Enhanced axion photon coupling in GUT with hidden photon

Norimi Yokozaki

Department of Physics, Tohoku University,
Sendai, Miyagi 980-8578, Japan

Abstract

We show that the axion-photon coupling is enhanced, if the gauge coupling unification is realized by a large kinetic mixing $\chi = \mathcal{O}(0.1)$ between $\mathrm{U}(1)_Y$ and unbroken hidden $\mathrm{U}(1)_H$. The key ingredient is that the $\mathrm{U}(1)_H$ gauge coupling should be rather large to induce large χ, leading to enhanced contributions to the electromagnetic anomaly from hidden matter fields. We find that the axion-photon coupling is enhanced by about a factor of 10 - 100 with respect to the GUT-axion models with $E/N = 8/3$.

1 Introduction

The axion, a, is a pseudo-Nambu-Goldstone boson associated with spontaneous breakdown of a global $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry in the Peccei-Quinn (PQ) mechanism [1–4]. The axion provides not only a solution to the strong CP problem but also an explanation for the observed dark matter [5–7].

The axion has been searched for by numerous experiments (see e.g. Refs. [8,9] for recent reviews). Many of the on-going and planned experiments utilize the axion-photon coupling,

$$\mathcal{L} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \tag{1}$$

where $F_{\mu\nu}$ is the photon field strength, and $\tilde{F}^{\mu\nu}$ denotes its dual. Therefore, the size of the axion-photon coupling $g_{a\gamma\gamma}$ is a very important input for such experiments.

Another important motivation for physics beyond the standard model (SM) is grand unified theories (GUTs). In a non-supersymmetric GUT, however, the unification scale tends to be too low to satisfy the proton decay constraint. Moreover, the gauge couplings fail to unify at a single scale. One of the remedies for the gauge coupling unification is to add a massless hidden photon which has a large kinetic mixing with hypercharge, $\mathrm{U}(1)_Y$ [10]. According to the recent analysis using the two-loop renormalization group (RG) equations [11], the unification scale is shown to be at $10^{16.5}$ GeV and the required kinetic mixing is $\chi(m_Z) \approx 0.37$. Interestingly, the unification with a hidden photon is rather robust against adding visible or hidden matters [11, 12]. This finding enables us to incorporate the axion into the framework in a consistent manner.

Here, we study the axion-photon coupling in a GUT scenario where a massless hidden photon has a large kinetic mixing with $\mathrm{U}(1)_Y$. Since the kinetic mixing between $\mathrm{U}(1)_Y$ and $\mathrm{U}(1)_H$ is induced by one-loop diagrams with bi-charged particles running in the loop, it requires rather strong hidden $\mathrm{U}(1)_H$ gauge coupling [11, 12]. As we shall see, the large kinetic mixing and strong $\mathrm{U}(1)_H$ gauge coupling enhance the electromagnetic anomaly, and the axion coupling to photons can be enhanced. Such enhancement is advantageous for the axion search experiments utilizing the the axion photon coupling.

2 Axion coupling to photons and kinetic mixing

First, let us briefly review the standard case without $\mathrm{U}(1)_H$. We introduce a single complex scalar field ϕ to break the global $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry spontaneously. The potential for ϕ is given by

$$V = \lambda_{PQ} \left(|\phi|^2 - \frac{v_{PQ}^2}{2} \right)^2, \tag{2}$$

with $\lambda_{PQ} > 0$, and ϕ contains the axion in its phase component:

$$\phi = \frac{v_{PQ} + \rho(x)}{\sqrt{2}} \exp\left(i \frac{a(x)}{v_{PQ}} \right). \tag{3}$$

The field $\rho(x)$ has a large mass around v_{PQ}, and it is irrelevant for our discussion.

