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Professional paper

WAVE-PARTICLE UNITY OF THE PHOTON

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Abstract

Einstein's photon theory accepts the co-existence of photons both as particles and as waves. They are opposite to each other but in unity. This wave-particle unity of photons signifies that the adequate manner of description is determined through the chosen method of observation (propagation or interaction).
The relationships, $E=\hbar\omega$ and $p=\hbar k$ allow to be passed from one manner of description to another. In this article, we will argue that the close relationship between these two manners of description has a statistical nature: the probability of photon localization to a point is proportional to the intensity of the light wave at that point, calculated by methods of classical optics.

Keywords: Photon, particle, unity, probability, wave functions.

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1. Introduction

Light is the best tool for communication with the world around us. By the light, we know better the natural part of which we are. The light arises from the matter, propagates through it, and interacts with it. Without light, there would be no radio, television, photography, holography, etc. So, we would not have the technology development. The development of optics during the second half of the twentieth century represents a rebirth in itself [1]. In the past half-century, many researchers combined optics with mathematical techniques and communication theory; The launch of digital computers with high speed, rapidly improved the construction of complex optical systems. Aspherical elements of lenses took a new meaning, and in practice, the limited diffraction system became a reality [5]. The technique of purification by ion bombardment, in which atoms disintegrate one after the other, was introduced to complete necessity the need for high precision in the preparation of optical elements. Using materials with one or more layers (reflective, anti-reflective, etc.) became something common. The optical fibers made practical use of light to carry information. Great attention was paid to the edge of the infrared spectrum (monitoring systems, rocket direction, etc.) leading to the stimulation and development of infrared technology. Plastics were widely used in optics (elements of lents, fibers, etc.). A new kind of glass ceramic was developed. In the 1960s there was a boom in the construction of astronomical observatories (terrestrial and extraterrestrial), which more developed during the 80s and 90s. The first laser was invented in 1960 and over a decade the laser beam changed from infrared to ultraviolet wavelength. The necessary technology to produce a practical communication system was rapidly developed [1]. The sophisticated use of crystals in instruments such as electro-optic and acoustic-optic modulators increased research on the optics of crystals. The technique of wavefront led to the increase of research known as holography (3-D display) [5]. This technique produces three-dimensional pictures (holographic images) and it can be widely used for the data. A great development in the military field during the '60s continued throughout the 70s and 80s, while further developed in the 90s. The technological interest in optics includes a whole spectrum of smart bombs, spy satellites, and infrared night vision devices. But, economic needs along with the need to improve the quality of life brought the products of this field into the consumer market as never before [8]. Today the laser is used everywhere, from the reading of video and discs to the steel cutter in the factory, or the supermarket barcode scanners to surgical procedures. Millions of optical systems are brightening the screens of calculators, computers, and watches everywhere in the world [2].

