Lepton flavour violation from an anomaly-free leptophilic axion-like particle

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Abstract

Motivated by the recent Xenon1T result, we study a leptophilic flavour-dependent anomaly-free axion-like particle (ALP) and its effects on charged-lepton flavour violation (CLFV). We present two representative models. The first one considers that the ALP originates from the flavon that generates the charged-lepton masses. The second model assumes a larger flavour symmetry such that more general mixings in the charged-lepton are possible, while maintaining flavour-dependent ALP couplings. We find that a keV ALP explaining the Xenon1T result is still viable for lepton flavour violation and stellar cooling astrophysical limits. On the other hand, if the Xenon1T result is confirmed, future CLFV measurements can be complementary to probe such a possibility.

I. INTRODUCTION

Recently, the Xenon collaboration reported the observation of an excess in the electron recoiling energy around the keV scale in the Xenon1T detector [1]. Shortly after its announcement, a lot of theoretical work has been done to interpret the results in the context of axion-like particles (ALPs) [2–8], dark matter [9–30], neutrinos [31–39] and solar axions [40–42], which, however, are subject to stringent constraints from stellar cooling [43–45]. In this work, we focus on the ALP framework. This possibility assumes the existence of an ALP with a mass of a few keV and a relatively weak coupling to the electron. However, constraints from X-ray observations forbid the existence of an anomalous coupling of the ALP to photons for $m_a \gtrsim 0.1$ keV. An anomaly-free ALP with respect to $U(1)_{em}$ can avoid these bounds. With the SM particle content (plus right-handed neutrinos), only hypercharge and $B − L$ are anomaly-free with family universal charges, but they cannot be used to explain this excess, as hypercharge can not be broken above the electroweak scale and $B − L$ breaking generates a Majoron coupling only to neutrinos at tree-level (if the scalar has $Y = 0$). Thus, we have to consider a $U(1)$ symmetry with family-dependent charges which, as we will see, necessarily implies flavour-changing couplings between the ALP and the SM-lepton sector. If the excess is confirmed in the future, it will be necessary to investigate the lepton flavour violating signatures of this particle in low-energy experiments. In this paper, we consider the flavour violation effects induced by such anomaly-free ALP, and we show that LFV measurements are essential to probe this possibility.

II. MODELS

We consider a $U(1)_\phi$ global symmetry spontaneously broken by the vev of a complex scalar field, $\phi$, whose angular component is identified with an ALP. We propose two models with flavour dependence on the lepton sector and evaluate the importance of present and future experiments on lepton flavour violating (LFV) decays. In the first model, the presence of the ALP is directly connected to the SM flavour puzzle and the breaking of the $U(1)_\phi$ is the only responsible of the observed hierarchy among the lepton generations. Instead, Model II generalizes the previous structure assuming the existence of a larger symmetry, which includes $U(1)_\phi$, whose breaking produces the Yukawa structures at high energies. In this way, we can partly decouple the non-anomalous flavour-dependent $U(1)_\phi$ charges from the observed leptonic masses and mixings. In both models, below the $U(1)_\phi$-breaking scale, the ALP has flavour-dependent couplings.

A. Model I: hierarchical mixing

Flavour symmetries à la Froggatt-Nielsen [46] offer an attractive solution to the origin of the observed hierarchy among the charged-fermion families. In its simplest version, the spontaneous breaking of a $U(1)$ flavour symmetry by the vev of a scalar field, usually called flavon, generates it as powers of the ratio between its vev, $v_\phi$, and $\Lambda$, the scale at which the heavy fields mediating the

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processes live, $\epsilon = |v_\phi/A|$. In Model I, we identify this symmetry with the global \(U(1)_\phi\) so that the angular component of the flavon corresponds to the ALP. The case of the anomalous QCD axion has been previously explored in [47, 48], with the scalar receiving the name of flavion or axiflavon.