The global $\mathrm{U(1)_{PQ}}$ symmetry is assumed to be explicitly broken by the QCD anomaly. For this purpose, one introduces heavy PQ fermions, $\psi_L^{(i)}$ and $\psi_R^{(i)}$, which couple to ϕ as

$$\sum_i \phi\, \bar{\psi}_L^{(i)} \psi_R^{(i)} + \mathrm{h.c.} \tag{4}$$

Here and in what follows we assign PQ charges 1 and 0 on $\psi_L^{(i)}$ and $\psi_R^{(i)}$, respectively. The PQ fermions include PQ quarks charged under $\mathrm{SU(3)}_C$. Through one-loop diagrams involving the PQ quarks, the axion couples to gluons as

$$\frac{g_s^2}{32\pi^2 f_a} a\, G^a_{\mu\nu} \tilde{G}^{a\mu\nu}, \tag{5}$$

where $G^a_{\mu\nu}$ is the gluon field strength, $\tilde{G}^{a\mu\nu}$ is its dual, and $f_a = v_{PQ}/N_{DW}$ is the decay constant of the QCD axion. In the above case, N_{DW} is equal to the number of the heavy PQ quarks. The axion acquires a mass due to topological fluctuations of the gluon fields in QCD [13],

$$m_a = 5.70(7)\, \mu\mathrm{eV} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right). \tag{6}$$

which is inversely proportional to f_a.

In general, the QCD axion also couples to photons through the electromagnetic anomaly and mixings with neutral mesons. The axion-photon coupling $g_{a\gamma\gamma}$ in Eq.(1) is given by [13]

$$g_{a\gamma\gamma} = \frac{\alpha_{\mathrm{EM}}}{2\pi f_a} \left(\frac{E}{N} - 1.92(4) \right), \tag{7}$$

where α_{EM} is the fine-structure constant, and E and N are the electromagnetic and color anomaly coefficients given by

$$E = \sum_i (Q_{\mathrm{EM}}^{(i)})^2 Q_{\mathrm{PQ}}^{(i)}, \quad N\delta_{ab} = \sum_i \mathrm{Tr}\lambda_a \lambda_b Q_{\mathrm{PQ}}^{(i)}, \tag{8}$$

where $Q_{\mathrm{EM}}^{(i)}$ is the electric charge of $\psi^{(i)}$, $Q_{\mathrm{PQ}}^{(i)}$ the PQ charge of $\psi_L^{(i)}$, λ_a the generators for the PQ quarks under SU(3). For the fundamental representation of $\mathrm{SU(3)}_C$, we have $N = \frac{1}{2}\sum Q_{\mathrm{PQ}}$. The ratio of the electromagnetic and color anomaly coefficients, E/N, is equal to 8/3 if the PQ fermions form complete multiplets under $\mathrm{SU(5)_{GUT}}$, and equal to 0 if the PQ fermions do not carry any electric charges. So the axion-photon coupling is determined by the gauge coupling constant and the anomaly coefficient.

Next, we consider the effect of $\mathrm{U(1)}_H$ and its kinetic mixing with $\mathrm{U(1)}_Y$. In the original basis where the kinetic mixing is present, the kinetic terms of the hypercharge and hidden gauge bosons, $A'_{Y\mu}$ and $A'_{H\mu}$, are

$$\mathcal{L}_K = -\frac{1}{4} F'^{\mu\nu}_Y F'_{Y\mu\nu} - \frac{1}{4} F'^{\mu\nu}_H F'_{H\mu\nu} - \frac{\chi}{2} F'^{\mu\nu}_Y F'_{H\mu\nu}, \tag{9}$$

where $F'_{\mu\nu}$ and $F'_{H\mu\nu}$ are field strengths of $\mathrm{U(1)}_Y$ and $\mathrm{U(1)}_H$, respectively. Let us introduce a PQ fermion $\psi(q_Y, q_H)$ charged under $\mathrm{U(1)}_Y$ and $\mathrm{U(1)}_H$. The relevant part of the Lagrangian is

$$\begin{aligned} \mathcal{L}_\psi &= -(k\phi\, \bar{\psi}_L \psi_R + h.c.) \\ &+ \bar{\psi}\gamma^\mu [q_Y g'_Y A'_{Y\mu} + q_H g_H A'_{H\mu}]\psi, \end{aligned} \tag{10}$$

where g'_Y and g_H are gauge couplings of $\mathrm{U(1)}_Y$ and $\mathrm{U(1)}_H$ in the original basis.

