Quantum Stud.: Math. Found. (2016) 3:147–160
DOI 10.1007/s40509-015-0063-5

CHAPMAN UNIVERSITY | INSTITUTE FOR QUANTUM STUDIES

REGULAR PAPER

Quantum mechanics without quanta: the nature of the wave–particle duality of light

Sergey A. Rashkovskiy

Received: 2 September 2015 / Accepted: 20 October 2015 / Published online: 31 October 2015

Abstract In this paper, I argue that light is a continuous classical electromagnetic wave, while the observed so-called quantum nature of the interaction of light with matter is connected to the discrete (atomic) structure of matter and to the specific nature of the light–atom interaction. From this point of view, the Born rule for light is derived, and the double-slit experiment is analysed in detail. I show that the double-slit experiment can be explained without using the concept of a "photon", solely on the basis of classical electrodynamics. I show that within this framework, the Heisenberg uncertainty principle for a "photon" has a simple physical meaning not related to the fundamental limitations in accuracy of the simultaneous measurement of position and momentum or time and energy.

Keywords Wave–particle duality of light · Classical electrodynamics · Double-slit experiment · Born rule · Heisenberg uncertainty principle

Mathematics Subject Classification 82C10

1 Introduction

There are two opposing perspectives on the nature of light.

According to the first perspective, i.e., 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].

S. A. Rashkovskiy (✉)
Institute for Problems in Mechanics, Russian Academy of Sciences,
Vernadskogo Ave., 101/1, Moscow 119526, Russia
e-mail: rash@ipmnet.ru

S. A. Rashkovskiy
Tomsk State University, 36 Lenina Avenue, Tomsk 634050, Russia

Such a perspective on the nature of light is now considered to be the official one, being described in all textbooks and monographs on quantum physics and optics. From this point of view, 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 because it is impossible to imagine a physical object that has the properties of both a wave (object continuously distributed in a space) and a particle (object localised in a small region of space). 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 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 [3]. These paradoxes gave rise to a whole new direction in quantum physics—the interpretation of quantum mechanics [3–12].

Experiments indicate that the wave properties of light cannot be explained as a result of the interaction of photons in the beam because they are manifested, even for a very weak light source, when "photons fly alone" [1,2]. This behaviour indicates that each individual photon should have wave properties. As a result, the representation that the photon interferes with itself has appeared.

The discovery of the wave–particle duality of light raised numerous fundamental questions among physicists, 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? These questions were considered by A. Einstein, who made several attempts to answer them [13–15]. On 12 December 1951, Albert Einstein wrote to M. Besso: "All these 50 years of conscious brooding have brought me no nearer to the answer to the question: What are light quanta?"

Despite the fact that the concept of a "photon" has become generally accepted, following A. Einstein, 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?

Quantum electrodynamics, which is based on the Copenhagen interpretation that postulates the wave–particle duality, approaches this problem formally, providing a mathematical formalism for the calculation of the various phenomena at the atomic and subatomic levels and, at the same time, abandoning the classical images of waves and particles. In fact, currently, we have an elegant mathematical theory that does not represent the object it actually describes.

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 $I \sim E^2$ at this point, calculated on the basis of the methods of wave optic [16]:

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

where $\mathbf{E}$ is the strength of the electric field of the classical light wave.

Equation (1) is a mathematical formulation of the wave–particle duality because the probability p refers to the particle (photon), while the intensity $I \sim \mathbf{E}^2$ refers to the wave, which, in many cases, can be calculated by the methods of classical wave optics.

The rule (1), underlying the photonic interpretation of experiments with light, is an independent postulate of quantum mechanics.

We will call Eq. (1) for brevity "the Born rule for light" by analogy with the same type of Born rule describing the probability of finding a nonrelativistic quantum particle.

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 [3].

At the same time, there is another point of view, according to which there are no photons; 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 and the most implacable defender of the Copenhagen interpretation, at the beginning, with his usual enthusiasm, was also an opponent of light quanta [17], although he implicitly placed photons into the basis of his mechanistic model of the hydrogen atom. The most consistent opponents of the concept of photons were the Nobel Prize Winner Lamb [18,19] and Lande [20]. Jaynes had questioned the need for a quantum theory of radiation [21].

Indeed, 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. These phenomena include the photoelectric effect [22,23], the Compton effect [24–28], the Lamb shift [29–32], radiative effects [30–33], spontaneous emission [29,32,33], the Hanbury Brown and Twiss effect [34,35], etc. In recent years, this point of view is again attracting the attention of physicists [21,36–41] who are not satisfied with existing interpretations of quantum mechanics.

I completely share this position: many well-known experimental facts, which are traditionally interpreted as a manifestation of the wave–particle duality of light, can in fact be explained on the basis of purely wave representations of light without involving the "photon" concept. In this article, I will describe the arguments in support of this point of view.

In the present paper, the author begins 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. In doing so, the Maxwell equations and the wave equations (Schrödinger, Dirac, etc.) describing the atoms are found to be sufficient for a complete and consistent description of the majority of well-known experiments involving light and matter.

