An extension of the Standard Model (SM) is studied in which two right-handed (RH) neutrinos per generation are incorporated, but considering the hypothesis of the symmetry of lepton and quark contents in order to deprive the number of RH neutrinos of freedom, generate Dirac neutrinos and accommodate naturally tiny values for their masses. The high scale type-I seesaw regime is applied to the first, ordinary RH neutrino, whereas a low scale pseudo-Dirac scenario is used for the second, adulterant RH neutrino, implying that the first RH neutrino decouples at the high scale, while the second RH neutrino survives down to the low scale to pair off in a Dirac-like form with the corresponding left-handed (LH) neutrino. The small mass and couplings of this extra RH neutrino are explained by means of the statement of the symmetry of fermionic content, only regarded as a guideline to the natural choice of parameters since it is not a proper symmetry in the Lagrangian.

**Keywords:** Dirac neutrinos; seesaw mechanism; extra right-handed neutrinos; symmetry of lepton and quark contents.

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### 1. Introduction

The tiny mass of neutrinos implied by neutrino flavor oscillation experiments is a clear indication of new physics beyond the Standard Model (SM).\(^1\) Neutrinos are massless in the SM because only left-handed (LH) neutrinos, Higgs doublets and renormalizable terms are included. The simplest possibility to generate neutrino masses is then via the incorporation of three right-handed (RH) neutrinos, maintaining the gauge and Higgs sectors of the SM. Moreover, the addition of these particles restores the chiral partners of neutrinos omitted by the SM. Allowing general couplings, such additional fermions permit to introduce both Dirac neutrino mass terms which conserve lepton number, and Majorana neutrino mass terms which violate lepton number conservation but are not forbidden by the gauge symmetry of the SM. The Dirac neutrino masses are assumed of the order of the charged lepton masses, while the Majorana masses are arbitrary, being unrelated to the electroweak scale.
There are two special limits that have been trending topics in the literature, relying on the magnitudes of Majorana masses relative to Dirac masses:

(a) The low scale pseudo-Dirac limit,\(^4\)\(^5\) in which the Majorana mass terms are assumed to be much smaller than the Dirac ones. It leads to Majorana eigenstates which are paired up into almost Dirac neutrinos, with tiny mass differences between the components of each pair. In this scenario there is a small violation of the lepton number conservation and a restoration of the symmetry between leptons and quarks in the sense of having a spectrum with equal numbers of LH and RH leptons and quarks in each generation. The smallness of Majorana masses is naturally attributed to the breaking of lepton number symmetry. However, there is no explanation of the smallness of Dirac masses relative to those of charged leptons. Moreover, the expected rich low-energy phenomenology of neutrino oscillations is essentially excluded by experiments. Thus only the Dirac limit is allowed from the viewpoint of phenomenology, although in this case the lepton number symmetry that forbids Majorana masses has an ad-hoc character.

(b) The high scale type-I seesaw limit,\(^6\)\(^9\) in which Majorana masses are supposed to be much greater than Dirac masses. The RH neutrinos are approximately Majorana mass eigenstates and become decoupled from the light, mainly LH, Majorana states. This scenario also repairs the asymmetry of the fermionic content of the SM, but provides a natural explanation for the large difference between neutrino and charged lepton masses. The lepton number conservation is restored when the tiny neutrino masses approach to zero. The possibility of a low scale seesaw regime has also been explored,\(^10\)\(^11\) where data on neutrino oscillations, charged lepton flavor violating processes and electroweak precision measurements are used to constrain their couplings.

Here the seesaw scenario for neutrino masses has been implemented by introducing extra RH neutrinos, in addition to the three RH states mentioned above. Models based on this so-called extended seesaw scenario have been proposed to allow for light neutrinos without inserting small mass scales, although using additional symmetries to forbid Dirac and/or Majorana mass terms for the extra RH neutrinos,\(^12\)\(^16\)

The seesaw mechanism predicts that massive neutrinos are Majorana fermions. However, this has been disfavored by recent experimental investigations on neutrinoless double-beta decay,\(^17\)\(^19\) the only feasible physical process with the possibility of determining at present the Majorana character of neutrinos. Although the issue on the nature of light neutrinos is still not resolved, the no observation of signals in the search for neutrino double-beta decay would strengthen their Dirac character, i.e. lighter neutrinos can be Dirac particles like charged leptons and quarks.

