On the notion of the photon

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ABSTRACT. It is shown that the photon, the quantum of electromagnetic field, allows the consideration in the framework of the scheme which in some aspects is typical for the phonon, an excitation of the crystal lattice of a solid. The conclusion is drawn that the photon may be interpreted as an elementary excitation in a fine-grained space. The corollary is in excellent agreement with the space structure and submicroscopic quantum mechanics, which have recently been constructed by the author in a series of works.

Key words: photon, phonon, space, quantum theory

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Louis de Broglie was the first who proposed the detailed wave theory of the photon [1]. In the theory, quanta of light were composite formations: the photon regarded as a couple of Dirac particles with very small masses. De Broglie equations decomposed to equations for a spinless particle and the Maxwell equations were complemented by correction terms with the electromagnetic potentials. Thus, de Broglie theory representing a grand synthesis of matter and light was excellently constructed in an ordinary space. The notions employed were very close to classical images and yet the quantization of fields was an integral part of the photon theory.

Today free photons and their interaction with particles are widely described in the framework of the second quantization methodology. However, the description of the electromagnetic field in terms of creation and annihilation operators is justified in the wave vector presentation. Quantum electrodynamics does not study the problem of spatial pattern of the photon. One can only assume that the problem is reduced to the imagination of an energetic object that moves as a "particle-wave" (i.e. something of an indeterminate nature) with the velocity of light c and occupies a volume $\sim \lambda^3$, where λ is the photon wavelength. However, on the other hand, photons obey the Bose statistics and therefore a number of photons may collect in a volume $v << \lambda^3$. This is why in the case of the high density of photons we meet with some conceptual difficulty.

One kind of such problems has been studied by the author in paper [2]. The work deals with the investigation of the interaction of an intensive photon pulse radiated by laser with atoms of gas and electrons of the metal. It has been argued that a photon flux can be regarded as a flow of corpuscles which are only several nm apart in spite of the fact that the wavelength of photons is of the order of several hundreds nm. Thus the examination [2] of numerous experiments has shown that photons, indeed, might be considered as very small corpuscles in a 3D space. But what is spatial pattern of the photon considered from the microscopic standpoint? To answer the question we should revise the modern views on notions of a particle and the quantum of a field.

Bussey [3] has recently considered the phonon as a model for elementary particles. He has analyzed "the phonon collapse" in the one-dimensional lattice and emphasized that this is exactly analogous to the familiar wavefunction collapse of a normal quantum particle, such as a photon, as he notes, observed by Mizobuchi and Ohtake [4]. Bussey notes that the atomic displacements u_l which create the phonon state resemble the field elements $\phi(x)$ of a particle, since quantum field theory describes elementary particles as excitations of fields whose ground state is the vacuum. He says [3] that the existence of such parallels between excitations of fields and phonons has long been recognized (see, e.g. Ref. [5]).

However, one may treat quantum field theory only as an approximation to the description of nature, just as the Fourier approximation is applied to a concrete continuous function in mathematics.

On the other hand, the photon might be considered as an aether wave, as has been pointed out by Meno [6]. Nonetheless, his model is restricted by a pure phenomenological description of a wave in an aether treated as a gas of incompressible "gyrons".

In the recent concept by the author [7-13] particles appear as stable local deformations of a degenerate space that is regarded as a 3D elastic cellular net with the size of a cell $\sim 10^{-28}$ cm (recall that at this scale all types of physical interactions come together) [12,13]. In this case we do not need abstract field elements $\phi(x)$. Any motion of the deformation is accompanied by excitations of the space net that were called inertons [7] and the motion of such a complex formation, i.e. a particle surrounded by its inerton cloud, falls within the formalism of quantum mechanics both Schrödinger's [7,8] and Dirac's [9]. In paper [10] we have theoretically studied the collective motion of atoms, i.e. phonons, in the crystal lattice assuming the existence of inerton clouds in their surrounding and then proved it experimentally (other manifestations of clouds of inertons have been demonstrated in Ref. [2]). Thus owing to a great success of the new concept we may assume that photons migrated in the space net might be considered as something similar to phonons which are excited in the crystal lattice.