2 Wave–particle duality of light

2.1 Interaction of a classical electromagnetic wave with an atom

The "corpuscular" properties of light are manifested in its interaction with matter. Precisely an interpretation of the results of experiments on the light–matter interaction has led to the emergence of the concept of a "photon" as a "particle of light". In the early years of the development of quantum theory, it was believed that only the quantisation of the light field can explain the processes of light–matter interaction; however, later, it became clear that these phenomena can be described within the limits of the so-called semi-classical theories [22–27,29–33,36–46].

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.

Common to all the semi-classical theories is that light is considered as a classical electromagnetic wave, which is described by Maxwell's equations, while the atoms of matter, with which this wave interacts, are described by the Schrodinger equation or other wave equations (Klein–Gordon, Pauli Dirac), depending on the degree of detail of the described process.

The question of why the atoms of matter are described by the wave equations will be discussed in subsequent articles of this series.

If the interaction of light (classical electromagnetic waves) with an atom is weak compared to the intra-atomic interactions (which is typical for the majority of experiments with light), then the process can be described within the limits of perturbation theory [47], according to which the probability of excitation (ionisation) of an atom in the field of a 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.

Expression (2) is sufficient to explain, without using the concept of a "photon", the many processes of light–matter interaction, in which the so-called "quantum" properties of light are manifested.

Note that unlike the Born rule (1), expression (2) is not a postulate; rather, it follows from the exact theory (exact in the sense in which, for example, the Schrodinger equation is an exact equation describing the atom).

Hereinafter, I will show that based on expression (2) and taking into account the discrete (atomic) structure of matter, it is easy to explain the "wave–particle duality" of light, remaining within the realm of classical electrodynamics, while the concept of a "photon" becomes superfluous.

2.2 Born rule for light

Suppose there is a wave field $\mathbf{E}$, which represents, generally, the result of the interference of classical electromagnetic waves. If we place a detector into this field, then 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. Thus, the random excitation of the atom (the detector operation) would occur under the action of a continuous electromagnetic wave and is not related to the discrete (quantum) structure of the light. Taking into account the fact that the detector consists of a plurality of atoms, the sequence of discrete events, i.e., excitations of different atoms of the detector, would be observed under the action of the electromagnetic wave, which can occur 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, non-random, deterministic macroscopic picture.

Let us introduce the probability $P_-(t)$ that a randomly selected atom located in the light field is not excited (ionised) for time t. Obviously, $P_-(t)$ satisfies the equation

$$\frac{\mathrm{d}P_-}{\mathrm{d}t} = -wP_- \tag{3}$$

with the initial condition

$$P_-(t_0) = 1, \tag{4}$$

where t_0 is the time of the beginning of irradiation of the atom by the electromagnetic wave; w is determined by expression (2).

The solution of Eqs. (3) and (4) is as follows:

$$P_-(t) = \exp\left(-\int_{t_0}^{t} w(t')\mathrm{d}t'\right). \tag{5}$$

Accordingly, the probability that the atom would be excited (ionised) at time t is

$$P_+(t) = 1 - P_-(t). \tag{6}$$

When the electromagnetic wave is weak and satisfies the condition

$$\int_{t_0}^{t} w(t')\mathrm{d}t' \ll 1 \tag{7}$$

one approximately obtains

$$P_+(t) \approx \int_{t_0}^{t} w(t')\mathrm{d}t'. \tag{8}$$

Taking into account expressions (2) and (8), for an atom in a weak electromagnetic wave, one obtains

$$P_+(t) \sim \mathbf{E}^2. \tag{9}$$

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. In this case, we need to assume that a "photon" hitting the given point in space inevitably causes a click of the detector or the appearance of a spot on the photographic plate. In this case, we can discuss the probability of finding the "photon" at the given point in space. 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, the number of excited atoms of matter (the detector) is considered to be equal to the number of "photons" that arrived at the detector. Let the total number of atoms in a selected volume V of matter (e.g., on a selected surface of the photographic plate) be equal to N and be uniformly distributed thereon. Let us choose a small volume $\mathrm{d}V$, in which $\mathrm{d}N = \frac{N}{V}\mathrm{d}V$ atoms are located. Then, for time t within volume $\mathrm{d}V$, $\mathrm{d}N_+ = P_+\mathrm{d}N$ atoms would be excited:

$$\mathrm{d}N_+ = P_+\frac{N}{V}\mathrm{d}V. \tag{10}$$

Because we interpret the excitation of the atoms as photons hitting the atoms, the number of photons entering the volume $\mathrm{d}V$ would be determined by expression (10). Accordingly, the probability of a photon entering into a given volume $\mathrm{d}V$ is

$$p\mathrm{d}V = \frac{P_+}{\int P_+\mathrm{d}V}\mathrm{d}V, \tag{11}$$

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

Thus, the probability density to detect a photon at a given point in space is given by

$$p = \frac{P_+}{\int P_+\mathrm{d}V} \sim P_+. \tag{12}$$

Using expressions (5) and (6), one obtains

$$p(t) \sim 1 - \exp\left(-\int_{t_0}^{t} w(t')\mathrm{d}t'\right). \tag{13}$$

In the case of weak electromagnetic waves satisfying condition (7), we have

$$p \sim \int_{t_0}^{t} w(t')\mathrm{d}t'. \tag{14}$$

Taking into account expression (2), one obtains

$$p \sim \mathbf{E}^2. \tag{15}$$

This expression is none other than the Born rule for "photons" (1).

