Results in Physics 16 (2020) 102866

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Rest mass of photon on the surface of matter

Mahendra Goray, Ramesh Naidu Annavarapu*

Department of Physics, School of Physical, Chemical and Applied Sciences, Pondicherry University, Puducherry 605 014, India

ARTICLE INFO

Keywords:
Illusive mass
Morphing
Photon rest-mass
Space-time curvature
Wavelength dependence
Wave-particle duality

ABSTRACT

The behavior of a photon is strange. It possesses both wave nature and particle nature. Some experiments show both behaviors of photons can exist simultaneously, while some other experiment state that both properties do not co-exists simultaneously. According to electromagnetic theory, the rest mass of photon in free space is zero and also photon has non-zero rest mass, as well as wavelength-dependent. The very recent experiment revealed its non-zero value as 10^{-54} kg(5.610×10^{-25} MeV c^{-2}). Even experimental results concluded that within matter (dispersive) the photon shows its imaginary rest mass. We have no exact answer as to why photon incarnates itself with versatile mass. Here we try to theoretically investigate about the rest mass of a photon. When it touches the surface of matter, it makes illusion and mathematically the rest mass is a complex number. Rest mass of photon depends upon scalar curvature of the surface of matter and wavelength of the photon. Photon itself reveals illusion posing with mass because of its dual nature. We have investigated the wave-particle duality of light, coexistence of wave and particle nature through morphing due to pliable character of light wave. Our theoretical work about the photon's *illusive mass* will have to be experimentally verified and it might open plausible new applications in the secure communication of information.

Introduction

Some of the physical laws of nature are very peculiar; especially whose velocity is nearly equal to the velocity of light in free space (quantum object). Light wave shows wave-particle duality theoretically [1–4] as well as experimentally [5–7] and *vice versa* material particle also shows dual nature but light wave and material wave is not same [1,4,8,9]. Wave-like and particle-like behavior of light wave depends upon the experimental setup; what we want to see the form of light [5,6,10]. Wave and particle nature comes due to the interference 'ability' and 'inability' of photon respectively [5,6] although this is the adopted functional definition [6]. Both properties of light are coexist simultaneously through continuous morphing [5–7,10]. But according to the complementary principle, both behavior of light does not co-exist simultaneously [9]. According to the special theory of relativity, speed of light in vacuum (c) is constant and nothing can exceed the speed of light [11–14]. But various experimental and theoretical proposals state that faster than '*c*' is possible [11–20]. Experimentally using anomalous dispersion nearby two Raman gain resonance line [11] and linear [15], nonlinear [16] gain lines; absorption line [17] and theoretically phase velocity (wave-like) of photon within the wave guide [14], group velocity (super light velocity with matter) [19], speed of sound in ultra-dense matter [20] are grater than '*c*'. Although the phase velocity (wave-like) of photon does not carry information [21,22], '*c*' has been made constant for the "purpose of metrology" [13], based only on Maxwell's equation without any proof [12]. So this is not absolutely true which we have taken one of the fundamental laws of nature. According to Electromagnetic theory the rest mass of light wave is zero, but there are so many theoretical and experimental approaches which reveal that it is very small [1,13,23–27]. De-Broglie assumed that the rest mass of photon is about 10^{-54} kg (5.610×10^{-25} MeV c^{-2}) [1]. Different types of experiments have been done which shows that rest mass of photon; by satellite measurement of earth's magnetic field is 4×10^{-51} kg (2.244×10^{-21} Me*V* c^{-2}) [24], low frequency parallel resonance circuits is 10^{-52} kg (5.610×10^{-23} MeV c^{-2}) [25], solar wind experiment is 1.5×10^{-54} kg (8.414×10^{-25} MeV c^{-2}) [26]. Using the frequency-dependent time delays in measurements of the dispersion measures (DMs) of fast radio bursts (FRBs) on FRB 150418 and FRB 121102, the photon mass measured is 3.2×10^{-50} kg (1.795×10^{-20} MeV c^{-2}) [28] and 3.9×10^{-50} kg (2.188×10^{-20} MeV c^{-2}) [29] respectively. All these data are calculated indirectly. Experimental verification is very difficult due to very *light* mass of light wave [26] and very large characteristic length ($\mu_\gamma^{-1} = 2 \times 10^{11}$ m) associated with the mass of photon [23]. However, photon has nonzero real mass, which depends on the wavelength of photon in free space [23,30–33] and inversely proportional to the wavelength when velocity of the photon does not depends up on the wavelength i.e. constant velocity [31]. Even

