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# Can a Free Electron Absorb a Photon?

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## Abstract

Contemporary physics holds that it is not possible for an electron to absorb a photon or to form a composite system as the resulting physics thereof leads to a scenario that can not be obtained in reality—*i.e.*, it leads to a situation that requires the electron's rest mass to be identically equal to zero. This position that a free electron cannot absorb a photon is correct if the photon is assumed to have an identically vanishing mass as is the case in contemporary physics. We herein argue otherwise—that an electron can indeed absorb a photon and this is on the *proviso* that the photon in question has a nonzero mass and obeys a specific dispersion relation. Further, we find that the electron can absorb a massive photon only with a frequency below the threshold determined by the photon mass and that of the electron.

## Keywords

Afterglow Emission, Gamma-Ray Bursts, Photon Mass, Plasma, Time-Lag, Time-Delay

## 1. Introduction

A simple and straightforward argument can be made within the domains and bounds of contemporary physics wherein it can be demonstrated that it should *in principle* be impossible for an electron to absorb a photon as this would require un-physical conditions in order for this to be realised. We will present this argument in Section 2. The reason this argument is true is because the photon is assumed to have a vanishing mass.

If the almost universally accepted assumption of a vanishing photon mass is dropped, one can demonstrate the contrary—namely that, an electron can indeed absorb a photon—*albeit*, one with a nonzero mass. We will present this argument in Section 3. Having presented our argument therein Section 3, we will proceed in Section 4 to seek recourse with observations and experimentation, namely, the observational status of this idea and the testability of this idea in the laboratory.

One may very well be tempted to ask the natural question: *Why bother presenting such a simple and almost trivial idea in a conventional journal*? There are two main reasons and these are:

1) In contemporary physics, the idea of an electron absorbing a photon has only been considered using a zero-mass photon and not with a massive photon. The result obtained with a massive photon upends the entrenched contemporary view, hence, the need to communicate this alternative result.

2) The second and real reason for us embarking on this exercise is that, we are currently working (see Refs.: [1]-[3], hereafter: Paper (I), (II), *&* (III), respectively) on a massive photon model of time delays in Gamma-Ray Bursts (GRBs), and in this model, it is assumed that as the photon moves through the Interstellar Medium (ISM) which is composed of a rarefied plasma, it interacts with the *in-situ* electrons thereof, in which process it absorbs an electron. It is this absorption of the electron by the photon that leads to the modification of its speed—*making it partially dependent on the inverse of the frequency of the photon*—thus, leading to photons of different frequencies having different speeds—hence, the observed time delay in the arrival of photons of different frequency from GRBs. These photons from these GRBs are assumed to be emitted simultaneously from the GRB events. Hence, it is expected that they should arrive at the telescope simultaneously if their speed is to be independent of their frequency.

Having presented our reasons to justify this research note, we now proceed to execute our promise of demonstrating that it should *in principle* be possible for a photon (*albeit*, a massive one) to be absorbed by an *in-situ* electron in a rarefied plasma medium leading to a frequency dependent speed of Light. In Section 2 and Section 3, we present the contemporary argument on massless and massive photons regarding their absorption by a free electron. In Section 4, we justify our argument with respect to observations. In Section 5, we present—*in brief*—the massive photon theory. Lastly, in Section 6 and Section 7, we present a general discussion and the conclusion drawn thereof — respectively.