The above analysis leads to the following conclusions: (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 and a relatively short exposure time, satisfying condition (7). For strong electromagnetic waves or for a longer exposure time for which condition (7) is not satisfied, the Born rule should be replaced by the stricter rule (13), according to which the dependence of probability p on $\mathbf{E^2}$ is more complicated:

$$p(t) \sim 1 - \exp(-\gamma\mathbf{E}^2\Delta t), \tag{16}$$

where taking into account (2), the following is introduced

$$\int_{t}^{t+\Delta t} w(t')\mathrm{d}t' = \gamma \mathbf{E}^2 \Delta t \tag{17}$$

and γ does not depend on $\mathbf{E}^2$.

Thus, instead of the postulated Born rule (1), the more general rule (2), following from quantum mechanics and classical electrodynamics, should be used; the more general rule does not lead to paradoxes, such as the wave–particle duality. If we accept the rule (2) as a basis, then the Born rule (1) will immediately follow from it, as a reasonable approximation, which is valid, however, only for weak waves or short exposure times.

We 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.

2.3 Double-slit experiment

Double-slit experiments [1,2], along with experiments involving standing waves [48–51], are 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 [4–12].

Here, I show that the double-slit experiment can be easily explained in terms of classical electrodynamics if we take into account the discrete structure of matter (a screen, a detector) 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 a weak classical electromagnetic wave pass through the diffractive device, such as a diffraction grating or a system of slits in an opaque screen, and impinge on the surface of the photoactive substance (conditionally, a photographic plate), the atoms of which can be excited by light.

For simplicity, I assume that the photographic plate represents a single layer of atoms, in which the atoms are placed randomly with surface density n (number of atoms per unit surface). The atoms are the quantum objects, which are described by the Schrodinger equation, whereas the light is a classical electromagnetic wave. The light intensity can be calculated using classical optics and is considered to be known on the surface of the photographic plate.

We are interested in the interaction of a weak light wave with matter, when the "photons" impinge on the surface of the photographic plates one by one. It is these conditions realised in the double-slit experiments [1,2] that demonstrate "the wave properties of individual photons".

The probability of excitation (ionisation) of any atom on the surface of photographic plates is described by expression (2).

Generally speaking, relation (2) itself explains the "wave–particle duality of light"; 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 plate, assuming that the excitation (ionisation) of an atom is perceived as blackening of the appropriate point of the photographic plate.

The calculation proceeds using the Monte Carlo method: at each time, the probability of excitation of each unexcited (non-ionised) atom will be calculated. The calculation for each atom is continued until its excitation (ionisation) occurs.

The rate of atomic excitation w does not depend on the concentration of atoms and is determined only by the intensity of the radiation at a given point of the screen. If the radiation intensity does not change with time, then the law of excitation of atoms will be similar to that of radioactive decay. In particular, the probability of excitation at time t of an atom located at a point on the screen with a given value w is

$$P_+(t) = 1 - \exp(-wt). \tag{18}$$

Taking into account (2), one obtains

$$P_+(t) = 1 - \exp(-bIt). \tag{19}$$

Let us introduce the nondimensional time

$$\tau = bI_0 t, \tag{20}$$

where I_0 is the maximum intensity of light on the screen (photographic plate).

In this case, the probability of excitation of the atom for time t at the points on the screen having the intensity of light I is

$$P_+(t) = 1 - \exp(-(I/I_0)\tau). \tag{21}$$

As an example, I consider the calculation of the double-slit experiment. In this case, the distribution of the light intensity on the screen is given by the well-known expression [51]

$$I(z) = I_0 \cos^2\left(\frac{d}{b}x\right)\left(\frac{\sin x}{x}\right)^2, \tag{22}$$

where

$$x = \frac{\pi b}{\lambda H}z, \quad z = H\sin\theta,$$

b is the width of the slits; d is the distance between the slits; λ is the wavelength of light; H is the distance from the slits to the screen; and θ is the angular coordinate.

For the calculation of the double-slit experiment using the Monte Carlo method, I create a system of randomly and uniformly distributed points $i = 1, \ldots, N$ in a given area $L_z \times L_y$, simulating the screen. These points are considered as the atoms of the material of the screen. I 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 expressions (21) and (22); at the same time, the random number $R_i \in [0, 1]$, $i = 1, \ldots, N$, 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 screen for different moments of time τ at $\frac{\pi b}{\lambda H}$ =0.03 and $d/b = 5$ are shown in Fig. 1 (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 (22), predicted by classical optics.

Comparing Fig. 1 with the real picture of the "accumulation of photons" on the photographic plate in the double-slit experiment [2], we 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 screen appears, which can be interpreted as the places of the "fall of the photons" on the screen, 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. Closing one of the slits, we obtain, in accordance with the considered calculation scheme, exactly the picture predicted by classical optics. In other words, we do not find the "wave–particle duality" of light and the related paradox.

Thus, we see that the double-slit experiments can be easily interpreted in terms of wave optics and quantum mechanics, based on the Schrödinger equation.

Obviously, this method also allows for reproduction of the results of the Wiener experiments with standing waves for low light intensity and, in particular, Lippmann fringes.