* Corresponding author.
E-mail address: rameshnaidu.phy@pondiuni.edu.in (R.N. Annavarapu).

https://doi.org/10.1016/j.rinp.2019.102866
Received 17 October 2019; Received in revised form 22 November 2019; Accepted 7 December 2019
Available online 08 January 2020

experimentally, it has been shown that electromagnetic wave (photon) has an imaginary rest mass in the medium (dispersive) which is comparable to electron-neutrino mass [34]. So photon has no fixed real mass like other particles and objects, it can be zero and have real; imaginary value again. If we consider photon has finite mass then the photon's velocity 'v' (in particle form of light wave) must be less than 'c' [1,4,14,30,35–37], which is different from electron in classical mode [34]. When light wave incident from vacuum into medium the phase velocity of photon (wave-like velocity) depends on frequency [34], and photon mass correspondingly depends on wavelength [23,26,30]. So, the wave-particle duality of light wave: particle velocity of a photon ($v < c$) and non-zero photon mass are co-related i.e. wave-particle duality of light says that when light wave has particle nature (non-zero mass) and it has non-zero mass then its particle velocity is less than 'c' according to special theory of relativity $m = m_0/\sqrt{1 - v^2/c^2}$ otherwise $m \to \infty$ if $v = c$ [35,36].

In this paper we have calculated the rest mass of photon when it comes into contact with the surface of matter and tried to explain the behaviour of photon.

Methods

In free space, light wave (massless) of wavelength λ morphing (let photon) according to wave-particle duality and constant velocity of photon is v_{ph}which is less than c [31] and falls into any surface of matter and in this situation (contact with surface of matter) velocity of photon (particle-like) is c_p and corresponding matter wave (wave-like) velocity of photon is c_w, wavelength λ_p, frequency ν_p, rest mass m_0 which depends upon velocity which depend on wavelength λin free space [23,26]; and $\lambda_p$within matter [34]. Rest mass energy of photon [1] $E = h\nu_p$ and $E = m_0c^2$ then the frequency becomes

$$\nu_p = \frac{m_0c^2}{h} \tag{1}$$

and momentum of photon $p = m_0c_p$, and hence according to de Broglie hypothesis [4] its wavelength becomes

$$\lambda_p = \frac{h}{m_0c_p} \tag{2}$$

and wave-like velocity (phase velocity) of photon according to the frequency wavelength relation is given by

$$c_w = \nu_p\lambda_p \tag{3}$$

Substitution of Eqs. (1) and (2) in Eq. (3) gives

$$c^2 = c_pc_w \tag{4}$$

Here $c_p < c$ [1,4,14], hence $c_w > c$ [14,21]. Now energy of photon on the surface of matter, using Eq. (4) can be written as

$$E_p = m_0c_pc_w \tag{5}$$

Same proof can be obtained from reference [1] "group velocity $U = \beta c$" and "phase velocity $V = (c/\beta)$" where "$\beta = (v/c)$". Now $UV = c^2$ as $U < c$ hence $V > c$ so, $c_p \equiv U$ and $c_w \equiv V$.

Computations and results

Now let the rest mass of photon (particle form) when it comes into contact with the surface of matter from free space is the linear combination of two terms due to velocity of photon ($v_{ph} \approx c_p$) for free space and surface of the matter.

$$\mathbf{m} = m_1 + m_2 \tag{6}$$

Here m_1 is the rest mass which depends upon velocity corresponding wavelength as mention earlier.