## 2. Scenario of a Massless Photon

Let us consider the interaction of a photon with an electron that is at rest in the observer's frame of reference. Let the energy of the photon, $E_\gamma$, be: $E_\gamma = h\nu$, where: $h = 6.62607015\times10^{-34}\ \mathrm{J\cdot Hz^{-1}}$ (CODATA, 2022), is Planck's constant and: $\nu$, is the frequency of the photon. Further, let the rest mass energy, $E_0^{\mathrm{e}}$ of the electron be: $E_0^{\mathrm{e}} = m_{\mathrm{e}}c_0^2$, where: $m_{\mathrm{e}} = 9.1093837139(28)\times10^{-31}\ \mathrm{kg}$ (CODATA, 2022), is the rest mass of the electron, and: $c_0 = 2.99792458\times10^{8}\ \mathrm{m\cdot s^{-1}}$, is the speed of Light in *vacuo*. Throughout this reading: $c$, shall denote the speed of Light in a non-*vacuo* medium, while: $c_0$, shall denote the speed of Light in *vacuo*, so that: $c = c_0/n_r$, where: $n_r$, is the refractive index of the said non-*vacuo* medium. The non-*vacuo* medium in the present reading is the rarefied plasma medium.

Now, these two particle systems will interact in such a way that the photon will collide with the *in-situ* electron in which event they will form a composite unit system. Taking this as given, clearly, the photon will approach the electron in a straight line along its direction of motion. We know that the total energy of this system before coalescence is: $h\nu + m_e c_0^2$, and, (b) that the momentum of the photon is: $p_\gamma = h\nu / c_0$, while that of the electron is zero. Therefore, the total energy and momentum of this system before the interaction is: $h\nu + m_e c_0^2$, and, $h\nu / c_0$, respectively.

The two particles now proceed to collide and coalesce into a composite system. The question is: *Can these two particle systems coalesce to form a single entity*? Said differently: can the free electron absorb the photon to form one conglomerate unit system? Contemporary physics says this scenario is not feasible as this could require that the electron's rest mass be zero and this is something that does not obtain in reality, hence the imagined scenario is not possible.

To see this, let us now consider the system after they have coalesced into a single unit system. According to Einstein [4]'s energy-momentum dispersion relation, the total energy, $E_e$, of the electron after coalescence is related to the electron's momentum, $p_e$, and rest energy ($m_e c_0^2$) by the relation: $E_e = \sqrt{p_e^2 c_0^2 + m_e^2 c_0^4}$. The *Law of Conservation of Energy* (LCE) requires that the energy ($h\nu + m_e c_0^2$) of the entire system before coalescence, must equal to energy ($E_e$) of the system after coalescence—*i.e.*:

$$E_e = h\nu + m_e c_0^2. \tag{1}$$

Given: $E_e = \sqrt{p_e^2 c_0^2 + m_e^2 c_0^4}$, it follows that:

$$p_e^2 c_0^2 + m_e^2 c_0^4 = \left(h\nu + m_e c_0^2\right)^2. \tag{2}$$

The *Law of Conservation Momentum* (LCM) requires that the momentum of the photon before coalescing: $h\nu / c_0$, must equal to the momentum, $p_e$, of the coalescent—*i.e.*:

$$p_e = \frac{h\nu}{c_0}. \tag{3}$$

Inserting this into Equation (2), we will have:

$$h^2\nu^2 + m_e^2 c_0^4 = \left(h\nu + m_e c_0^2\right)^2, \tag{4}$$

which expands to:

$$h^2\nu^2 + m_e^2 c_0^4 = h^2\nu^2 + 2h\nu m_e c_0^2 + m_e^2 c_0^4, \tag{5}$$

resulting in:

$$\nu m_e = 0. \tag{6}$$

Since: $\nu \neq 0$, the only way Equation (6) can hold true is if: $m_e = 0$. This contradicts the known fact that the electron mass is not zero. The only reasonable conclusion that can be drawn from this simple and instructive analysis is that this kind of interaction of the electron and photon is not possible, hence "*a free electron cannot possibly absorb a photon*." In the next section, let us consider the hypothetical scenario of a massive photon.

## 3. Scenario of a Massive Photon

Now—under the same scenario as described in the case of a massless photon, let us consider a massive photon whose dispersion relation is given by:

$$E_\gamma = p_\gamma c + m_\gamma c^2 = h\nu, \tag{7}$$

where: $m_\gamma c^2$, is the (rest) mass of the photon in the non-*vacuo* medium that it finds itself in. We shall present further justification of our photon model [*i.e.*, Equation (7)] in Section 5. For now, we ask for the reader's due indulgence in the form of acceptance of this dispersion relation Equation (7) as the dispersion relation describing the proposed hypothetical massive photon.