Note that according to expression (21), the change in light intensity I_0 does not result in changes in the pattern in Fig. 1; only the time scale is changed: at high light intensity, the same pattern is reached at a shorter exposure time. At high light intensity or at a long exposure time, condition (7) may be violated, and the pattern on the photographic plate 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 (21).

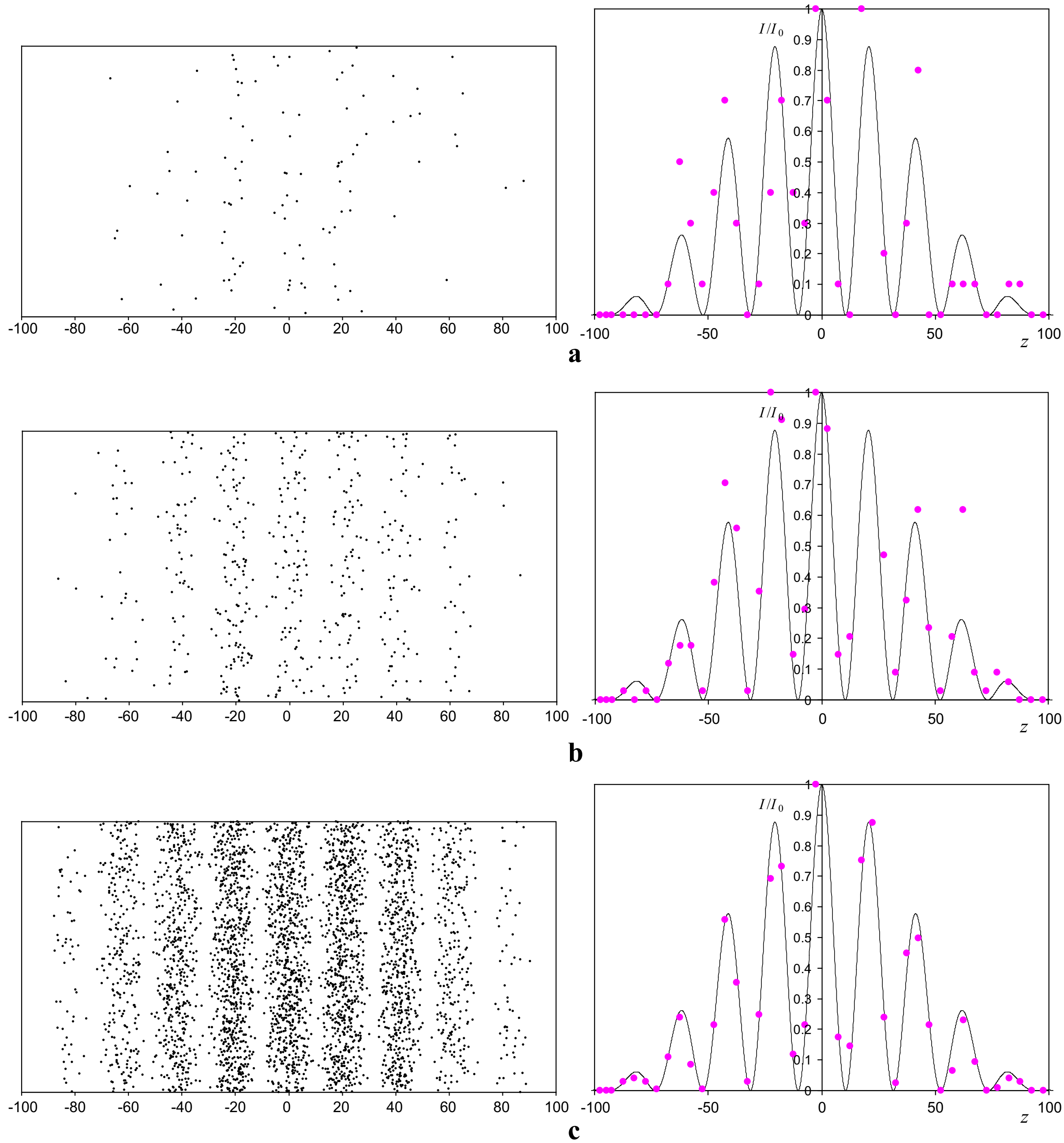
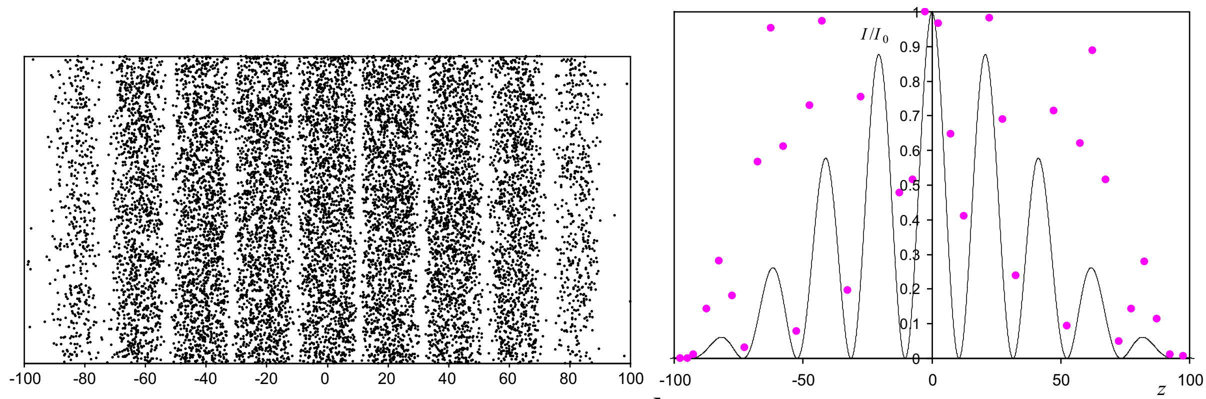


