Are there photons in fact?

S.A. Rashkovskiy
Institute for Problems in Mechanics of the Russian Academy of Sciences, Vernadskogo Ave., 101/1,
Moscow, 119526, Russia, Tomsk State University, 36 Lenina Avenue, Tomsk, 634050, Russia

ABSTRACT

There are two opposing points of view on the nature of light: the first one manifests the wave-particle duality as a fundamental property of the nature; the second one claims that photons do not exist and the light is a continuous classical wave, while the so-called "quantum" properties of this field appear only as a result of its interaction with matter. In this paper we show that many quantum phenomena which are traditionally described by quantum electrodynamics can be described if light is considered within the limits of classical electrodynamics without quantization of radiation. These phenomena include the double-slit experiment, the photoelectric effect, the Compton effect, the Hanbury Brown and Twiss effect, the so-called multiphoton ionisation of atoms, etc. We show that this point of view allows also explaining the "wave-particle duality" of light in Wiener experiments with standing waves. We show that the Born rule for light can easily be derived from Fermi's golden rule as an approximation for low-intense light or for short exposure time. We show that the Heisenberg uncertainty principle for "photons" has a simple classical sense and cannot be considered as a fundamental limitation of accuracy of simultaneous measurements of position and momentum or time and energy. We conclude that the concept of a "photon" is superfluous in explanation of light-matter interactions.

Keywords: Wave-particle duality of light, classical electrodynamics, Wiener experiments with standing waves, Born rule, Heisenberg uncertainty principle

1. INTRODUCTION

There are two opposing perspectives on the nature of light.

According to the first perspective (orthodox), light has both wave- and particle-like properties: in some experiments (diffraction and interference experiments), light behaves as a classical electromagnetic wave, while in other experiments (interaction with matter), light behaves as a flux of particles, i.e., photons. This property of light was called the wave-particle duality. Directly, the wave-particle duality of light can be observed in many optical experiments; the duality is manifested in the observation that light interacting with matter induces discrete events (clicks of detector or the appearance of spots on a photographic plate), which are interpreted as the interactions of single photons; however, after prolonged exposure, these discrete events merge into a single continuous pattern, well described by classical electrodynamics or even classical optics [1,2].

Compatibility between the wave and corpuscular properties of light in quantum theory is achieved by using a probabilistic interpretation of optical phenomena: the probability p of finding a photon at some point in space is proportional to the intensity of the classical light wave $I \sim \mathbf{E}^2$ at this point, calculated on the basis of the methods of wave optic [3]:

$$p \sim \mathbf{E}^2 \tag{1}$$

where E is the strength of the electric field of the classical light wave.

The rule (1) (for brevity "the Born rule for light"), underlying the photonic interpretation of experiments with light, is an independent postulate of quantum mechanics. Thus, the description of optical experiments within the framework of the photon hypothesis consists of two independent parts: (i) the Maxwell equations describing the propagation of light and (ii) the Born rule (1). Precisely, the Born rule (1) results in a paradox in explaining the wave-particle duality of light [4].

From this point of view (which is now considered to be the official one), the wave-particle duality is considered to be a fundamental property of nature. At the same time, the wave-particle duality is one of the greatest mysteries of modern physics. Most clear and impressively, the paradoxes associated with the wave-particle duality of light are manifested in Young's double-slit experiment and in Wiener's experiments with standing waves: the closing of one of the slits in the

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double-slit experiment changes the “behaviour” of the photons that pass through the open slit, while the installation or removal of a mirror in the Wiener experiments results in a “spatial redistribution” of photons in the incident beam [4]. These paradoxes gave rise to a whole direction in quantum physics - the interpretation of quantum mechanics [4-13].

The discovery of the wave-particle duality of light raised numerous fundamental questions, the most difficult of which are the following: (i) What is a photon? (ii) How may one and the same matter (light) have such incompatible properties in terms of classical physics: both wave and particle? Despite the fact that the concept of a “photon” has become commonplace in modern physics, philosophy and even in culture, we can say that even now, after more than 100 years since the introduction of the concept of the wave-particle duality in physics, we are unable to answer the fundamental question: what is a photon?

In fact, currently, we have an elegant mathematical theory (quantum electrodynamics) that does not represent the object it actually describes.

It should be noted that in any experiment, we cannot directly see the photon: we judge of the presence of a photon only indirectly on the basis of discrete events, registered by a detector. Attempts of the author, in conversations with experimentalists, working with so-called “single photons”, to find out how they imagine a “single photon”, have shown that none of them cannot articulate what it is: a “photon”. For most of them, the photon is some intuitive, vague, fuzzy concept that exists on a subconscious level, what, however, does not prevent them from getting the practically important and interesting results. As this survey has shown, most often, for experimentalists, a “photon” associates with an isolated wave packet in which the wave is considered a quite classical. This shows once again that not only theorists but also experimentalists who manipulate by the “single photons”, do not imagine the object with which they work.

At the same time, there is another point of view, according to which there are no photons in Nature; in this perspective, light is a continuous classical electromagnetic wave that is completely described by Maxwell equations, while the so-called “quantum properties” of light are “manifested” only during the interaction of light with matter, which is connected to the specific nature of this interaction. This point of view is now shared by only a small part of physical community, but at a different time, this point of view was supported by many authoritative physicists, such as M. Planck, E. Schrödinger, W.E. Lamb, Jr., A. Lande, E.T. Jaynes et al. For example, Planck was a proponent of a semi-classical theory, in which only the atoms and their interactions were quantised, while the free fields remained classical. We note that even N. Bohr, one of the authors of the Copenhagen interpretation of quantum mechanics, at the beginning, was also an opponent of light quanta [14]. The most consistent opponents of the concept of photons were the Nobel Prize Winner Willis E. Lamb, Jr. [15,16] and Alfred Lande [17]. E.T. Jaynes has questioned the need for a quantum theory of radiation. In his view, semi-classical theory, with the addition of a radiation reaction field acting back on the atom was sufficient to explain the Lamb shift, which is considered to be the best vindication of Dirac’s field quantization and QED theory [18]. “I doubt that QED is necessary,” declared Jaynes [18].