One can make the gauge bosons canonically normalized by the following transformation:

$$A'_{Y\mu} = \frac{A_{Y\mu}}{\sqrt{1-\chi^2}}, \quad A'_{H\mu} = A_{H\mu} - \frac{\chi}{\sqrt{1-\chi^2}} A_{Y\mu}, \tag{11}$$

$$\mathcal{L}_K = -\frac{1}{4} F^{\mu\nu}_Y F_{Y\mu\nu} - \frac{1}{4} F^{\mu\nu}_H F_{H\mu\nu}. \tag{12}$$

Then, in the canonical basis, the gauge interaction terms of ψ are given by

$$\begin{aligned} \bar{\psi}\gamma^\mu(q_Y g'_Y A'_{Y\mu} + q_H g_H A'_{H\mu})\psi = \\ + \bar{\psi}\gamma^\mu[(q_Y - q_{\rm eff}) g_Y A_{Y\mu} + q_H g_H A_{H\mu}]\psi, \end{aligned} \tag{13}$$

with

$$g_Y = \frac{g'_Y}{\sqrt{1-\chi^2}}, \quad q_{\rm eff} = q_H \frac{\chi}{\sqrt{1-\chi^2}} \frac{g_H}{g_Y}. \tag{14}$$

One can see that hypercharge gauge coupling g_Y in the canonical basis is larger than g'_Y in the original basis, while g_H remains unchanged under the transformation. Note that the hidden charged particle acquires an effective hypercharge $q_{\rm eff}$ in the canonical basis even if $q_Y = 0$. In this section we set $q_Y = 0$ for simplicity. (In the next section we also consider a case with $q_Y \neq 0$.)

Due to the effective hypercharge, the hidden charged particle also contributes to the electromagnetic anomaly. Its contribution ΔE is

$$\Delta E = \frac{q_H^2 \chi^2}{1-\chi^2} \frac{g_H^2}{g_Y^2} \tag{15}$$

where the right-hand side is evaluated at the mass of ψ, $m_\psi = k v_{PQ}/\sqrt{2}$. Note that $g_{a\gamma\gamma}$ can be significantly enhanced for $\chi = \mathcal{O}(0.1)$ and $q_H g_H = \mathcal{O}(1)$. For instance, we obtain $\Delta E \approx 23$ for $\chi = 0.44$, $q_H g_H = 4.4$ and $g_Y = 0.45$, where those values are motivated by the GUT scenario with $m_\psi = 10^{16}$ GeV.

3 Enhanced axion-photon coupling in GUT with U(1)$_H$

We have shown that $g_{a\gamma\gamma}$ is significantly enhanced if both χ and g_H are large. In fact, such large χ and g_H are strongly favored by the GUT with U(1)$_H$, as we shall see below. Here and in what follows we consider only complete multiplets under SU(5)$_{\rm GUT}$.

Firstly, the SM gauge couplings unify at around $M_{\rm GUT} = 10^{16.5}$ GeV with the kinetic mixing of $\chi(m_Z) \approx 0.37$ according to the analysis using the two-loop RGEs [11]. The unification is essentially determined only by $\chi(m_Z)$ and is insensitive to the size of g_H nor the presence of visible and hidden matter fields at an intermediate scale [11, 12].

Secondly, a rather large g_H is required to induce such large kinetic mixing via loop diagrams involving bi-charged fields. To see this, let us introduce N_f bi-charged matter fields, Ψ_{5_i}, which transform as **5** under SU(5)$_{\rm GUT}$ and has U(1)$_H$ charge of $q_H = -1$. In order for Ψ_{5_i} to induce a large kinetic mixing at the GUT scale, one needs to pick up GUT-breaking effects because of the vanishing sum of hypercharge in the GUT complete multiplets. After the GUT breaking, Ψ_{5_i} generically splits into SU(3)$_C$ triplet Ψ_{D_i} and SU(2)$_L$ doublet $\Psi_{\bar{L}_i}$, respectively;

$$-\mathcal{L} \supset \sum_{i=1}^{N_f} \left(M_5 \overline{\Psi}_{5_i} \Psi_{5_i} + k \overline{\Psi}_{5_i} \langle \Sigma_{24} \rangle \Psi_{5_i} \right) = \sum_{i=1}^{N_f} \left(M_D \overline{\Psi}_{D_i} \Psi_{D_i} + M_L \overline{\Psi}_{\bar{L}_i} \Psi_{\bar{L}_i} \right), \tag{16}$$