Under these assumptions, we now present an analysis similar to the one presented above for the case of a massless photon. For the momentum conservation — the momentum of the composite system must be the same as momentum of the photon before being absorbed by the electron. Taking from the previous analysis, this leads to Equation (2) changing to:

$$p_\gamma^2 c^2 + m_e^2 c^4 = \left(h\nu + m_e c^2\right)^2, \tag{8}$$

From Equation (7), we have that: $p_\gamma c = h\nu - m_\gamma c^2$, and from this it follows that Equation (8), will become:

$$\left(h\nu - m_\gamma c^2\right)^2 + m_e^2 c^4 = \left(h\nu + m_e c^2\right)^2. \tag{9}$$

which expands to:

$$h^2\nu^2 - 2h\nu m_\gamma c^2 + m_\gamma^2 c^4 + m_e^2 c^4 = h^2\nu^2 + 2h\nu m_e c^2 + m_e^2 c^4, \tag{10}$$

thus leading to the following falsifiable relation:

$$\nu\left(m_\gamma + m_e\right) = \frac{m_\gamma^2 c^2}{2h}. \tag{11}$$

Using the relation: $c = c_0/n_r$, Equation (11), can be written as follows:

$$\nu\left(m_\gamma + m_e\right) = \frac{m_\gamma^2 c_0^2}{2n_r^2 h}, \tag{12}$$

As long as this relationship is physically permissible, an electron can absorb a photon. In the next section, we shall now try to address the question of the predictions that follow directly from Equation (12), *i.e.*, whether or not these conform with physical reality.

## 4. Recourse to Physical Reality

From Equation (12), assuming: $m_\gamma$, and, $m_e$, are constants, it follows that:

$$n_r = \sqrt{\frac{m_\gamma^2 c_0^2 / 2h\left(m_\gamma + m_e\right)}{\nu}} = \sqrt{\frac{\nu_\star}{\nu}}, \tag{13}$$

where: $\nu_\star = m_\gamma^2 c_0^2 / 2h\left(m_\gamma + m_e\right)$, is a constant since: $m_\gamma$, and, $m_e$, are constants. Just as we did in Paper (I), we can compute the time delay that arises from such a refractive index.

To that end, let: $\mathcal{D}_{LT}$, be the Light travel distance to our GRB event of interest. Further—let, $\nu_L$ and $\nu_H$, be the low and high frequencies of the two $\gamma$-rays that come racing to our telescope. The speeds: $c_L$, and, $c_H$, of these two (low and high frequency) photons is such that: $c_L = c_0/n_L$, and, $c_H = c_0/n_H$, respectively, where: $n_L$, and $n_H$ are the refractive indices experienced by the low and high frequency photons, respectively. The times: $t_L$ and $t_H$, it will take these $\gamma$-rays to arrive at Earth is: $t_L = \mathcal{D}_{LT}/c_L = n_L \mathcal{D}_{LT}/c_0$, and, $t_H = \mathcal{D}_{LT}/c_H = n_H \mathcal{D}_{LT}/c_0$, respectively. From this, it is clear that the time delay: $\Delta t = t_L - t_H$, will be given by:

$$\Delta t = \frac{\mathcal{D}_{LT}\sqrt{\nu_\star}}{c_0}\left(\frac{1}{\sqrt{\nu_L}} - \frac{1}{\sqrt{\nu_H}}\right). \tag{14}$$

Clearly and without an *iota or dot* of doubt, from the work [*i.e.*, Paper (I), (II) & (III)] that we have carried out thus far, this prediction runs contra-variant to physical and natural reality as we know it. In order to improve on this, we realise that we can salvage the situation by revisiting the basic assumption here made of the constancy of: $m_\gamma$, and, $m_e$.