In paper [19], we have begun a series of articles involving the justification and development of the point of view that the photon does not exist and that light is a classical wave field described by the Maxwell equations.

We have shown [19] that in many cases the “wave-particle duality” of light can be explained without using the concept of the “photon” by only using the Fermi’s golden rule: the probability of excitation (ionisation) of an atom in the field of a classical monochromatic electromagnetic wave for time Δt is equal to

$$w\Delta t = bI\Delta t \tag{2}$$

where w is the probability of excitation (ionisation) of atoms per unit time; $I \sim \mathbf{E}^2$ is the intensity of the classical electromagnetic wave at the location of the atom; and b is a constant depending on the characteristics of the atom, the frequency of the incident electromagnetic wave and the states between which the transition of the atom occurs under the action of the electromagnetic wave. Unlike the Born rule (1), the Fermi’s golden rule (2) is not a postulate; rather, it is an exact result of perturbation theory [20] in which light is considered as a classical electromagnetic wave.

In this paper, we continue a discussion of this problem.

2. QUANTUM EFFECTS WHICH CAN BE DESCRIBED WITHOUT USING THE CONCEPT OF THE "PHOTON"

Many quantum phenomena, traditionally described by quantum electrodynamics, can in fact be explained within the framework of so-called semi-classical theory, in which atoms are described by the wave equations of quantum mechanics (Schrödinger, Dirac, etc.), while light is described by classical electrodynamics without quantisation of the radiation. Note that many of these results have been known since the dawn of quantum mechanics; however, in view of the rapid and certainly remarkable successes of quantum electrodynamics, they have not received proper attention and development.

Let us consider the most important "quantum" effects for which the theoretical calculation does not require the quantisation of radiation.

Born rule for light

As we noted above, the Born rule for light (1) is an independent postulate of quantum mechanics. The direct application of Born rule for explaining the results of experiments on light-detector interaction leads to a paradox (the wave-particle duality of light) [4].

At the same time, as we have shown in [19], the Born rule can simply be derived using the Fermi's golden rule (2), if we take into account the atomic structure of a detector. If a detector is placed in the field of classical electromagnetic wave, an excitation of an arbitrarily chosen atom of the detector occurs with probability (2); this interaction would be perceived as a triggering of the detector, which occurs either in the form of clicks of the detector or in the form of the appearance of spots on a photographic plate. These events occur randomly in space and time, but after a prolonged exposure, they form a continuous, deterministic picture.

The probability that an arbitrarily chosen atom of the detector would be excited (ionised) at time t is equal to [19]

$$P_+(t) = 1 - \exp\left(-\int_0^t w(t')dt'\right) \tag{3}$$

This expression was obtained without quantization of radiation, i.e. without using the concept of the "photon".

But if we use the "photonic" interpretation of the observed process, each excitation of the atom would be interpreted as a "photon" hitting the point that is the location of the atom. Such an analysis implies that we apply a discreteness of matter (detector), consisting of atoms, to the "structure" of light: instead of discrete matter, we consider it a continuous one, while instead of a continuous electromagnetic (light) wave, we consider the flux of discrete quanta – "photons". As a result, we interpret a single event (a click of the detector or the appearance of a spot on the photographic plate) as hitting the "photon" at some point in space filled with continuous matter. In this case, we need to consider the probability of finding the "photon" at the given point in space [19]

$$p = \frac{P_+}{\int P_+ dV} \sim P_+ \tag{4}$$

where the integral is taken over the entire volume or surface of the detector (e.g., the photographic plate).

For weak electromagnetic wave or for short exposure time for which

$$\int_{t_0}^t w(t')dt' << 1 \tag{5}$$

one approximately obtains

$$P_+(t) \approx \int_{t_0}^t w(t')dt' \tag{6}$$

In this case, taking into account expressions (2) and (4), one obtains

$$P_+(t) \sim \mathbf{E}^2 \tag{7}$$

and

$$p \sim \mathbf{E}^2 \tag{8}$$

This expression is exactly the Born rule for "photons" (1).

The analysis [19] shows that (i) the Born rule for light (1) is a trivial consequence of quantum mechanics if the electromagnetic wave is considered as a classical field, while the matter (detector) is considered as consisting of discrete atoms; (ii) the Born rule (1) is valid only for weak electromagnetic waves or for a relatively short exposure time, satisfying condition (5). For strong electromagnetic waves or for a longer exposure time for which condition (5) is not satisfied, the Born rule should be replaced by a stricter rule [19].

It is easy to see, that the direct application of the Born rule (1) as the primary principle leads to the wave-particle duality, while the more general rule (2) does not lead to paradoxes in interpreting the experimental data.

Double-slit experiment

The double-slit experiments [1,2] are considered to be the direct and evident "demonstrations" of the wave-particle duality of light and the related paradox. Numerous attempts to explain these experiments by unusual (non-classical) motion of point "photons" were unsuccessful [5-13]. The reason of this paradox is the direct application of the Born rule (1) as the primary principle for interpreting the results of experiments. Application of the Fermi's golden rule (2) for explaining the double-slit experiments (taking into account the atomic structure of a detecting screen) allows avoiding the paradox [19].

The probability of excitation (ionisation) of an atom on the surface of the detecting screen for the time *t* is described by expressions (4) and (3).

$$P_+(t) = 1 - \exp(-wt) \tag{9}$$

Taking into account (2), one obtains

$$P_+(t) = 1 - \exp(-bIt) \tag{10}$$

Introducing the nondimensional time

$$\tau = bI_0 t \tag{11}$$

one can write

$$P_+(t) = 1 - \exp\left(-(I/I_0)\tau\right) \tag{12}$$

where I is the intensity of light in given point of the detecting screen which can be calculated within the limits of classical optics; I_0 is the maximum intensity of light on the screen.

The comparison of the results of calculations of the double-slit experiment, obtained by using the Monte Carlo method [19], with the real picture of the "accumulation of photons" on the detecting screen in the double-slit experiment [2], have shown that the calculated pattern is completely consistent with the experimental interference pattern and the model completely reproduces the results of these experiments: at short exposure times or at low intensities of the light, the random system of dots on the screen appears, which can be interpreted as the places of the "fall of the photons" on the screen, although no photons were considered in the theory. At the same time we have found out the difference in predictions of the results of double-slit experiment by using our theory and by using the direct application of Born rule for calculation of the interference pattern [19]. This gives a tool for verification of the theory.