where $M_5 \sim M_{\rm GUT}$, Σ_{24} is a GUT breaking Higgs, $g_{\rm GUT}$ is a coupling constant of SU(5)$_{\rm GUT}$, and M_D and M_L are masses of Ψ_{D_i} and $\Psi_{\bar{L}_i}$, respectively. Then, the induced kinetic mixing at one-loop level is estimated as

$$\begin{aligned} \chi(M_{\rm GUT}) &\approx 0.12 N_f \left(\frac{g_{\rm GUT}}{0.53} \right) \\ &\times \left[\frac{g_H(M_{\rm GUT})}{4\pi} \right] \left[\frac{\ln(M_D/M_L)}{\ln 4} \right]. \end{aligned} \tag{17}$$

We see that $N_f = \mathcal{O}(1)$ and $g_H(M_{\rm GUT}) \sim 4\pi$ induces the kinetic mixing of $\chi(M_{\rm GUT}) = \mathcal{O}(0.1)$ with a slight mass splitting between M_D and M_L.

With the large χ and g_H motivated by the GUT with U(1)$_H$, the axion-photon coupling $g_{a\gamma\gamma}$ is significantly enhanced. We consider the following two cases:

$$\begin{aligned} &\text{Case (i)} : \mathcal{L} \supset - \left[\sqrt{2}\phi(\overline{\psi}_{5L}\psi_{5R} + \overline{\psi}_{HL}\psi_{HR}) + h.c. \right], \\ &\text{Case (ii)} : \mathcal{L} \supset - \left[\sqrt{2}\phi \overline{\psi}^{\rm b}_{5L} \psi^{\rm b}_{5R} + h.c. \right], \end{aligned} \tag{18}$$

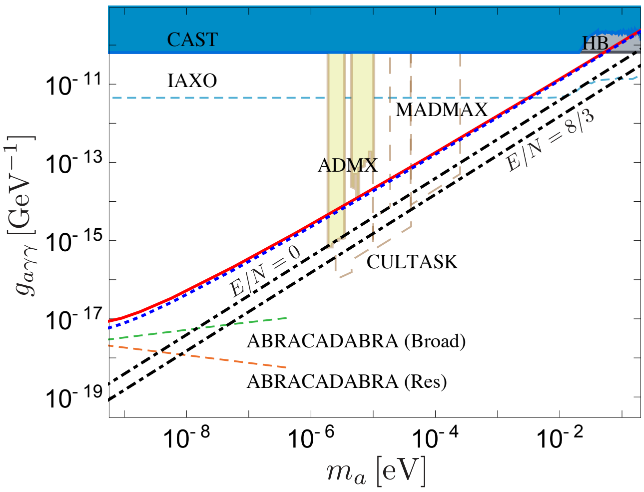

Fig. 1: The predicted axion-photon couplings as a function of the axion mass and experimental constraints. The sensitivity reaches of future experiments are shown as dashed-lines. The figure is taken from Ref. [14].

where ψ_H is a hidden matter field with a charge of $q_H = 1$, which is a SM gauge singlet; $\psi_5(0)$ and $\psi_5^{\flat}(-1)$ transform as **5** under $\mathrm{SU}(5)_{\mathrm{GUT}}$ and their $\mathrm{U}(1)_H$ charges are shown in the parentheses. In Fig 1, we show the predicted $g_{a\gamma\gamma}$ in the cases (i) and (ii), as well as experimental/astrophysical constraints. We take $\chi(m_Z) = 0.365$. The hidden gauge coupling, g_H, is taken as the largest possible value for a fixed f_a, avoiding the Landau pole below the GUT scale. The blue dotted (red solid) line corresponds to the case (i) (case (ii)), where the mass of the matter fields are set to be f_a. Interestingly, some part of the predicted region is already excluded by the ADMX experiment [15,16], and a large part will be tested by future axion haloscopes such as ADMX [17], CULTASK [18], MADMAX [19], ABRACADABRA [20]. The enhanced $g_{a\gamma\gamma}$ can be also reached by the next generation helioscopes. The sensitivity reach of IAXO [16,21] is shown as blue-dashed line.