$$m_1 = m(\lambda)\sqrt{1 - \frac{v_{ph}^2}{c^2}}, \tag{7}$$

where $m(\lambda)$ is the relativistic mass of photon and

$$m_2 = m_0'\mathbf{R} \tag{8}$$

where $\mathbf{R}$ is the scalar quantity. $\mathbf{m}$ depends upon each point on the surface of matter where the photon touches the matter. $\mathbf{R}$ is called Ricci scalar curvature [38,39]. $\mathbf{R} = g^{\mu\nu}R_{\mu\nu}$, and $\mu, \nu = x^0, x^1, x^2, x^3$ are the four dimensional space-time coordinates. $g^{\mu\nu}$ is the inverse metric tensor. $g^{\mu\nu}$ = (cofactor of $g_{\mu\nu}$ in $|g|$)/$|g|$ [39]. $g_{\mu\nu}$is the fundamental tensor or metric tensor and its determinant form is

$$|g| = \begin{bmatrix} g_{11} & g_{12} & \cdots & g_{1n} \\ g_{21} & g_{22} & \cdots & g_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ g_{n1} & g_{n2} & \cdots & g_{nn} \end{bmatrix}$$

and $R_{\mu\nu}$ is the Ricci tensor which is the contraction form of Riemannian-Christoffel curvature tensor $R^{\rho}_{\mu\nu\sigma}$ [39,40].

$$\begin{aligned} R_{\mu\nu} &= R^{\rho}_{\mu\nu\rho} \\ &= \partial_\nu\Gamma^{\rho}_{\mu\rho} - \partial_\rho\Gamma^{\rho}_{\mu\nu} + \Gamma^{\alpha}_{\mu\rho}\Gamma^{\rho}_{\alpha\nu} - \Gamma^{\alpha}_{\mu\nu}\Gamma^{\rho}_{\alpha\rho} \end{aligned}$$

Here we consider $\mu, \nu = x^1, x^2, x^3$are space coordinate part. Replacing $\mathbf{R}$ by I^n, we get

$$I^n = g^{\mu\nu}R_{\mu\nu} \tag{9}$$

From Eq. (8), m_0' is the rest mass of photon when it touches the surface of the matter which depends upon the wavelength (λ_p) corresponding velocity c_w (wave-like) at the time of when light incident from free space. As rest mass of photon within the medium is imaginary [34], here we have considered the wave-like velocity of photon c_w for calculating m_0' which is obtained as follows.

$m_0' = m'(\lambda_p)\sqrt{1 - {c^2w}/{c^2}}$, where $m'(\lambda_p)$is the relativistic mass of the photon.

$$\begin{aligned} \therefore m_0' &= \frac{m'(\lambda_p)}{c}\sqrt{-1(c_w^2 - c^2)} \\ &= i\frac{m'(\lambda_p)}{c}\sqrt{c_w^2 - c^2} \end{aligned}$$

substituting the value of c_w from Eq. (5) we get

$$\begin{aligned} &= i\frac{m'(\lambda_p)}{c}\sqrt{\frac{E_p^2}{m_0^2c_p^2} - c^2} \\ &= i\frac{m'(\lambda_p)}{c}c\sqrt{\frac{E_p^2}{m_0^2c_p^2c^2} - 1} \\ &= im'(\lambda_p)\sqrt{\frac{E_p^2}{E_g^2} - 1}, \end{aligned}$$

where $E_g = m_0c_pc$. So,

$$m_0' = im'(\lambda_p)\sqrt{E_i^2 - 1}, \tag{10}$$

where $E_i = E_p/E_g > 1$ as $c_w > c$. By substituting Eqs. (9) and (10) in Eq. (8), we get

$$m_2 = im'(\lambda_p)\sqrt{E_i^2 - 1}\,g^{\mu\nu}R_{\mu\nu} \tag{11}$$

Now substituting Eq. (11), Eqs. (9) and (7) in Eq. (6) gives

$$\mathbf{m} = m(\lambda)\sqrt{1 - \frac{v_{ph}^2}{c^2}} + im'(\lambda_p)I^n\sqrt{E_i^2 - 1}$$

$$\mathbf{m} = m_x + im_y, \tag{12}$$

where $m_x = m(\lambda)\sqrt{1 - (v_{ph}^2/c^2)}$ and $m_y = m'(\lambda_p)I^n\sqrt{E_i^2 - 1}$ and in free space $R_{\mu\nu} = 0$ then $I^n = 0$ and hence $\mathbf{m} = m_x$ only. Hence

$$m_0(\lambda) = m(\lambda)\sqrt{1 - (v_{ph}^2/c^2)}$$

$$\Rightarrow m(\lambda) = \frac{m_0}{\sqrt{1 - (v_{ph}^2/c^2)}}$$

This is the relativistic mass equation of moving photon (particle form) in free space. It can morph to light (wave form) posing with zero rest mass, *vice versa* light wave can morph to photon (particle form) [11–13]. The rest mass depends upon the wavelength in free space and photon (particle) when comes in contact with the surface of matter, shows *complex rest mass* which depends up on the wavelength as well as scalar curvature of the surface and can be manifested as imaginary rest mass within the medium (dispersive) [34].