Compton effect

In quantum mechanics, the Compton effect occupies a special place. This effect is considered to be direct proof of the existence of photons. Exactly after the discovery of the Compton effect and its explanation based on photonic representations, many physicists began to perceive photons as the real physical objects. In the canonical, for quantum mechanics, explanation of the Compton effect, it is considered an elastic scattering of photons by free electrons. In this case, photons are considered as massless relativistic particles that have energy $\hbar\omega$ and momentum $\hbar\omega/c$.

However, even at the dawn of quantum mechanics, the Compton effect was explained without using the concept of the photon [21-26]: light was considered as a classical electromagnetic wave, while electrons were described by Klein-Gordon or Dirac equations. From the considered points of view, the approach [23] based entirely on classical electrodynamics is of particular interest. In that paper, the classic electric current, which creates the scattered electromagnetic wave, was calculated on the basis of the solution of the Klein-Gordon equation. At the same time, in papers [21,22], the wave equation was used only as a tool for calculating the matrix elements; this approach makes the obtained results more formal and less clear from the physical point of view. A pictorial explanation of the Compton effect was proposed by E. Schrödinger [25] on the basis of purely wave representations: he considered light as a classical electromagnetic wave and drew an analogy between the scattering of this wave on the de Broglie wave and the Bragg scattering of light on ultrasonic waves considered by L. Brillouin.

Photoelectric effect

All the known regularities of the photoelectric effect are explained if light is considered as a classical electromagnetic wave, whereas atoms are described by the wave equation, e.g., Schrödinger or Dirac [26-28]. From perturbation theory, it follows [20,29] that a threshold effect occurs at the transition of an atomic electron into the continuum: if the frequency of the incident light is less than the threshold frequency $U_i/\hbar$, where U_i is the ionisation potential of the atom, then ionisation does not occur and $w = 0$. Otherwise, the ionisation probability is determined by expression (2). This completely explains the photoelectric effect without invoking the concept of a “photon”.

Hanbury Brown and Twiss effect

Hanbury Brown and Twiss effect [30,31] has a simple classical explanation [32-36] if expression (2) is used and we assume that the components of the electric field vector of the light wave $\mathbf{E}$ are random variables and have a Gaussian distribution. In this case, each click of the detector is considered to be the result of the excitation of one of the atoms under the action of light.

Interaction of an intense laser field with an atom

One of the striking examples of how “photons” appear in theory that does not consider the quantisation of light is the Keldysh theory [37], which describes the multiphoton and tunnel ionisation of atoms in an intense laser field. In the Keldysh theory, atoms are described by the Schrodinger equation, while light is considered as a continuous classical electromagnetic wave. Nevertheless, the obtained continuous solution of the Schrodinger equation is interpreted from the standpoint of “photonic” theory, which allows for the conclusion that, under certain conditions, “multiphoton” ionisation of an atom occurs when the atom “simultaneously absorbs several photons”. Such an interpretation is based on the fact that the solution of the Schrodinger equation contains components with a phase factor $n\hbar\omega$, where n=1,2,..., which is interpreted as a result of the simultaneous absorption of n “photons”. From the mathematical point of view, these “multiphoton” terms are simply the conventional terms of the expansion of solutions in the Fourier series, and in any other (“non-quantum”) theories, they would be perceived as quite trivial. It is paradoxical that radiation is not quantised in the Keldysh theory and in its solution and is considered as a continuous wave; the “photons” appear only at the stage of interpreting the results of the solution. This situation is typical for many processes in which the “quantum effects” are manifested.

We can also note that many other quantum phenomena, traditionally described by quantum electrodynamics, can in fact be explained within the framework of so-called semi-classical theory without quantisation of the radiation. These phenomena include the Lamb shift [38-41], radiative effects [39-42], spontaneous emission [38,41,42],

3. WIENER EXPERIMENTS WITH STANDING WAVES

The double-slit experiment is traditionally used for direct demonstrating the wave-particle duality of light.
However, in my opinion, the Wiener experiments [43] are more suitable for this purpose: if we accept the photonic

hypothesis, these experiments are the direct demonstration of unusual behaviour of photons in space due to the interference of plane light waves.

Wiener [43] investigated the field of a standing light wave that was formed by reflection of an incident plane wave from a mirror. A thin photographic emulsion film, which was located at a very small angle relative to the reflecting surface, was placed in the field of the standing light wave (Fig. 1). In the first experiment, Wiener investigated the normal incidence of the light beam on the mirror. After developing the film, black equidistant fringes and transparent intervals between the fringes were found. If one repeats this experiment with a low-intense light we would observe the system of discrete dots on the photographic emulsion film which can be interpreted as the places of hitting the "photons"; however, after prolonged exposure, these discrete dots merge into a single continuous pattern corresponding to the results of Wiener experiment [43]. Analysis of the optical field in these experiments and comparison with the pattern on the photographic film shows that the black fringes correspond to the areas in the vicinity of the maxima of $\mathbf{E}^2$, in complete agreement with interpretation (1). If we remove the mirror and act on the same film by only a single incident plane wave, the blackening of the film, as expected, would be uniform. Thus, the interaction of the incident and reflected light beams leads to a redistribution of photons in space; the uniform distribution of the photons in the incident and reflected waves becomes significantly non-uniform in the standing wave.

Similar experiments were performed with fluorescent [45] and photoemission films [46], which were used as standing wave detectors, instead of the photographic emulsion used by Wiener. In these cases, the maximum effect was also found in the antinodes of the electric field, which from the corpuscular perspective means that in these areas there is an "enhanced concentration of photons".