To that end, we shall make the hypothesis that under the envisaged interaction of the electron and photon particles systems, the electron and photon rest masses are related as follows:

$$m_e = \zeta_\nu m_\gamma, \tag{15}$$

where: $\zeta_\nu$, is a function of the photon frequency $\nu$, *i.e.*: $\zeta_\nu = \zeta_\nu(\nu)$. Inserting this into Equation (12), one obtains:

$$\nu\left(1 + \zeta_\nu\right) = \frac{m_\gamma c_0^2}{2n_r^2 h}, \tag{16}$$

Further, we shall assume that the mass, $m_\gamma$, of the photon in a *non-vacuo*, will be different from that in a *vacuo*—let the *vacuo* photon mass be denoted by the symbol: $m_{0\gamma}$, and this mass is a fundamental and natural constant. Let these two masses $\left(m_\gamma, m_{0\gamma}\right)$ be related by the following relation:

$$m_\gamma = \eta m_{0\gamma}, \tag{17}$$

where: $\eta$, is a function that we shall assume to depend on the refractive index of the medium in question—*i.e.*, $\eta = \eta(n_r)$. Clearly—*by definition thereof*—in a *vacuo* where: $n_r = 1$, we will have: $\eta = 1$, and this constraint is a *sine qua non* boundary condition.

Now, inserting into Equation (16), $m_\gamma$ as it is given in Equation (17), we will have:

$$\nu\left(1 + \zeta_\nu\right) = \frac{\eta m_{0\gamma} c_0^2}{2n_r^2 h} = \frac{\eta \nu_{max}}{n_r^2}, \tag{18}$$

where we have '*judiciously*' set: $\nu_{\max} = m_{0\gamma} c_0^2 / 2h$. We say '*judiciously*' because (soon) this frequency shall turn out to be the maximum possible frequency of a massive photon that is permitted by this model in the case of a positive mass ($m_0 > 0$) photon. This is the reason for the insertion of the subscript 'max' in $\nu_{\max}$.

Proceeding — we can re-write this Equation (18), as follows:

$$\eta = n_r^2 \left(1 + \zeta_\nu\right) \left(\frac{\nu}{\nu_{\max}}\right). \tag{19}$$

This Equation (18) must hold not only for all frequencies $\nu$, but all refractive indices $n_r$, as-well and in *vacuo* where by definition: $\eta = 1$, whenever: $n_r = 1$. From this constraint (boundary condition), it thus follows that:

$$\zeta_\nu = \frac{\nu_{\max}}{\nu} - 1, \tag{20}$$

hence:

$$\eta = n_r^2. \tag{21}$$

As long as Equations (20) *&* (21) hold true, not only will an electron be able to absorb a photon to form a single entity—*in addition to this*, these massive photons should be able to travel through space in a manner suggested in our on-going work [*i.e.*, Paper (I), (II) *&* (III)].

In summary, Equations (20) *&* (21) imply that the masses: $m_\gamma$ and $m_e$, of the photon and electron are thus related to the refractive index: $n_r$, and the photon *vacuo* mass: $m_{0\gamma}$, as follows:

$$m_\gamma = n_r^2 m_{0\gamma}, \tag{22}$$

$$m_e = n_r^2 \left(\frac{\nu_{\max}}{\nu} - 1\right) m_{0\gamma}. \tag{23}$$

If Equations (22) and (23) are to hold true, so will our model being pursued in Papers (I), (II) *&* (III).

In closing this section, we must take notice that from Equations (15) and (20), it follows that for a positive mass photon: $m_{0\gamma} > 0$, we must have: $\zeta_\nu > 0$, hence:

$$\nu < \nu_{\max}, \tag{24}$$

thus, there sure will be a maximum permissible massive photon frequency for which this massive photon absorption by the electron can occur.

## 5. Massive Photon Theory

The massive photon model on which our present work is based has been presented in Ref. [5] where we have argued that massive photons should in principle be possible provided the rest mass, $m_0$, in Einstein [4]'s Special Theory of Relativity is modified such that it is not a constant scalar for a given particle system system but has been made a variable scalar that depends on momentum. That is to say—it [Einsteinian rest mass, $m_0$] is replaced by a new mass, $m_E$, that we have coined the name—*Einstein Mass*, and this mass is momentum dependent [*i.e.*: $m_E = m_E(p)$].

