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# A phenomenological model for photon mass generation *in vacuo*

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**A phenomenological model is presented here arguing that photon mass is an induced effect rendered in the form of vacuum potential arising from vacuum natural modes. An elementary vacuum potential is defined as a function of vacuum zero-point fields, which yields an expression for effective photon mass generation. A Lagrangian is constructed for this model which incorporates photons with effective mass *in vacuo*. It is suggested that photons may acquire or present an effective mass while interactions with vacuum or other fields but they do not have an intrinsic rest mass. The photon mass emerges as a dynamical variable which depends on the coupling strength of electromagnetic fields to the vacuum natural modes and on the value of vector potential.**

**Key words:** Photon mass, Maxwell-Proca equations, vacuum potentials, Higgs potential.

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## INTRODUCTION

There have been numerous studies in the past investigating the problem of photon mass and some comprehensive reviews (Lakes, 1998; Tu et al., 2005) on the problem can be found in literature. Photons are assumed massless as per the Standard Model of physics and Quantum Electrodynamics, however the possibility of photons with non-vanishing mass cannot be excluded. In classical formalism, photonic fields with mass are defined by the Maxwell-Proca equations (Lakes, 1998). These equations, in relativistic form, may be expressed as:

$$\partial_\mu F^{\mu\nu} + \mu^2 A^\nu = 0, \\ \left(\mu^2 + \mu^2\right) A^\mu = 0 \tag{1}$$

Where μ is the hypothetical mass of the electromagnetic field (photon), $F_{\mu\nu}$ is electromagnetic tensor and $A^\mu$ is electric vector potential (a gauge field).

Experimentally, so far, all the searches for a significant photon mass have been negative and an upper limit of approximately $2.0\times10^{-16}$ eV (Particle Data Book, 2012) has been set after a series of terrestrial and celestial searches. Nevertheless, photon mass problem remains an active area of physics.

It may be hypothesized that while photons remain massless gauge bosons responsible for mediating the electromagnetic interaction (as per the Standard Model), it may be possible that they can acquire or present an effective mass while undergoing interactions with other fields. In order for this to happen, the most suitable

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candidate is perhaps the vacuum and its natural mode fields, also known as zero-pint energy fields, arising from inherent fluctuations in the vacuum. It is a well-established and empirical fact that these fluctuations in vacuum lead to a number of observable effects, most importantly vacuum screening currents (Aitchison and Hey, 1982), and the Casimir force and corresponding energy (Casimir, 1948). The Casimir force and energy (in a three-dimensional plane-wave model and under absolute conditions) have a form (Casimir, 1948; Mostepenenko and Trunov, 1997).

$$F_{cas} = \frac{\hbar c \pi^2}{240} \frac{A}{L^4}$$
$$E_{cas} = \frac{\hbar c \pi^2}{720} \frac{A}{L^3} \quad (2)$$

Where A is the area of each of the two plates and L is the separation between them, and h-bar is the Planck's constant divided by $2\pi$.

Possibility for a so-called dynamic form of the Casimir effect (Dodonov, 2010) has also been suggested in recent times. It is argued that it is possible that a mechanism of parametric resonance Dodonov (1996, 2010) takes place in such cases, whereby photons are created in an empty cavity by means of resonant processes, such as resonance excitation of electromagnetic modes (Dodonov, 1996; Schwinger, 1992).

Vacuum is, in its simplest form, the quantum state corres-ponding to minimum energy, with a value of constant electrical field as the amplitude of the quantum fluctuations, which designates vacuum fluctuations as real electromagnetic fields propagating in space with speed of light, like an ordinary free field. The energy of an individual zero-point field in vacuum, corresponding to the ground state (principal quantum number n=0), is expressed as:

$$E_i = \frac{1}{2} \hbar \omega \quad (3)$$

Then, the collective energy of this vacuum can be described as:

$$E_0 = \frac{1}{2} \sum_i \sqrt{\bar{p}^2 + m^2} \quad (4)$$

Planck was the first to propose, in 1911, the existence of zero-point energy associated with the black body radiation modes (Planck, 1911), with a statistical physical description. He expressed a zero-point energy superimposed onto the black-body radiation energy, giving the mean energy per mode as:

$$\bar{E} = \bar{E}_{bbr} + \frac{1}{2} \hbar \omega \quad (5)$$

Where $\bar{E}_{bbr}$ is the mean value of black body radiation.