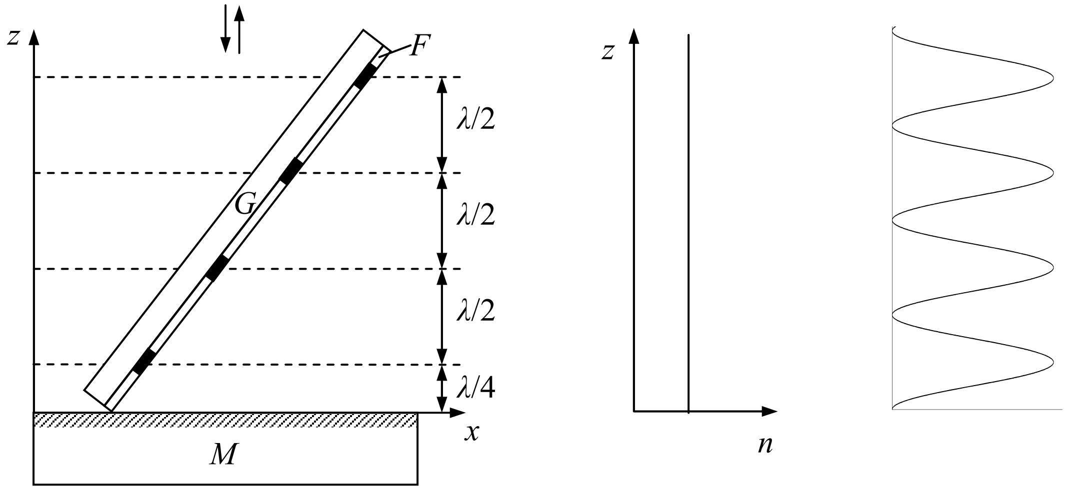


Figure 1. Scheme of Wiener experiments with standing light wave [44]. The angle between the plate and the mirror greatly exaggerated. Graphs show the distribution of the photons in space calculated by using the expression (1) for experiments with a mirror (right) and in the absence of mirror (left). M - mirror, G - glass plate, F - photographic emulsion film.

We can see that the Wiener experiments [43] give us more reasons to be surprised by behavior of photons than the traditional double-slit experiment.

All known alternative interpretations of the wave-particle duality [5-13] allow explaining the double-slit experiment in some way; however, they often find themselves powerless to explain the Wiener experiments with standing light waves.

In paper [4], a model was suggested which allows explaining such unusual behavior of the photons both in the double-slit experiment and in the Wiener experiments; however this model requires an essential nonlinearity of electromagnetic field even in vacuum.

Here, we will show that the Wiener experiments can be easily explained in terms of classical electrodynamics similar to that of double-slit experiment [19], if we take into account the discrete structure of photographic emulsion film and the specific nature of the interaction of light with matter, which is described by the Schrodinger equation (or other wave equation of quantum mechanics).

Let us consider a normal incident of a weak classical electromagnetic wave on the mirror. According to classical optics [44], a standing wave is formed with the distribution of light intensity

$$I = 2I_0 \sin^2 kz$$

where I_0 is the intensity of incident light; k is the wavenumber of light; z is the normal-to-mirror coordinate (see Fig. 1).

If α is the angle between the mirror and a photographic emulsion film, then the coordinate along the photographic emulsion film $z' = z/\sin\alpha$. Then the distribution of the intensity of light along the photographic emulsion film is

$$I = 2I_0 \sin^2 (kz'/\sin\alpha) \tag{13}$$

Let us consider the calculation of Wiener experiment for low-intense light when the “photons” impinge on the surface of the photographic emulsion film one by one, by the Monte Carlo method [19].

For simplicity, we assume that the photographic emulsion film represents a single layer of atoms, in which the atoms are placed randomly with surface density n (number of atoms per unit surface).

Generally speaking, relation (2) itself explains the “wave-particle duality of light” in Wiener experiment; nevertheless, for a clear “demonstration” of the “wave-particle duality of light”, we will perform the direct calculation of the interaction of light with a photographic emulsion film, assuming that the excitation (ionisation) of an atom is perceived as blackening of the appropriate point of the photographic plate.

The probability of excitation at time *t* of an atom located at a point on the screen with a given value *w* is described by expression (9) or in nondimensional variables by expression (12).

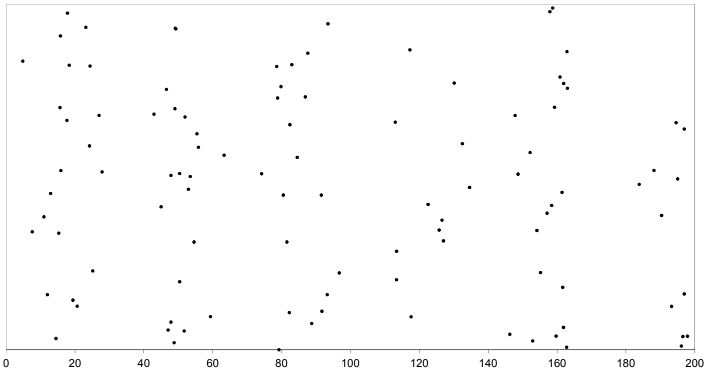
Taking into account expression (13) one can write

$$P_+(t) = 1 - \exp\left(-2\tau \sin^2 (kz'/\sin\alpha)\right) \tag{14}$$

For the calculation of the Wiener experiment using the Monte Carlo method, we create a system of randomly and uniformly distributed points $i = 1,...,N$ in a given area $L_z \times L_y$, simulating the photographic emulsion film. These points are considered as the atoms of the material of the film. We use the average distance between atoms as a length scale; in these units, the concentration of the atoms on the surface of the screen is equal to unity.

At each moment of time τ for each yet unexcited atom, the probability P_{+i} is calculated by expression (14); at the same time, the random number $R_i \in [0,1]$, $i = 1,...,N$, is generated by a random number generator. If the condition $R_i \le P_{+i}$ is satisfied, then the given atom is considered to be excited, and it is depicted by a black dot. Unexcited atoms are not depicted.