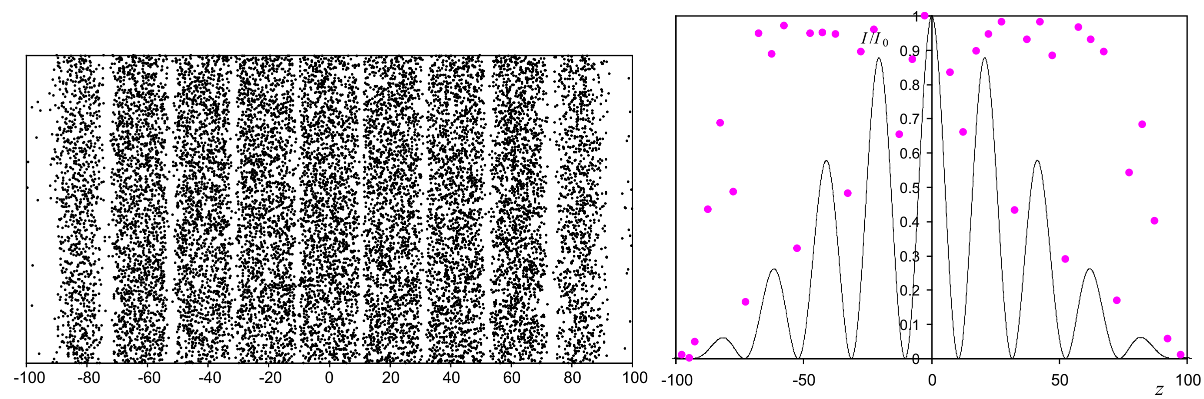
Fig. 1 (*Colour online*) Interference pattern buildup (*left*) and the corresponding distribution functions of *dots on the screen* (*right*) for different exposure times τ, obtained using the Monte Carlo simulation of the interaction of light with the detecting screen. **a** $\tau = 0.02$ (100 "photons"); **b** $\tau = 0.1$ (424 "photons"); **c** $\tau = 1$ (3452 "photons"); **d** $\tau = 10$ (11,600 "photons"); **e** $\tau = 30$ (14,530 "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 (22), predicted by classical optics

For an arbitrary exposure time, the probability "to detect a photon" at a given point of the photographic plate is determined by expression (12), which, taking into account expression (22), can be written as

$$\frac{p}{p(0)} = \frac{1 - \exp(-(I/I_0)\tau)}{1 - \exp(-\tau)}, \tag{23}$$



d



e

Fig. 1 continued

where $p(0)$ is the probability "to detect a photon" in the middle of the photographic plate (at $I = I_0$). The ratio $p/p(0)$ in the double-slit experiments with the "single photons" plays the same role as the ratio I/I_0 in the optical experiments. In particular, at the short exposure times $\tau \ll 1$, we obtain from expression (23) the Born rule: $p/p(0) \approx I/I_0$.

At a long-term exposure, the diffraction pattern will qualitatively appear as that predicted by wave optics, i.e., a system of periodic fringes, but quantitatively, it will be significantly different from both the predictions of wave optics (the line in Fig. 1, right) and the predictions based on the simple Born rule (1). The quantitative agreement with the wave theory will be observed only at relatively short exposure times, when condition (7) is satisfied. Note that the quantitative disagreement with the wave theory is observed also at very short exposure times (Fig. 1a, b); however, if for a long exposure time, this difference is due to the approximate nature of the Born rule (1), for short exposure times, this difference is connected to the random scatter due to the small number of recorded events. If one performs a large number of similar tests with a short exposure time and averages the results of these tests, then for $\tau \ll 1$, the obtained pattern will exactly correspond to the predictions of classical optics (22) and the Born rule for light (1). This result is confirmed by Fig. 2 (left), which presents the results of the calculations for $\tau = 0.1$ averaged over ten statistical realisations. A similar result corresponding to the long exposure ($\tau = 5$) is shown in Fig. 2 (right). The lines in Fig. 2 (right) show expression (23) corresponding to $\tau = 0$ (it coincides with expression (22)) and $\tau = 5$. In this case, the distribution of dots on the screen is found to be significantly different from that predicted by classical optics (22) and the Born rule (1); however, the distribution is well described by the general expression (23). For comparison, Fig. 3 shows the normalised distribution function calculated by expression (23) for different exposure times τ.

