Electroweak Axion in Light of GRB221009A

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Very high energy (VHE) photons may have a higher survival rate than that expected in standard-model physics, as suggested by the recently reported gamma ray burst GRB221009A. While a photon-axion like particle (ALP) oscillation can boost the survival rate of the VHE photons, current works have not been based on concrete particle models, leaving the identity of the corresponding ALP unclear. Here, we show that the required ALP scenario is consistent with the electroweak axion with an anomaly free Z_{10} Froggatt–Nielsen symmetry.

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Recently, an unexpectedly bright and long-duration gamma ray burst (GRB), GRB221009A, has been detected at redshift $z = 0.15$ (corresponding to a comoving distance of $\sim 600\,\mathrm{Mpc}$).[1] LHAASO reported more than 5000 very-high-energy (VHE) photons with energies up to $\sim 18\,\mathrm{TeV}$ associated with this event.[2] Later, Carpet-2 reported a 251 TeV photon-like air shower.[3]

The detection of VHE photons at such a distance is difficult to explain with conventional physical processes. In particular, due to the interaction with the extragalactic background light (EBL) via an electron-positron pair production, VHE photons have a large optical depth and their survival rate is extremely low.[4]

While the GRB221009A anomaly of VHE photons still needs close examinations, it is soon pointed out in Refs. [5,6] that the survival rate can be significantly increased by a photon-ALP oscillation. The VHE photons may convert back and forth to photon-axion like particles (ALPs) in the presence of a magnetic field in the host galaxy, the intergalactic medium and the Milky Way. During the ALP phase, they evade the interaction with EBL, and hence the optical depth is reduced. With the benchmark ALP mass $m_A = 10^{-10}\,\mathrm{eV}$ and photon-ALP coupling constant $g_{A\gamma\gamma} = 0.5 \times 10^{-11}\,\mathrm{GeV}^{-1}$, the survival rate for photons with $E \gtrsim 10^{13}\,\mathrm{eV}$ is significantly boosted.[5] This benchmark value of $g_{A\gamma\gamma} = 0.5 \times 10^{-11}\,\mathrm{GeV}^{-1}$ is consistent with the constraints from both the star cooling effects (see Ref. [7] and references therein) and laboratory experiments.[8] The benchmark ALP mass is within the region of ALP mass ($m_A > 10^{-12}\,\mathrm{eV}$) that allows such a high $g_{A\gamma\gamma}$.[7]

However, the suggested ALP mass is far smaller than that of the QCD axion given $g_{a\gamma} \simeq 10^{-11}\,\mathrm{GeV}^{-1}$. In this Letter, we point out that the suggested parameter space is consistent with the electroweak (EW) axion whose mass is generated by the electroweak instantons.[9,10]

The EW axion is a hypothetical pseudo-Nambu–Goldstone boson field that couples to the $SU(2)$ EW gauge fields with the following interaction:

$$\mathcal{L} \supset \frac{g_2^2}{32\pi^2}\frac{A}{F_A} W^i_{\mu\nu}\widetilde{W}^{i\mu\nu}, \tag{1}$$

where $W^i_{\mu\nu}$ ($i = 1, 2, 3$) is the weak $SU(2)$ gauge field tensor and $\widetilde{W}^{i\mu\nu}$ is its dual tensor. (We consider that the Planck scale $M_{\rm Pl} \simeq 2.4 \times 10^{18}\,\mathrm{GeV}$ is the cut-off scale of the theory as explained in Ref. [11].) The EW axion was originally proposed to explain why the age of the universe appeared to be shorter than that of some old stars.[9] The potential generated by the EW instanton effect is comparable to the magnitude of dark energy density observed.[9,10] (It is also shown to be able to explain the recently observed cosmic birefringence.[11,12]) The version considered in Ref. [10] is a supersymmetric model and the EW instanton effect generates the axion potential, which reads

$$V_A = \frac{\Lambda_A^4}{2}\big[1 - \cos(A/F_A)\big], \tag{2}$$

with

$$\begin{aligned}\Lambda_A^4 &\simeq 2e^{-\frac{2\pi}{\alpha_2(M_{\rm Pl})}} c\,\epsilon^{10} m_{3/2}^3 M_{\rm Pl} \\ &\simeq c\Big(\frac{\epsilon}{1/17}\Big)^{10}\Big(\frac{m_{3/2}}{1\,\mathrm{TeV}}\Big)^3 (1.4\times 10^{-3}\,\mathrm{eV})^4,\end{aligned} \tag{3}$$

where c is a dimensionless constant of $\mathcal{O}(1)$, $\epsilon \simeq 1/17$ is the suppression factor due to the Froggatt–Nielsen $U(1)_{\rm FN}$ flavor symmetry, $m_{3/2}$ is the graviton mass and F_A is the decay constant. (This result does not change even if some $SU(2)$ charged particles exist at the intermediate energy scale owing to the SUSY miracle.[10]) The axion potential Eq. (2) gives us the EW axion mass m_A around the potential minimum as

$$\begin{aligned}m_A &= \frac{\Lambda_A^2}{\sqrt{2}F_A} \\ &\simeq \Big(\frac{\epsilon}{1/17}\Big)^{10}\Big(\frac{m_{3/2}}{1\,\mathrm{TeV}}\Big)^{3/2}\Big(\frac{M_{\rm Pl}}{F_A}\Big)\times 6\times 10^{-34}\,\mathrm{eV},\end{aligned} \tag{4}$$

taking $c = 1$.

