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What is a Photon?

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Abstract

The observed interference of single photons is explained without contradiction using the indivisibility principle.

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In the recent years, due to the development of the techniques aimed at generation of high-coherent optical radiation, the question of the photon nature has become a topical problem again, i.e. *what is a quant of electromagnetic radiation.* A lot of publications, experiments and theoretical investigations have been devoted to this problem [Roychoudhuri et al. (2008), Greenstein and Zajonc (2006)].

Historically, the photon as a particle with the finite energy $\hbar\omega$ was introduced by M. Planck in 1900 in order to explain the radiation spectrum of a “black body” in the high frequency range $\hbar\omega > kT$, where the intensity exponentially decreases with the frequency growth. This circumstance is very important, because it allows one to define at once the energy localization area, and, therefore, the energy of material object – the electromagnetic field. Turning from the frequency to the spatial value, we get the spatial concentration area of energy concentration equal to the wavelength

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$$\lambda = \frac{2\pi c}{\omega} \ ,$$

where c is the velocity of light, i.e.,

$$\lambda p = 2\pi\hbar \ , \qquad (1)$$

here p is the photon momentum

$$p = \frac{\hbar\omega}{c} \ .$$

Relation (1) reminds the uncertainty relation in quantum physics, but it is more concrete here, it defines the size of the area of electromagnetic field localization, i.e., the photon size in the longitudinal direction (equal to the radiation wavelength). It should be noted that this directly follows from the experimental works, and, to a certain extent, explains the “threshold” character of the photon energy.

The idea of Schrödinger equation for the photon was introduced in [Akhiezer and Berestetsky (1957), Berestetsky et al. (2006)]. If one follows the logic from [Akhiezer and Berestetsky (1957)], then the following relation can be written for the wave equation for the case of a plane wave propagating along the x axis

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2}\right)\vec{E} = \left(\frac{1}{c}\frac{\partial}{\partial t} - \frac{\partial}{\partial x}\right)\left(\frac{1}{c}\frac{\partial}{\partial t} + \frac{\partial}{\partial x}\right)\vec{E} = 0 \ . \qquad (2)$$

It is clear that the first and the second brackets correspond to different directions of motion, i.e. they are equivalent, and it is sufficient to write

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \frac{\partial}{\partial x}\right)\vec{E} = 0 \ . \qquad (3)$$

This equation can be considered as the Schrödinger equation. And this is especially clear if one multiplies the equation by the Planck constant $\hbar$. Here arises an important question: what does the symbol $\vec{E}$ mean? The field or the wave function ψ - probability amplitude? A correct answer implies both quantities, and this is not surprising, since the photon is a purely wave structure.

So, we have two similar equations: one for the material medium – the field, and the second – for the ψ function, which determines the motion of the particle – the photon. One should try to find the answer in the wave-particle duality. Where one finds a symbol $\vec{E}$, the equation describes the material component, i.e. the particle – photon, produced due to the field localization in a certain space area. In other words, according to St. Weinberg, “…quantum mechanics tells us that these ripples come in bundles, or quanta, that are recognized in the laboratories as elementary particles” [Weinberg (2012)].

There is one more question: if the elementary particle is a 3D object, then what is the value of a transverse size of a photon? The size can be found from direct measurement, i.e. it is defined by effective cross-section of photon interaction with an object which is capable of absorbing the photon, and this is an atomic dipole (just this dipole emits the photon), and the size of the dipole is significantly smaller than the photon transverse size. The oscillation frequency of the dipole should be resonant with the photon, and the dipole properties must be defined by the quantum state of the atom.

This problem has been solved by R. Fisher and Ch. Pole. The Russian translation was published in [Fisher and Paul (1983)]. In this formulation of a problem a plane monochromatic wave falls onto the quantum dipole and