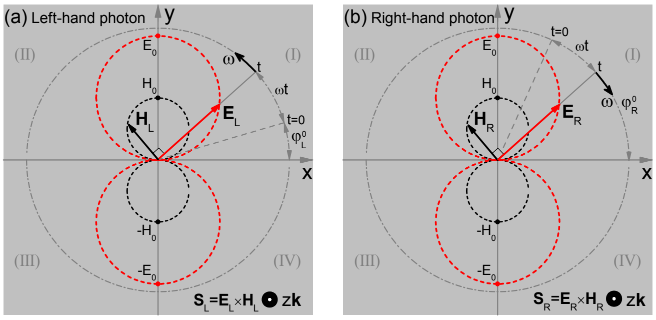

Figure 4: Schematics of chiral photons: (a) the left-handed photon rotate counterclockwise in the order of I-II-III-IV, and (b) the right-handed photon rotate clockwise in the order of I-IV-III-II. When looking at the direction of propagation of left-handed or right-handed photons, it can be found that the electric field vector $\mathbf{E}_L$ (or $\mathbf{E}_R$) and the magnetic field vector $\mathbf{H}_L$ (or $\mathbf{H}_R$) are always perpendicular at any time t and any spatial position z, in addition,the trajectories of the electric field vectors (red arrow) and magnetic field vectors (black arrow) are two pairs of tangent circles

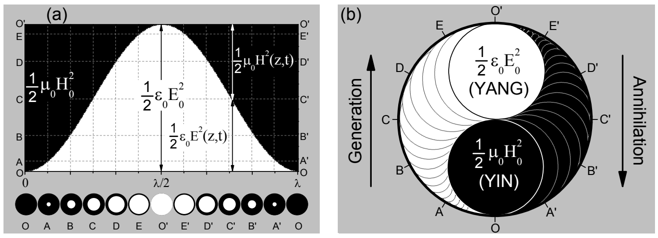

Figure 5: (a) Graphical diagram of the electric field energy and magnetic field energy of a left-handed or right-handed photon as a function of one propagation period, where $\lambda = \lambda_0/2$. (b) The ancient Chinese Taiji diagram explanation of the energy complementary relationship of chiral photons suggested in this Letter.

the Maxwell's equations [13]. We also tried to use Maxwell's equations, but soon ran into insurmountable theoretical difficulties. This is because of the relationship between the electric field $\mathbf{E}$ and the magnetic field $\mathbf{H}$ in Maxwell's equation:

$$\mathbf{k}\times\mathbf{E} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\mathbf{H}, \tag{1}$$

Although, a dual-energy photon can be defined by Maxwell's equation with the electric field energy $E_k(z,t) = \varepsilon_0 E^2(z,t)/2$ and the magnetic field energy $E_p(z,t) = \mu_0 H^2(z,t)/2$. But $E_p(z,t)$ and $E_k(z,t)$ are always in-phase which is different from the out-phase energy relation of the spring and LC oscillators. In other words, the photons defined by Maxwell's equations do not follow the energy complementarity principle. Is it possible to force them to be in phase? If this is done, a serious consequence is that the direction of the Poynting vector $\mathbf{k}$ is no longer consistent, and we soon realized that this is because the electric field $\mathbf{E}$ and magnetic field $\mathbf{H}$ of Maxwell's equation are linearly polarized. Based on the above failed attempts, we proposed a theoretical model of chiral photons that simultaneously satisfy the wave-particle duality and energy conservation laws (see Fig. 4). The electric field and magnetic field of the left-handed photon of Fig. 4(a) are given by

$$\mathbf{E}_L(z,t) = E_0\left|\cos(\tfrac{2\pi z}{\lambda_0}+\varphi_L^0)\right|\exp\left[i(\varphi_L^0+\omega t)\right], \tag{2}$$

$$\mathbf{H}_L(z,t) = H_0\left|\sin(\tfrac{2\pi z}{\lambda_0}+\varphi_L^0)\right|\exp\left[-i(\varphi_L^0+\omega t)\right], \tag{3}$$

while the right-handed photon is defined by

$$\mathbf{E}_R(z,t) = E_0\left|\cos(\tfrac{2\pi z}{\lambda_0}+\varphi_R^0)\right|\exp\left[i(\varphi_R^0-\omega t)\right], \tag{4}$$

$$\mathbf{H}_R(z,t) = H_0\left|\sin(\tfrac{2\pi z}{\lambda_0}+\varphi_R^0)\right|\exp\left[-i(\varphi_R^0-\omega t)\right]. \tag{5}$$