This provides a crude estimate of the zero-point energy and length in the form of a one-dimensional harmonic oscillator formalism:

$$E_0(x) = \frac{1}{2} \sum_{\omega} \hbar \omega f(\omega),$$
$$x = \pi n / \omega \quad (6)$$

Here, a cutoff is mandatory to avoid the so-called *'vacuum catastrophe'* (Itzykson and Zuber, 1985), and f($\omega$) is the required cutoff function, defined as:

$$f(\omega) = 1,\ f(\omega) \xrightarrow[\omega \to \infty]{} 0 \quad (7)$$

The vacuum energy can be equated to the zero-point energy per unit volume (in discrete to continuum limits) as:

$$\langle 0 | \underline{E}^2 | 0 \rangle = \frac{1}{2\Omega} \sum_{\underline{k}s} \omega_k = \frac{1}{(2\pi)^3} \int d^3k |\underline{k}|. \quad (8)$$

The integral diverges for large frequency modes, leading to *vacuum catastrophe*, but for short frequencies, part of these fluctuating modes results in observable effects, such as the Casimir effect. After introducing the cutoff, the mean energy density for vacuum is described by summing over all filled modes up to the introduced cutoff, $\omega_{max}$:

$$\bar{\rho}_{vac} = \frac{(\hbar \omega_{max})^4}{8\pi^2 (\hbar c)^3} \quad (9)$$

This remains valid until the cut-off frequency diverges and the density becomes infinite.

## MODEL

One assumes that a massive photon field is confined within vacuum which serves as a background potential, defined here as the vacuum potential V($\eta$), where $\eta$ is a complex field;

$$V_{vac} = V(\eta) \quad (10)$$

The potential defines the energy contained in the fluctuating zero-point fields within a physical vacuum.

Assuming a simple scalar theory, one asserts that this potential has a quartic form (which is minimum possible form in the problem at hand), and expresses this potential as follows (here the Casimir sign convention is used, otherwise negative sign is required for an attractive potential):

$$V(\eta) = \frac{1}{2}\mu^2\eta^2 + \frac{g}{2}\eta^4 \tag{11}$$

Where, g is a dimensionless coupling strength, depicting the strength of interaction of the  field with the vacuum.

From the minimum or extreme lowest state of this potential, that is,

$$\frac{\partial}{\partial\eta}V(\eta) = 0 \tag{12}$$

One gets;

$$\frac{\partial}{\partial\eta}V(\eta) = \mu^2\eta + 2g\eta^3 = 0$$

One can calculate and see that the result yields the ground state value for the field as:

$$\eta_0 = \left(-\frac{\mu^2}{2g}\right)^{1/2}$$

$$|\eta_0| = +\left(-\frac{\mu^2}{2g}\right)^{1/2} \tag{13}$$

Then, the state of this vacuum is obtained as:

$$\eta_{vac} = \begin{pmatrix} 0 \\ . \\ . \\ \sqrt{-\frac{\mu^2}{2g}} \end{pmatrix} \tag{14}$$

The form of this vacuum is similar to the Higgs vacuum, as per the Higgs theory (Guralnik et al., 1969). The vacuum expectation value of the field is determined to be:

$$\langle\eta\rangle_0 = \langle 0|\eta|0\rangle = \begin{pmatrix} 0 \\ \eta_{vac} \end{pmatrix} \tag{15}$$

Vacuum expectation value (*vev*), $\langle 0|\eta|0\rangle$ is the non-zero equilibrium value of vacuum potential (our argument here is based upon non-perturbative aspects of vacuum). To simplify this statement, we can say that it is the macroscopic manifestation of the vacuum fluctuations, or the vacuum electromagnetic fields normal modes, which exist ubiquitously in the vacuum in an equilibrium situation, having a non-zero observable value.

