On nonzero photon mass within wave-particle duality

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Abstract

The mass of a photon is one of the most intriguing ideas of theoretical physics, and their existence is consistently justified in the light of certain experimental data. In this paper the proposal for explanation of the nonzero photon mass in frames of the wave-particle duality is concisely presented. The standard formulation of the wave-particle duality is modified by the constant frequency field, which can be interpreted as the Zero-Point Frequency field.

Keywords: photon; mass; Lorentz violation; wave-particle duality; Laurent series expansion

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1 Introduction

One of the most intriguing ideas of modern theoretical physics is existence of the mass of a photon. Recall that the belief about nonzero value of the mass of a photon in deeply rooted in experimental data, and was deduced in early 1970s by A. Mazet, C. Imbert, and S. Huard [1] by observations of total internal reflection to test the Goos–Hänchen effect [2] of the beam shift. Soon after this essential analysis L. De Broglie and J.-P. Vigier [3] discussed this contradiction in the context of the quantum theory of radiation and generalized it to the quantum theory of massive spin-1 photons.

Albeit, still the question of nonzero value of the mass of a photon is one of the most important and actual problem of physics. The possibility of nonzero photon mass has been suggested in the investigation by Bass and Schrödinger [4] performed in the mid-1950s. In early 1980s H. Georgi, P. Ginsparg, and S.L. Glashow [5] have been suggested that nonzero photon mass is the justification for cosmic microwave background radiation.Another good example is the analysis performed by R. Lakes [6], in which the mass of a photon is analyzed in the framework of the Maxwell–Proca equations. The diverse approaches to the problem of nonzero photon mass have been recently reviewed by A.S. Goldhaber and M.M. Nieto [7].

Today the problem of nonzero photon mass is also often discussed, for the most recent studies see e.g. the papers in the Ref. [8]. The question about nonzero value of the mass of a photon straightforwardly arises from the experimental data, which manifestly demonstrate that the photon mass is small but detectable. Interestingly, in common understanding the concept of nonzero photon mass can not be described within the framework based on the standard considerations of the wave-particle duality, i.e. by involving the fundamental ideas based on Special Relativity and Quantum Theory.

In this brief paper we shall to present the concise and consistent proposal for constructive explanation of the nonzero mass of a photon. The construction is solely based on the most fundamental arguments following from the wave-particle duality. The nontrivial modification is the contribution due to the constant frequency field, which can be interpreted as the presence of Zero-Point Frequency field.

2 The Nonzero Photon Mass

In Special Relativity, the energy E of a particle possessing the mass m and moving with a three-momentum $\vec{p} = [p_x, p_y, p_z]$ is described by the Einstein energy-momentum relation

$$E^2 = m^2c^4 + p^2c^2, \tag{1}$$

where $p = \sqrt{p_x^2 + p_y^2 + p_z^2}$ is the value of three-momentum of a particle. The formula (1) can be treated as the definition of the rest mass m

$$m^2 = \frac{E^2}{c^4} - \frac{p^2}{c^2}, \tag{2}$$

when the values of energy and momentum of a moving particle is known from experimental data. Recall that the wave-particle duality establishes the physical equivalence between the description in terms of energy E and momentum p appropriate for particles and the description in the language of frequency f and involves wavelength λ suitable for waves. The first relation is the Planck energy-frequency formula

$$E = hf, \tag{3}$$

and the second one is the De Broglie momentum-wavelength formula

$$p = \frac{h}{\lambda}. \tag{4}$$

Their empirical legitimacy has been established by a number of experiments. Applying these fundamental relations within the equivalence principle (2) one receives

$$m^2 = \frac{h^2}{c^4}\left(f^2 - \frac{c^2}{\lambda^2}\right). \tag{5}$$

It is evidently seen that if one considers the nonzero value of the mass of a photon one should have

$$f^2 - \frac{c^2}{\lambda^2} > 0. \tag{6}$$

Such a conclusion is manifestly wrong in the light of the standard formula for frequency $f = \dfrac{c}{\lambda}$ which is usually applied in description of wave phenomena. It suggests, however, that for the consistent and constructive explanation of the nonzero photon mass within the wave-particle duality, this celebrated formula should be modified.