The EW axion has, in general, a coupling to the electromagnetic gauge fields as

$$\mathcal{L} \supset -c_\gamma \frac{\alpha}{4\pi}\frac{A}{F_A} F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{5}$$

where $\alpha \simeq 1/137$ is the fine structure constant, c_γ is an anomaly coefficient, $F_{\mu\nu}$ and $\tilde{F}^{\mu\nu}$ are the Faraday tensor

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and its dual. The EW axion interaction to the weak gauge field in Eq. (2) itself leads to the above axion-photon coupling after the electroweak phase transition. In this minimal model, $c_\gamma = 1$,[11] which we assume below. (While c_γ is defined via Eq. (6), it can have other contributions in some models. It is in a minimal model as considered here that we have $c_\gamma = 1$.) We identify the EW axion-photon coupling constant as

$$g_{A\gamma\gamma} = \frac{c_\gamma \alpha}{\pi F_A}. \tag{6}$$

The benchmark value $g_{A\gamma\gamma} = 0.5 \times 10^{-11}\,\mathrm{GeV}^{-1}$ corresponds to $F_A = 5 \times 10^8\,\mathrm{GeV}$, which gives too a small EW axion mass $m_A \simeq 10^{-22}\,\mathrm{eV}$ for $m_{3/2} = 10\,\mathrm{TeV}$ compared to the required $m_A \simeq 10^{-10}\,\mathrm{eV}$ taken in Ref. [5].

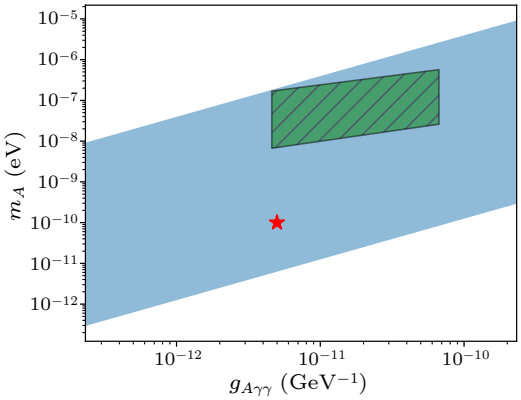

Fig. 1. Parameter space in the EW axion model with an anomaly free Z_{10} Froggatt–Nielsen symmetry. The shaped band corresponds to that with a range of the graviton mass $m_{3/2} = 1$–$1000\,\mathrm{TeV}$. The red star denotes the benchmark parameters adopted in Ref. [5]. The green and hatched region represents the constraint given in Ref. [13].

However, the above discussion has another option of flavor symmetry, in which we have assumed the Froggatt–Nielsen $U(1)_{\mathrm{FN}}$ flavor symmetry. This symmetry must be a global symmetry since it has gauge anomalies. However, a discrete Z_{10} subgroup of the $U(1)_{\mathrm{FN}}$ is anomaly free and can be a gauge symmetry.[14,15] If we assume this anomaly-free Z_{10} gauge symmetry, we can remove the suppression factor ϵ^{10}. In that case, the EW axion mass is given by[14,15]

$$m_A \simeq \left(\frac{m_{3/2}}{1\,\mathrm{TeV}}\right)^{3/2}\left(\frac{M_{\mathrm{Pl}}}{F_A}\right) \times 1.2 \times 10^{-21}\,\mathrm{eV}. \tag{7}$$

Then, for $g_{A\gamma\gamma} = 0.5 \times 10^{-11}\,\mathrm{GeV}^{-1}$ (again corresponding to $F_A = 5 \times 10^8\,\mathrm{GeV}$), we get an EW axion mass $m_A \simeq 10^{-10}\,\mathrm{eV}$ for $m_{3/2} \simeq 7\,\mathrm{TeV}$, which is well consistent with the benchmark ALP mass taken in Ref. [5]. We show the predicted mass-coupling constant relation of the EW axion in Fig. 1 taking the graviton mass $m_{3/2} = 1$–$1000\,\mathrm{TeV}$ which is consistent with experimental constraints.[16,17] For the relevant range of m_A, this value of $g_{A\gamma\gamma}$ (and hence F_A) is allowed by the constraint $g_{A\gamma\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$ from the CERN Axion Solar Telescope (CAST).[8]

We have shown that the ALP scenario to boost the survival rate of VHE photons is consistent with the EW axion. Since the required coupling constant $g_{A\gamma\gamma}$ is only about one order of magnitude lower than the constraint from CAST that searches for hypothetical ALPs emitted from the Sun,[8] we may be able to detect the EW axion by the next-generation solar axion experiment such as IAXO.[18–21] It should be pointed out that a significant portion of parameter space of this version of EW axion, especially the parameter space required to explain the GRB221009A anomaly obtained in another analysis[13] can be probed by the future Any Light Particle Search (ALPS-Ⅱ) laboratory experiment.[22]

Note Added. After our work appeared on arXiv, we found Ref. [13] that explores the ALP parameter space and explains the increased survival rate of the VHE photos. While the result of Ref. [13] is somewhat different from the benchmark parameters adopted in Ref. [5] due to different scenarios considered, it is consistent with the predicted mass-coupling constant relation of the EW axion. We show in addition the constraint from Ref. [13] to Fig. 1. Note that the lower bound of m_A will be smaller if the intergalactic magnitude field is smaller.[13]

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