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POSSIBILITY FOR THE EXISTENCE OF PHOTON MASS: A THEORETICAL FRAMEWORK

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Abstract

The existence of the photon mass is evident from the various experiments. Theoretical aspect for the existence of such mass is explored in terms of the mass generation mechanism through the breaking of gauge symmetry. It is proposed that the photon mass is generated by the spontaneous $U(1)_{em}$ symmetry breaking in low energy limit. The possibility for the existence of new kind of Higgs is also predicted.

Introduction

In the present circumstances most of the physical phenomena are explained by a natural assumption that the photons are massless. Classically, the electromagnetic field is described by the Maxwell equations, and in the framework of Quantum Field Theory (QFT) that field gives rise to massless photon particle as a result of second quantization. The masslessness implies that the photon is characterized by two degrees of freedom. It is also experimentally observed that most of the electromagnetic waves have transverse polarizations, which is consistent with the masslessness of the photons. In the standard model of the electro-weak theory all the

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particles are basically massless; the mass of the fundamental particle is generated by the spontaneous breaking of gauge symmetry. In that framework of standard model all the gauge bosons get the mass when $SU(2)_L \times U(1)_Y$ is broken down spontaneously into the gauge group $U(1)_{em}$. That symmetric group $U(1)_{em}$ remains unbroken and as a result that photon does not have any mass. The Maxwelian electromagnetic theory has been well verified in the classical domain and therefore, it is not very easy to explore the possibility of the existence of photon mass. The electromagnetic law is described by the Maxwell-Proca equations [1] if the photon has non-zero mass. In this system of equations there is a characteristic length, called the Compton wave length of the photon, given by $l_\gamma = m_\gamma^{-1}$ (in the natural unit). If m_γ vanishes the Maxwell-Proca equations become ordinary Maxwell equations. A non-zero photon mass gives rise to a wavelength dependence of the speed of light in free space, the possibility of longitudinal wave. A various tests have been carried out to measure the characteristic length of the photon and hence to find the upper bound of the photon mass. A details are given in the Table-1. We would like to explore the theoretical possibility for the generation of photon mass. Motivation comes from the standard model of the electro-weak theory. If the photon has a tiny mass it must be generated, somehow, through the spontaneous breaking of a gauge symmetry. Such possibility is framed in the next paragraph.

In the electro-weak theory since the $U(1)_{em}$ symmetry remains unbroken so the photon field A_μ cannot acquire any mass. But, one cannot reject the idea of the generation of photon mass in the little extension of this theory. There exists another kind of the extension of standard model in which the neutrino is considered to have the mass. In such theory the generation of gauge symmetry group is taken to be $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, which is broken down spontaneously into $SU(2)_L \times SU(1)_Y$ and thus the neutrino mass is generated. In the present discussion we are not interested about that stage of symmetry breaking, rather we shall start from the point where $SU(2)_L \times SU(1)_Y$ would remain intact. At some energy the said symmetry is broken down spontaneously into $U(1)_{em}$. In this stage all the gauge bosons and all the charged fermions acquire the mass, where still the photon particle remains massless. Now, if there is any photon mass, however small it may be, then it is guaranteed that somehow the $U(1)_Q$ is broken down spontaneously. The gauge invariant Lagrangian having the scalar field $\Phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$, given by

$$\mathcal{L} = (D^{\mu}\Phi^* \,)(D_{\mu}\Phi) - \mu^2(\Phi^* \, \Phi) - \lambda(\Phi^* \, \Phi)^2 - \frac{1}{4}F^{\mu\nu}F\mu\nu, \tag{1}$$

where,

$$D_{\mu} \equiv \partial_{\mu} - ieA_{\mu}.$$

A small perturbation $\frac{1}{\sqrt{2}}(\eta, \xi)$ about the ground state $\frac{1}{\sqrt{2}}(v, 0)$ changes the Lagrangian into

$$\begin{aligned}\mathcal{L}' = {} & [\tfrac{1}{2}(\partial_{\mu}\eta)(\partial^{\mu}\eta) - v^2\lambda\eta^2] + \tfrac{1}{2}(\partial_{\mu}\xi)(\partial^{\mu}\xi) + [\tfrac{1}{2}ev^2A^{\mu}A_{\mu} - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}] \\ & + eA^{\mu}[\xi(\partial_{\mu}\eta) - \eta(\partial_{\mu}\xi)] + [evA^{\mu}A_{\mu}\eta - \lambda v\eta^3 - \lambda v\xi^2\eta] + [\tfrac{e}{2}A^{\mu}A_{\mu}(\eta^2 + \xi^2) \\ & - \tfrac{\lambda}{4}(\eta^2 + \xi^2)^2] + \tfrac{1}{4}v^4\lambda. \end{aligned} \tag{2}$$