Phonons appear due to spontaneous vibrations of atoms in the crystal lattice. Actually owing to the atom-atom interaction, one can write the Lagrangian

$$L = \frac{1}{2}\sum_{\vec{n}} m \dot{\vec{r}}_{\vec{n}}^{\,2} - \frac{1}{2}{\sum_{\vec{n},\vec{n}'}}' \gamma_{\vec{n}\,\vec{n}'} \vec{r}_{\vec{n}} \vec{r}_{\vec{n}'} \tag{1}$$

where m is the mass of the $\vec{n}$th atom, $\vec{r}_{\vec{n}}$ and $\dot{\vec{r}}_{\vec{n}}$ are the displacement of the atom from the equilibrium position and the velocity of the atom respectively, $\gamma_{\vec{n}\,\vec{n}'}$ is the tensor of elasticity interaction of atoms, the dot over the vector $\vec{r}_{\vec{n}}$ means the differentiation with respect to the proper time of the crystal (compare with Ref. [8]). As is well known, expression (1) can be rewritten via the generalized, or canonical, coordinates $A_{\vec{k}s}$ and $\dot{A}_{\vec{k}s} \equiv P_{\vec{k}s}$ (see, e.g. Ref. [14])

$$L = \frac{1}{2}\sum_{\vec{k},\, s} \Big(\dot{A}_{\vec{k}s} \dot{A}_{-\vec{k}s} - \Omega_s^2(\vec{k}) A_{\vec{k}s} A_{-\vec{k}s} \Big) \tag{2}$$

where $\Omega_s^2(\vec{k})$ is the frequency of the sth branch of acoustic vibrations of atoms. $\dot{A}_{-\vec{k}s}$ denotes the generalized momentum $P_{\vec{k}s}$. Coordinates $A_{\vec{k}s}$

and $P_{\vec{k}s}$ are substituted for the corresponding operator

$$A_{\vec{k}s} \to \hat{A}_{\vec{k}s} = \sqrt{\hbar/2\Omega_s(\vec{k})}\ (\hat{b}_{\vec{k}s} + \hat{b}^{\dagger}_{-\vec{k}s}); \qquad (3)$$
$$P_{\vec{k}s} \to \hat{P}_{\vec{k}s} = i\sqrt{\hbar\Omega_s(\vec{k})/2}\ (\hat{b}^{\dagger}_{\vec{k}s} - \hat{b}_{-\vec{k}s}).$$

Here, $\hat{b}^{\dagger}_{\vec{k}s}$ $(\hat{b}_{\vec{k}s})$ is the Bose operator of creation (annihilation) of a phonon. In terms of the second quantization operators the energy operator of the lattice vibrations takes the form

$$\hat{H} = \sum_{\vec{k},\, s} \hbar\Omega_s(\vec{k})\Big(\hat{b}^{\dagger}_{\vec{k}s}\hat{b}_{\vec{k}s} + \frac{1}{2}\Big). \qquad (4)$$

Now let us proceed to the inspection of the energy operator of a free electromagnetic field, which has the same form

$$\hat{\mathcal{H}} = \sum_{\vec{k},\, s} \hbar\omega_s(\vec{k})\Big(\hat{a}^{\dagger}_{\vec{k}s}\hat{a}_{\vec{k}s} + \frac{1}{2}\Big) \qquad (5)$$

where $\hat{a}^{\dagger}_{\vec{k}s}$ $(\hat{a}_{\vec{k}s})$ is the Bose operator of creation (annihilation) of a photon, an elementary excitation of the electromagnetic field; $\omega_s(\vec{k})$ is the cyclic frequency of the photon with the wave vector $\vec{k}$ and the s polarization. In spite of the similarity of expressions (4) and (5), their original classical Lagrangians are absolutely different. In the case of phonons we start from the discrete function (1), but in the case of photons we emanate from the Lagrangian density of the continual electromagnetic field

$$\mathcal{L} = \frac{1}{8\pi}\Big\{\frac{1}{c^2}\Big(\frac{\partial\vec{A}}{\partial t}\Big)^2 - (\nabla\times\vec{A})^2\Big\} \qquad (6)$$

where $\vec{A}$ is the vector potential of the field. However if we formally do an analysis trying to advance from the energy operator (5) to an initial classical Lagrangian keeping the phonon scheme above, we will come to a very interesting finding.