Our aim in this paper is to study an extended mass model with general couplings in which two RH neutrinos per generation of leptons and quarks are incorporated, giving place for a general mass matrix structure. Our main motivation is to generate Dirac neutrinos and accommodate naturally tiny values for their masses in a minimal extension of the SM, involving the popular high scale type-I seesaw scenario.
on the one hand and the low scale pseudo-Dirac scenario on the other hand. The hypothesis of the symmetry of lepton and quark contents is used to deprive the number of RH neutrinos of freedom and the seesaw mechanism is applied to allow neutrinos having small masses and appearing to have a Dirac nature, with a parameter region not excluded by experiments. At this point we stress that the symmetry of fermionic content is actually a lepton–quark correspondence but not a symmetry in the Lagrangian of the model, which means that in the electroweak sector of the SM extended with RH neutrinos one cannot define a set of transformations between leptons and quarks that keeps the Lagrangian invariant. Yet, this correspondence of contents may serve as a guideline to the natural choice of parameters leading to Dirac-like neutrinos with small masses, expecting that further studies can attach it a proper symmetry but in a different context. We do not address here aspects related with leptonic mixing angles.

The work is organized as follows. In Sec. 2 we describe the neutrino mass model in the simple case of one generation, extending the results to three families in Sec. 3. In Sec. 4 we consider the effective model at low energies. Phenomenological remarks are given in Sec. 5. In Sec. 6 we summarize our conclusions.

2. Neutrino Masses with One Left-Handed and Two Right-Handed Neutrinos

We first consider the extended scenario in the simplest case of just one generation of neutrinos, so paving the way for the three-generation extended model to be treated in the next section. Two RH neutrinos are added to the SM in the approximation of one generation, preserving its gauge and Higgs structure, i.e. only one doublet of Higgs fields. The first RH neutrino is the ordinary one denoted as $\nu_R$, which may carry a $B - L$ charge and form a doublet with its RH charged lepton partner $e_R$, as in models of left–right symmetry. The other, denoted as $\nu'_R$, is a secondary singlet with small couplings in comparison to the ones of $\nu_R$. Invoking the 't Hooft’s criterion, this smallness appears natural since a symmetry of lepton and quark contents is reestablished if these couplings are set to be zero. In particular, we start taking a light Majorana mass $m'_R$ for $\nu'_R$, and assuming a heavy $m_R$ for $\nu_R$ as in the canonical high scale type-I seesaw scenario. The question, however, is if the symmetry of lepton and quark contents is good enough to ensure the naturalness of the values chosen for the parameters of the model. As noted in Sec. 1 our assumption is that at least it serves, invoking the ’t Hooft’s argument for small numbers in the Lagrangian, as a guideline to the selection of parameters, although the lepton–quark correspondence should have attached a proper symmetry in a Lagrangian somehow connected with the SM extended with RH neutrinos, which goes beyond the scope of this work.

Following the notation of Ref. 24, the Yukawa Lagrangian containing the RH neutrinos $\nu_R$ and $\nu'_R$ and expanded with their respective Majorana mass terms,
becomes
\[
\mathcal{L} = -y_v \bar{L} \tilde{\phi} \nu_R - y'_v \bar{L} \tilde{\phi} \nu'_R - \frac{1}{2} m_R \bar{\nu}_L \nu_R - \frac{1}{2} m'_R \bar{\nu}'_L \nu'_R
\]
where \( L \) and \( \phi \) are the lepton and Higgs doublets, \( y_v \) and \( y'_v \) are the Yukawa couplings, the mixing term \( \mu' \) of \( \nu'_R \) to \( \nu_R \) is allowed, and \( \nu'_R = C \nu^T_L \). The classical mass terms after spontaneous electroweak breaking can be written as
\[
\mathcal{L}_\nu = -\frac{1}{2} \left( \bar{\nu}_L \begin{pmatrix} 0 & m_D & m'_D \\ m_D & m_R & \mu' \\ m'_D & \mu' & m'_R \end{pmatrix} \nu_R \right) + h.c.,
\]
where \( m_D = y_v \langle \phi^0 \rangle \) and \( m'_D = y'_v \langle \phi^0 \rangle \) refer to the Dirac mass terms.