As usual, in flavour models, distinct mixing patterns can be derived for different charge assignments. Here we focus on the leptonic sector, hence quarks are assumed to be uncharged under the symmetry. Besides, a sufficient condition to obtain an electromagnetic anomaly-free ALP is:

$$\sum_i Q_{L_i} = 0 , \quad \sum_i Q_{e_i} = 0 . \quad (1)$$

Then, we choose the charges under \(U(1)_\phi\) of the left-handed leptons as \(L(1,0,-1)\) and those of right-handed leptons to be \(e(-1,0,1)\). Such charge assignment is crucial to generate the Froggatt-Nielsen structure. Two Higgs doublets are introduced with charge 0 and -2, and an additional \(Z_2\) symmetry is imposed as in the type-X 2HDM [49] so that the only odd fields are \(H_2 \rightarrow -H_2\), \(e \rightarrow -e\) and \(N_R \rightarrow -N_R\). The Higgses, \(H_1\) and \(H_2\), only couple to quarks and leptons, respectively. To summarize, the following particles and charges under \(U(1)_\phi \times Z_2\) are considered for Model I:

$$H_1(0; 1), \quad H_2(2; -1), \quad \phi(1; 1), \quad L(1, 0, -1; 1), e(-1, 0, 1; -1), \quad N_R(0, 0, 0; -1). \quad (2)$$

From (2), it can be seen that the anomalies cancel for both the left- and right-handed sector. The most general scalar potential is

$$V(H_1, H_2, \phi) = m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 + \lambda_1 (H_1^\dagger H_1)^2$$
$$+ \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$$
$$+ \lambda_4[H_1 \cdot H_2]^2 + m^2 H_1 \cdot H_2 + \lambda(\phi^4 - v_\phi^2)^2, \quad (3)$$

where we also add a soft breaking term \(m^2 H_1 \cdot H_2\) for the \(U(1)_\phi \times Z_2\) symmetry, then the ALP gets a mass around \(m^2/v_\phi^2\). The corresponding Yukawa terms are:

$$\mathcal{L}_Y \ni Y_{\phi} \bar{Q} H_1 u + Y_d \bar{Q} H_1 d + c_{ij}^e e^{n_{ij}} \bar{L}_i H_2 e_j$$
$$+ c_{ij}^n n^{n_{ij}} \bar{L}_i H_2 N_j + (M_{ij})_{\phi} N_R, N_{R}, \quad (4)$$

with \(c_{ij}^e\) and \(c_{ij}^n\) \(\mathcal{O}(1)\) coefficients and \(n_{ij} = [q_L - q_e + q_{H_2}], \quad n_{ij}^e = [q_L - q_e + q_{H_2}]. \quad (5)\)

Once the EW symmetry is broken by the Higgs vev, \(v_{H_2}\), the Dirac mass matrices are simply given by

$$M_{ij}^e = \frac{v_{H_2}}{\sqrt{2}} c_{ij}^e e^{n_{ij}}, \quad M_{ij}^n = \frac{v_{H_2}}{\sqrt{2}} c_{ij}^n e^{n_{ij}}. \quad (6)$$

At leading order, the charged lepton masses are

$$\frac{m_e}{m_\tau} = \frac{(c_{12}^e - c_{23}^e)^2}{c_{23}^e - 1} \epsilon^4, \quad \frac{m_\mu}{m_\tau} = (1 - c_{23}^e)^2 \epsilon^2. \quad (7)$$

Taking $\epsilon = 0.1$, the following matrix of \(c_{ij}^e\) coefficients reproduce the correct hierarchy between generations:

$$c_{ij}^e = \begin{pmatrix} 1.0 & 1.6 & 1.0 \\ 1.0 & -2.7 & 1.0 \end{pmatrix}. \quad (8)$$

Since the tau mass is not suppressed by any additional factor, we expect \(v_{H_2} = \epsilon^2 v_{EW}\), with \(v_{EW} \simeq 246\) GeV. For this hierarchical scenario, the mixing pattern is

$$\left(U_{\nu}^L\right)_{ij} \approx \delta_{ij} + \epsilon^{n_{ij}}/\epsilon^{n_{ij}} \quad \text{with } i \leq j. \quad (9)$$

Then, the \(e - \mu\) mixing is \(\mathcal{O}(\epsilon) \sim 0.1\). The masses of the active neutrinos are produced through the usual type-I seesaw. Notice that, in this kind of formulations, the PMNS matrix can always be generated by a proper structure of the \(M_R\)-matrix [50].