The results of the calculations of the process of the “accumulation of photons” on the photographic emulsion film for different moments of time τ at $k/\sin\alpha$ =0.09 are shown in Fig. 2 (left). The markers on the graph on the right are the histogram obtained by treating the corresponding picture on the left; the line on the graph on the right is the theoretical dependence (13), predicted by classical optics.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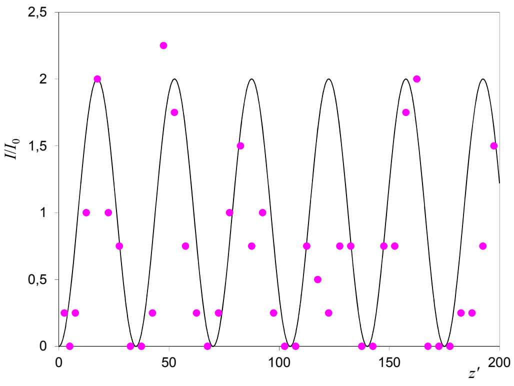
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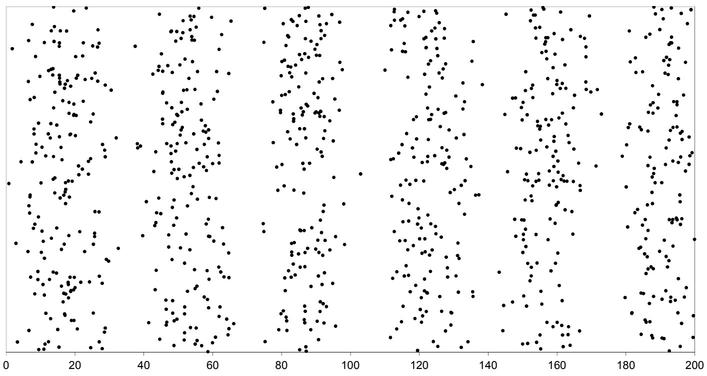
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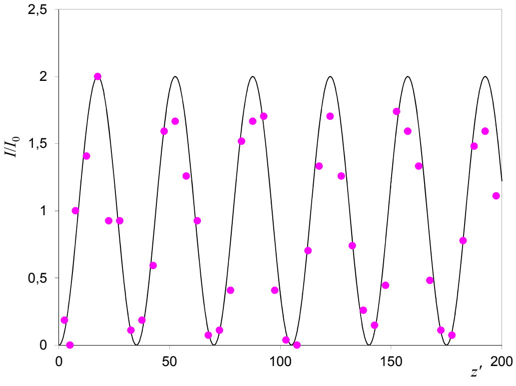
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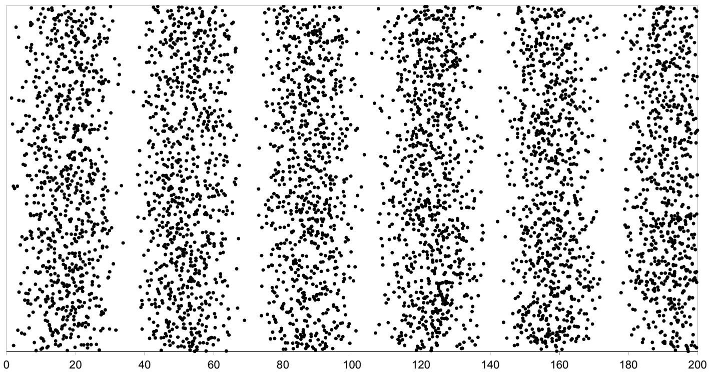
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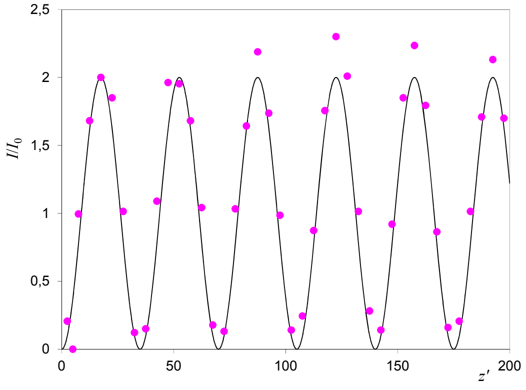
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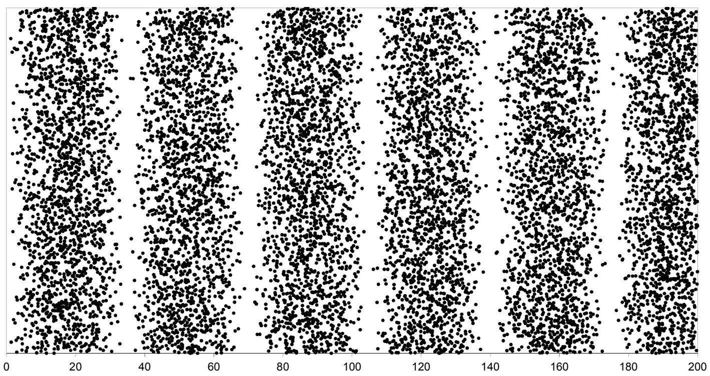
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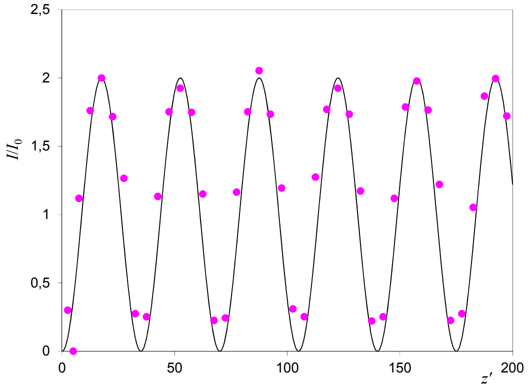
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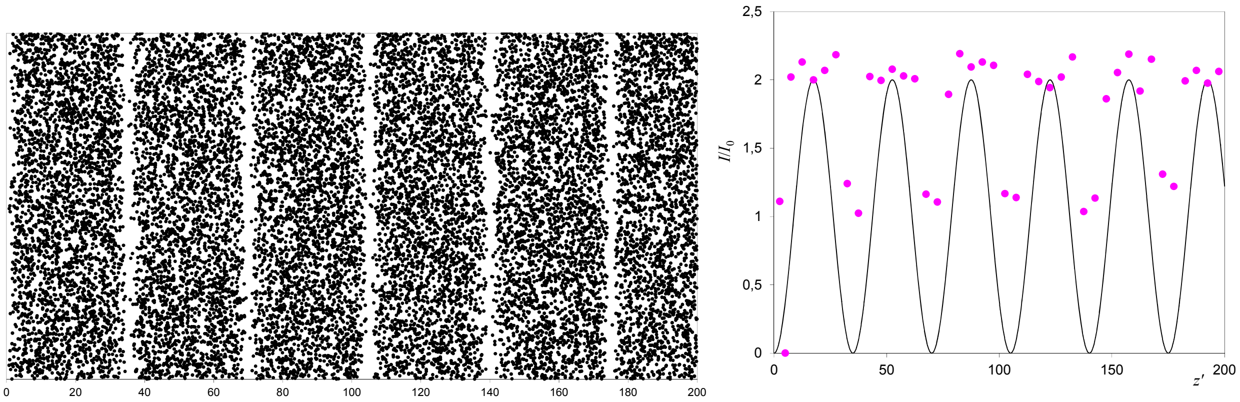

