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Photon: Mass less or Massive?

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ABSTRACT

The existence of the mass of a photon is one of the most intriguing issues in physics. According to Einstein's special theory of relativity (STR), photon is a mass less particle and travels at the speed of light. But some scientists claim that photon has a nonzero rest mass however small it may be. Although up to now there has been no conclusive evidence of a finite mass for the photon, there are stringent upper bounds on the size of it.

Keywords: *Photon; special theory of relativity; general theory of relativity; wave-particle duality; cosmic microwave background radiation.*

1. INTRODUCTION

The electromagnetic theory failed to explain several phenomena like blackbody radiation, photoelectric effect, Compton effect etc. relating about the emission and absorption of light. In 1901 Max Planck [1] tried to resolve a problem in the classical theory of electromagnetic radiation by using his quantum theory. He assumed that the atoms in the walls of a black body behave like simple harmonic oscillators, and each has a characteristic frequency of oscillation. These oscillators do not emit or absorb energy continuously. The energy lost or gained is in the form of discrete quanta each of energy $h\nu$, where h is Planck's constant and ν is the frequency of oscillation. In 1902 Lenard [2] discovered that energy of emitted electrons in photoelectric effect does not depend on the intensity of light, but depends on the wavelength of the latter. In 1905 Einstein [3] pointed out that the discovery of Lenard that the energy of light distributed in space not uniformly, but in a form of localized light quanta. He showed that all experiments related to the black body radiation, photoluminescence and production of cathode rays by ultraviolet light can be explained by the quanta of light. The proof that Einstein's light quanta behave as particles, carrying not only energy but also momentum, was given in 1923 in the experiments by Compton on scattering of X-rays on electrons. The term "PHOTON" for particles of light was coined by G. N. Lewis in 1926 in an article "The Conservation of Photons" [4] considering photons to be "atoms". According to Einstein's special theory of relativity (STR), only mass less particles (e.g. photons) travel at the speed of light. In other words, any particle that travels at the speed of light must be mass less.

A nonzero photon mass has been under experimental and theoretical studies for years. The belief about nonzero value of the mass of a photon arose from the experimental data in early 1970s by A. Mazet et al. [5] from the observations of total internal reflection to test the Goos-Hanchen effect [6] of the beam shift. Soon after Louis de Broglie and Jean Pierre Vigier [7] interpreted that photon has a nonzero rest mass. In 1955, the possibility of nonzero photon mass has been suggested by L. Bass and E. Schroedinger [8]. In early 1980s H. Georgi, P. Ginsparg and S. L. Glashow [9] have been suggested that nonzero photon mass is the justification for cosmic microwave background radiation (CMBR). While photons are moving along a waveguide they obey an equation appropriate for a particle of nonzero mass [10,11]. Similarly, when photons are propagating in plasma they obey an equation applicable to massive particles [12]. In classical electrodynamics, a massive photon can be incorporated by adding a mass term to the Lagrangain density of the electromagnetic field, which results Proca equations [13,14]. If photon rest mass m_γ = 0, the Proca equations reduce to Maxwell's equations. Recently, the problem of nonzero photon mass is studied by several scientists [15–21]. Mass less photons are stable in quantum electrodynamics (QED). Whereas a nonzero photon mass opens up the possibility of photon decay. Using the allowed value for photon mass from other experiments, authors [21] find a lower limit of about 3 years on the photon rest-frame lifetime. For photons in the visible spectrum, lifetime becomes around 10^{18} years. The photon mass changes the spectral energy density of blackbody radiation. Glinka [18] has shown that the mass of a photon is nonzero in the framework of the wave-particle duality.

2. DISCUSSIONS IN FAVOR OF NONZERO PHOTON MASS

In this section, we have discussed some points to support that photons have nonzero rest mass.

(i) According to Einstein's special theory of relativity, the energy-momentum dispersion relation for a particle can be written as:

$$E^2 = p^2c^2 + m_0^2c^4, \qquad (1)$$

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where *E* is the total energy of the particle, $|\vec{p}|$ = p is this particle's momentum, m_0 is the rest mass of the particle and c = 3 x 10^8 m/sec is the speed of light in vacuum.

Again, the energy of the photon is given by

$$E = pc \qquad (2)$$

If both these two equations are applicable to the photon with all the identical symbols then the rest mass of photon is zero $(m_0 = 0)$. According to Einstein's special theory of relativity (STR), only mass less particles (e.g. photons) travel at the speed of light. In other words, any particle that travels at the speed of light must be mass less. This assumption led to the neutrino mass problem - if it has mass? Neutrinos travel at the speed of light and according to the afore-stated, they must be mass less. But mass less neutrinos are unable to explain the phenomenon of neutrino oscillation because this requires massive neutrinos. Hence, neutrinos must have mass however small it may be.