After the breaking of the flavon symmetry, the flavon field can be parametrised as

$$\phi = \frac{1}{\sqrt{2}} (v_\phi + s) \epsilon^a/x_0, \quad (10)$$

with \(s(x)\) a CP-even scalar and \(a(x)\) the ALP. If all the interactions respect the \(U(1)_\phi \times Z_2\) symmetry, after the spontaneous breaking, \(a(x)\) should be the massless Nambu-Goldstone boson (NGB). In our model, we included a soft-breaking term, \(m^2 H_1 \cdot H_2\) to give a mass to it. Alternatively, a hidden strong sector coupling to the ALP can be assumed. In the following, we treat the ALP mass as a free parameter and, as preferred by the Xenon1T data, it should be around the keV scale.

The interaction between the pseudo Nambu-Goldstone boson (pNGB) and the charged leptons, in the mass basis, is:

$$-\mathcal{L}_{ae} = \frac{f_a}{2} \bar{e}_i \gamma^\mu (V^c_{\nu} \gamma^\nu A^e_{ij}) e_j, \quad (11)$$

where \(f_a \sim \mathcal{O}(v_\phi)\). The axial and vector couplings in eq. (11) are defined as

$$V^c_{\nu} = \frac{1}{2} \left(U_R^c \right)^T x_R U_R^c + U_L^c x_L U_L^c, \quad (12)$$

$$A^e_{ij} = \frac{1}{2} \left(U_R^c \right)^T x_R U_R^c - U_L^c x_L U_L^c, \quad (13)$$

with \(x_L\) and \(x_R\) the diagonal \(3 \times 3\) matrices whose elements are the charged-lepton \(U(1)_\phi\) charges and \(U_L, U_R\) the unitary transformations that diagonalise the mass matrices. In general, eqs. (12) and (13) induce FV effects which are subject to constraints from different experiments, as it is discussed in section III.

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1. For \(i = j\), we can always redefine the fields to have \(V^c_{\nu} = 0\) [51]
2. In our convention: \(U_R^c \dagger M_e U_R^c = \text{Diag}(m_e, m_\mu, m_\tau)\)
B. Model II: general mixing

In model II, we generalize the previous structure to allow for arbitrary leptonic mixings. To do this, we consider the $U(1)_{\phi}$ global symmetry as only part of a larger flavour symmetry, $\mathcal{F}$, that will determine the Yukawa structure with the observed hierarchy among generations in the lepton sector. In this way, the $U(1)_{\phi}$ symmetry remains flavour dependent, but masses and mixings are not fixed by the $U(1)_{\phi}$ charges. As an example, we use the same $U(1)_{\phi} \times Z_2$ charges as in Model I although now we can take $v_\phi/\Lambda \simeq \mathcal{O}(1)$. The scalar potential and Yukawa terms remain as in eqs. (3) and (4) but, in this case, we highlight that the coefficients $c_{ij}^e$ and $c_{ij}^\nu$ are NOT forced to be $\mathcal{O}(1)$. Adjusting them, different mixing patterns can be obtained. In particular, we are interested in the case of large PMNS-like mixing for charged leptons. As a typical benchmark model, we assume that the breaking of the symmetry $\mathcal{F}$ produces Yukawa couplings with PMNS-like mixing in the left-handed sector while the right-handed mixing is absent. The couplings with the ALP are determined by eqs. (12) and (13), but now

$$V(A)_{ij}^e = \frac{1}{2} \left( x_R \pm U_{PMNS}^e x_L U_{PMNS}^e \right).$$

Then, for example, we can deduce the size of the 12-couplings to be as large as $V_{12}^e = A_{12}^e \simeq 0.34$.

III. CONSTRAINTS FROM LFV AND ASTROPHYSICS

Non-universal charges of the charged leptons under the $U(1)_{\phi}$ global symmetry, together with non-trivial rotations to the mass basis, imply FV interactions between the ALP and these fermions. The absence of the anomalous coupling between the ALP and photons at tree-level makes the search for ALPs by charged-lepton flavour-violating (CLFV) processes impossible. The absence of the anomalies to the mass basis, imply FV interactions between $U(1)_{\phi}$ charges.

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TABLE I - Limits over the axion decay constant from lepton decays. The * signals future bounds. Belle-II limits are derived from the simulated result at Belle [58] by rescaling the luminosity [51].

