Massive Long Range Photons and the Variation of the Fine Structure Constant

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Abstract. Prevailing and conventional wisdom holds that intermediate gauge Bosons for long range interactions such as the gravitational and electromagnetic interactions must be massless as is assumed to be the case for the photon which mediates the electromagnetic interaction. We have argued in Nyambuya (2013) that it should *in-principle* be possible to have massive photons. The problem of whether or not these photons will lead to short or long range interactions has not been answered. Naturally, because these photons are massive, one would without much pondering and excogitation on the matter assume that these photons can only take part in short range interactions. Contrary to this and to conventional wisdom; *via* a subtlety, we show within the confines of Proca Electrodynamics, that massive photons should be able to take part in long range interactions without any problem. While leaving the speed of light as an invariant fundamental constant, the resulting theory leads to a time variation in the Fundamental Constants *of* Nature, namely the permittivity (ε_0) and permeability (μ_0) of free space. In-turn, this leads to a plausible explanation as to why the fine structure constant strongly appears to be varying over cosmological times.

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1 Introduction

Despite the lack of solid experimental proof (see *e.g.* Hojman & Benjamin 2012, Burman 1972a,2,3, Goldhaber & Nieto 1971), it is generally agreed (perhaps believed) that photons have no mass. Though this notion of a zero-mass photon has been questioned over the years (see *e.g.* Nakamura 2010, Tu et al. 2005, Weinberg 1972), this deeply entrenched fact has been deduced from two (seemingly) immutable facts of experience so well supported by experimental evidence. The first is Professor Albert Einstein (1905b)'s energy-momentum dispersion relation, namely:

$$E^2 = p^2c^2 + m_0^2c^4, \tag{1}$$

where E is the total energy of the particle, $p = |\boldsymbol{p}|$ is this particle's momentum, m_0 is this same particle's rest mass and $c = 2.99792458 \times 10^8 \text{ ms}^{-1}$ is the speed of light in vacuum[1]. The

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[1]Here and after, all the fundamental constants of *Nature* are adapted from Mohr & Taylor (2010) exactly as they are given therein;.

second fact is that the energy of the photon has been found from experience to be given by:

$$E = pc. \tag{2}$$

If (1) and (2) are both applicable to the photon with all the identical symbols holding the same meaning, then, it follows directly that $m_0 = 0$; that is, the rest mass of the photon must be zero. This is generalised and stated by saying a photon has no mass. It is thus accepted that if a particle has zero rest mass, it will travel at the speed of light. Conversely, if a particle travels at the speed of light, its rest mass must vanish identically. Herein, we place the two dispersion relations (1) and (2) into the dock for some *cross-examination*, where-after we come to the interesting conclusion that it must *in-principle* be possible to have massive photons (*i.e.* non-zero rest mass photons) obeying these two relations simultaneously and concurrently *i.e.*, massive particles that travel at the speed of light c.

The hidden assumption in all the reasoning leading to the fact that for photons $m_i = 0$, is that the energies (E) in the formulae $E^2 = p^2c^2 + m_0^2c^4$ and $E = pc$ are identical. On a more fundamental level, there is no *priori* nor *posteriori* justification for this clandestine assumption. If these two energies are different, that is, say the E in $E^2 = p^2c^2 + m_0^2c^4$ is the total gravitational energy $E_{\rm g}$ of the photon so that $E_{\rm g}^2 = p^2c^2 + m_0^2c^4$; and the E in $E = pc$ is say total kinetic energy $E_{\rm K}$ of the photon so that $E_{\rm K} = pc$, then, it is possible for $m_i \neq 0$. Combining these (*i.e.*, $E_{\rm g}^2 = p^2c^2 + m_0^2c^4$ and $E_{\rm K} = pc$) would lead to $E_{\rm g}^2 = E_{\rm K}^2 + m_0^2c^4$ where generally $m_0 \neq 0$.