Thus, if photon has zero rest mass, both energies (Eq. (1) and (2)) are identical. If these two energies are different then let us say that *E* in equation (1) is the total gravitational energy E_g of the photon and *E* in equation (2) is the total kinetic energy E_K [19]. Thus, we can write $E_g^2 = p^2c^2 + m_0^2c^4 = E_K^2 + m_0^2c^4$, where generally $(m_0 \neq 0)$. Thus, photon has a nonzero rest mass.

(ii) Generally *mass* is thought to be the quantitative measure of the amount of matter in a particle (subastance). If photon has zero mass, no (zero) amount of matter should be present. But as per present knowledge photon has not only stuff in it, but lots of it [19]. Hence, photon has a nonzero rest mass.

(iii) *Wave-particle duality*: According to de Broglie's hypothesis matter have dual nature of both particle and wave like light. de Broglie's relation $(\lambda = h/p)$ [22] is derived from equation (1) $E^2 = p^2c^2 + m_0^2c^4$ and Planck-Einstein equation $E = h\nu$. In Einstein's STR, equation (1) is derived (as shown below) from two equations: $E = \gamma m_0 c^2$ which is the total energy of the particle and $p = \gamma m_0 v$ which is the relativistic momentum of the particle, where

$\gamma = 1/\sqrt{1 - v^2/c^2}$.

$$p = \gamma m_0 v = m v \quad \Rightarrow v = \frac{p}{m}$$

$$E = \gamma m_0 c^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{m_0 c^2}{\sqrt{1 - \frac{p^2}{m^2 c^2}}}$$

$$= \frac{m_0 c^2}{\sqrt{1 - \frac{p^2 c^2}{m^2 c^4}}} = \frac{m_0 c^2}{\sqrt{1 - \frac{p^2 c^2}{E^2}}}$$

Squaring both sides we get,

$$E^2 = \frac{m_0^2 c^4}{1 - \frac{p^2 c^2}{E^2}}$$

$$\Rightarrow E^2\left(1 - \frac{p^2 c^2}{E^2}\right) = m_0^2 c^4$$

$$\Rightarrow E^2 = p^2 c^2 + m_0^2 c^4$$

If we consider these two fundamental equations $E = \gamma m_0 c^2$ and $p = \gamma m_0 v$, it is clear that a zero-mass particle must have zero energy and momentum [19,22]. This problem is overcome by treating quantum mechanics as more fundamental than Einstein's STR. Thus, the mass of a photon is nonzero in the framework of the wave-particle duality [18]. de Broglie himself [7] believed that the photon has a mass.

(iv) Recently, Kamal L. Rajpal [20] has discussed a peculiar property of a photon that it is the only elementary particle wherein a high energy photon can split up into two or more low energy photons and vice versa. For example, in the sun, when a gamma photon in the radiation zone moves towards the photosphere it transforms into a large number of visible light optical photons during its journey. This transformation obeys the conservation laws of mass, momentum and energy. In order to satisfy the conservation law of mass, a high frequency photon should have more rest mass or invariant mass than a low frequency photon.

From the above discussions we can say that photon has a nonzero mass, however small it may be.

3. GRAVITATIONAL DEFLECTION OF MASSIVE PHOTONS

In 1973, scientist D. D. Lowenthal proposed [24] a method for setting limits on the photon mass by studying the gravitational deflection of electromagnetic radiation. The general theory of relativity (GTR) predicts a deflection of starlight by the sun of 1.75 sec of arc. If the photon has a nonzero rest mass m_γ, this deflection angle would become

$$\theta = \theta_0 \left(1 + \frac{m_\gamma^2 c^4}{2 h^2 \nu^2} \right) , \qquad (3)$$

where θ is the deflection angle for photons of finite mass, $\theta_0 = 4\,MG / Rc^2$ is the deflection angle for a mass less photon, M is the solar mass, G is the Newtonian gravitational constant, R is the photon impact parameter (normally the solar radius), c the speed of light, h Planck's constant and ν the frequency. If $\Delta = \theta - \theta_0 = \theta_0 m_\gamma^2 c^4 /(2h^2\nu^2)$ is the difference between the measured deflection angle and the deflection angle calculated for photons with zero rest mass, then an expression setting an upper limit on the photon can be written as

$$m_\gamma^2 \le \frac{h\nu}{c^2}\sqrt{\frac{2\Delta}{\theta_0}} \qquad (4)$$

Using the above equation and data available on the deflection of electromagnetic radiation by the sun, Lowenthal obtained an upper limit for visible light: $m_\gamma < 10^{-33}$g = 0.56 eV with $\nu = 5 \times 10^{15}$ Hz and $\Delta \cong 0.1$ sec of arc; for radio source 3C 279: $m_\gamma < 7 \times 10^{-33}$g $= 4 \times 10^{-7}$ eV with $\nu = 3 \times 10^9$ Hz and $\Delta \cong 0.1$ sec of arc.