The masses and couplings of RH neutrinos should be fixed. Since the origin of the phenomenological SM itself is even unknown, this specification could not be expressed in a well defined form. Here we follow the arguments of Shaposhnikov in favor of the hypothesis of a lepton–quark symmetry regarding the particle content (see Ref. [25] and references therein). At the level of the SM there is an asymmetry between leptons and quarks: every LH charged lepton and quark has its RH charged lepton or quark partner, while the RH partner of the neutrino is absent. The introduction of one RH neutrino, say \( \nu'_R \), simply reestablishes the symmetry between leptons and quarks.\[26\] Within the context of Eqs. (1) and (2), it is given by \( m'_D = 0 \) (or \( y'_v = 0 \)), \( \mu' = 0 \) and \( m'_R = 0 \), so that only \( m_D \) and \( m_R \) are different from zero. Here our proposal takes the logic of the type-I seesaw mechanism: It is natural to have \( m_D \) of the same order of the magnitude as charged leptons or quarks, and then \( m_R \) sufficiently large to suppress \( m_D \) according to \( m'_D^2/m_R \).

The inclusion of a second RH neutrino, \( \nu''_R \), breaks such a lepton–quark correspondence. This is regarded as a reason for having small couplings \( m'_D, \mu', m'_R \) for \( \nu''_R \) in comparison to \( m_D, m_R \) of \( \nu_R \), as the ’t Hooft’s naturalness criterion applied to this symmetry of lepton and quark contents in the Lagrangian gives a ready explanation. It can be said that this extra RH neutrino sets an alternative lepton–quark symmetry, but very weakened. Thus, the lepton–quark symmetry distinguishes \( \nu_R \) from \( \nu''_R \) by requiring a large difference between \( m_D, m_R \) and \( m'_D, m'_R \), respectively, which parameterize the two forms of the symmetry of fermionic content. Here it is worth emphasizing that this symmetry of particle content cannot be conceived as a symmetry of the electroweak Lagrangian under transformations on the lepton and quark fields, because these have different hypercharges and the Majorana mass terms for RH neutrinos do not have counterparts in the quark sector. Since everything may not be understood yet, our assertion is that the ’t Hooft’s naturalness criterion as a guide of model construction can be used in this case. In the following we show that a soft breaking of the correspondence between leptons and quarks, stated by the hypothesis of the symmetry of fermionic content, through extra RH neutrinos can lead to light neutrinos of Dirac type, where the questioned Majorana...
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Mass terms are suppressed or decoupled from the low-energy effective model. It can be seen that the high scale type-I seesaw is mimicked with \( m'_D = \mu' = m'_R = 0 \), while the low scale pseudo-Dirac neutrino pair is done with \( m_D = \mu' = m_R = 0 \).

With all of the above in mind, we assume \( m'_R, \mu', m'_D, m_D \ll m_R \), extending the high scale seesaw scenario. In this limit we would anticipate suppressions of the Dirac mass \( m_D \) and the coupling \( \mu' \) according to \( m'_D/m_R \) and \( \mu'/m_R \), respectively. Also, now following our motivations stated in Sec. 1, in order to have a low scale pseudo-Dirac regime we assume the inequalities

\[
m'_R, \mu'^2/m_R, m_D^2/m_R, m_D\mu'/m_R \ll m'_D.
\]

As a matter of fact, in the case of these mass hierarchies we obtain, by applying directly the Cardano’s formula for the roots of a cubic equation, the mass eigenvalues

\[
m_1 \simeq -m'_D + \frac{1}{2} m'_R - \frac{1}{2} \frac{(m_D - \mu')^2}{m_R} \simeq -m'_D,
\]

\[
m_2 \simeq m_R,
\]

\[
m_3 \simeq -m'_D + \frac{1}{2} m'_R - \frac{1}{2} \frac{(m_D + \mu')^2}{m_R} \simeq m'_D,
\]

where only the leading terms in \( m'_R, m'_D, \mu', m_D, \) and \( m_R \) are shown. As expected, \( m'_D \) and \( m'_R \) are not suppressed by \( m_R \). We find that the mass matrix is diagonalized by the approximately unitary matrix

\[
U^\dagger \simeq \left( \begin{array}{ccc} \left( \frac{1}{\sqrt{2}} + w \right) & \frac{m_D}{m_R} \left( \frac{1}{\sqrt{2}} + w \right) + \frac{\mu'}{m_R} \left( \frac{1}{\sqrt{2}} - w \right) & -\frac{1}{\sqrt{2}} + w \\ \frac{m_D}{m_R} & 1 & \frac{\mu'}{m_R} \\ \left( \frac{1}{\sqrt{2}} - w \right) & \frac{m_D}{m_R} \left( \frac{1}{\sqrt{2}} - w \right) - \frac{\mu'}{m_R} \left( \frac{1}{\sqrt{2}} + w \right) & \left( \frac{1}{\sqrt{2}} + w \right) \end{array} \right) \\
\left( \begin{array}{ccc} \frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{array} \right),
\]