The exclusive using of electrical signals for the transmission of data these last hundred years is leaving the place for more efficient optical techniques. So, a revolution in methods of processing and the communication of information has taken place. This revolution will change our lives in the future. The progress of optics makes actual the statement of Bragg W. "With the word, light is synthesized all the physics and thus all the science". However, on the horizon of physical science is the question "What is light" always remains open. Einstein was the first who identify the coexistence of waves and particles with light. He showed that the hypothesis on the light, as a limited portion in space, necessarily leads to its description with determined the energy hν and momentum hν/c. In relations E=hν and p=hν/c, on the left sides are respectively the energy and impulse of the particle (photon), which can be taken localized at a point of space, while on the right - the monochromatic wave frequency which is required for its localization in an infinite space. Note that photons are neither pure particles nor pure waves (in their classical meaning). Both these images, taken separately, cannot explain the new experimental facts [3]. Nature appeared with features, which were never seen. Wave and particles in the same object-the opposite, but in the unity. In this way, we have to deal with the propagation of light in a vacuum. The difference between electromagnetic theory (wave theory) and Einstein's photonic theory (particle theory) is reduced in that, in the first one, it is assumed that light energy is scattered continuously over space. Whereas in the second one, it is practically concentrated in particular points or very small volumes. This distinction has a dual meaning. Firstly, it shows that atoms can lose energy (during the radiation of light) or can gain it (during absorption) only by finite portions determined by hν, and not in a continuous way, as classical physics predicts. Secondly, it follows that during the emission of light as well as during its absorption, we have a directed action [4]. Applying in this act the law of conservation of impulse, we conclude that during the emission of light with frequency ν, in the form of quanta with energy hν and momentum hν/c, the atom must undergo a recoil in the opposite direction, taking in this case the momentum (hν/c). Contrary, during absorption, the quanta above mentioned, gives its momentum and energy completely to the respective atom. These images are necessary to be completed with another assumption based on the analogy between photonic and wave theory. According to the latter, the absorption of light occurs in this way: the electric force of incident waves (electric field intensity E of the wave) causes in atoms the oscillating motion of electrons [6]. This oscillating motion, on its own, would cause secondary electromagnetic waves. If the energy of the atom increases, i.e., the amplitude of forced electronic oscillations increases, then the secondary electric forces become opposite to the initial and weaken them. In this case, the atom undergoes a positive light pressure directed along the propagation of waves. If, otherwise, the energy of the atom decreases, i.e. the amplitude of forced electronic oscillation decreases, then the secondary electric forces have the same direction with initials ones and increase them. In this case, the atom undergoes a negative light pressure opposite to the direction of propagation of waves. This relation is derived directly from the formula p=S/c2 that connects the energy with the density of electromagnetic momentum. It was preserved by Einstein even in photonic theory [7]. Precisely, along with common absorption of quanta he introduced the concept of negative absorption or stimulated emission, during which the quanta of light is not absorbed by the atom, but comes out from it together with other quanta emitted by the atom itself, having the same magnitude and direction with them. In this case, the atom, as well as during common spontaneous radiation, undergoes retail in the opposite direction of quanta emission, taking the momentum (hν/c). We know that the mechanical properties of photons such as energy, mass, and impulse are characteristic even for electromagnetic waves. But these mechanical quantities are, let's say, only secondary derivative properties of electromagnetic waves. The fundamental quantities for these waves are the electric field intensity E and the magnetic field intensity H, which do not exist in themselves but only together: one cannot exist without the other. They are orthogonal to each other and move perpendicular to the direction of propagation. As it is known, from their orthogonality is derived the polarization of light.

The question is: How can be imagined this polarization from a photonic point of view? The electric field intensity of the light wave can be considered in the photonic theory with the electric moment of the photon, p, which characterizes the linearly polarized light. This electric moment can be interpreted as a vector and not as a scalar quantity oscillating. By analogy, the magnetic field intensity, μ, of the photon is perpendicular to the electric one and numerically equal to it. Two vectors, p, and μ, must be perpendicular to the direction of propagation of the photon. Meanwhile, this motion occurs in such a side that is determined by turning the right screw from μ to p. Since electric and magnetic fields represent a reality not separated, but always exist together, then the same thing is valid for the electric and magnetic moment which in photonic theory represent the intensity of the electric and magnetic field. They have invariant meaning determined only taken together, numerically equal to each other, mutually perpendicular, and also perpendicular to the direction of propagation. Therefore, the accordance between photons and waves of electromagnetic light theory is obtained. Without deepening these conceptions, which are based on the theory of relativity, it is noted that polarized light can be imagined with photons having complex values of the vectors p and μ. Regarding the oscillating properties, i.e., that characterize the periodicity in time and space, the photonic theory is powerless. So, how can be imagined from the photonic viewpoint, wave propagation of light? The answer to this question is given by quantum mechanics according to de Broglie's hypothesis on the existence of waves of matter, as probability waves [8].

2. Theory of photons and interference

We shall now explain how the hypothesis of photons can be consistent with phenomena such as interference and diffraction of light waves that have essentially wave characteristics. Here we will not make a distinction between these two phenomena, because there is no physical distinction between them. The only difference, if we may call so, is: when we have a few sources, for example, two slits of Young (Fig.1) then the result of their common action is called interference, whereas their number is very large (diffraction grid) it is often called diffraction [4].