The idea of a zero-mass particle usually presents a challenge to freshman students encountering this for the first time (Robles & Claro 2012) because, mass is generally thought to be the measure of the amount of matter in a substance. Based on this kind of thinking, zero-mass must mean no amount of matter present yet for the photon whose mass is zero, it has not only stuff in it, but lots of it. Can a massive photon solve this problem?

Using the arguments just presented in the ante-penultimate, together with *de* Brogile's wave-particle duality hypothesis, we argue herein that it must in-principle be possible to have non-zero rest mass photons. Actually, it is suggested that all photons may very well be massive all having the mass, in the same manner that electrons (and protons) have mass. One other strong reason why photons are thought to be massless is that the Electromagnetic force is a long range force, for this to be so, the mass of the photon must be identically zero.

2 Proca Electrodynamics

As is well known, Maxwellian Electrodynamics is based on the hypothesis of a massless photon. What evidence there is for this, experience is yet to furnish us with a solid answer. As regards the quintessence of a zero-mass photon is the resulting gauge invariance of Maxwellian Electrodynamics *i.e.*, to those that seek beauty in a physical theory, one appealing feature of Maxwellian Electrodynamics is that it is constructed from a gauge invariant Lagrangian. Gauge invariance was first introduced by Herman Weyl; it plays a central role not only in field theory but in physics as a whole. However, if one abandons this, they can – as the Romanian physicist Alexandru Proca $(1897 - 1955)$ did; construct an electrodynamic theory were the photon has a non-zero mass *via* the Proca Lagrangian $\mathscr{L}$, that is:

$$\mathscr{L} = \overbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \mu_0 J_\mu A^\mu}^{\textbf{Maxwellian Terms}} \pm \overbrace{\frac{1}{2}\mu^2 A_\mu A^\mu}^{\textbf{Proca Term}}, \tag{3}$$

where A_μ is the electrodynamic four vector potential, J_μ is the four electrodynamic current, $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{kgmC^{-2}}$ is the permeability of free space, $\mu^2 > 0$ is mass term of the photon and:

$$F_{\mu\nu} = \frac{\partial A_\mu}{\partial x^\nu} - \frac{\partial A_\nu}{\partial x^\mu}, \tag{4}$$

is the electromagnetic field tensor. As usual, the Greek indices $(\mu, \nu \ldots)$ run from 0 to 3, *i.e.* $(\mu, \nu = 0, 1, 2, 3)$. The equations of motion associated with the $\mathscr{L}$ are obtained from the usual Lagrangian equation of motion:

$$\frac{\partial}{\partial x^{\nu}}\left(\frac{\partial \mathscr{L}}{\partial(\partial^{\nu} A_{\mu})}\right) - \frac{\partial \mathscr{L}}{\partial A_{\mu}} = 0, \tag{5}$$

and the resulting equation is:

$$\partial^{\mu} F_{\mu\nu} + \mu^2 A_{\nu} = -\mu_0 J_{\nu}. \tag{6}$$

By taking into account the Lorentz gauge condition $\partial^{\mu} A_{\mu} = 0$, the above equation can further be written as:

$$\Box A_{\nu} + \mu^2 A_{\nu} = \mu_0 J_{\nu}, \tag{7}$$

where:

$$\Box = \boldsymbol{\nabla}^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}, \tag{8}$$

is the usual D'Alembert operator. For simplicity, we shall assume that spatially, A_{μ} only has a radial dependence. In the static limit[2] (7) truncates to:

$$\boldsymbol{\nabla}^2 A_{\nu}(r) + \mu^2 A_{\nu}(r) = -\mu_0 J_{\nu}, \tag{9}$$

and in empty space, the electric potential $A_0(r) = \Phi_{\mathrm{em}}(r)$ is given by the Yukawa potential:

$$\Phi_{\mathrm{em}}(r) = \frac{1}{4\pi\varepsilon_0}\frac{qe^{-\mu r}}{r}. \tag{10}$$

