Slightly Massive Photon and Equivalence Principle

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Abstract

We show that in the Higgs model leading to a slightly massive photon there are one-loop diagrams which induce equivalence principle violations. This and other considerations implicate rather stringent constraints in the parameter space of the model.

1 Introduction

The possibility of a non-zero photon mass $m_A$, tiny as it should be, is connected to fundamental questions in Physics as conservation of electric charge, charge quantization, etc. This is the main reason why the topic of the photon mass has been considered along the years from a theoretical perspective [1]. Also, there has been the effort to constrain $m_A$ using laboratory experiments and astrophysical observations [2]. Some of the bounds, particularly the most stringent, are obtained using the argument that a massive Proca field would acquire an energy density in an ambient magnetic field. Non-observation of the effects of such energy density, the argument follows, leads to bounds on $m_A$.

A turning point in this issue was the realization by Adelberger, Dvali and Gruzinov [3] that bounds obtained using the argument above were not valid when the photon mass generation was due to the Higgs mechanism related to the electromagnetic gauge group $U(1)_{em}$. It was shown by these authors that the presence of vortices invalid such bounds, and one is left with the good old bound [4] obtained testing Coulomb’s law by a Cavendish-type laboratory experiment

$$m_A < 10^{-14} \text{ eV}. \quad (1)$$

Although in [3] it is shown that in some specific conditions it is possible to obtain stronger bounds on $m_A$, we do not know whether such conditions are met; thus we are left a priori with (1) as the most restrictive bound on $m_A$. 


According to our present knowledge of fundamental physics, the most plausible way for the photon to acquire a mass is through the abelian Higgs mechanism. To obtain a very small photon mass in agreement with (1) one ends up with a Higgs scalar which is very weakly coupled, so that it may seem difficult to constrain the model. Perhaps for this reason we have not found in the literature any attempt to constrain the massive photon Higgs model. In this paper we try to fill this gap. We show that the model induces a violation of the equivalence principle (EP). When the Higgs mass is small, the experimental bounds on EP violation lead to very tight constraints. We also examine the consequences of the experimental limit (1) on the model parameters. Finally, when the symmetry is restored we use bounds on minicharged particles.

2 Higgs Scenario and Equivalence Principle

To recall the basics of the abelian Higgs model we write the Lagrangian involving the Maxwell field $A^\mu(x)$ and a scalar $\varphi(x)$ charged under $U(1)_{em}$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + |(\partial_\mu + ig A_\mu) \varphi|^2 - V(\varphi)$$

with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The potential

$$V(\varphi) = \frac{\lambda}{2} (\varphi^\ast \varphi - v^2)^2$$

is such that the field acquires a vacuum expectation value $v$. The shift of the field

$$\varphi(x) = v + \frac{1}{\sqrt{2}} h(x)e^{i\theta(x)}$$

leads to

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} (\partial_\mu h)(\partial^\mu h) + \frac{m_A^2}{2} A_\mu A^\mu + \frac{m_h^2}{2} h^2 + \mathcal{L}_{int}$$

i.e., we obtain a massive photon

$$m_A = \sqrt{2} g v$$

and a massive Higgs scalar $h$

$$m_h = \lambda^{1/2} v.$$}

Of course the Higgs is not the one that appears in the spontaneous breaking of the electroweak symmetry.

In (3) the final term $\mathcal{L}_{int}$ stands for the interactions; we display here the part we are interested for our purposes, namely, the coupling of Higgs to photons,

$$\mathcal{L}_{int} = \sqrt{2} g^2 v h A_\mu A^\mu + \frac{g^2}{2} h^2 A_\mu A^\mu + \ldots$$
The violation of the EP in the photon-mass Higgs model comes from the loop diagram in Figure 1 which has the Higgs $h$ and a charged fermion $f$ as external particles, and two (massive) photons as virtual particles. The diagram leads to a Yukawa term

$$yh \bar{f}f$$

We have computed the diagram in Figure 1 and obtained a finite result, as expected because the term (9) is not present at tree level. In the relevant limit of small photon mass compared to the fermion mass, $m_A \ll m_f$, we obtain the value of the Yukawa coupling $y$,

$$y = \frac{3}{4\pi} \alpha g$$

with $\alpha$ the electromagnetic fine structure constant. We notice that the result is independent of $m_f$, a fact valid only in the limit of small photon mass. We performed the calculation in the $R_\xi$ gauge, and checked that the result for arbitrary $m_A$ is $\xi$-independent.

