We show that a very simple solution to the strong CP problem naturally leads to Dirac neutrinos. Small effective neutrino masses emerge from a type I Dirac seesaw mechanism. Neutrino mass limits probe the axion parameters in regions currently inaccessible to conventional searches.

I. INTRODUCTION

Despite its tremendous success, the standard model has many drawbacks and theoretical loose ends. Amongst them the lack of neutrino masses and mixings [1], and of a viable dark matter candidate [2]. Both issues require new physics, beyond the standard model. Moreover, the standard model also leaves unexplained the lack of CP violation in the strong interaction [3–5]. Aware that the list of shortcomings is much longer, here we focus on whether the above three aspects may be closely interconnected in the context of the Peccei-Quinn (PQ) mechanism. In fact, there have already been recent attempts to connect it to neutrino mass generation, both in the Majorana [6–9] and Dirac [10–12] frameworks.

In axion models quarks carry a non-zero PQ charge, so two Higgs doublets \( H_u \) and \( H_d \) are typically required. In order to be phenomenologically viable, the PQ symmetry must break at high energies, implying the need for a \( SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \) singlet scalar boson, carrying PQ charge, denoted as \( \sigma \sim (1, 1, 0) \). Moreover, the \( H_{u,d} \) fields must couple to \( \sigma \) in such a way that the only \( U(1) \) symmetries are \( U(1)_Y \otimes U(1)_{PQ} \). There are two ways of doing this, depending on the form of the mixing terms in the scalar potential. These yield two possible choices for the PQ charge of \( \sigma \), that may be taken as 2 or 4, for one of the simplest Higgs doublet charge assignments. When the PQ charge is 2, the spontaneous breaking of the Peccei-Quinn symmetry can be connected to the breaking of lepton number by two units [13] leading to Majorana neutrinos [14].

In this letter we challenge the view that linking spontaneous Peccei-Quinn symmetry breaking to neutrino mass generation leads to Majorana neutrinos. This is achieved by making the alternative choice for the PQ charge. We show how it leads to a novel class of minimal axion models that effectively imply Dirac neutrinos. For definiteness, we take as reference the simplest DFSZ axion scheme [15, 16], taking the associated field with PQ charge 4. We also provide the simplest UV-completion of the new “Diraxion” scheme, where the neutrino masses are naturally small, implemented through the type-I Dirac seesaw mechanism. Neutrino mass limits, such as the recent one of the Katrin tritium \( \beta \) decay experiment [17], provide new ways to probe the axion parameter space.

II. MINIMUM SETUP

As mentioned, here we depart from the canonical choice for axion quantum numbers. We focus on the minimal DFSZ model where the Higgs fields \( H_u \) and \( H_d \) have PQ charge 2, while the symmetry breaking field \( \sigma \), associated with the axion field, has PQ charge 4. In this case there is a term in the potential of the form

\[
V_{mix}(H_u, H_d, \sigma) \propto H_u H_d \sigma^*,
\]

involving a dimensionful coupling. The crucial observation is that with such assignment as in Table I there is no way to form the dimension-five Weinberg operator for the light neutrino masses, nor any other operator with powers of \( \sigma \) and or powers of \( H_u \) and \( H_d \). Indeed, we first notice that with two Higgs doublets there are three
TABLE I: Quantum numbers in the DFSZ axion model. All fermions are left-chiral.

| Fields/Symmetry | $Q_i$ | $u^c_i$ | $d^c_i$ | $l_i$ | $l^c_i$ | $H_u$ | $H_d$ | $\sigma$ |
|-----------------|-------|--------|--------|-------|--------|-------|-------|--------|
| SU(2)$_L \times U(1)_Y$ | (2,1/6) | (1,-2/3) | (1,1/3) | (2,-1/2) | (1,1) | (2,-1/2) | (2,1/2) | (0,0) |
| $U(1)_{PQ}$ | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 4 |