Under this hypothesis, the relativistic energy-momentum dispersion relation: $E^2 = p^2c_0^2 + m_0^2c_0^4$, changes to: $E^2 = p^2c_0^2 + m_E^2c_0^4$. In this new setting, the momentum and energy of any given particle system is now given by: $\boldsymbol{p} = m_E\boldsymbol{v}\big/\sqrt{1-v^2/c_0^2}$, and, $E = m_Ec_0^2\big/\sqrt{1-v^2/c_0^2}$, respectively, and not: $\boldsymbol{p} = m_0\boldsymbol{v}\big/\sqrt{1-v^2/c_0^2}$, and, $E = m_0c_0^2\big/\sqrt{1-v^2/c_0^2}$, respectively, as is the case in Einstein [4]'s STR. At a *prima facie* level of analysis, this appears more or less like a relabelling of the rest mass by way of replacing the '0' with '$E$'; this is not the case.

It is important to understand the difference between: $E^2 = p^2c_0^2 + m_0^2c_0^4$, and: $E^2 = p^2c_0^2 + m_E^2c_0^4$. In the former: $m_0$, is a constant for a given particle system, while in the latter: $m_E$, is not, it is a function of momentum—*i.e.*: $m_E = m_E(p)$. Equipped with the fore-knowledge that the group velocity $v_g$, is such that: $v_g = \partial E/\partial p$; the difference in: $m_0$ and $m_E$, is readily appreciated if one where to differentiate this equation: $E^2 = p^2c_0^2 + m_E^2c_0^4$, twice with respect to momentum—so doing, one obtains: $2\left(\partial v_g/\partial p\right)E + 2v_g^2 = 2c_0^2 + \partial^2\left[m_E^2(p)c_0^4\right]\big/\partial p^2$, and after dividing throughout by $2c_0^2$, and assuming that: $\partial v_g/\partial p = 0$, they could obtain:

$$\frac{v_g^2}{c_0^2} = 1 + \frac{1}{2}\frac{\partial^2\left[m_E^2(p)c_0^2\right]}{\partial p^2}. \tag{25}$$

From this simple looking equation, it is crystal clear that three scenarios will arise and these are:

$$\frac{\partial^2\left[m_E^2(p)c_0^2\right]}{\partial p^2} := \begin{cases} >0 & \Rightarrow \ (v_g > c_0) \quad \text{Case (I)} \\ <0 & \Rightarrow \ (v_g < c_0) \quad \text{Case (II)} \\ =0 & \Rightarrow \ (v_g = c_0) \quad \text{Case (III)} \end{cases} \tag{26}$$

In Case (I), we have faster than Light (superluminal) massive particles, while in Case (II), we have the usual subluminal massive particles and in the third case, we have massive particles that travel at the speed of Light: $v_g = c_0$. From: $\partial^2\left[m_E^2(p)c_0^2\right]\big/\partial p^2 = 0$, the Einstein mass of such a particle system is given by:

$$m_E^2 = m_{0\gamma}^2\left[1 + 2\left(\frac{p}{m_{0\gamma}c_0}\right)\right]. \tag{27}$$

The assumption: $m_E = m_E(p)$, pretty much allows us to obtain massive photons that travel at the speed of Light provided the condition Equation (27) holds true—against this backdrop, in contemporary physics, a massive photon is expected to violate five main cardinals—the: (a) Lifetime Problem (b) Range Problem (c) Vacuo Speed Problem (d) Degrees of Freedom Problem and lastly (e) Gauge Invariance Problem. These problems will briefly be explained shortly. If the proposed massive photon theory is to be acceptable—*at a bare minimum*—it must overcome these five problems. Indeed, the theory does overcome these five cardinal problems. While pointing at the references where these issues have been tackled, we shall briefly say something to that effect:

1) **Short Life Problem:** In contemporary physics, a massive photon is believed to be shortlived and this is as a result of a Yukawa-term [6] in the architecture of its wavefunction and this leads to the massive photon to be short lived. In the present model, this is solved by the introduction of *Special Gauge Condition* (see Ref. [5]).