In the above equation, η represents the Higgs field, whereas ξ is associated with unwanted massless goldstone boson field. Such goldstone boson disappears when a proper unitary gauge is chosen. The Lagrangian given by (2) becomes

$$\begin{aligned}\mathcal{L}' = {} & [\tfrac{1}{2}ev^2A^{\mu}A_{\mu} - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}] + [\tfrac{1}{2}(\partial_{\mu}\eta)(\partial^{\mu}\eta) - \tfrac{1}{2}(2v^2\lambda)\eta^2] \\ & + [evA^{\mu}A_{\mu}\eta - \lambda v\eta^3] + [\tfrac{e}{2}A^{\mu}A_{\mu}\eta^2 - \tfrac{\lambda}{4}\eta^2] + \tfrac{1}{4}v^4\lambda. \end{aligned} \tag{3}$$

Such Lagrangian indicates that the scalar field ϕ acquires a mass $m_{\eta} = \sqrt{2\lambda v^2}$, whereas the photon field A_{μ} gets the mass $m_{\gamma} = \sqrt{ev^2}$. It is now important to estimate the upper limit of vacuum expectation value v from the various experimental values of the photon mass. It is found from the Table-1 that the upper bound of the photon mass is 4.2×10^{-44}gm; i.e., the photon mass must lie somewhere in the region $0 \le \mathrm{m}_{\gamma} \le 2.356 \times 10^{-11}$ (in eV). Thus the upper bound of the vacuum expectation value is found to be 10^{-9}eV. It is observed that a new kind of Higgs field (the scalar field ϕ) is generated in this framework. Such Higgs field, being a scalar singlet, is essentially different from the Higgs generated in the $SU(2)_L \times SU(1)_Y$ breaking. Essentially that Higgs mass is supposed to be very small, although such mass depends on the coupling constant λ. It is to be noted that there exists a possibility that the said Higgs mass may be considerably high for a extremely large value of λ, which is not consistent to the well known ϕ^4 theory, however it is not a big issue in the photon mass generation if the Higgs mass is high enough. Such possibility is discarded for the small value of λ. Now, the framework designed above is an example of the $U(1)$ symmetry breaking phenomenon, although it is quite different from that developed in case of superconductivity. In that framework the photon acquires mass in very low energy scale, which must belong to the radio wave having extremely low frequency.

Summarizing the above, we it can be said that $SU(2)_L \times SU(1)_Y$ symmetry is broken spontaneously to result 3 massive gauge bosons, whereas photon remains massless as $U(1)_{em}$ remains intact. That is what the standard model of electro-weak theory infers. We have proposed a consistent theory by extending the standard model in which the $U(1)_{em}$ symmetry no longer persists, but ultimately breaks down spontaneously in the very low energy scale and thus the photon gets a very small mass. That we can say a bare minimum extension of the standard model to include the photon mass in this framework.

In the high energy phenomena it is immaterial whether the photon has any mass, since its upper limit is extremely small. As it has already been mentioned that the photon mass is important in the radio wave, in particular, in the range of Very Low Frequency (VLF) wave. We have proposed a symmetry breaking model for the generation of the photon mass and consequently a new Higgs is generated in this model. Of course this model is subject to the experimental detection of such Higgs in the extremely low energy region. It is to be noted that there may arise another unusual phenomenon if the photon has a mass. Below the energy range $2.356 \times 10^{-11}\text{eV}$, where photon gets the mass, the speed of the photon becomes slightly lesser than c, and as a result the phase velocity of the radio wave below the said energy must be deviated from that of other electromagnetic wave with larger frequency. Therefore, it is quite clear that the mass generation phenomenon of the photon splits the electromagnetic spectrum into two categories. That may be an important consequence of the photon mass generation.

Table 1. Results of various tests for the non-zero photon mass

Authors	Mode of Experiment	Photon mass in gram
Plimpton and Lawton [2]	Test of Coulomb's Law	$\leq 3.4 \times 10^{-44}$
Schrodinger [3]	Test of Ampere's Law from Geomagnetic Data	$\sim 2 \times 10^{-47}$
Gintsburg [4]	Test of Ampere's Law from Geomagnetic Data	$\leq 8 \times 10^{-48}$
Cochran and Franken [5]	Test of Coulomb's Law	$\leq 3 \times 10^{-45}$
Nieto and Goldhaber [6]	Test of Ampere's Law from Geomagnetic Data	$\leq 4 \times 10^{-48}$
Feinberg [7]	Dispersion of light	10^{-44}
Bartlett et al. [8]	Test of Coulomb's Law	$\leq 3 \times 10^{-46}$
Williams et al. [9]	Test of Coulomb's Law	$\leq 1.6 \times 10^{-47}$
Williams et al. [10]	Test of Coulomb's Law	$\leq 2 \times 10^{-47}$
Davis et al. [11]	Analysis of Jupiter's magnetic field	$\leq 8 \times 10^{-49}$
Crandall [12]	Test of Coulomb's Law	$\leq 8 \times 10^{-48}$
Chernikov et al. [13]	Test of Ampere's Law	$\leq 8.4 \times 10^{-46}$
Fischbach et al. [14]	Analysis of Earth's magnetic field	$\leq 10^{-48}$
Lakes [15]	Static torsion balance	$\leq 2 \times 10^{-50}$
Shaefer [16]	Measurement of the speed of light	$\leq 4.2 \times 10^{-44}$
Luo et al. [17]	Dynamic torsion balance	$\leq 1.2 \times 10^{-51}$

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