Figure 2. Interference pattern buildup (left) and the corresponding distribution functions of dots on the photographic emulsion film (right) for different exposure times τ, obtained by the Monte Carlo simulation of the interaction of low-intense light with the photographic emulsion film in Wiener experiment with standing wave. a) $\tau = 0.005$ (100 "photons"); b) $\tau = 0.05$ (960 "photons"); c) $\tau = 0.3$ (5004 "photons"); d) $\tau = 1.0$ (11004 "photons"); e) $\tau = 10$ (17650 "photons"). The markers on the graphs (right) show the histograms obtained by treating the corresponding picture on the left picture; the line is the theoretical dependence (13), predicted by classical optics.

We can see that the calculated pattern is completely consistent with the experimental interference pattern and the model completely reproduces the results of these experiments: at short exposure times or at low intensities of the light, the random system of dots on the film appears, which can be interpreted as the places of the "fall of the photons" on the film, although no photons were considered in our model. With increasing exposure time or intensity of light, these dots form clear interference patterns corresponding to the theoretical distribution of intensity, as follows from wave optics. By deleting the mirror, we obtain, in accordance with the considered calculation scheme, the uniform distribution of the dots on the photographic emulsion film, and for long exposure, the uniform blackening of the photographic emulsion film, what can be interpreted as an action of uniform flux of photons in incident light, although there are no photons in our calculations. In other words, we do not find the "wave-particle duality" of light and the related paradox.

Note that at high light intensity or at a long exposure time, condition (5) may be violated and the pattern on the photographic emulsion film will be different from the predictions of wave optics. This means that the simple Born rule (1) for light in these cases ceases to work, and we need to use the common rule (4), (14) [19].

In the second experiment, Wiener [43] used his setup to investigate interference phenomena in linearly polarized light at an incidence angle of 45°. He found that if the direction of electrical oscillations in the incident light was perpendicular to the incidence plane, the dark areas in the emulsion form a set of equidistant parallel fringes; this corresponds to essentially a non-uniform distribution of photons in space. However, if the vector of electrical oscillations in the incident light lay in the plane of incidence, the blackening of the film was uniform, and consequently, the photons in space were distributed uniformly. Thus, changing only the polarization of the light one can achieve a substantial redistribution of photons in space from a uniform distribution (if the electrical oscillations in the incident light lay in the plane of incidence) up to essentially non-uniform (if the direction of electrical oscillations in the incident light are perpendicular to the plane of incidence).

The second Wiener experiment with standing waves can also be easily explained and calculated by using considered method and again we will not find the "wave-particle duality" of light and the related paradox.

4. HEISENBERG UNCERTAINTY RELATIONS

The Heisenberg uncertainty principle, along with the Born rule and the complementarity principle is the basis of the Copenhagen interpretation of quantum mechanics. It is considered as a quantitative justification of wave-particle duality. This is achieved by interpreting the uncertainty relations as the constraints imposed by Nature on the precision of simultaneous measurements of position and momentum of a quantum object.

The point of view developed in this paper allows giving the simple and completely classical explanation of Heisenberg uncertainty principle as applied to "photons".

Beginning from A. Einstein, the momentum $p = \frac{\hbar\omega}{c}$ is attributed to the "photon" as the particle. The concept of "momentum of the photon" is the basis of elemental and "clear" explanation of a number of processes of light-matter interaction, the first of which was the Compton effect.

According to classical electrodynamics the electromagnetic field has energy and momentum, continuously distributed in space. For a plane electromagnetic wave, the energy ε and a momentum $\mathbf{p}$ which are contained in a certain volume of space are related by the expression $\mathbf{p} = \mathbf{n}\varepsilon/c$, where $\mathbf{n}$ is the unit vector indicating the direction of wave propagation. For a plane monochromatic wave $\mathbf{n} = \frac{c}{\omega}\mathbf{k}$ and $\mathbf{p} = \frac{\varepsilon}{\omega}\mathbf{k}$ where $\mathbf{k}$ is the wave vector. This relationship follows from classical electrodynamics; it can formally be written in the form

$$\mathbf{p} = \frac{\varepsilon}{\hbar\omega}\hbar\mathbf{k} \tag{15}$$

Thus, even in classical electrodynamics, an absorption or emission of an arbitrary portion of a monochromatic electromagnetic wave by some object may be perceived as the absorption or emission of particles with energy ε and momentum (15).

In particular, if some object (atom, electron, etc.) has absorbed (has radiated) a portion of energy $\varepsilon = \hbar\omega$ in the form of electromagnetic wave with propagation direction $\mathbf{n}$, this object gained (lost) the momentum

$$\mathbf{p} = \hbar\mathbf{k} \tag{16}$$

Let us consider the classical electromagnetic wave packet $\mathbf{E}(\mathbf{r},t)$ having a finite dimension in space and time. It represents a superposition of monochromatic waves with the wave numbers lying in a limited range. The distribution of the wave numbers in the wave packet is given by the Fourier transform $\mathbf{E}_k(\mathbf{k},\mathbf{r},t)$ of the original wave field $\mathbf{E}(\mathbf{r},t)$.