Interaction of electromagnetic vector potential in this background potential has to satisfy the equation:

$$\mu A^{\mu} = \langle 0|j^{\mu}(\eta)|0\rangle \tag{16}$$

Where $j^{\mu}$ is the electromagnetic four-current associated with the potential in vacuum, expressed here as its vacuum expectation value.

Vacuum potential has to satisfy the current screening condition for massive fields, as described earlier. The screening condition becomes:

$$\langle 0|j^{\mu}(\eta)|0\rangle = -\mu^2 A^{\mu} \tag{17}$$

It is obvious that the vacuum expectation value of potential is expressed in the form of electromagnetic currents, where the screening is underlying mechanism or condition that yields an effective mass.

One can proceed to the next step and incorporate the defined vacuum potential into the Klein-Gordon equation for the massive fields (Itzykson and Zuber, 1985) obtaining:

$$\left(\mu^2 - \mu^2\right)\eta - V^2(\eta) = 0 \tag{18}$$

Now one can write down a general Lagrangian for this theory (in Adjoint representation) as:

$$L = \frac{1}{2}\partial_{\mu}\eta^a\partial_{\mu}\eta^a - \frac{1}{2}\mu^2(\eta^a\eta^a) + \frac{1}{4}g(\eta^a\eta^a)^2 \tag{19}$$

First of all, in order to incorporate the electromagnetic field, as well as to preserve gauge invariance, we introduce a specific form of the Lagrangian, called the *'Stueckelberg's Lagrangian'* (Itzykson and Zuber, 1985), and modify it to include photons with a mass μ and vector potential $A_{\mu}$ as:

$$L_{em}^{\gamma} = \frac{1}{2}\mu^2 A_{\mu}^a A_{\mu}^a - \frac{1}{4}F_{\mu\nu}^a F_{\mu\nu}^a - \frac{1}{2}(\partial\cdot A_{\mu}^a)(\partial\cdot A_{\mu}^a) \tag{20}$$

and perform a covariant derivative gauge transformation:

$$\partial^{\mu} \longrightarrow D_{\mu} = \partial^{\mu}\eta^a - gc_{abc}A_{\mu}^b\eta^c \tag{21}$$

where $c_{abc}$ are the relevant non-abelian structure constants (Frampton, 2000). With this change, the invariant electromagnetic field tensor becomes:

$$F_{\mu\nu}^a = \partial_{\mu}A_{\nu}^a - \partial_{\nu}A_{\mu}^a - gc_{abc}A_{\mu}^b A_{\nu}^c \tag{22}$$

An interaction term is required in the Lagrangian, which would depict the form of interaction between vector potential of the free electromagnetic field and the vacuum potential. This term takes the form:

$$L_{\text{int}} = \frac{1}{2}g^2(A_{\mu}^a A_{\mu}^a)(\eta^a\eta^a)^2 \tag{23}$$

Here, g is the coupling strength between these two potentials or fields. But, we already have an interaction term in form of the vacuum potential we defined earlier:

$$L_{\text{int}} = V(\eta) = \frac{1}{2}\mu^2\eta^2 + \frac{g}{2}\eta^4 \tag{24}$$

On comparing the two expressions of Equations (25) and (26), one can instantly identify:

$$\frac{1}{2}\eta^2(\mu^2 + g\eta^2) = \frac{1}{2}g^2 A_\mu^2 \eta^2 \tag{25}$$

$$\mu^2 + g\eta^2 = g^2 A_\mu^2 \tag{26}$$

Or

$$\mu^2 = g(gA_\mu^2 - \eta^2)$$
$$\mu = \sqrt{g(gA_\mu^2 - \eta^2)} \tag{27}$$

$$\mu = \sqrt{g(gA_\mu A^\mu - \eta'\eta)} \tag{28}$$

(Here $\eta'\eta$ implies η†η)