where $\varepsilon_0 = 8.854187817 \times 10^{-12}\,\mathrm{C^2 s^2 m^{-3} kg^{-1}}$ is the permittivity of free space. As is well known, this potential can only explain short and not long range forces such as the electromagnetic force. To explain the long range interaction, $\mu = 0$, that is, the mass of the photon with mediate the electromagnetic force, must vanish identically. This is one of the strongest reasons for assuming that the photon mass must be zero. What is we can show that within the framework of the same theory just laid down above, one can obtain the long range Coulomb potential for a non-vanishing photon mass? Would the above reason for assuming a non-zero photon mass still hold? We think not. This is what we shall do in the next section; we shall present a trivially simple condition for attaining the said.

3 Massive Long Range Photon Theory

The reasons why the photon is considered massless have been discussed in the previous sections. Of particular concern here is the fact that because the electromagnetic interaction is a long range interaction, therefore, the intermediate vector Boson – the photon; must be massless for this to be so. If we can demonstrate that even a massive photon can mediate long range interactions, will the above reason for vanishing photon mass still hold? We think not.

A deep look inside both Maxwellian and Proca Electrodynamics, one will notice that there is critical assumption made about the temporal nature of the electromagnetic field, and this assumption is that A_{μ} is static. Why? We have no answer as to why really this is the case, but to say that this assumption can be dropped in such a manner that the resulting electrodynamic equations of motion constructed from the dynamic field potential $A_{\mu}(r, t)$ have exactly the same form as Maxwellian Electrodynamics, *albeit*, with the important addition

[2] As will be demonstrated soon, this *assumption* of a *static* A_{μ} is were we believe lies the greatest shortcoming insofar as completely understanding fully the latent power of Proca Electrodynamics.

that the resulting electric and magnetic potentials are time varying and this time variation can be attributed to the time variation of the fundamental constants ε_0 and μ_0. However, this variation does not lead to the time variation in the speed light! For this to be so – *i.e.*, the above stated; the field A_μ will have to satisfy the constraint:

$$\frac{1}{c^2}\frac{\partial^2 A_\mu}{\partial t^2} = \pm \upmu^2 A_\mu. \tag{11}$$

Applying this constraint to (7), one obtains:

$$\nabla^2 A_\nu(r,t) = \mu_0 J_\nu. \tag{12}$$

In form and structure, equation (12) is exactly the same as Maxwell's static electrodynamic equations *albeit*, with the important difference being the new and subtle injection of time variation in the potentials A_μ. According to (11)

Before we proceed, let us first solve that nature of the time variation of these potentials. Let us seek natural solutions. Natural solutions of $A_\mu = A_\mu(r,t)$ will be those for which $A_\mu(r,t)$ seperable in both its variables (r,t), that is, $A_\mu = A_\mu(r)A_\mu(t)$. This assumption leads (11) to reduce to:

$$\frac{1}{c^2}\frac{\partial^2 A_\mu(t)}{\partial t^2} = \pm \upmu^2 A_\mu(t). \tag{13}$$

This equation has three solutions and these are presented in Table (I). We have introduced the English alphabet superscript index $a = (1,2,3)$ to label these three solutions. These solutions are normalized and by this we mean that $A_\mu(t=0) = 1$.

Table (I): **Solutions for Non-Static Component of** $A_\mu(r,t)$

Case	$+\upmu^2$		$-\upmu^2$
Solution	1	2	3
$A^a_\mu(t)$	$e^{+\upmu ct}$	$e^{-\upmu ct}$	$\cos(\upmu ct)$

Now, considering only the electric potential $A^a_0(r,t) = \Phi^a_{\mathrm{em}}(r,t)$ where it is understood that the a-index runs over the time varying component of the potential; then, in empty space, the spacial part of (12) is exactly the Coulomb potential $\Phi(r) = q/4\pi\varepsilon_0 r$. This means, the total potential in empty space of (12) including the time variation in the potential is given by:

$$\Phi^a_{\mathrm{em}}(r,t) = \frac{A^a_\mu(t)}{4\pi\varepsilon_0}\frac{q}{r}. \tag{14}$$