We now turn to the question of generating finite Dirac neutrino masses. One option is to include the “right-handed” neutrinos $\nu_{Ri}$ with PQ charge 1. In this case the Yukawa Lagrangian is

$$L_Y = y^u_{ij} \bar{Q}_i H_u u_j + y^d_{ij} \bar{Q}_i H_d d_j + y^l_{ij} \bar{L}_i H_d l_j + y^\nu_{ij} \bar{L}_i H_u \nu_{Rj} + h.c.,$$

so that neutrinos are Dirac particles and the Yukawa couplings $y^\nu_{ij}$ must be of the order $O(10^{-12})$ in order to account for the recent Kamland bound. Such a small coupling suggests the need for a dynamical explanation. Let us now explore the possibilities to generate such a small coupling in a natural way.

III. TYPE I DIRAC SEESAW

In the presence of adequate protective symmetries, there are many pathways to generate naturally small Dirac neutrino masses. This can be done à la seesaw, using dimension-5 and/or dimension-6 operators [18–20]. Many full-fledged UV-complete seesaw-based as well as radiative theories of Dirac neutrino mass generation have been proposed [21–27]. The task here is to do the same using realizations of the PQ symmetry. For definiteness we stick to the type I seesaw mechanism.
TABLE II: Proposed assignment of our “Diraxion” model. The sequential chiral fermions $F^c$ and $F$ merge to form the Dirac fermions that mediate neutrino mass generation through Fig. 1.

| Fields/Symmetry | $Q_2^i$ | $u_i^c$ | $d_i^c$ | $L_i$ | $e_i^c$ | $\nu_i^c$ | $F_i$ | $F_i^c$ | $H_u$ | $H_d$ | $\sigma$ |
|-----------------|---------|---------|---------|-------|---------|---------|-------|---------|-------|-------|-------|
| $SU(2)_L \times U(1)_Y$ | (2,1/6) | (1,2/3) | (1,1/3) | (2,-1/2) | (1,1) | (1,0) | (1,0) | (1,0) | (2,-1/2) | (2,1/2) | (0,0) |
| $U(1)_{PQ}$     | 1       | 1       | 1       | 1     | 1       | 5       | -1    | 1       | 2     | 2     | 4     |

The sequential chiral fermions $F$ and $F_c$ merge to form the Dirac fermions that mediate neutrino mass generation through Fig. 1. The relevant neutrino mass Lagrangian will be

$$\mathcal{L}_{\text{Dirac}} = \lambda_{ij} \bar{L}_i H_u F_R^j + \kappa_{ij} \bar{F}_L^i \sigma \nu_R^j + M_{ij} \bar{F}_L^i F_R^j + h.c.$$  

For axion decay constants around $f_a \sim 10^8$ GeV, the minimum value allowed from astrophysical constraints [29], and reasonable Yukawa couplings $\sim 10^{-3}$, neutrino masses in the eV scale would correspond to the UV scale $\Lambda_{UV} \sim M_{GUT}$, which is suggestive.

Majorana seesaw mechanism. Indeed, it can lie at the Planck scale $\Lambda_{UV} \sim M_{Planck}$ or be associated to some Grand unification (GUT) group, $\Lambda_{UV} \sim M_{GUT}$.

The unusual dependence in Eq. (8) implies that the heavier – and hence the more strongly coupled – is the QCD axion, the lighter are the neutrinos. This offers the possibility of probing the QCD axion physics with neutrino physics considerations.

We start by setting $\Lambda_{UV}$ to the Planck scale $M_{Planck}$ or be associated to some Grand unification (GUT) group, $\Lambda_{UV} \sim M_{GUT}$.

For Planck-scale lepton number violation schemes see [33, 34].

Notice that this dependence is quite generic, and applies to any UV completion of the effective operator in Eq. (5).
one can use neutrino mass bounds, such as the recent Katrin results \[17\] to probe part of the axion parameters, as seen in Fig. 2. Indeed, the new neutrino mass upper bound would place an upper bound to \(f_a\), and hence a lower bound to the axion-photon coupling due to Eq. (9). One sees that neutrino experiments such as Katrin can probe the parameter space towards the bottom, where no experiment can look for axions directly. Likewise, this sensitivity would also apply for generic ALPs coupled to photons, as indicated in Fig. 2. In short, our model illustrates the interplay and potential complementarity between axion searches and neutrino experiments, which is a characteristic feature of our proposal.