Let us assume that the frequency f of a photon is in general given by the Laurent series expansion in wavelength λ

$$f(\lambda) = \sum_{n=-\infty}^{\infty} a_n \lambda^n, \tag{7}$$

where a_n are some coefficients having the dimension $[a_n] = T^{-1}L^{-n}$. In such a situation the speed of light in vacuum $a_{-1} = c$ is the value of the residue of the function $f(\lambda)$. Let us consider the particular situation

$$f = f_0 + \frac{c}{\lambda}, \tag{8}$$

where f_0 is certain reference constant frequency, Zero-Point Frequency field say. It can be seen by straightforward and easy calculation that in such a situation one has

$$f^2 - \frac{c^2}{\lambda^2} = f_0^2 + 2f_0\frac{c}{\lambda}, \tag{9}$$

and by this reason the rest mass of a particle becomes

$$m^2 = \frac{h^2}{c^4}\left(2f_0\frac{c}{\lambda} + f_0^2\right). \tag{10}$$

Let us apply now the following formula

$$m^2 = m_0^2 + \delta m^2, \tag{11}$$

in which the background term

$$m_0^2 = \frac{h^2}{c^4} f_0^2, \tag{12}$$

is square of the Zero-Point Mass following from the duality between the rest energy $E = mc^2$ and the Planck energy $E = hf$. The correction δm^2 to this background contribution has the form

$$\delta m^2 = \frac{h^2}{c^4}\frac{2f_0 c}{\lambda}. \tag{13}$$

If one presents the background frequency in the following form

$$f_0 = \frac{c^2}{h} m_0, \tag{14}$$

then the mass of a particle can be rewritten in the form

$$m = m_0\sqrt{1+\frac{2\ell_0}{\lambda}}, \tag{15}$$

which for small values of the wavelength λ in comparison to the scale ℓ_0 behaves like

$$m \approx m_0\left(1+\frac{\ell_0}{\lambda}\right). \tag{16}$$

here ℓ_0 is the Compton wavelength of the mass m_0

$$\ell_0 = \frac{h}{m_0 c}. \tag{17}$$

Interestingly, when value of the background frequency f_0 is small, say is $f_0 = E_P/h$ where $E_P = \sqrt{\frac{\hbar c^5}{G}}$ is the Planck energy, then the term $\frac{h^2}{c^4}f_0^2$ has the value

$$m_0^2 \approx M_P^2 \approx 4.73\cdot 10^{-16}\mathrm{kg}^2. \tag{18}$$

In such a situation the correction (13) is

$$\delta m^2 = 4\pi M_P^2\frac{\ell_P}{\lambda} \approx \frac{9.62084\cdot 10^{-50}\mathrm{kg}^2\cdot\mathrm{m}}{\lambda}. \tag{19}$$

In other words when the wavelength of a particle is

$$\lambda \ll 4\pi\ell_P, \tag{20}$$

then the correction is much more bigger then the contribution due to the background Zero-Point Frequency field. In such a situation the mass of a particle is given by the formula

$$m = M_P\sqrt{1+\frac{4\pi\ell_P}{\lambda}} \approx M_P\left(1+\frac{2\pi\ell_P}{\lambda}\right). \tag{21}$$

3 Discussion and Conclusion

The construction presented in this paper consistently explains the particular case given by a photon. In such a situation the mass formula (15) leads to clear and unambiguous explanation of the nonzero value of the mass of a photon, which up to the constant multiplier is the reciprocal of its wavelength. In the unmodified scenario in such a situation the rest mass of a photon is exactly equal to zero, and this case is described by Special Relativity in which the Lorentz symmetry works. However, the construction proposed above does not lead to this classical result, and the mass of a photon is manifestly nonzero in the framework of the wave-particle duality, so that the Lorentz symmetry is violated manifestly.

The presented approach is strictly based on the Laurent series, which is the most general possible series expansion, relation between frequency and wavelength certainly works for the photon if value of its mass lies below the measured threshold determined by experimental data. The dispersion relation which has been proposed in this paper would be essential over a large distance, like for the galaxies which are very far from the terrestrial observer point of view.

Standardly a complex value to a frequency is characteristic for a quantum particle in a tunneling potential. In this manner in our scenario the massive photon is such a particle. The scenario indicates that the zero term or the residue term in the Laurent series corresponds to propagation of the light in vacuum, but the physical meaning of the another contributions to the series is presently unclear.

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