This development gives a phenomenological expression for the photon mass under the framework of this model. The mass depends on coupling strength, as expected, as well as on the vector potential (of the electromagnetic field) and the intrinsic vacuum field, η. Now substituting all the terms, we are led to the appropriate Yang-Mills (non-abelian) Lagrangian for the theory as:

$$\begin{aligned} L = {} & \frac{1}{2}(D_\mu \eta^a)(D_\mu \eta^a) - \frac{1}{2}\mu^2 \eta^a \eta^a \\ & - \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \frac{1}{2}\mu^2 A^a_\mu A^a_\mu - \frac{1}{2}(D_\mu A^a_\mu)(D_\mu A^a_\mu) \\ & + \frac{1}{2}g(\eta^a\eta^a)^2 + \frac{1}{2}g^2(A^a_\mu A^a_\mu)(\eta^a\eta^a)^2 \end{aligned} \tag{29}$$

Or in a simple representation:

$$\begin{aligned} L = {} & \frac{1}{2}D_\mu \eta^2 - \frac{1}{2}\mu^2\eta^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\mu^2 A_\mu^2 \\ & - \frac{1}{2}D_\mu A_\mu^2 + \frac{1}{2}g\eta^4 + \frac{1}{2}g^2 A_\mu^2 \eta^4 \end{aligned} \tag{30}$$

The first two terms define the vacuum potential η in covariant derivative form (including a mass term); the third, fourth and fifth terms depict the electromagnetic field; the sixth term represents the vacuum potential and the last term is the interaction of photons with vacuum potential. This Lagrangian defines a system of a vacuum potential interacting with enclosed electromagnetic fields, and has all the terms for the defined vacuum potential and the massive electromagnetic field, as well as their interaction.

## DISCUSSION

A brief review of the origin and the form of photon mass problem has been given in the preceding sections. It is shown that photon mass arises in a simple fashion in the form of interactions between the natural modes of vacuum and the electromagnetic fields, under a gauge formalism. A possibility exists that the electromagnetic fields may interact with the vacuum modes in the form of a resonant interaction. Resonance is a well-observed phenomenon in both classical and quantum mechanics, with a myriad number of manifestations seen at both microscopic and macroscopic level systems. In quantum fields, resonance is identified and quantized in the form of a condition, the quantum mechanical resonance (QMR), wherein fields resonantly interact with each other and may result into observable effects. It is believed that the wave interactions are most efficient if they are resonant, that is, if the two or more frequencies satisfy matching conditions and the relative wave phase remains unchanged for a long time, and where in such resonant interactions, the energy conversion takes place on a much short time scale (Servin and Brodin, 2003). This is similar to other cases in quantum mechanics involving adiabatic evolution of quantum states (Lai and Ho, 1932) and in specific to the adiabatic conversion in neutrino mass generation mechanism, the so-called *MSW effect*, explained by the Mikheyev-Smirnov-Wolfenstein model (Wolfenstein, 1978). There is one more possibility for resonance to occur in these fields. This is the phenomenon of parametric resonance (Goldstein, 2002) that is, a resonance arising in an oscillating system with change of parameters, which can be applied in understanding of the vacuum and electromagnetic modes. Some ideas have been suggested in this direction in the domain of neutrino oscillations (Akhmedov, 1988), but so far a similar study in the realm of vacuum fluctuations has not been attempted.

A number of other possibilities have been alluded to the origin of photon mass. Masood (1991) has carried out a perturbative calculation for the self-mass of photon in the limit of finite-temperature and -density, in which it was suggested that the photon mass may be square of the cyclic frequency and acquired from plasma screening of photons at high frequencies. In essence, the study suggested a dynamical generation of photon mass in the form of an effective mass mechanism, rising out of the change in electromagnetic properties of certain highly dense media and resulting into modified propagator of the photon. Another possibility is suggested elsewhere (Weldon, 1982) in the case of very high-temperature backgrounds with low densities, where photons acquire dynamically-generated masses.