2) **Short Range Problem:** Further—in contemporary physics, a massive photon is believed to not be able to travel long distances such as intergalactic space because of the short life of the photon stated above. Just as is the case with the short-life-problem, this short-range-problem of the massive photon is solved by the same introduction of *Special Gauge Condition* (see Ref. [5]) stated above.

3) **Vacuo Speed Problem:** Furthermore—in contemporary physics, a massive photon is believed to travel not at the expected speed of Light $c_0$ but a speed less than this. In the present model, as already demonstrated above, this is solved by the momentum dependent Einstein mass assumption: $m_E = m_E(p)$.

4) **Degrees of Freedom Problem:** In addition to the above three problems, contemporary physics holds true that a massive photon will have an *extra* degree of freedom (2 transverse modes and 1 longitudinal mode (*see e.g.* Refs. [7]-[12])—whereas, a massless photon has 1 transverse mode and 1 longitudinal mode) and this degree of freedom will add to the total energy of the photon and must manifest in the Planck radiation Law (*e.g.*, [8] [12] [13]). This arises because when one goes into the Lorentz frame in which the photon is at rest, ($\boldsymbol{k} = 0$), one will see that there must be three independent polarization directions for a massive photon, since the plane transverse to $\boldsymbol{k}$ is undefined in this frame ($\boldsymbol{k}$ is the usual wavevector). The arguments fail for a massless photon since it can never have, $\boldsymbol{k} = 0$. In the present, since the massive always travels at the *vacuo* speed of Light $c_0$, it does not have the rest-state, hence, like a massless photon, it has no rest state, hence this problem does not apply to massive photon described in the present massive photon model.

5) **Gauge Violation Problem:** A nonzero photon mass term in Quantum Electrodynamics (QED) would break the highly regarded sacrosanct *Gauge Invariance Principle*, and this gauge invariance violation may very well spoil the renormalizability of the resulting massive QED theory, thus rendering the theory quantum-mechanically inconsistent [14] [15].

We must say that—in Ref. [5], all these paramount issues are adequately resolved leading to a long ranged, long lived and gauge invariant massive photon that travels in a *vacuo* at the *vacuo* speed of Light $c_0$, thus setting the strong foundations and seamless stage for us to further explore these hypothetical massive photons.

## 6. General Discussion

We have, within the realms of contemporary physics, shown that an electron cannot absorb a photon as it leads to a condition where the electron mass must be identically equal to zero. Contrary to this well established position, we have herein argued otherwise—that an electron can indeed absorb a photon and this is on the *proviso* that the photon in question has a nonzero mass. Further, we find that the electron can absorb a massive photon only with a frequency below the threshold determined by the photon mass and that of the electron. Most importantly, this electron-photon absorption will occur for any medium of whatever refractive index.

Clearly, our massive photon model discussed here opens up a plethora of possibilities of interesting research in Physics. As for our Gamma Ray Time Delay Model [presented in: Paper (I), (II) *&* (III)] which is currently under investigation, what this means is that, we can safely continue our exploration without the constraint and handicap that a photon is incapable of being absorbed by an electron.

## 7. Conclusions

Based on our model presented here, we can safely say that—*in principle*:

1) It should be possible for a massive photon governed by the dispersion relation: $E_\gamma = p_\gamma c + m_\gamma c^2$, to be wholly absorbed by an electron to form one conglomerate unit system.

2) The union of the electron and photon herein suggested leads to the alteration of the speed of Light as it traverses the vast cosmic expanse. This alteration of the speed of Light leads to the speed of Light having a partial inverse frequency dependence. This results in the lower frequency photons propagating at lower speeds than their higher frequency counterparts, hence the observed time delays.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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