We can associate the time variation with the time variation of the fundamental physical constant ε_0 by writing:

$$\varepsilon^a_0(t) = \frac{\varepsilon_0}{A^a_\mu(t)}, \tag{15}$$

in which case (14) can now be written as:

$$\Phi^a_{\mathrm{em}}(r,t) = \frac{1}{4\pi\varepsilon^a_0(t)}\frac{q}{r}. \tag{16}$$

Since the speed of light is such that $c = 1/\sqrt{\mu_0\varepsilon_0}$, a variation in ε_0 directly leads to a time variation in the speed of light unless μ_0 also varies in such a way as to cancel this time variation. For this to be so, we must have:

1. If $\varepsilon_0(t) = \varepsilon_0 e^{+\upmu ct}$ then $\mu_0(t) = \mu_0 e^{-\upmu ct}$. For this to be so $A_\mu = e^{-\upmu ct}[A_0(r), A_j(r)]$.
2. If $\varepsilon_0(t) = \varepsilon_0 e^{-\upmu ct}$ then $\mu_0(t) = \mu_0 e^{+\upmu ct}$. For this to be so $A_\mu = e^{+\upmu ct}[A_0(r), A_j(r)]$.

3. If $\varepsilon_0(t) = \varepsilon_0 \sec(\mu ct)$ then $\mu_0(t) = \mu_0 \cos(\mu ct)$. For this to be so $A_\mu = \cos(\mu ct)\,[A_0(r), A_j(r)]$.

The potentials $A_0(r)$ and $A_j(r) : j = 1, 2, 3$ are the usual static electric and magnetic potentials of Maxwellian Electrodynamics. The solution $\varepsilon_0(t) = \varepsilon_0 \sec(\mu ct)$ and $\mu_0(t) = \mu_0 \cos(\mu ct)$ has the annoying and nagging problem of infinities because at the particular moments $t = t_n$ were $t_n = \pi/2\mu c + 2\pi n/\mu c : n = 0, 1, 2, 3, etc$, we would have $\varepsilon_0(t_n) = \infty$ and $\mu_0(t_n) = 0$. We do not rule this solution as un-physical. We strongly believe it is worthy being explored. For the time being, we would like to explore solutions that are free of the polemical infinities. Given that the Universe can only be described by one of the two Lagrangians (3), that is, for the Proca term, there is the $\pm$ case, only one of the two cases must describe the Universe. The " $+$ " case leads to the solutions with infinities $A^3_\mu(t)$ while the " $-$ " case leads to the exponential time dependent solutions $A^1_\mu(t)$ and $A^2_\mu(t)$. If we seek a Universe without the said infinities and concurrently a Universe in which the relative strength of the electromagnetic force diminishes with time, then, the Proca Lagrangian for such a Universe is:

$$\mathscr{L} = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \mu_0 J_\mu A^\mu - \frac{1}{2} \mu^2 A_\mu A^\mu. \tag{17}$$

Actually, this solution with the annoying and nagging infinities may prove vital for and to researchers that seek to understand the infinities associated with the moment of creation in the so-called Big Bang Cosmology Theory which currently is the highly favoured and preferred theory of the origins, evolution and ultimate fate of the Universe.

Undoubtedly, the constraint (13) leads to massive photons ($\mu \neq 0$) that can mediate in long range interactions in the same manner as happens in the theory of the massless photon of Maxwellian Electrodynamics. Unexpectedly and surprisingly, this constraint (13) leading to massive long range photons implies that *Nature's* supposed sacrosanct and scared fundamental constants ε_0 and μ_0 must vary with time. This opens a fresh new door to the exploration of the fundamental constants of *Nature*. Some researchers have in recent times made the *bold claim* that the fine structure constant, which is one of the most important and arcane fundamental constants of *Nature*, has changed over cosmic times. Other than polemical speculative theories (*e.g.* Barrow & Lip 2012, Barrow et al. 2002), there currently is no widely accepted fundamental theory that explains why this must be so. The present discovery, proposal or hypothesis – which undoubtedly is well within the vein, provinces, domain and confines of accepted physics; if correct, this may very well provide an acceptable fundamental theoretical basis as to why and how this comes to be that the fine structure constant appears to be varying over cosmic epochs. We shall tackle this issue of the variation in the fine structure constant in section (5). Before that, we need to say something on the efforts so far made to measure the photon mass.