First, the operators of canonical variables expressed in terms of $\hat{a}^{\dagger}_{\vec{k}s}$ and $\hat{a}_{\vec{k}s}$ are

$$\hat{\mathcal{A}}_{\vec{k}s}(t) = \sqrt{2\pi\hbar c^2/\omega_{\vec{k}}}\ \big(\hat{a}_{\vec{k}s}(t) + \hat{a}^{\dagger}_{-\vec{k}s}(t)\big); \qquad (7)$$
$$\hat{\mathcal{P}}_{\vec{k}s}(t) = i\sqrt{\hbar\omega_{\vec{k}}/8\pi c^2}\ \big(\hat{a}^{\dagger}_{\vec{k}s}(t) - \hat{a}_{-\vec{k}s}(t)\big).$$

Then the corresponding canonical variables are

$$\vec{\mathcal{A}}(\vec{r},t) = \frac{1}{\sqrt{V}} \sum_{\vec{k},\, s} \vec{e}_{\vec{k}s} \mathcal{A}_{\vec{k}s}(t) e^{i\vec{k}\vec{r}}; \qquad (8)$$

$$\vec{\mathcal{P}}(\vec{r},t) = \frac{1}{\sqrt{V}} \sum_{\vec{k},\, s} \vec{e}_{\vec{k}s} \mathcal{P}_{\vec{k}s}(t) e^{-i\vec{k}\vec{r}}.$$

Formulas (8) present the Fourier-series expansion of the classical variables $\vec{\mathcal{A}}(\vec{r},t)$ and $\vec{\mathcal{P}}(\vec{r},t) \equiv (1/4\pi c^2)\partial\vec{\mathcal{A}}/\partial t$ in the volume V. And the expansion, indeed, adequately depicts the actual discrete structure of electromagnetic field, i.e., photonic nature of the field. Thus one can rewrite the Lagrangian density (6) as

$$\mathcal{L} = \frac{1}{8\pi V} \sum_{\vec{k},\, s} \Big[\frac{1}{c^2} \frac{\partial \mathcal{A}_{\vec{k}s}}{\partial t} \frac{\partial \mathcal{A}_{-\vec{k}s}}{\partial t} - \big(\nabla \times \vec{e}_{\vec{k}s} \mathcal{A}_{\vec{k}s}\big)\big(\nabla \times \vec{e}_{\vec{k}s} \mathcal{A}_{-\vec{k}s}\big) \Big]. \qquad (9)$$

Let us invert expression (9) written via the wave vector presentation to that written in terms of discrete spatial variables

$$\mathcal{L} = \frac{1}{8\pi V} \sum_{\vec{n}} \Big[\frac{1}{c^2} \Big(\frac{\partial \vec{\mathcal{A}}_{\vec{n}}}{\partial t} \Big)^2 - \big(\nabla_{\vec{n}} \times \vec{\mathcal{A}}_{\vec{n}}\big)^2 \Big]. \qquad (10)$$

Under this new description, the vector $\vec{n}$ plays the role of the radius vector that defines knots of a lattice of space or cells of a space net. The most credible speculation is that the space consists of cells (or balls, or superparticles) which are closely packed [7-9,11-13]. Then the equation of motion

$$\frac{\partial^2 \vec{\mathcal{A}}_{\vec{n}}}{\partial t^2} - \frac{1}{c^2} \nabla^2_{\vec{n}} \vec{\mathcal{A}}_{\vec{n}} = 0 \qquad (11)$$

followed by expression (10) specifies the behavior of some kind of a polarization $\vec{\mathcal{A}}_{\vec{n}}$ localized in the cell which position in the space net is defined by the $\vec{n}$th radius vector in the moment t.