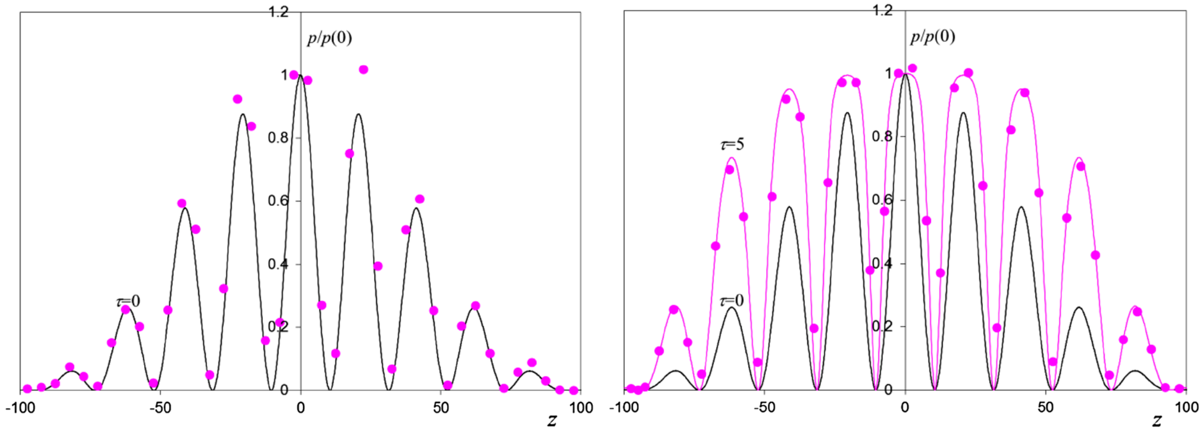
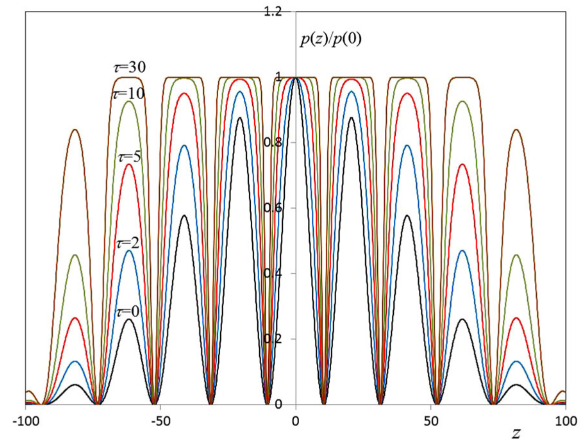


Fig. 2 (*Colour online*) Comparison of the results of Monte Carlo simulations using expression (21) for $\tau = 0.1$ (*left*) and $\tau = 5$ (*right*) and averaged over ten statistical realisations (*markers*), with expression (22) [predicted by classical optics (*line* $\tau = 0$)] and with dependence (23) [predicted by classical electrodynamics, taking into account expression (2) (*line* $\tau = 5$)]. The data shown in Fig. 1 correspond to one particular test

Fig. 3 (*Colour online*) Normalised distribution functions of the number of "photons" calculated using expression (23) for different exposure times τ



Note that the theoretical dependence (22) (line $\tau = 0$ in Figs. 1, 2, 3) describes the distribution of dots on the screen, which must be obtained within the "photon" theory if we assume that the probability of finding a photon at a given point is determined by the Born rule (1) and all the photons falling on the photographic plate cause its blackening with the same probability. Thus, according to the "photon" theory, the normalised distribution of dots on the screen should not depend on the exposure time (at least as long as the fraction of excited atoms on the surface of the screen is small). In contrast, according to the "photon-free" theory, when light is considered as a classical electromagnetic wave, the distribution of dots on the screen (23) will substantially depend on the exposure time, and already at $\tau > 1.5$, the distinction from the "photon" theory (22) will be clearly visible (Figs. 2, 3). This fact can be used for experimental verification of the theory.

3 Concluding remarks

The following are the most important "quantum" effects for which the theoretical calculation does not require the quantisation of radiation:

1. Double-slit experiment and the Wiener experiments with standing waves.

2. 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 $\hbar\omega c$. Such an explanation of the Compton effect is included in all textbooks and books on physics.
   However, even at the dawn of quantum mechanics, the Compton effect was explained without using the concept of the photon [24–27,52,53]: 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 [26] 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 [24,25], 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 Schrödinger [52] 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.
3. 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 [22,23,53]. From perturbation theory, it follows [47,54] 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".
4. Hanbury Brown and Twiss effect [34,35]. This effect has a simple classical explanation [42–46] if expression (2) is used and we assume that the components of the electric field vector of the light wave 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.
5. 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 [55], 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 $n = 1, 2, \ldots$, 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.
6. The Heisenberg uncertainty principle, along with the Born rule and the complementarity principle, is the basis of the Copenhagen interpretation of quantum mechanics. The Heisenberg uncertainty principle is considered as a quantitative justification of the wave–particle duality. This justification is achieved by interpreting the uncertainty relations as the constraints imposed by nature on the precision of simultaneous measurements of the position and momentum of a quantum object.

Let us consider the classical electromagnetic wave packet $E(r,t)$. From the properties of the Fourier transform, which is the basis of an elementary proof of the uncertainty relations (see, e.g., [16,51]), it follows that

$$\Delta x \Delta k_x \geq \frac{1}{2}, \tag{24}$$

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.