(4)

where

\[
w = \frac{1}{4\sqrt{2}} \frac{m'_R}{m'_D} + \frac{1}{4\sqrt{2}} \frac{m_D^2 - \mu'^2}{m_R m_D},
\]

(5)

so that

\[
U^\dagger \mathcal{M} U = \left( \begin{array}{ccc} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{array} \right),
\]

(6)

with \( \mathcal{M} \) being the symmetric mass matrix of Eq. (2). The mass eigenvalues can be made positive by suitable phase choice in the chiral fields.
Thus the state $\nu_R$, the natural partner of $\nu_L$, approximately becomes mass eigenstate and is decoupled at low energy. The LH state then combines with almost maximal mixing with the secondary RH state, its unconventional partner whose mass couplings are relatively small. Specifically, the mass eigenstates correspond to the three Majorana combinations given by $\nu_{iM} = \nu_{iL} + \nu_{c_iR}$, with $i = 1, 2, 3$, related to the weak states through the transformations

$$
\begin{bmatrix}
\nu_{1L} \\
\nu_{2L} \\
\nu_{3L}
\end{bmatrix}
= U^\dagger
\begin{bmatrix}
\nu_L \\
\nu_{c_2L} \\
\nu_{c_3L}
\end{bmatrix}
\simeq
\begin{bmatrix}
\frac{1}{\sqrt{2}}(\nu_L - \nu_{c_1L}) \\
\nu_L \\
\frac{1}{\sqrt{2}}(\nu_L + \nu_{c_1L})
\end{bmatrix},
$$

(7)

$$
\begin{bmatrix}
\nu_{1R} \\
\nu_{2R} \\
\nu_{3R}
\end{bmatrix}
= U^T
\begin{bmatrix}
\nu_R \\
\nu_{c_2R} \\
\nu_{c_3R}
\end{bmatrix}
\simeq
\begin{bmatrix}
\frac{1}{\sqrt{2}}(-\nu_{c_1R} + \nu_{c_1R}) \\
\nu_R \\
\frac{1}{\sqrt{2}}(\nu_{c_1R} + \nu_{c_1R})
\end{bmatrix}.
$$

Clearly, there is a suppression of the mixing of the neutrino $\nu_L$ with its ordinary partner $\nu_R$, and a suppression of the usual Dirac mass $m_D$ relative to $m'_D$. This situation leads to an almost degenerate pair of eigenstates with a small mass difference given by $\Delta m \simeq |m'_R - (m^2_D + \mu'^2)/m_R| \ll m'_D$.

Now, since $m'_R$ is not suppressed and not needed as another small mass scale, we set $m'_R = 0$ and the pseudo-Dirac regime may proceed via the suppressed terms containing $m_D$ and $\mu'$. This is equivalent to effectively having a lepton number conservation at low energies, assuming a high seesaw scale.

Within the standard pseudo-Dirac framework, with only one RH neutrino, a small value for the Dirac neutrino mass $m_D$ is considered unnatural. In our extended pseudo-Dirac scenario, however, a small Dirac neutrino mass $m'_D$ becomes natural in the sense of ‘t Hooft because a symmetry of lepton and quark contents is restored if the mixing couplings of the adulterant state $\nu'_{R}$ vanish (see Eq. (1)). Again, as stressed above, this lepton–quark correspondence only serving as a guideline to the choice of parameters.