Discussion

Due to wave-particle duality of light wave, it makes itself illusive mass when it comes in close contact with matter. Because of wave-particle duality, photon rest mass and wave-like velocity of photon (phase velocity) are correlated. Here 'illusion' does not mean it is not the truth but it appears as something else. In case of light, sometimes manifested as mass-less, sometimes wavelength-dependent real mass; sometimes imaginary; sometimes inversely wavelength dependent when velocity is constant. But we don't know why light wave shows these various *incarnation*…indeed due to *mass illusion*. Mathematically, we represented 'illusion' as a complex number. That's why we realize wave-velocity of photon (phase-velocity) does not carry any information [21,22]. Simultaneously coexisting wave nature and particle nature of light with continuous alternation between wave and particle form (morphing) [11,12]. This statement is true but without morphing, photon does not show wave-like and particle-like behaviours simultaneously i.e. complementary principle is also true. So there is no disagreement between these two statements. Photon appears to us whatever we want to realize it as a wave or as a particle or both; so it comes to us as per our desire because of its *pliable* character, due to this character photon show wave-particle duality. We hope this theoretical enlightenment about photon *illusive mass* will be experimentally verified in coming future and it will bring renaissance in the secure information communication.

Conclusions

Photon itself reveals illusion posing with mass on the surface of matter because of wave-particle duality. Illusive mass depends upon the scalar curvature of the surface of matter and wavelength of the photon. The wave-particle duality of light, coexistence of wave and particle nature through morphing due to *pliable* character of light wave have been discussed. Our theoretical framework on the photon's illusive mass will open up new avenues in quantum information processing. The conception of considering imaginary mass and its physical realization requires more work to be done in collaboration with the theoretical physicists to unravel some of its practical implications. Our work shows some new directions for further research in the areas of theoretical physics where the rest mass of photon becomes imaginary. With this new analysis, the subject of considering imaginary mass will witness the possible openings of several new avenues of research. They may open up problems in theoretical and computational physics and hence its practical implications.

CRediT authorship contribution statement

Mahendra Goray: Writing - original draft. **Ramesh Naidu Annavarapu:** Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

One of the author M.G wants to acknowledge CSIR-UGC for providing scholarship.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttps://doi.org/10.1016/j.rinp.2019.102866.