4 Measurements of Photon Mass

Tu et al. (2005)'s excellent review article brilliantly touches on the many efforts that have been conducted to measure the mass of the photon. These efforts can be classified into two categories: (1) Laboratory Experiments, and (2) Large Scale Observations. In these measurements, derivations from Maxwellian Electrodynamics are sought because the addition of the Proca term invariably modifies two of Maxwell's four equations *i.e.*, the source coupled field equations. These two equations are:

$$\nabla \times \boldsymbol{E}(\boldsymbol{r}) = \varrho/\varepsilon_0 \pm \mu^2 \Phi_{\rm em}(\boldsymbol{r}), \tag{18}$$

where $\boldsymbol{E}(\boldsymbol{r})$ and $\varrho(r)$ are the electric field at the position vector $\boldsymbol{r}$ and the charge density enclosed in the sphere of radius $r = |\boldsymbol{r}|$ respectively. The second equation is:

$$\nabla \times \boldsymbol{B}(\boldsymbol{r}) = \mu_0 \boldsymbol{J}(\boldsymbol{r}) + \frac{1}{c^2} \frac{\partial \boldsymbol{E}(\boldsymbol{r})}{\partial t} \pm \mu^2 \boldsymbol{A}(\boldsymbol{r}), \tag{19}$$

where $\boldsymbol{B}(\boldsymbol{r})$, $\boldsymbol{A}(\boldsymbol{r})$ and $\boldsymbol{J}(\boldsymbol{r})$ are the magnetic field, the vector potential, and the current density, respectively. In these equations (*i.e.* 18 and 19), ε_0 and μ_0 are pure constants – this is a central clandestine assumption of Maxwellian Electrodynamics. Further, in equation (19), the displacement current which is represented by the term $\dot{\boldsymbol{E}}(\boldsymbol{r})/c^2$ is neglected in the experiments because in the kind of settings in which these experiments are done, one is dealing with static non-relativistic electric fields.

In the large scale observations, the deviations are sought from Solar and planetary magnetic fields while in laboratory experiments these deviations are sought from usual laboratory magnetic fields and electric circuits. In both the laboratory and large scale observational measurements, the mass of the photon is not measured directly but limits to the photon mass are derived. Laboratory measurements find upper limits in the range $m_\gamma \simeq (10^{-47} - 10^{-40})\,\mathrm{kg}$ while large scale measurements find $m_\gamma \simeq (10^{-47} - 10^{-40})\,\mathrm{kg}$ (Tu et al. 2005, pp.94,106).

Now, if for a massive photon the constraint (13) is to govern A_μ, then, it should not be possible to use these same experiments that seek derivations from Maxwellian Electrodynamics as has been described above because the resulting equations do not contain the necessary Proca term found in (18) and (19). The equivalent of (18) and (19) under the constraint (13) are:

$$\boldsymbol{\nabla} \times \boldsymbol{E}(\boldsymbol{r}, t) = \varrho(r)/\varepsilon_0(t), \tag{20}$$

and:

$$\boldsymbol{\nabla} \times \boldsymbol{B}(\boldsymbol{r}, t) = \mu_0(t)\boldsymbol{J}(\boldsymbol{r}) + \frac{1}{c^2}\frac{\partial \boldsymbol{E}(\boldsymbol{r}, t)}{\partial t}. \tag{21}$$

Clearly (20) and (21) contain no mass terms hence they can not be used to measure this mass term directly as happens when using (18) and (19), except by way of measuring the time variation in the fundamental physical constant ε_0 and μ_0. On the other hand, if one assumed that (18) and (19) is what describe physical and natural reality and they went on measure μ while in actual fact the photon has mass and the potential A_μ was governed by (13), then, it goes without much say that they must obtain a mass of the photon that is compatible with zero. They would reach a wrong conclusion.