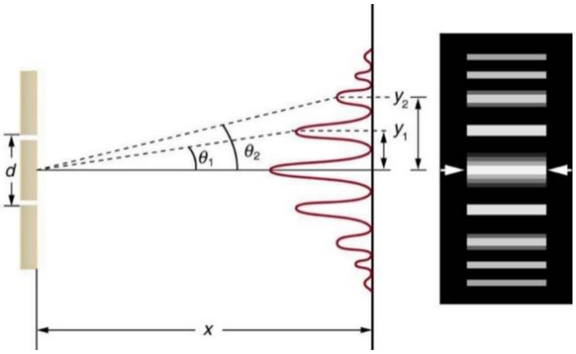

Figure 1. Young's Double Slit Experiment

Consider the known example of the distribution of monochromatic light beams in a diffraction grid with parallel slits. If instead of the screen, where the pattern of interference is displayed, we put a photographic plate, then in this case in the negative, seen the pattern of interference, as darkening of special parts of the plate, while this darkness is proportional to the amount (intensity) of light falling in these parts.

Indeed, the absorption of light from the photonic plates occurs with individual quanta: each photon entering in photographic plate excites the microcrystal sensitive to the light which, during the exposure, gives a dark point. A free eye cannot distinguish individual points, therefore we also observe dark areas depending on the number of photons that hits the plate per unit area. But, the existence of an individual can be recorded if we observe the photographic plate with a powerful microscope [5].

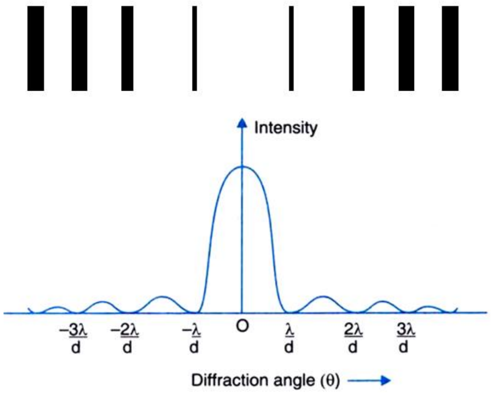

Figure 2. Intensity distribution

Classical electromagnetic theory for the intensity distribution (Fig. 2) to the right of screen C gives this value:

$$I(r,\theta)=A^2=4I(r,\theta)=|A|^2=4I_0(r,\theta)\cos^2\left(\frac{2\pi a}{\lambda}\sin\theta\right) \qquad (1)$$

Where $I_0=|A_0|^2$, is the intensity by a slit.

The term $\cos^2\left(\frac{2\pi a}{\lambda}\sin\theta\right)$ is known that arises as a result of interference of waves emitted by two slits. Due to interference, the intensity in some directions will be zero, while in some other directions, it will be $4I_0$. The relationship between intensity I and intensity I_0 given by (1) is a consequence of classical wave images. *Is the equation true (1) with the photon imagined as indivisible?* We reason in this way: since the photon cannot be divided, then it will pass either one or the other slit. Assume that it passes through the upper slit. In this case, the presence of the bottom slit can not affect the diffraction of the photon and the intensity distribution of all photons that pass through the upper slit will be given by the expression: $I_0(r, \theta)$. The same can be said for the photons that pass through the bottom slit. As a result of these arguments, we conclude that the resultant intensity from two slits must be equal:

$$I(r,\theta)=2I_0(r,\theta) \qquad (2)$$

This expression shows that the diffraction waves from two slits do not interfere and if it is true for the experiments with two slits, then no interference in diffraction grids or crystals must be observed. However, the experiment shows in favor of the expression (1) which is taken based on wave properties. But, in reality, the indivisible photons exist. *So how can be explained the phenomenon of diffraction?* A solution might be this: considering the interference as a result of the interaction of many photons. Such an assumption leads us to think that the expression (2) will be true for the very low intensities of light ie when the photons pass slits one by one, while the expression (1) is valid for the very large intensities of light: ie is it true that the pattern of diffraction is changed from (1) to (2) if the intensity of the light source increases? The experiments made to verify this yield a negative answer. The pattern of diffraction does not change even for very small intensities of light. This means that the diffraction pattern does not arise from the interaction of a large number of photons. Then, there is no nothing else to consider, so we have to assume that since the pattern of diffraction exists, it shows that the photon passes through two slits: partially in the first slit and partially in the second one. From the classical viewpoint, such an assumption is paradoxical, because the classical particles pass through one or the other slits. There is no other alternative. But we are dealing with photons and such an assumption responds to the fact that it exists. If you want to know in which slits the photon passes then we will cover one of them, but in this case, we cannot observe a diffraction pattern by two slits. To observe this pattern two slits should be open. It cannot be established the mechanisms which would tell us at which slit the photon passes without destruct the diffraction pattern by two slits. Such a pattern could arise only when the photon passes through two slits and the question "at which slit will pass the photon", does not make sense. *What does the screen register?* He never registers the part of the photon but always the photon as a whole. From here we can say that when the photon passes through the slits exhibits its wave properties, and when it falls into the photo element exhibits its particle properties, ie the photon passes through the slits "as a wave" and is recorded as "a particle".

3. Light waves as probability waves

The statistical distribution of photons observed in the experiment of diffraction requires their consideration by probability method. This statistical distribution is subject to interference law (1). Taking into account$I=|E_0|^2$ we arrive at this conclusion: the square of the electric field amplitude of light waves in an area of space is not equal to the photon energy$|E_0|^2$ in this case area [9]. It is proportional to the probability of finding a photon in this area if we try to localize it by the detector. Analogously, the radiation flux (calculated according to the classical theory) in the slits should be interpreted according to this new idea as a magnitude proportional to the probability of detection of the photon, if we put the detector directly behind the slit. Since the energy given to the detector is always hν, this means that the photon is registered as a particle and in this sense, it carries momentum and mass [10]. If somewhere in space we will register the photon (eg with the help of the detector) then the energy given to the detector is always equal to hν. Since the probability of detecting the photon is proportional to the sum of the squares of amplitudes E and B then we conclude that the classical energy density, integrated by area, is equal to the product of the photon energy and detection probability of the photon in this area. So, in the case of a common light source that emits a very large number of photons, the average energy in the given area is equal to the energy calculated by classical theory. In this way, the theory of light does not require absolute removal from the old images for light, but it only requires combining the concept of photons with electromagnetic waves [13][14]. So, we can treat some new ideas that end up as follows: Quadratic quantities which depend on the amplitude of the electromagnetic field are interpreted as probabilities. We can continue to apply this to the propagation of photons in space Maxwell's equations but the energy density and its flux, calculated classically, are interpreted through the new idea as the average values observed for a large number of photons. Therefore, in the experiments where we measure the average values and do not try to observe individual photons, the classical theory is completely true [11][12]. On the other side, during the observation of individual photons, for example, by detectors (photo elements) becomes more evident the limitation of classical theory and the use of photonic theory ideas.

4. Conclusions

Finally answering the question of what is light: wave or particle we answer: that light is a particle as well as a wave! As a particle, it carries energy, momentum, and mass and as a wave, it determines the probability of finding the photon in a defined area of space. So the light during its propagation appears as a wave, while during its interaction with matter appears as a particle. This is the nature of light. In this end the physical meaning of wave-particle unity of light. This wave-particle unity indicates that the appropriate way of describing is determined by the observation chosen method (propagation or interaction). Relations $E= \hbar\omega$ and $p=\hbar k$ allow passing from one description way to another. The close relationship between these two ways of description has a statistical nature: the probability of photon localization to a point is proportional to the intensity of the light wave at this point and is calculated according to the methods of classical optics. The idea of wave particles became a universal idea of matter as well as the field. This wave-particle unity can be seen as the potential ability of physical matter which once appeared once wave properties, and also particle properties depending on experimental conditions. The recognition of these properties as unity is also the recognition of specific characteristics of the micro world of its motion. "The connection between waves and particles - De Broglie noted - is the greatest law of nature, while such a unity is connected with the existence and the essence of quanta"

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