References

[1] De Broglie L. Recherches sur la théorie des quanta [Ph.D. thesis]. Migration-université en cours d'affectation; 1924.
[2] Pauli W. General principles of quantum mechanics. pub 1980.
[3] Leighton R, Sands M. Lecture on physics vol. iii. 1965.
[4] MacKinnon E. De broglie's thesis: a critical retrospective. Am J Phys 1976;44(11):1047–55.
[5] Rab AS, Polino E, Man Z-X, An NB, Xia Y-J, Spagnolo N, Franco RL, Sciarrino F. Entanglement of photons in their dual waveparticle nature. Nat Commun 2017;8(1):915.
[6] Ionicioiu R, Terno DR. Proposal for a quantum delayed-choice experiment. Phys Rev Lett 2011;107(23):230406.
[7] Roy SS, Shukla A, Mahesh T. Nmr implementation of a quantum delayed-choice experiment. Phys Rev A 2012;85(2):022109.
[8] Weinstein G. The 1905 relativity paper and thelight quantum. arXiv:1307.2132; 2013.
[9] Tan C. Non-separable wave particle in space–time. Optik 2015;126(20):2640–2.
[10] Shadbolt P, Mathews JC, Laing A, O'brien JL. Testing foundations of quantum mechanics with photons. Nat Phys 2014;10(4):278.
[11] Wang LJ, Kuzmich A, Dogariu A. Gain-assisted superluminal light propagation. Nature 2000;406(6793):277.
[12] Mugnai D, Ranfagni A, Ruggeri R. Observation of superluminal behaviors in wave propagation. Phys Rev Lett 2000;84(21):4830.
[13] Schaefer BE. Severe limits on variations of the speed of light with frequency. Phys Rev Lett 1999;82(25):4964.
[14] Giovannini D, Romero J, Potocek V, Ferenczi G, Speirits F, Barnett SM, Faccio D, Padgett MJ. Spatially structured photons that travel in free space slower than the speed of light. Science 2015;347(6224):857–60.
[15] Fisher D, Tajima T. Superluminous laser pulse in an active medium. Phys Rev Lett 1993;71(26):4338.
[16] Basov N, Ambartsumyan R, Zuev V, Kryukov P, Letokhov V. Nonlinear amplification of light pulses. Sov Phys JETP 1966;23(1):16–22.
[17] Chu S, Wong S. Linear pulse propagation in an absorbing medium. Phys Rev Lett 1982;48(11):738.
[18] Liberati S, Sonego S, Visser M. Faster-than-c signals, special relativity, and causality. Ann Phys 2002;298(1):16–185.
[19] Tanaka S. Theory of matter with super light velocity. Prog Theor Phys 1960;24(1):171–200.
[20] Bludman SA, Ruderman M. Possibility of the speed of sound exceeding the speed of light in ultradense matter. Phys Rev 1968;170(5):1176.
[21] Kuila S. Perspective of quantum mechanics; 2008.
[22] Grant WPIS. Electromagnetism; 1980.
[23] Lakes R. Experimental limits on the photon mass and cosmic magnetic vector potential. Phys Rev Lett 1998;80(9):1826.
[24] Goldhaber AS, Nieto MM. New geomagnetic limit on the mass of the photon. Phys Rev Lett 1968;21(8):567.
[25] Franken P, Ampulski G. Photon rest mass. Phys Rev Lett 1971;26(2):115.
[26] Ryutov D. Using plasma physics to weigh the photon. Plasma Phys Control Fusion 2007;49(12B):B429.
[27] Ryutov D. Relating the proca photon mass and cosmic vector potential via solar wind. Phys Rev Lett 2009;103(20):201803.
[28] Bonetti L, Ellis J, Mavromatos NE, Sakharov AS, SarkisyanGrinbaum EK, Spallicci AD. Photon mass limits from fast radio bursts. Phys Lett B 2016;757:548–52.
[29] Bonetti L, Ellis J, Mavromatos NE, Sakharov AS, SarkisyanGrinbaum EK, Spallicci AD. Frb 121102 casts new light on the photon mass. Phys Lett B 2017;768:326–9.
[30] Tan C. Mass change of dielectric media induced by propagation of electromagnetic waves. Optik 2012;123(21):1952–4.
[31] Grado-Caffaro M, Grado-Caffaro M. Photon rest-mass and velocity versus wavelength. Optik 2013;124(16):2549–50.
[32] Grado-Caffaro M, Grado-Caffaro M. An ultrarelativistic approach to derive the photon rest-mass as a function of wavelength. Optik 2010;121(2):214–5.
[33] Grado-Caffaro M, Grado-Caffaro M. Theoretical determination of the photon rest-mass. Optik 2003;114(3):142–3.
[34] Tan C. Imaginary rest mass of a photon in a dispersive medium. Optik 2015;126(24):5304–6.
[35] Grado-Caffaro M, Grado-Caffaro M. A brief quantitative approach to determine the wavelength of photons as ultrarelativistic quantum particles. Optik 2012;123(9):816–7.

[36] Grado-Caffaro M, Grado-Caffaro M. On the wavelength dependence of the refractive index of photons. Optik 2001;112(5):221–2.
[37] Grado-Caffaro M, Grado-Caffaro M. Photon mass and negative index of refraction. Optik 2007;118(7):353–4.
[38] Sotiriou TP. The viability of theories with matter coupled to the ricci scalar. Phys Lett B 2008;664(4–5):225–8.
[39] Puri SP. General theory of relativity. India: Pearson Education; 2013.
[40] Loveridge LC. Physical and geometric interpretations of the Riemann tensor, ricci tensor, and scalar curvature. arXiv preprint gr-qc/0401099; 2004.