Obviously, the uncertainty relation (2) does not have the mystical meaning that is ascribed to the Heisenberg uncertainty principle in the Copenhagen interpretation. The relation 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 (2) by the Planck constant and using the formal expression $p = \hbar k$, we obtain the Heisenberg uncertainty relation

$$\Delta x \Delta p_x \geq \frac{1}{2}\hbar. \tag{25}$$

This relation 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 $E(r,t)$ is less than the energy of one "photon" $\hbar\omega$, then it is necessary to resort to the probabilistic interpretation (1), and expression (3) should be interpreted as the limitations on the accuracy of simultaneous measurements of the position and momentum of the "photon". As we have shown above, the explanation of many "quantum effects" does not require the use of the concept of a "photon" as a real physical object. Therefore, in reality, expression (3) contains no more meaning than expression (2). A similar conclusion can be made regarding the Heisenberg uncertainty relation for time and energy.

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.

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).

We see that 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. However, we can save the notion a "photon" as a synonym for discrete events—clicks of a detector, appearance of spots on a photographic plate, etc. In other words, the photon should not be seen as a physical object ("particle of light"); rather, the photon is only a discrete event that is observed in experiments, which actually arises from the interaction of a continuous electromagnetic wave with discrete objects (atoms of a detector).

Here, it is possible to reproach the author that he rejects the notion that photons are real physical objects while considering atoms as quantum objects, thereby involuntarily considering that atoms emit and absorb electromagnetic energy in the form of discrete portions (quanta) due to jump-like transitions. We note only that the wave–particle duality of nonrelativistic matter will be considered in the next papers, in which this contradiction will be eliminated. 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 also consider other "quantum" effects and show that they can also be explained without the quantisation of radiation.

Acknowledgments Funding was provided by Tomsk State University competitiveness improvement program.

References

1. Taylor, G.I.: Interference fringes with feeble light. Proc. Camb. Philos. Soc. **15**(1), 114–115 (1909)
2. Dimitrova, T.L., Weis, A.: The wave-particle duality of light: a demonstration experiment. Am. J. Phys. **76**(2), 137–142 (2008)