Because ε_0 and μ_0 appear to be true constants of *Nature*, a time variation of these constants is expected to be secular over cosmic times. This means that one will need to appeal to cosmology for answers by comparing their past values with the present values of these constants as measured on Earth for the present cosmic epoch. Light travelling across the vast expanse of the Universe from distant objects carry the fossil record of what these constants were in the distant past. If ε_0 and μ_0 did vary markedly over relatively small time scales, this would easily be noticeable in the atomic transition lines of nearby astronomical objects.

The fact that ε_0 and μ_0 appear to be true constants of *Nature* strongly suggests that if these constants really did vary in time, this variation must be extremely small, implying that one would have to seek answers from cosmology since on cosmological time scales, a significant shift in these value must be detectable. A time variation of ε_0 has implications on the time variation of the fine structure constant α. In the next section, we shall look into this matter of the variation of the fine structure constant.

5 Variation of the Fine Structure Constant

Just before the dawn of the 21^{th} century, that is in 1999, high-redshift cosmological and astronomical observations (Webb et al. 1999) were brought forth that seem to strongly suggest that one of the supposed sacrosanct and finest constants of physics – the dimensionless and seemingly arcane fine-structure constant α; may not be a constant as we have long believed as these observations indicate that this constant may very well have been significantly larger in the past than it is today. These observations have further been supported by the observations of Webb et al. (2001), Murphy et al. (2001,3), Webb et al. (2011), King et al. (2012).

If conclusively this is proven to be true (as we strongly believe), then, this has far reaching implications on the nature of the fundamental Laws *of* Nature. The fine structure constant is given by:

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} = \frac{1}{137.035999074(44)}, \tag{22}$$

where $e = 1.602176565(35) \times 10^{-19}\,\mathrm{C}$ is the magnitude of the elementary electronic charge of the electron and proton and $\hbar = 1.054571726(47) \times 10^{-34}\,\mathrm{Js}$ is Planck's normalised constant. If α is to vary over cosmic epochs, then, all or some of the four constants making-up this dimensionless constant must also vary with time over cosmic epochs. If we are to go by what we have discovered in §(3), then our foremost culprit that should cause α to change is ε_0. For simplicity, we can choose to hold all the other constants as "true constant" and allow only ε_0 to change. So doing, it follows that:

$$\frac{\Delta\alpha}{\alpha} = -\frac{\Delta\varepsilon_0}{\varepsilon_0} = -\mu c\Delta t. \tag{23}$$

Now, if $\Delta\alpha < 0$ as observations (Webb et al. 1999, 2001, 2011, Murphy et al. 2001,3, King et al. 2012) seem to indicate, then $\Delta\varepsilon > 0$. For this $(\Delta\varepsilon > 0)$ to be so, it follows that $A_\mu = e^{-\mu ct}\left[A_0(r), A_j(r)\right]$. This means the relative strength of the electric and magnetic forces must have been larger in past that they are today. This setting were the electric and magnetic forces should have been larger in past than they are now appeals to the Big Bang cosmologist as this is one of the central (unproven) tenants of the Big Bang Cosmology Theory. The Big Bang proponents hold that at the moment of creation, the relative strengths of all the forces of *Nature i.e.* the gravitational, electromagnetic, weak and the strong nuclear force were all equal and their relative strength changed (by becoming weaker) over time leading to the decoupling of these forces where-after they become distinct from each-other. Clearly, the present ideas have something important to cosmology.