Regarding astrophysics bounds, interesting limits can be derived from stellar evolution. In particular, the cooling of white dwarfs [59] (WD) and red giants [60, 61] (RG) impose strong constraints over the ALP interactions to matter and radiation. For massless ALP, the limits at 95% CL are

$$f_a \gtrsim 2.3 \times 10^9 \left| C_{11}^e \right| \text{ GeV},$$

$$f_a \gtrsim 1.2 \times 10^9 \left| C_{11}^\nu \right| \text{ GeV}.$$  

For ALP masses above 1 keV, the cooling rate is Boltzmann-suppressed and the limits above should be rescaled by the factor $\sqrt{\xi(m_a,T)/\xi(0,T)}$, where [61]

$$\xi(m_a,T) = \frac{1}{2\pi^2} \int_{m_a}^{\infty} E^2 \sqrt{E^2 - m_e^2} e^{E/T - 1}.$$

IV. RESULTS

In [2], the authors conclude that an ALP satisfying

$$C_{11}^e \simeq 10^{-13} \frac{f_a}{m_e}, \text{ for } m_a \in [2, 3] \text{ keV},$$

can reproduce the Xenon1T signal, together with some reported anomalies in stellar cooling [59, 61]. In the same work, it is argued that such possibility can be realised in the context of anomaly-free DM ALPs, provided that the ALP constitutes only a 7% of the total DM abundance. The discussion is however restricted to astrophysical and cosmological constraints and flavour observables are not discussed. Here, we aim to highlight the role of flavour observables to (dis)prove this kind of models.

Figures 1 and 2 show the Xenon1T favoured prediction for $f_a$, based on the result in eq.(19) (black diamond). Similarly, current and expected sensitivity from Jodidio...
FIG. 1: Results for Model I with hierarchical Yukawa couplings generated à la Froggatt-Nielsen.

FIG. 2: Results for Model II with general Yukawa matrices and mixing.

et al. [53] (green continuous line) and Mu3e [55] (red dashed line) in dedicated searches for $\mu \rightarrow e\gamma$ are displayed as a function of $m_a$. We also show the projection of the proposal by Calibbi et al. [51], MEGII-fwd (yellow dashed line), for MEGII [62] to improve the detection of the process of interest, $\mu \rightarrow e\gamma$. Finally, limits due to white dwarfs and red giants (gray shaded regions) also impose relevant bounds on our models [51].

From figure 1, we notice that testing Model I (small mixing) with LFV observables remains quite challenging, even for future sensitivities. On the other hand, scenarios with larger mixing effects in the charged-lepton sector provide better prospects. For Model II, in figure 2, we observe that while current limits are not sufficient to constrain the model, more stringent bounds coming from Mu3e or the implementation of MEGII-fwd are enough to probe this formulation. One may then conclude that LFV can clearly complement astrophysics searches and, in some cases, go beyond them. Flavoured ALP models provide a rich phenomenology to be investigated with present and future data.

A final remark about the ALP explanation to the anomalous magnetic moment of the electron and the muon can be made at this point. Two solutions have been presented in the literature to explain the observed discrepancies by means of flavour-conserving [64, 65] $\Delta a_\ell \propto m_{\ell_i}^2 |C_{ii}|^2/(16\pi^2 f_a^2)$, and flavour-violating [63], $\Delta a_\mu \propto m_{\mu}^2 |C_{12}|^2/(32\pi^2 f_a^2)$ and $\Delta a_e \propto m_e m_{\mu} C_{12}^c/(32\pi^2 f_a^2)$ ($C_{12}^c = |V_{12}^c|^2 - |A_{12}^c|^2$), interactions between an ALP and charged leptons. The models discussed in this letter contains both effects so we have evaluated the size of those contributions. We observe that the required values of $f_a$ to reproduce the observed measurement are in the range $\sim 10^{-10} - 10^{-8}$ GeV which, according to the limits derived from LFV processes, are too low and in conflict the limits collected in table I. We, therefore, conclude that our models cannot provide an explanation to these observables.

V. CONCLUSIONS

In this paper, we considered the LFV effects from a keV scale flavour-dependent ALP which is motivated by recent Xenon1T results. We find that, for a general mixing in the lepton sector, the leptonic flavour changing experiments could confirm or exclude the possibility of explaining the Xenon1T result by an ALP, while being consistent with all phenomenological and astrophysical constraints. On the other hand, if the leptonic mixing originating from the Froggatt-Nielsen symmetry are small, CKM-like, the measurement of their LFV effects would constitute a challenge for future experiments.

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