3. Rashkovskiy, S.A.: A rational explanation of wave-particle duality of light. In: SPIE Optical Engineering + Applications, pp. 88321O–88321O. International Society for Optics and Photonics (2013)
4. Holland, P.R.: The Quantum Theory of Motion: An Account of the De Broglie–Bohm Causal Interpretation of Quantum Mechanics. Cambridge university press, Cambridge (1995)
5. Auletta, G.: Foundations and Interpretation of Quantum Mechanics. World Scientific, Singapore (2000)
6. Bacciagaluppi, G.: The Modal Interpretation of Quantum Mechanics. Cambridge University Press, Cambridge (2006)
7. Bohm, D., Hiley, B.J.: The Undivided Universe: An Ontological Interpretation of Quantum Theory. Routledge, London (2006)
8. Ballentine, L.E.: The statistical interpretation of quantum mechanics. Rev. Mod. Phys. **42**(4), 358 (1970)
9. Cramer, J.G.: The transactional interpretation of quantum mechanics. Rev. Mod. Phys. **58**(3), 647 (1986)
10. Omnès, R.: Consistent interpretations of quantum mechanics. Rev. Mod. Phys. **64**(2), 339 (1992)
11. Schlosshauer, M.: Decoherence, the measurement problem, and interpretations of quantum mechanics. Rev. Mod. Phys. **76**(4), 1267 (2005)
12. Tegmark, M.: The interpretation of quantum mechanics: many worlds or many words? Fortschr. der Phys. **46**, 855–862 (1998)
13. Einstein, A.: Zum gegenwärtigen Stande des Strahlungsproblems. Phys. Z. **10**, 185–193 (1909)
14. Einstein, A.: Über die Entwicklung unserer Anschauungen über das Wesen und die Konstitution der Strahlung. Phys. Z. **10**, 817–825 (1909)
15. Pais, A.: Inward Bound: Of Matter and Forces in the Physical World. Oxford University Press, Oxford (1986). (Specifically, Born mentioned about Einstein's never-published attempts to develop a "ghost-field" theory, in which point-like photons are guided probabilistically by ghost fields that follow Maxwell's equations)
16. Messiah, A.: Quantum Mechanics. Dover Publications Inc., New York (1999)
17. Bohr, N., Kramers, H.A., Slater, J.C.: LXXVI. The quantum theory of radiation. Lond. Edinb. Dublin Philos. Mag. J. Sci. **47**(281), 785–802 (1924)
18. Lamb Jr, W.E.: Anti-photon. Appl. Phys. B **60**, 77–84 (1995)
19. Lamb, W.E.: The Interpretation of Quantum Mechanics. Rinton Press, Inc., Princeton (2001). (Edited and annotated by Mehra, Ja.)
20. Lande, A.: New Foundations of Quantum Mechanics. Cambridge Univ. Press, Cambridge (1965)
21. Muthukrishnan, A., Scully, M.O., Zubairy, M.S.: The concept of the photon-revisited. OPN Trends Suppl. Opt. Photonics News **14**(10), 18–27 (2003)
22. Lamb, W.E., 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)
23. Scully, M.O., Zubairy, M.S.: Quantum Optics. Cambridge University Press, Cambridge (1997)
24. Dirac, P.A.M.: Relativity quantum mechanics with an application to Compton scattering. Proc. R. Soc. Lond. A **111**, 405-423 (1926)
25. Dirac, P.A.M.: The Compton effect in wave mechanics. Proc. Camb. Philos. Soc. **23**, 500–507 (1926)
26. Gordon, W.: Der Comptoneffekt nach der Schrödingerschen Theorie. Zeit. f. Phys. **40**, 117–133 (1926)
27. Klein, O., Nishina, Y.: Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac. Z. Phys. **52**(11–12), 853–869 (1929)
28. Klein, O., Nishina, Y.: On the scattering of radiation by free electrons according to Dirac's new relativistic quantum dynamics. In: The Oskar Klein Memorial Lectures: 1988–1999, vol. 1, pp. 253-272 (2014)
29. Barut, A.O., Van Huele, J.F.: Quantum electrodynamics based on self-energy: lamb shift and spontaneous emission without field quantization. Phys. Rev. A **32**(6), 3187–3195 (1985)
30. Stroud, C.R. Jr., Jaynes, E.T.: Long-term solutions in semiclassical radiation theory. Phys. Rev. A **1**(1), 106-121 (1970)
31. Crisp, M.D., Jaynes, E.T.: Radiative effects in semiclassical theory. Phys. Rev. **179**(5), 1253–1261 (1969)
32. Barut, A.O., Dowling, J.P.: Self-field quantum electrodynamics: the two-level atom. Phys. Rev. A **41**(5), 2284–2294 (1990)
33. Nesbet, R.K.: Spontaneous emission in semiclassical radiation theory. Phys. Rev. A **4**(1), 259–264 (1971)
34. Hanbury Brown, R., Twiss, R.Q.: Correlation between photons in two coherent beams of light. Nature (London) **177**, 27–29 (1956)
35. Brown, R.H., Twiss, R.Q.: A test of a new type of stellar interferometer on Sirius. Nature (London) **178**, 1046–1048 (1956)
36. Kracklauer, A.F.: What do correlations tell us about photons? In.: Roychoudhuri C., Kracklauer A.F., Creath K. (eds.) The Nature of Light: What Are Photons? Art-Number 66640H, Proc. SPIE 6664 (2007)
37. Kracklauer, A.F., Rangacharyulu, C., Roychoudhuri, C., Brooks, H.J., Carroll, J., Khrennikov, A.: Is indivisible single photon really essential for quantum communications, computing and encryption? In.: Roychoudhuri, C., Kracklauer, A.F., Khrennikov, A.Y. (eds.) The Nature of Light: What are Photons? III, Art.-Number 74210Y, Proc. SPIE 7421 (2009)
38. Roychoudhuri, C., Kracklauer, A.F., Creath, K. (eds.): The Nature of Light: What Are Photons? Proc. SPIE 6664 (2007)
39. Roychoudhuri, C., Kracklauer, A.F., Khrennikov, A.Y. (eds.): The Nature of Light: What are Photons? III, Proc. SPIE 7421 (2009)
40. Khrennikov, A.: Nonlinear Schrödinger equations from prequantum classical statistical field theory. Phys. Lett. A **357**, 171–176 (2006)
41. Khrennikov, A.: Quantum probabilities and violation of CHSH-inequality from classical random signals and threshold type detection scheme. Prog. Theor. Phys. **128**(1), 31–58 (2012)
42. Purcell, E.M.: The question of correlation between photons in coherent light rays. Nature (London) **178**, 1449–1450 (1956)
43. Mandel, L.: Fluctuations of photon beams and their correlations. Proc. Phys. Soc. **72**(6), 1037 (1958)
44. Mandel, L.: V fluctuations of light beams. Prog. Opt. **2**, 181–248 (1963)
45. Mandel, L.: Intensity fluctuations of partially polarized light. Proc. Phys. Soc. **81**(6), 1104 (1963)

46. Mandel, L., Sudarshan, E.G., Wolf, E.: Theory of photoelectric detection of light fluctuations. Proc. Phys. Soc. **84**(3), 435 (1964)
47. Landau, L.D., Lifshitz, E.M.: Quantum Mechanics: Non-Relativistic Theory, vol. 3, 3rd edn. Pergamon Press, USA (1977)
48. Wiener, O.: Stehende Lichtwellen und die Schwingungsrichtung polarisirten Lichtes. Ann. Phys. Chem. **40**, 203–243 (1890)
49. Drude, P., Nernst, W.: Wiedem. Ann **45**, 460 (1892)
50. Ives, H.E., Fry, T.C.: J. Opt. Soc. Am. **23**, 73 (1933)
51. Born, M., Wolf, E.: Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light. Cambridge University Press, Cambridge (1999)
52. Schrödinger, E.: Uber den Comptoneffekt. Ann. Phys. **82**, 257–264 (1927)
53. Sommerfeld, A.: Wave-Mechanics: Supplementary Volume to Atomic Structure and Spectral Lines. Dutton, New York (1934)
54. Berestetskii, V.B., Lifshitz, E.M., Pitaevskii, L.P.: Quantum Electrodynamics, vol. 4, 2nd edn. Butterworth-Heinemann, London (1982)
55. Keldysh, L.V.: Ionization in the field of a strong electromagnetic wave. Sov. Phys. JETP **20**, 1307 (1965)
56. Landau, L.D., Lifshitz, E.M.: The Classical Theory of Fields, vol. 2, 4th edn. Butterworth-Heinemann, London (1975)