3. Extension to Three Generations of Neutrinos

We now generalize the results of Sec. 2 to the more realistic scenario of three generations of LH neutrinos. The particle content of the SM is augmented by two RH neutrinos per generation. The three LH neutrinos $\nu_L$, the three ordinary RH neutrinos $\nu_R$, and the three adulterant RH neutrinos $\nu'_{R}$ have mass terms that can be written in a form similar to Eq. (2), with the mass matrix replaced by

$$
\mathcal{M} = \begin{pmatrix}
0 & M_D & M'_D \\
M^T_D & M_R & M'^T_R \\
M'^T_D & M'_R & M'_R
\end{pmatrix},
$$

(8)
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where $M_R, M'_R, M_D, M'_D,$ and $M'$ are $3 \times 3$ complex matrices. It can be diagonalized by the unitary transformation

$$U^\dagger MU^* = \begin{pmatrix} D_L & 0 & 0 \\ 0 & D_R & 0 \\ 0 & 0 & D'_R \end{pmatrix},$$

(9)

where $D_L, D_R$ and $D'_R$ are diagonal, real and non-negative $3 \times 3$ matrices. We consider

$$U^\dagger = \begin{pmatrix} V_L^\dagger & 0 & 0 \\ 0 & V_R^\dagger & 0 \\ 0 & 0 & V_R'\dagger \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} I + W_{LL}^\dagger & V_{RL}^\dagger & -\frac{1}{\sqrt{2}} I + W_{RL}^\dagger \\ V_{LR}^\dagger & I & V_{RR}^\dagger \\ \frac{1}{\sqrt{2}} I + W_{LR}^\dagger & V_{RR}^\dagger & \frac{1}{\sqrt{2}} I + W_{RR}^\dagger \end{pmatrix},$$

(10)

where $V_L, V_R$ and $V_R'$ are unitary $3 \times 3$ complex matrices. Assuming that $M_R$ and $M'_D$ are nonsingular and symmetric matrices, and that $M'_R, M', M'_D, M_D \ll M_R$ as well as $M'_R, M_D M_R^{-1} M'_D, M'M_R^{-1} M' T, M'M_R^{-1} M'_D \ll M'_D$, we use the constraints from unitarity and the matrix $MU^*$ as in the ordinary seesaw mechanism to finally obtain:

$$W_{LL}^\dagger \simeq \frac{1}{4\sqrt{2}} M_R' M_D^{-1} + \frac{1}{4\sqrt{2}} (M_D - M') M_R^{-1} (M_D^T + M'T) M_D^{-1},$$

$$W_{RR}^\dagger \simeq \frac{1}{4\sqrt{2}} M_R' M_D^{-1} + \frac{1}{4\sqrt{2}} (M_D + M') M_R^{-1} (M_D^T - M'T) M_D^{-1},$$

$$W_{RL}^\dagger \simeq W_{LL}^\dagger,$$

$$W_{LR}^\dagger \simeq -W_{RR}^\dagger,$$

$$V_{RL}^\dagger \simeq -(\frac{1}{\sqrt{2}} I + W_{LL}^\dagger) M_D M_R^{-1} + (\frac{1}{\sqrt{2}} I - W_{LL}^\dagger) M'R_R^{-1},$$

$$V_{LR}^\dagger \simeq -(\frac{1}{\sqrt{2}} I - W_{RR}^\dagger) M_D M_R^{-1} - (\frac{1}{\sqrt{2}} I + W_{RR}^\dagger) M'R_R^{-1},$$

$$V_{LR}^\dagger \simeq M_R^{-1} M_D,$$

$$V_{RL}^\dagger \simeq M_R^{-1} M'_D.$$

Thus, we get

$$D_L \simeq V_L^\dagger [-M'_D + \frac{1}{2} M_R' - \frac{1}{2} (M_D - M') M_R^{-1} (M_D^T - M'T)] V_L^*,$$

$$D_R \simeq V_R^\dagger M_R V_R^*,$$

$$D'_R \simeq V_R^\dagger [M'_D + \frac{1}{2} M_R' - \frac{1}{2} (M_D + M') M_R^{-1} (M_D^T + M'T)] V_R^*,$$

(12)

In the pseudo-Dirac limit with $M'_R = 0$ and $M_D, M'$ suppressed, there are three light almost degenerate pairs of mass eigenstates with small mass differences, with almost maximal mixing of LH neutrinos $\nu_L$ and adulterant RH neutrinos $\nu_R$, and
three heavy, mostly ordinary RH neutrinos \( \nu_R \) with mass matrix \( M_R \). The masses of light neutrinos are of the order of \( M'_D \) instead of \( M_D \), which are suppressed by the seesaw mechanism. The matrices \( V_{LR}, V_{RL}, V'_{LR} \) and \( V'_{RL} \) are suppressed by \( M_R \), whereas \( W_{LL}, W'_{RR}, W'_{LR} \) and \( W'_{RL} \) are suppressed by \( M_R \) and/or \( M'_D \). We note that the results in Eqs. (11) and (12) reproduce those obtained in Sec. 2 in the case of one generation, which were calculated following a completely different method.