Let us now consider the effects of the Yukawa coupling (9). When the Higgs scalar $h$ is sufficiently light, coherent $h$-exchange among bodies generates a new long range force. Since $h$ couples to charged particles only, it does not couple proportionally to mass, and therefore the new force would manifest as a violation of the EP. The force among two bodies of masses $m_1$ and $m_2$ at a distance $r$ contains the usual gravitational force with strength $G_N$ but it would also contain an EP-violating component. In the simple case that the two test bodies are constituted each by a single element, with atomic numbers $Z_1$ and $Z_2$, and mass numbers $A_1$ and $A_2$, respectively, the total potential reads

$$V(r) = G_N \frac{m_1 m_2}{r} \left[ 1 + \frac{1}{G_N u^2} \frac{y^2}{4\pi} \left( \frac{2Z_1}{A_1} \right)_1 \left( \frac{2Z_2}{A_2} \right)_2 e^{-m_h r} \right]$$

where $u$ is the atomic mass unit. The factors $2Z$ come from the fact that the new force couples with the same strength to electrons and protons.
3 Constraints on the Model

Although the second term inside the parentheses in (11) is expected to be very small, relevant constraints can be obtained because the experimental EP tests are wonderfully stringent [5]. Using the experimental limits on EP violation, we reach the constraints shown in Figure 2. We take as free parameters $g$, $v$ and $\lambda$. In Figure 2 we fix $\lambda = 1$ and plot results in the plane $g, v$.

Figure 2: In this Figure we fix $\lambda = 1$. The solid red curve stands for the limit obtained using EP tests, and the red-shadowed area is the excluded region in the parameter space. The red dot-dashed line stands for the values of $g$ and $v$ which lead to $B_c = 1$ G. The solid black line corresponds to the values for which $m_A = 10^{-14}$ eV, the experimental upper bound (1), and the barred area is the region excluded by this experiment. The green line is the minicharged limit (13), and the corresponding excluded region is colored in green.

The new potential in (11) appears in the broken phase of the $U(1)_{em}$ symmetry. This happens when the background magnetic field is below the critical value

$$B_c = \frac{\lambda v^2}{g}$$

(See for example [6].) The relevant experiments on EP-violation which we use are performed in the terrestrial magnetic field $B_\oplus \simeq 1$ G. It is for this reason that the region of the parameter space which we are able to exclude is the one above the solid-red curve in Figure 2 but extending up only until the critical line $B_c = 1$ G. Above this line, $B_c < B_\oplus$ on a $B_\oplus$ coherence length about the Earth radius $R_\oplus \sim 10^3$ km $\gg m_h^{-1}$, therefore the
symmetry is restored and the process in Figure 2 is not generated. Of course our bound does not apply in such a region.

In Figure 2 we also show the line corresponding to \( m_A = 10^{-14} \) eV, corresponding to Eq. (1), and where we make use of (6). The region above this line is experimentally excluded. However, the exclusion is only valid in the broken phase, so it is does not go beyond values for which \( B_c < B_{\odot} \) because the experimental bound leading to (1) is performed in a terrestrial laboratory. Notice that the limit (1) is valid in all generality because in the restored phase we actually have \( m_A = 0 \).

In the broken phase the vertex \( h\gamma\gamma \) is also constrained by \( h \)-emission from stellar systems due to a Primakoff-like process. Using the standard procedure [7] we get the limit \( vg^2 \lesssim 10^{-7} \) eV, which is much weaker than the others limits we consider in this paper.

Let us now consider the region in Figure 2 on the left of the critical line, where symmetry is restored, corresponding to values of the parameters leading to \( B_c < 1 \) G. To constrain this region we should look for effects of a light scalar particle with a small electric charge \( g \). Such a particle would be emitted from stellar cores, which have magnetic fields \( B > 1 \) G. The main production processes is plasmon decay into scalar pairs which leads to [7, 8]

\[
\left(13\right)
g < 10^{-14}.
\]

There are other (weaker) contraints on minicharged particles [8] which we do not plot in the Figure.

In Figure 2 we have fixed \( \lambda = 1 \). Just to illustrate how things change with \( \lambda \), we present in Figure 3 the results for \( \lambda = 10^{-6} \). We see how the limits depending on \( \lambda \) get shifted, but the parameters of the model are still quite constrained.

![Figure 3: Same than Figure 2 with \( \lambda = 10^{-6} \) fixed.](image-url)
In conclusion, in this paper we have considered the Higgs model for a photon mass and we have showed that there are stringent constraints on the model. We have distinguished among cases where symmetry is broken and cases where the symmetry is restored. In the broken phase, there are one-loop diagrams which lead to a Yukawa coupling of the Higgs to charged particles. The corresponding EP-violation is severely constrained by existing experiments. We have also considered the constraints coming from the existing Cavendish-type laboratory limit on $m_A$ and from potential effects of minicharged particles in stellar evolution. All in all, we are able to present the excluded regions in the parameter space of the massive photon Higgs-model.

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