Here, λ_0 is the original wavelength, ω is the circular frequency, $z = ct$ ($c = 1/\sqrt{\mu_0\varepsilon_0}$ is the speed of light in a vacuum), and E_0,H_0, φ_L^0 and φ_R^0 are the maximum electric field intensity and magnetic field intensity, the initial phases of the left- and right-handed photons, respectively. Moreover, when $\varphi_L^0 = \varphi_R^0 = \varphi_0$, it is quite easily to prove that the combined light $\mathbf{E}_L(z,t)+\mathbf{E}_R(z,t)$ is a linearly polarized light along the φ_0 direction. By using the relationship $E_0 = \sqrt{\mu_0/\varepsilon_0}H_0$, it can be verified from Eqs. (2)-(5) that they satisfy the energy conservation relationship: $\varepsilon_0\mathbf{E}_L^2(z,t)/2 + \mu_0\mathbf{H}_L^2(z,t)/2 = \varepsilon_0\mathbf{E}_R^2(z,t)/2 + \mu_0\mathbf{H}_R^2(z,t)/2 = \varepsilon_0 E_0^2/2 = \mu_0 H_0^2/2$.

Figure 5(a) shows the energy complementary relationship of the chiral photons. It must be pointed out that the period (λ in the figure) of the energy exchange is the wavelength of light measured in the experiment, which is only half of the original wavelength λ_0 in our theory. Further, it must be emphasized that only the electric field energy $\varepsilon_0 E^2(z,t)/2$ of the photon can induce the observable optical effects, which implies that the unused magnetic field energy $\mu_0 H^2(z,t)/2$ of the photon is a kind of hidden energy (or dark energy), and hence we can describe the single photon using only the part of the electric field energy. In this simplified framework, a single photon is an energy particle with its "size" (the electric field energy) changing periodically, as shown at the bottom of Fig. 5. Now we can answer the question: what is the wave-particle duality of light? On the one hand, at any given moment the photon behaves as a particle with a definite electric field energy, on the other hand, at any time interval, the photon exhibits wave property with uncertain electric field energy, this is the physical nature of the wave-particle duality of light.

If we interpret the evolution from O to O' and from O' to O in Fig. 5(a) as the generation and annihilation of photons, we will be surprised to find that Fig. 5(a) can be expressed as the Taiji diagram of the ancient Chinese Yin-Yang complementary philosophy, as illustrated in Fig. 5(b). Can we say that Chinese philosophers had predicted that photons are Taiji particles with wave-particle duality about 6,000 years ago?

With the above theoretical and experimental research, we now focus on the single-slit experiment that has confounded the scientific community for hundreds of years. To our knowledge, whether it is the Fresnel'shalf-band method of classical optics or the complicated wave function treatment of quantum mechanics [12], their researches were based on a false conjecture that diffraction patterns are formed by transmitted light through the slit rather than the scattered light by the two edges as disclosed by our experiments of Fig.2. Figure 6(a) illustrates how a single-slit (double-edges) creates the characteristic diffraction pattern on the screen. As can be seen from the figure, there are two kinds of light arriving at the screen, one is the transmitted light $[I(T)]$ directly passing through the slit, and the other is the scattered light $[I(S_1)$ and $I(S_2)]$ from the edges S_1 and S_2 of the slit, respectively. It must be stressed again that there exists an essential difference between our theory and the traditional mainstream theories. We believe that the pattern is produced by $I(S_1)$ and $I(S_2)$ independently of $I(T)$, but mainstream physicists insist that it is the only contribution of $I(T)$.

Without any sophisticated mathematical treatments, the present technique enables us to obtain the diffraction pattern of single-slit straightforwardly. As shown in Fig. 6(a), when the photons from edges S_1 and S_2 are both at the maximum electric field energy state (Yang), the screen at that place will appear the brightest stripe, conversely, when they are at the same maximum magnetic field energy state (Yin), the darkest stripe will appear at the corresponding position. Hence, the conditions for the appearance of dark and bright stripes on the screen can be expressed as follows:

$$PS_1 - PS_2 \approx a\cos\theta = \begin{cases} k\lambda & k = 0, \pm1, \pm2, \cdots \\ \frac{2k+1}{2}\lambda & k = 0, \pm1, \pm2, \cdots \end{cases}, \quad (6)$$

where a is the slit width and θ is indicated in Fig. 6(a). Correspondingly, the positions of dark and bright stripes on the screen x_k are respectively given by

$$x_k = L\cot\theta = \begin{cases} k\Lambda_a & k = 0, \pm1, \pm2, \cdots \\ \frac{2k+1}{2}\Lambda_a & k = 0, \pm1, \pm2, \cdots \end{cases}. \quad (7)$$