For comparison, the predicted $g_{a\gamma\gamma}$ in the usual case without $\mathrm{U}(1)_H$ are also shown ($E/N = 8/3$ and $E/N = 0$). Here, $E/N = 8/3$ corresponds to the case with $\mathcal{L} \supset -\sqrt{2}\phi(\overline{\psi}_{5L}\psi_{5R} + h.c.)$, which preserves the gauge coupling unification. We see that $g_{a\gamma\gamma}$ in the case (ii) is enhanced by about a factor 10 - 100 for $f_a = 10^{10}$-10^{16} GeV compared to the case of $E/N = 8/3$.

4 Conclusions

We have shown that the axion-photon coupling is enhanced, if the gauge coupling unification is realized by a large kinetic mixing between $\mathrm{U}(1)_Y$ and unbroken hidden $\mathrm{U}(1)_H$. The $\mathrm{U}(1)_H$ gauge coupling should be rather large to induce the large kinetic mixing. Consequently, the axion-photon coupling is enhanced by about a factor 10 - 100 for $f_a = 10^{10}$-10^{16} GeV, which can be tested in on-going and future experiments.

References

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).

[2] R. D. Peccei and H. R. Quinn, Phys. Rev. D **16**, 1791 (1977).

[3] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978).

[4] F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[5] J. Preskill, M. B. Wise and F. Wilczek, Phys. Lett. **120B**, 127 (1983).

[6] L. F. Abbott and P. Sikivie, Phys. Lett. **120B**, 133 (1983).

[7] M. Dine and W. Fischler, Phys. Lett. **120B**, 137 (1983).

[8] P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner and K. A. van Bibber, Ann. Rev. Nucl. Part. Sci. **65**, 485 (2015) [arXiv:1602.00039 [hep-ex]].

[9] I. G. Irastorza and J. Redondo, arXiv:1801.08127 [hep-ph].

[10] J. Redondo, arXiv:0805.3112 [hep-ph].

[11] R. Daido, F. Takahashi and N. Yokozaki, Phys. Lett. B **768**, 30 (2017) [arXiv:1610.00631 [hep-ph]].

[12] F. Takahashi, M. Yamada and N. Yokozaki, Phys. Lett. B **760**, 486 (2016) [arXiv:1604.07145 [hep-ph]].

[13] G. Grilli di Cortona, E. Hardy, J. Pardo Vega and G. Villadoro, JHEP **1601**, 034 (2016) [arXiv:1511.02867 [hep-ph]].

[14] R. Daido, F. Takahashi and N. Yokozaki, Phys. Lett. B **780**, 538 (2018) [arXiv:1801.10344 [hep-ph]].

[15] S. J. Asztalos *et al.* [ADMX Collaboration], Phys. Rev. Lett. **104**, 041301 (2010) [arXiv:0910.5914 [astro-ph.CO]].

[16] G. Carosi, A. Friedland, M. Giannotti, M. J. Pivovaroff, J. Ruz and J. K. Vogel, arXiv:1309.7035 [hep-ph].

[17] S. J. Asztalos *et al.* [ADMX Collaboration], Phys. Rev. D **69**, 011101 (2004) [astro-ph/0310042].

[18] E. Petrakou [CAPP/IBS Collaboration], EPJ Web Conf. **164**, 01012 (2017) [arXiv:1702.03664 [physics.ins-det]].

[19] A. Caldwell *et al.* [MADMAX Working Group], Phys. Rev. Lett. **118**, no. 9, 091801 (2017) [arXiv:1611.05865 [physics.ins-det]].

[20] Y. Kahn, B. R. Safdi and J. Thaler, Phys. Rev. Lett. **117**, no. 14, 141801 (2016) doi:10.1103/PhysRevLett.117.141801 [arXiv:1602.01086 [hep-ph]].

[21] I. G. Irastorza *et al.*, JCAP **1106**, 013 (2011) [arXiv:1103.5334 [hep-ex]].