From the properties of the Fourier transform, which is the basis of an elementary proof of the uncertainty relations (see, e.g. [3,44]), it follows that

$$\Delta x \Delta k_x \geq \frac{1}{2} \tag{17}$$

where Δx is the characteristic width of the wave packet; Δk_x is the characteristic width of the range of wave numbers k_x of monochromatic waves entering into the packet. Similar relations can be written for y and z coordinate. This is the "uncertainty relation" for classical waves. Obviously, with respect to the classical wave packet, the uncertainty relation (17) does not have the mystical meaning which is ascribed to the Heisenberg uncertainty principle in the Copenhagen interpretation of quantum mechanics, because it does not impose restrictions on the measurement accuracy of quantum particle - a "photon" (which simply does not exist in our reasoning), but it simply states a mathematical fact: the greater the width of the wave packet, the smaller the range of wave numbers of monochromatic waves entering into the wave packet and vice versa.

Multiplying expression (17) by Planck constant, and using expression (16), we obtain the Heisenberg uncertainty relation

$$\Delta x \Delta p_x \geq \frac{1}{2}\hbar \tag{18}$$

and the similar relations for y and z coordinates. Taking into account expression (16), these relations can be interpreted as a formal connection between the spatial width of the wave packet and a range of momentum of the "photons" entering into the packet. If the energy of the classical wave packet $\mathbf{E}(\mathbf{r},t)$ is less than the energy of one "photon" $\hbar\omega$, it is necessary to resort to the probabilistic interpretation (1), then the expression (18) should be interpreted as the limitations on the accuracy of simultaneous measurement of the position and momentum of the "photon". As we have shown above, to explain many "quantum effects" no necessary to use such a notion as a "photon", as a real physical object. Therefore, in reality, the expression (18) contains no more meaning than expression (17).

Similarly, it follows from the properties of Fourier transforms, if a wave packet has duration Δt, it contains a monochromatic waves of a certain frequency range, the width $\Delta\omega$ of which satisfies the relation

$$\Delta t \Delta\omega \geq \frac{1}{2} \tag{19}$$

This expression is also devoid of any mystical meaning and means only one thing: the shorter the electromagnetic pulse, the wider the range of frequencies of electromagnetic waves that form this pulse. Using the expression $\varepsilon = \hbar\omega$, the inequality (19) can be formally written as the Heisenberg uncertainty relation for time and energy: $\Delta t \Delta\varepsilon \geq \frac{1}{2}\hbar$, however, and this expression contains no more meaning than classical expression (19).

5. CONCLUDING REMARKS

We see that many so-called quantum phenomena (even the most iconic for quantum theory) can be described in detail without the quantisation of radiation within the images that are contained already in classical field theory (electrodynamics).

It should be recognized that some of these quantum phenomena have a quite simple and, at first glance, seemingly visual explanation, based on the concept of "photon", as a "particle of light". But here we should recall the philosophical principle known as "Occam's Razor": "Do not multiply entities without absolutely necessary". From this point of view the concept of a "photon" becomes superfluous in explanation of these experiments.

W.E. Lamb wrote [15]: "…there is no such thing as a photon. Only a comedy of errors and historical accidents led to its popularity among physicists and optical scientists."

I think we should agree with him!

The electromagnetic radiation is a continuous classical electromagnetic wave that is completely described by the Maxwell equations, while the so-called "quantum" properties of light are only a result of the interpretation of the interaction of these waves with the atoms of a detector.

From this point of view, the "photons" are the result of the incorrect interpretation of optical phenomena, where, instead of the actual process of the interaction of a continuous classical electromagnetic wave with a detector, which has a discrete (atomic) structure, a fictitious system is considered, in which the flux of discrete particles of light (the "photons") interacts with a continuous (structureless) detector. In this case, the real discrete structure of the detector is replaced by a fictitious discrete structure of radiation (e.g., light).

It is interesting to note that a single event, the excitation of an atom of a detector by a classical electromagnetic wave can be formally considered as the appearance (birth) of a "photon" at a given point of space and its absorption by the atom. Then the interaction of the classical electromagnetic wave with quantum objects (the atoms) can be conditionally represented as the process of birth of the "photon" in electromagnetic wave, while the process of "photon absorption" by the atom can be considered as the death of the "photon". Such a model has been analyzed in [4], where it was shown that it allows combining the wave-particle duality of light with images of classical physics, however, this model requires to postulate the non-linearity of the electromagnetic field even in vacuum, what is contrary to Maxwell's electrodynamics. Now we see that the photon, as a physical object, is not needed for explanation of many quantum phenomena.

Of course, although the use of the concept of "photons" as the real "particles of light" in all the above cases is not required to explain the interaction of electromagnetic waves with a detector, we can use the notion a "photon" as a synonym for discrete events – clicks of a detector, appearance of spots on a photographic plate, etc.

In the next papers we will develop this concept for other forms of matter and show that the emission of light by atoms also occurs continuously, while the observed discrete spectrum of atom emission has a simple classical explanation. We will show that other "quantum" effects can also be explained without the quantisation of radiation.