From Eqs. (6) and (7), we have the following relationship: $a\sin\theta/L = \lambda/\Lambda_a$, in the approximation of θ close to $\pi/2$, thus we directly get the familiar formula:

$$\Lambda_a = \Delta x_k = |x_{k+1} - x_k| \approx \frac{L}{a}\lambda. \quad (8)$$

The total light intensity that reaches the screen consists of two parts, one is the left- and right-handed photons [Eqs. (2)-(5)] scattered by the slit edges and form the stripe, and the other is the direct transmitted light that does not form the stripe. By insert Eq. (8) into Eqs. (2) and (4), furthermore, if we assume that the transmitted light from the slit is a Gaussian beam, then the total light intensity on the screen can be analytically expressed as

$$I = \sum_{i=1,2} I_0(S_i)\sin^2\left(\pi\frac{x - x_i}{\Lambda_a}\right) + I_0(T)\exp\left(-\frac{2x^2}{a^2 + \Lambda_a^2}\right), \quad (9)$$

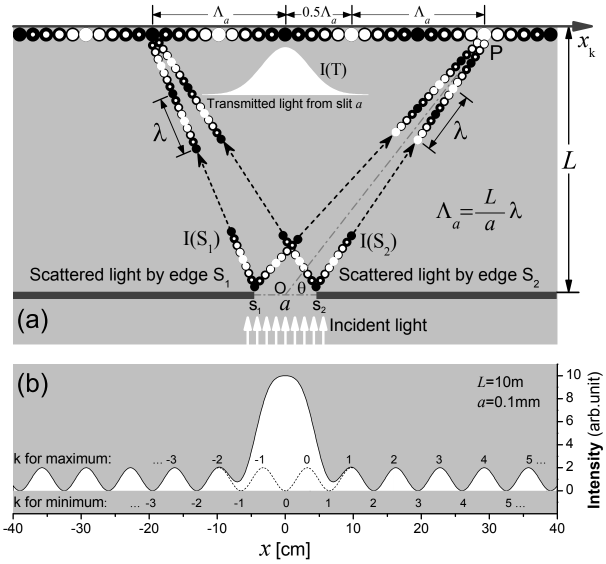

Figure 6: (a) A schematic how the bright and dark pattern built up in the single slit (double edges) experiment. (b) The numerical simulation of analytical expression (12) , consistent with experimental result of Fig. 2(a).

where $I_0(S_i)$ and $I_0(T)$ are the maximum values of the scattered and transmitted light intensity, respectively.

Figure 6(b) shows the numerical simulation result of Eq. (9) for $I_0(S_i)$=1, $I_0(T) = 10$, $\lambda = 650nm$, $a = 0.1mm$, $x_1 = -a/2$, $x_2 = a/2$ and $L = 10m$, note that the parameters a and L are the same as those in Fig, 2(a). By comparing Fig. 2(a) with Fig, 6(b), one can see a good agreement between the experiment and the theory. In addition, the integer k of Eq. (7) corresponding to the maximum and minimum of light intensity are indicated in Fig. 6(b). It should be noted that the center $x = 0$ is originally the minimum becoming the maximum is caused by the superposition of the transmitted light, which in turn doubles the width of the brightest center stripe. Finally, we briefly discuss the formation of double-slit interference pattern. In our theoretical framework, the double slit (four-edges) is just a trivial extension of a single slit (two-edges). The four edges of the double slit can provide two independent interval parameters $\Lambda_a = L\lambda/a$ and $\Lambda_{a+b} = L\lambda/(a+b)$ with the light intensity $I(a+b) = \sum_{i=1,4} I_0(S_i)\cos^2[\pi(x - x_i)/(a+b)]$, qualitatively, the pattern is formed by merging the patterns corresponding to Λ_a and Λ_{a+b} .

In conclusion, we have established a new theory of the wave-particle duality of photons. Contrary to the mainstream quantum probabilistic explanation, our theory provides a unified and deterministic explanation for single- and double-slit experiments. Both theoretical and experimental results indicated that the "bright" and "dark" fringes are formed by the electric field energy and magnetic field energy of the quantized chiral photons scattered by slit edges, respectively. There is no doubt that the proposed theory can provide new interpretations of various physical problems, such as the Compton effect, photoelectric effect, atomic spectrum, black-body radiation.

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