In contrast, note that by choosing a lower \(\Lambda_{UV} = M_{GUT}\), the allowed parameter space in Fig. 2 would be substantially reduced.

![FIG. 2: Landscape of axion parameters \((m_a, g_{a\gamma})\), adapted from \[29\]. We show the constraints from cosmology \[35\] (green), astrophysics \[36, 37\] (blue) and haloscopes \[38, 39\] (dark red), together with the predicted QCD band (shaded yellow) and the KSVZ line (brown). The pink horizontal band illustrates neutrino masses obtained by setting \(\Lambda_{UV}\) to the Planck scale \(M_P\) and fixing Yukawa couplings in the indicated range. One sees that the Katrin limit \(m_\nu \leq 1.1\) eV \[17\] would place an upper bound on the axion decay constant, hence a lower bound on the axion-photon coupling.](image)

\begin{align*}
\text{V. UNIFICATION} \\
\end{align*}

We now comment on the fact that the quantum numbers in Tables (I) and (II) are suggestive of the idea of unification. Here we sketch an SO(10) embedding. By appropriate assignment of the PQ charges one can achieve the seesaw mechanism in Fig.1 within the framework of SO(10). For example, in addition to the three standard model families embedded in the \(16^F\) spinors, one introduces the fields:

\[
1^S_4, \ 10^S_2, \ 16^S_0, \ 1^F_{-1}, \ 1^F_5,
\]

where \(F,S\) stand for fermions and scalars, respectively. Notice the unusual embedding of the “right-handed” neutrino: while the \(F_R\) field lies in the \(16^F\) spinor, the “right-handed” piece \((\nu_R_i)\) of the standard model neutrino comes as an SO(10) singlet, with PQ charge -5, \(1^S_5\). The scalar spinor \(16^S_0\) is responsible for giving a Dirac mass to \(F\), breaking SO(10) down to SU(5), but preserving the PQ symmetry. The latter will be broken by \(1^S_1\). As usual, the \(H_u, H_d\) fields will reside inside the \(10^S_2\). They will give masses to the charged fermions and contribute to Dirac neutrino mass generation, which in the Dirac basis of \((\bar{\nu}_L, \bar{F}_L)^T\) and \((\nu_R, F_R)\) can be written as

\[
M_{\text{seesaw}} = \begin{pmatrix}
0 \\
\kappa \langle \sigma \rangle_{1^S_1} \\
\kappa \langle \chi \rangle_{16^S_0}
\end{pmatrix}
\]

where \(\lambda, \kappa, \kappa_F\) are the Yukawa couplings. The resulting
light seesaw neutrino mass is similar to Eq. (8) above, by identifying $\Lambda_{UV}$ in Eq. (5) with the scale of the breaking $SO(10) \to SU(5)$, $\Lambda_{UV} \sim M_{GUT}$. Of course, for a fully consistent GUT construction additional multiplets would be needed, though are not expected to affect the mass mechanism proposed above.

VI. CONCLUSIONS

Here we have proposed a simple solution to the strong CP problem in which neutrinos are naturally predicted to be Dirac fermions. Small effective neutrino masses, directly proportional to the PQ breaking scale, emerge from a type I Dirac seesaw mechanism. By embedding the DFSZ axion into a full-fledged neutrino mass generation setup, we have shown how neutrino mass limits provide independent probes of the axion parameters. Interestingly enough, due to the special form of Eq. (8), this new probe is complementary to those accessible to the existing axion searches. Our “Diraxion” scheme is compatible with the idea of unification, providing a counter-example to the common belief that GUTs, and in particular SO(10), must lead to Majorana neutrinos.

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