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REFERENCES

[1] Taylor, G. I., "Interference fringes with feeble light," Proceedings of the Cambridge Philosophical Society 15(1), 114-115 (1909).
[2] Dimitrova, T. L. and Weis, A., "The wave-particle duality of light: A demonstration experiment," American Journal of Physics 76(2), 137-142 (2008).
[3] Messiah, A., [Quantum Mechanics], Dover Publications Inc. New York (1999).
[4] Rashkovskiy, S. A., "A rational explanation of wave-particle duality of light," Proc. SPIE 8832, The Nature of Light: What are Photons? V, 88321O (October 1, 2013).
[5] Holland, P. R., [The quantum theory of motion: an account of the de Broglie-Bohm causal interpretation of quantum mechanics], Cambridge university press (1995).
[6] Auletta, G., [Foundations and interpretation of quantum mechanics], World Scientific (2000).
[7] Bacciagaluppi, G., [The modal interpretation of quantum mechanics], Cambridge University Press (2006).
[8] Bohm D., and Hiley, B. J., [The undivided universe: An ontological interpretation of quantum theory], Routledge (2006).
[9] Ballentine, L. E., "The statistical interpretation of quantum mechanics," Reviews of Modern Physics, 42(4), 358 (1970)
[10] Cramer, J. G., "The transactional interpretation of quantum mechanics," Reviews of Modern Physics, 58(3), 647 (1986).
[11] Omnès, R., "Consistent interpretations of quantum mechanics," Reviews of Modern Physics, 64(2), 339 (1992).
[12] Schlosshauer, M., "Decoherence, the measurement problem, and interpretations of quantum mechanics," Reviews of Modern Physics, 76(4), 1267 (2005).
[13] Tegmark, M., "The Interpretation of Quantum Mechanics: Many Worlds or Many Words?," Fortschritte der Physik, 46, 855-862 (1998).
[14] Bohr, N., Kramers, H. A., and Slater, J. C., "The quantum theory of radiation," The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 47(281), 785-802 (1924).
[15] Lamb, W.E., Jr., "Anti-photon," Appl. Phys. B 60, 77–84 (1995).
[16] Lamb, W.E., [The Interpretation of Quantum Mechanics], (Edited and annotated by Mehra, Ja.) Rinton Press, Inc., Princeton (2001).
[17] Lande, A., [New Foundations of Quantum Mechanics], Cambridge Univ. Press, Cambridge (1965).
[18] Muthukrishnan, A., Scully, M.O., and Zubairy, M.S., "The concept of the photon—revisited," OPN Trends, supplement to Optics & Photonics News, 14(10), 18-27 (2003)
[19] Rashkovskiy, S.A., "Quantum mechanics without quanta. 1. The nature of the wave-particle duality of light," arXiv 1507.02113 [quant-ph] (2015).
[20] Landau, L.D., and Lifshitz, E.M., [Quantum Mechanics: Non-Relativistic Theory], Vol. 3 (3rd ed.). Pergamon Press (1977).
[21] Dirac, P.A.M., "Relativity Quantum Mechanics with an Application to Compton Scattering," Proc. Roy. Soc, London. A 111, 405-423 (1926).

[22] Dirac, P.A.M., “The Compton Effect in Wave Mechanics,” Proc. Cambr. Phil. Soc. 23, 500-507 (1926).

[23] Gordon, W., “Der Comptoneffekt nach der Schrödingerschen Theorie,” Zeit. f. Phys. **40**, 117-133 (1926)

[24] Klein, O., and Nishina Y., “Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac,” Z. Phys. **52** (11-12): 853 and 869 (1929) (Klein, O., and & Nishina, Y. “On the scattering of radiation by free electrons according to Dirac's new relativistic quantum dynamics,” The Oskar Klein Memorial Lectures: 1988-1999, 1, 253-272) (2014).

[25] Schrödinger, E., “Uber den Comptoneffekt,” Ann. Physik, 82, 257-264 (1927).

[26] Sommerfeld, A., [Wave-Mechanics: Supplementary Volume to Atomic Structure and Spectral Lines], Dutton, New York (1934).

[27] Lamb, W.E. and Scully, M.O., “The photoelectric effect without photons,” In: Polarization, Matter and Radiation. Jubilee volume in honour of Alfred Kasiler, pp.363-369. Press of University de France, Paris (1969).

[28] Scully, M.O., and Zubairy, M.S., [Quantum optics], Cambridge University Press, Cambridge (1997).

[29] Berestetskii, V.B., Lifshitz, E.M., and Pitaevskii, L.P., [Quantum Electrodynamics], Vol. 4 (2nd ed.). Butterworth-Heinemann (1982).

[30] Hanbury Brown, R. and Twiss, R. Q., “Correlation between photons in two coherent beams of light,” Nature (London) **177**, 27–29 (1956).

[31] Hanbury Brown, R. and Twiss, R. Q., “A test of a new type of stellar interferometer on Sirius,” Nature (London) **178**, 1046-1048 (1956).

[32] Purcell, E. M., “The question of correlation between photons in coherent light rays,” Nature (London) **178**, 1449-1450 (1956).

[33] Mandel, L., “Fluctuations of photon beams and their correlations,” Proceedings of the Physical Society, 72(6), 1037 (1958).

[34] Mandel, L., “V Fluctuations of Light Beams,” Progress in optics, 2, 181-248 (1963).

[35] Mandel, L., “Intensity fluctuations of partially polarized light,” Proceedings of the Physical Society, 81(6), 1104 (1963).

[36] Mandel, L., Sudarshan, E.G., and Wolf, E., “Theory of photoelectric detection of light fluctuations,”Proceedings of the Physical Society, 84(3), 435 (1964).

[37] Keldysh, L.V., Sov. Phys. JETP 20, 1307 (1965).

[38] Barut, A.O., and Van Huele J.F., “Quantum electrodynamics based on self-energy: Lamb shift and spontaneous emission without field quantization,” Physical Review A, 32 (6), 3187-3195 (1985).

[39] Stroud, C.R., Jr., and Jaynes, E.T., “Long-Term Solutions in Semiclassical Radiation Theory,” Physical Review A, 1(1), 106-121 (1970).

[40] Crisp, M.D., and Jaynes, E.T., “Radiative Effects in Semiclassical Theory,” Physical Review 179(5), 1253-1261 (1969).

[41] Barut, A.O., and Dowling, J.P., “Self-field quantum electrodynamics: The two-level atom,” Physical Review A, 41(5), 2284-2294 (1990).

[42] Nesbet, R.K., “Spontaneous Emission in Semiclassical Radiation Theory,” Physical Review A, 4(1), 259-264 (1971).

[43] Wiener, O. “Stehende Lichtwellen und die Schwingungsrichtung polarisirten Lichtes,“ Annalen der Physik und Chemie 40, 203-243 (1890).

[44] Born, M., and Wolf, E., [Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light], Cambridge University Press, (1999).

[45] Drude, P., and Nernst, W., Wiedem. Ann **45**, 460 (1892).

[46] Ives, H. E., and Fry T. C., J. Opt. Soc. Amer. **23**, 73 (1933).