Thus, if the present ideas are acceptable, then, the authenticity of the high-redshift cosmological and astronomical observations of Webb et al. (1999, 2001, 2011), Murphy et al. (2001,3), King et al. (2012) need to be verified at a level confidence allowing for a universal acceptance of these observations as authentic, because at present, their authenticity is a matter that is yet to be settled. For example, these measurements have found no support from recent preliminary laboratory measurements made by Rosenband et al. (2008). These researchers (Rosenband et al. 2008) find:

$$\frac{\dot{\alpha}}{\alpha} = -(1.60 \pm 2.30) \times 10^{-17}\,\mathrm{yr}^{-1}, \tag{24}$$

which is compatible with a null result. This present day null constraint by Rosenband et al. (2008) on the time variation of α does not necessarily rule out a possible time variation of α in the past[3]. Further in the same vein of a null result, Chand et al. (2004), Srianand et al. (2004) found a cosmological result that is consisted with a null result, *i.e.* $\dot{\alpha}/\alpha = -(0.60 \pm 0.60) \times 10^{-6}$. This result was rebutted and disputed by Murphy et al. (2007, 2008) who showed that this result (Chand et al. 2004, Srianand et al. 2004) had been derived from a seriously flawed analysis. On the result of Rosenband et al. (2008), as urged in the previous section, we strongly feel this result must be recalibrated on the basis of the constraint (11), if this experiment really seeks to measure a time variation in α.

Therefore, there still is a ranging debate as to whether or not these supposed cosmological variations of the fine structure constant are real or not. Given our major result that points to a plausible variation in the fine structure constant, we surely are in a position not to

[3]Despite Rosenband et al. (2008)'s experiment's amazing accuracy to measure accurately $1/\alpha$ to the seventeenth decimal place, it is our feeling and submission that this experiment needs to be conducted over a sufficiently long period of time, say 10 years or so, before one can conclusively dismiss that α might not be a time variable physical quantity.

doubt the analysis and conclusion drawn from these observations, but to take them in good scientific faith that the analysis and conclusion drawn thereof are authentic or that these will tend to that end as more and more observations trickle in.

Now, in-order that we calculate the implied mass of the photon, for $\Delta\alpha/\alpha$, we shall adopt the value given by Murphy et al. (2004), which is:

$$\frac{\Delta\alpha}{\alpha} = -(5.70 \pm 1.00) \times 10^{-6}. \tag{25}$$

We shall use this value to compute the implied mass of the photon m_γ. From (23), it follows that:

$$\mu = \frac{m_\gamma c}{\hbar} = -\left(\frac{\Delta\alpha/t_u}{\alpha}\right)\frac{1}{c}, \tag{26}$$

where t_u is the estimated age of the Universe. We shall adopt the Hubble time as the age of the Universe and by so doing, we are consciously making the fundamental assumption that all matter and energy was created at a instant of time – *i.e.*, we are consciously assuming that the Big Bang Cosmology model of the Universe holds true. For the Hubble parameter, we shall adopt Freedman et al. (2012)'s value which is, $H_0 = 74.10 \pm 2.10\,\mathrm{km/s/Mpc} = (2.40 \pm 0.07) \times 10^{-18}\mathrm{s}^{-1}$, so that $t_u = (13.20 \pm 0.40) \times 10^9\,\mathrm{yr}$. From all this, it follows that:

$$\frac{\dot{\alpha}}{\alpha} = \frac{\Delta\alpha/t_u}{\alpha} = -(4.30 \pm 0.80) \times 10^{-16}\,\mathrm{yr}^{-1}. \tag{27}$$

For the photon mass m_γ, we will have:

$$m_\gamma = -\left(\frac{\Delta\alpha}{\alpha}\right)\frac{H_0\hbar}{c^2} = (9.00 \pm 1.00) \times 10^{-39}\,\mathrm{eV/c^2} = (1.60 \pm 0.20) \times 10^{-74}\,\mathrm{kg}. \tag{28}$$

This mass is extremely small – *be that it may*, it is not identically equal to zero! This very "fact" has serious implications on the whole of physics if proven to be have a direct correspondence with physical and natural reality.