In 2004, A. Accioly and R. Paszko [25] analyzed the energy-dependent deflection of a massive photon by an external gravitational field. They found the same expressions for setting upper limits on the photon mass as in equation (4). Using the best measurement of the deflection of radio waves by the gravitational field of the sun, they obtained an upper limit for the photon rest mass $m_\gamma < 10^{-40}$g.

4. FURTHER DISCUSSIONS

(a) In 1943, E. Schrodinger [26,27] proposed a method for determining the photon rest mass by studying electromagnetic fields of certain strength in empty space, and neglecting gravitation. By studying a modified version of Maxwell's equations, especially Ampere's law, he obtained an upper limit on the photon rest mass. In 1955, L. Bass and E. Schrodinger obtained an upper limit for the photon mass $m_\gamma \le 2 \times 10^{-47}$g.

(b) Magneto hydrodynamic (MHD) phenomena are described by the combination of ordinary hydrodynamics and Maxwell's equations of electromagnetism [28], where the interactions between magnetic fields and a free fluid [29] are described. If the photon has a finite rest mass, MHD phenomena within the interplanetary plasma would be used to determine the size of that mass due to its effect on Maxwell's equations.

(c) Scientists have studied different phenomena related to massive photon and given upper bounds on the photon mass (Table 1). [1 eV = 1.78×10^{-33}g &1 eV $=(1.97 \times 10^{-10}\,\text{km})^{-1}$ [10].

(d) Some scientists have set an upper limit on the photon mass $m_\gamma < 2 \times 10^{-51}$g or $\sim 10^{-18}$eV [17,28]. Recently, particle data group (PDG) [30] has set an upper limit on the photon mass $m_\gamma < 1 \times 10^{-18}$eV and charge of photon $< 1 \times 10^{-35}$e, where e is the charge of an electron.

Table 1: Upper bounds on the photon mass

Author (Year)	**Type of measurement**	**Limits on m_γ (g)**
Ross et al. (1937)	Radio waves transmission overland	5.9×10^{-42}
Mandelstam and Papalexi (1944)	Radio waves transmission over sea	5.0×10^{-43}
Florman (1955)	Radio-wave interferometer	5.7×10^{-42}
Loyell et al. (1964)	Pulsar observations on four flare stars	1.6×10^{-42}
Frome (1958)	Radio-wave interferometer	4.3×10^{-40}
Warner et al. (1969)	Observations on Crab Nebula pulsar	5.2×10^{-41}

Brown et al. (1973)	Short pulsar radiation	1.4×10^{-33}
Bay et al. (1972)	Pulsar emission	3.0×10^{-46}
Schaefer (1999)	Gamma ray bursts (GRB980703)	4.2×10^{-44}

5. CONCLUSIONS

A mass less photon is neither a theoretical prediction nor a necessity, but rather a phenomenological curiosity [21]. Like other particles, photon has a real physical identity, not just a conceptualization of the physicist's mind [28]. Although till today there is no conclusive evidence of a finite mass for the photon, there are stringent upper bounds on the size of it. Again failure to find a finite photon mass in any one experiment or class of experiments is not the proof that it is identically zero. In this article, we have discussed some points to support that photons have nonzero rest mass. Then, we discuss upper limits on the nonzero rest mass of photon collected from different sources. Physics never ruled out massive photons [17,28,30]. Although a massive photon is not consistent with gauge invariance of renormalizability, theory of massive photons can be derived through Proca Electrodynamics [28]. Although finding a nonzero value for photon rest mass would have no visible impact on everyday life and work, it has a lot of implications in the region of astrophysics and cosmology. Determination of a nonzero value for the photon mass has encouraged work on the formation and early evolution of stars and stellar systems, the properties of the interstellar media and plasma, dissipation of the interplanetary magnetic fields, cosmic microwave background radiation, dispersion of hydro magnetic waves, and so on. The existence of massive photon creates some important problems in physics like "What is the absolute rest mass of a photon?", "How can massive particles travel at the speed of light?" etc. A proper study of these challenging issues is required in future. We hope these problems will be addressed in the Large Hadron Collider (LHC) experiment at CERN, Geneva.

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