From the results obtained it may be deduced that the photon should be regarded as an elementary excitation, or quasi-particle of some sort that migrates hopping from cell to cell in the space net rather than a canonical particle-wave of an undetermined nature that moves in an empty space, or a dim vacuum. In this case the vector potential $\vec{\mathcal{A}}_{\vec{n}}$

should be interpreted as some kind of polarization/deformation that is induced in an incoming cell along a path of the corresponding photonic excitation. The vector of local peculiar deformation $\vec{\mathcal{A}}_{\vec{n}}$ changes in any point (i.e. cell) that is characterized by the radius vector $\vec{n}$ according to Eq. (11). But the migration of the photon "core" features the equation

$$\frac{d}{dt}\vec{n} = \frac{\vec{n}}{n}c \qquad (12)$$

where the proper time $t > \tau$ and τ is the "inoculating" time (i.e. photon lifetime in a cell, see below). Thus, a couple of equations (11) and (12) completely describe the behavior of the photon.

Consequently, we may conclude that unlike the phonon that envelopes a great number of the lattice sites (the phonon is enclosed in a volume $\sim k_{\rm ac}^{-3}$ where $k_{\rm ac} = 2\pi/\lambda_{\rm ac}$ is the wave number and $\lambda_{\rm ac}$ is the wavelength of the appropriate acoustic excitation), the photon may be considered as something that is located only in one cell of the space. However, the lifetime of the photon in one cell whose size $a \sim 10^{-28}$ cm should be extremely short. It can be estimated if we divide the period T of the photon by a number N of cells that cover the section of spatial period $\lambda = 2\pi/k$ of the photon. Therefore $N = \lambda/a$ and hence the lifetime $\tau = Ta/\lambda$. For instance in the case of an optical photon $\lambda \sim 10^{-8}$ cm, $N \sim 10^{36}$ and then $T \sim 1$ fs and $\tau \sim 10^{-35}$ s.

The notion of the wavelength λ of the photon specifies the spatial period at which the cell's polarization restores its initial state. In other words, the photon wavelength λ is a distance which the photon should run hopping from cell to cell in order that the initial phase of the photon polarization be restored. The period of polarization oscillations $T = 1/\nu$ is connected with λ by relation $c = \lambda/T$. Yet the real size of the photon, i.e. size of its "core", is limited by the size of a cell of the space net $a \sim 10^{-28}$ cm.

Thereby, the photon that is characterized by the energy $\varepsilon = h\nu$ makes up an excitation of the space net, which migrates by structural cells of the net and carriers a polarization from cell to cell. This hopping motion is similar to the migration of Frenkel, or molecular excitons in molecular crystals.

The interaction of the photon with a matter is realized by means of the interaction of the photon with inerton clouds of the matter entities such as electrons, atoms, etc. as the radius of the dense inerton cloud that surrounds an electron or an atom much exceeds the mean distance between the entities in condensed media [2,10]. One can raise the question, how can inertons which represent a substructure of the matter waves of any charged particle be distinguished from the particle's virtual photons which feature the particle's electromagnetic field? Inertons were uniquely determined [7,8,12,13] as elementary excitations, or quasi-particles of the space net, which carry a local deformation of the net. In order for agreement the particle's electrodynamics to particle's quantum mechanics, photons must be treated as the same quasi-particles, i.e. massive inertons, which however are endowed with an additional property. Thereby the notion of electromagnetic "polarization" of a cell, i.e. a special additional deformation of a cell, should be clarified and this indeed is quite possible in the framework of the model that is developing.

A theory of the photon-inerton interaction being constructed will allow concrete practical applications. Namely, it will make possible: (i) the disclosing a microscopic mechanism of the phenomenon of the diffraction of light, which so far is still described in pure geometrical (i.e. phenomenological) terms; (ii) a microscopic description of the phenomenon of the bending of a luminous ray in the vicinity of a star, which is till now considered solely in the framework of the general relativity macroscopic approach; (iii) a detailed theoretical analysis of entangled states; (iv) the construction of submicroscopic models describing the photon-photon cross-section into hadrons (modern models, see e.g. Refs. [15,16], operate with γ-photons as very complicated formations. We may assume that those γ-photons are not canonical photons described above but rather peculiar cooperative excitations of a sort. In fact, the concept is not contradictory to elementary particle physics: the photon is not included in the list of *elementary particles* [17]).

Thus, the results presented in this work permits the tracing a microscopic physical pattern of the photon in a 3D space, or 4D space-time. The new concept of the photon turns the study of the photon properties to an inner structure of a cell, or superparticle, the building block of the real space.

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