Finally, a conspicuous possibility for the origin of photon mass lies in the realm of gravitation, or the curvature of space-time. With the advent of Einstein's General Theory of Relativity, gravitation received a new explanation in the form of inherent curvature of space-time near massive objects. Although efforts have been underway to find a quantum version of the theory and reconcile all the four fundamental interactions, there has been little success. The strongest evidence comes from the general theory of relativity. Recently, an experiment (Mueller, 2010) recording bending of matter waves under gravitation with high precision has further reinforced the metric nature of gravitation. Thus, it is not a far-fetched idea that just as gravitational bending of light has its origin in the space-time curvature, the same curvature can also lead to the generation of mass in electromagnetic fields.

Depending upon space-time curvature, photons can undergo interaction with gravitation. A strong evidence of this kind of interaction comes from the observed deflection of light in the proximity of heavy celestial objects (Misner et al., 1973). The bending is described in the form of a deflection angle, expressed as (Tu et al., 2005):

$$\theta = \vartheta\left(1 + \frac{m_\gamma^2 c^4}{2h^2 \nu^2}\right) \quad (31)$$

Where $\vartheta$ is the bending angle for photons without mass, given as;

$$\vartheta = \frac{4GM}{c^2 R} \quad (32)$$

Here, M and R are the mass and radius of the celestial object (star, quasar, black hole etc.) causing deflection and G is the Universal Gravitational Constant. Therefore, it becomes extremely important to study the behavior of photons under the influence of gravitational curvature, especially studying the effects of gravitation on the geodesic path that a photon takes.

## Conclusion

Based on the foundations of existing empirical framework in quantum field theory, a model and some ideas are presented which bear potential in the study of the problem of photon mass. Ideas and formulation outlined in this paper may be summarized in the form of a few careful suggestions.

It may be suggested that the term *'rest mass'* cannot be attributed to a photon because photon is not an electrostatic concept and mass can only be ascribed to it in the form of a relativistic electrodynamic framework. Moreover, incorporating both the intrinsic properties of vacuum and the gravitational interaction are important. Mass is intrinsically a property which quantifies the quantity of matter and/or inertia in an extended object, and since the object is itself under the influence of gravitation, as defined by the general theory of relativity, it has influence from the magnitude of space-time curvature as well. It may be possible that photon (and possibly other field quanta) does not have an intrinsic mass like other fundamental particles, but in fact an effective mass, rendered to it either from the vacuum normal modes (as we saw in preceding sections) or the curvature of gravitation. This effective potential endows a proportional, observable, mass to the photon by means of an effective mass generation in the ambient vacuum or gravitational potentials.

As the mass depends on the effective potential, it does not remain a constant and in fact becomes a variable, which depends on the magnitude of potential and the interaction. In the case of vacuum, the effective mass of the photon is in fact the coupling of a photon's scalar field to the intrinsic normal modes of the vacuum, which creates an effective vacuum potential.

In the case of gravity, the effective potential of the photon mass is modified by the gravitational contributions (that is, from the gravity-induced variation in the curvature). It may possibly be a consequence of a gravitational-electromagnetic interaction of some kind as well, which has yet to be established. Serious investigations are needed on these lines.Thus, it may be possible that the interaction of photon with vacuum natural modes, either under a resonant mechanism or without resonance, can induce significant effects, including but not limited to production of photons as well as effective mass generation.

We may also surmarise that the current upper limits imposed on the photon mass may in fact be the magnitude of our best estimate on the limits of its measurement, or it may be the measurement of the limits of the effect of effective potential (attributed to the particle from the ambient vacuum potential and/or the curvature of space-time under gravity) as measured while a particular observation was carried out. It is suggested here that a more viable place to understand the origin of photon mass is in the vacuum rather than in terrestrial or celestial effects or processes which may have other influencing factors interfering with the measurement. On the basis of this study, it is summarized that photon does not have an intrinsic rest mass, however a possibility of an effective mass is not ruled out. Based upon a model presented here, the photon mass becomes a variable which depends on coupling of electromagnetic fields to vacuum modes.

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## Conflict of Interests

The author(s) have not declared any conflict of interests.

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