Now, to add on to the controversy of the variation of the fine structure constant, King et al. (2012), Webb et al. (2011) report not only on a plausible time variation of α, but further on a plausible spatial dependence of this so-called constant! If these observations are to be interpreted directly from the present ideas, then, according to (23), these objects from which this spatial variation has been found must have different ages. Simple, these objects are not the same age. This does not violate both objective and subjective logic or common sense.

Further, King et al. (2012), Webb et al. (2011) report from these same observations that not only a negative change in the fine structure constant, but a positive one as-well. Again, if these observations of a positive change in α are to be interpreted directly from the present ideas, then according to (23), the mass of the photons from which these measurements have been deduced must be negative. This does violate subjective logic and common sense somehow. However, we do not feel this threatens the plausibility of the present ideas. To avoid entering into these somewhat polemical waters, we will not go further into trying to interpret these observations of a positive spatially varying α. We strongly feel this may very well be a premature thing to do.

6 Discussion, Conclusion and Recommendations

6.1 General Discussion

It is with great confidence that we say that the present reading, together with Nyambuya (2013), are a significant contribution to physics. The reason for saying this is because we have shown from within the confines, provinces and domains of acceptable contemporary physics without the infusion of exogenous and exotic ideas that, *in principle*, it must be possible to have massive long range photons that travel at the speed of light. We have argued that evidence of this must come in the form of the variation of the permittivity and permeability of free. Such evidence already exists in the form of the variation in the fine structure constant (Webb et al. 1999, 2001, 2011, Murphy et al. 2001,3, King et al. 2012). This evidence gives impetus to the ideas presented herein. Given that massive photons have serious implications on the broad spectrum of physics at its most fundamental level, this reading may prove to be very useful and significant on the fundamental level.

6.2 Conclusion

Assuming the correctness (or acceptability) of the ideas presented herein, we hereby make the following conclusions:

1. It is *in principle* possible to have a massive photon that takes part in long range interactions for as long as the electormagnetic field satisfies the constraint (13).
2. The existence of massive photons provides an explanation as to why the fine structure α must vary through the passages of cosmic time.
3. The variation of the fine structure constant (or simple ε_0 and or μ_0) accordingly, provides a way to measure the mass of the photon. Taking the current measurements of the variation of the fine structure constant, the mass of the photon must be $m_\gamma = (1.60 \pm 0.20) \times 10^{-74}\,\mathrm{kg}$.
4. Massive photons must *in principle* be able to travel at the speed of light and also at speeds less than the speed of light.
5. Combined with the observational result of a decreasing fine structure constant α, the proposed "Massive Long Range Photon Theory" invariably points to the idea that the relative strengths of the electric and magnetic forces must be decreasing through the passages of cosmic time; these forces must have been larger in the past than at present.

6.3 Recommendations

There is need to study the present findings much further than has been done herein because a massive photon has serious implications on the broad spectrum of physics. For example on p.85, Tu et al. (2005) points that:

> *"If the photon had a nonzero rest mass, one might initially expect a photon gas to have two transverse degrees and one longitudinal degree of freedom. This would alter Planck's radiation law by a factor of 3/2, in contradiction with experience."*

Obviously, there is need to check if the present findings do lead to a modified Planck Radiation Law. If it is found that this leads to a radiation law that runs contrary to experience, there is no other way, the present edifice together with all its beautiful and grandeur, will have no choice but to come down crushing!

Further, in field theory, a nonzero photon mass leads to the unceremonious and undesired breaking of the seemingly sacrosanct $\mathrm{U}(1)$ gauge invariance of the resultant electrodynamics. This has serious implications on the general nature of the Standard Model *of* Particle Physics. The list of the many areas that one would need to revisit is very long. To cut the long story short, at the end of the day when all has been said and done, the point is that, there is need to *rethink our physics* in the light of the present findings of the plausibility of a massive long range photon.

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