4. Low-Energy Effective Model of Neutrino Masses

The RH neutrinos with huge masses can be integrated out using the equation of motion

\[
\frac{d\mathcal{L}_\nu}{d\nu_R} = 0. \tag{13}
\]

In the approximation of one generation, it leads to

\[
\bar{\nu}^c_L = -\frac{m_D}{m_R} \bar{\nu}^c_L - \frac{\mu'_D}{m_R} \nu^c_R, \quad \nu_R = -\frac{m_D}{m_R} \nu_R - \frac{\mu'_D}{m_R} \nu^c_R. \tag{14}
\]

The effective Lagrangian we then have is

\[
- \mathcal{L}_\nu = \frac{1}{2} \left( \bar{\nu}^c_L \right) \begin{pmatrix} -\frac{m_D^2}{m_R} & m'_D - \frac{\mu'_D m_D}{m_R} \\ m'_D - \frac{\mu'_D m_D}{m_R} & -\frac{\mu'^2}{m_R} \end{pmatrix} \begin{pmatrix} \nu_R \\ \nu^c_R \end{pmatrix} + \text{h.c.}, \tag{15}
\]

where \( m'_R = 0 \) is used, so that the pseudo-Dirac scenario proceeds via suppressed mass terms, without the need of inserting a second small mass scale. The mass matrix is diagonalized by the approximately unitary matrix

\[
\mathcal{U} \simeq \begin{pmatrix} \frac{1}{\sqrt{2}} + w & \frac{1}{\sqrt{2}} - w \\ -\frac{1}{\sqrt{2}} + w & \frac{1}{\sqrt{2}} + w \end{pmatrix}, \tag{16}
\]

such that

\[
\mathcal{U}^\dagger \mathcal{M} \mathcal{U} = \begin{pmatrix} m_1 & 0 \\ 0 & m_3 \end{pmatrix}, \tag{17}
\]

where \( w, m_1 \) and \( m_3 \) are given in Eqs. (5) and (3), with \( m'_R = 0 \).

On the other hand, assuming the mass hierarchy

\[
\frac{m_D^2}{m_R}, \frac{\mu'_D m_D}{m_R}, \frac{\mu'^2}{m_R} \ll m'_D \ll m_D \ll m_R, \tag{18}
\]

we end up with the mass matrix

\[
\mathcal{M} \simeq \begin{pmatrix} 0 & m'_D \\ m'_D & 0 \end{pmatrix}. \tag{19}
\]
This result is consistent with a generation of standard leptons $L = (\nu_L, e_L)$, $e_R$ extended with the extra RH neutrino $\nu'_R$ and a Lagrangian which includes the Yukawa terms related to $\nu'_R$:

$$\mathcal{L} = -y'_\nu \bar{L} \phi \nu'_R + h.c. \quad (20)$$

In the limit in which the small values $m^2_D/m_R$, $\mu' m_D/m_R$, $\mu'^2/m_R$ are equal to zero, a lepton number conservation and a lepton–quark symmetry are set up at low energies, below the mass scale of the ordinary RH neutrino $\nu_R$. It is the lepton–quark symmetry in terms of $\nu'_R$ defined in Sec. 2 with all couplings of $\nu_R$ removed ($m_D = m_R = \mu' = 0$). Now, a neutrino Dirac mass $m'_D$ much smaller than $m_D \sim m_e$ appears natural because $m'_D = 0$ (with $\mu' = m'_R = 0$) recovers an enhanced symmetry in the original Lagrangian, namely, the symmetry of lepton and quark contents involving the natural neutrino partner $\nu_R$. Thus light Dirac neutrinos with small masses or Yukawa couplings may be accommodated naturally, as written in Eq. (20), although the arguments are based on the correspondence between lepton and quark contents which is merely a guideline to the choice of parameters and not a proper symmetry in the Lagrangian, as emphasized above. It appears as an alternative to the usual approach which extends the SM with the Yukawa terms $\mathcal{L} = -y_{\nu \nu} \bar{L} \phi \nu_R$ in order to have Dirac neutrinos.

The above results can be generalized to three generations. Equation (13) now leads to

$$\bar{\nu}_L = -\bar{\nu}_L M_D M^{' -1}_R - \bar{\nu}'_L M'_D M^{' -1}_R, \quad \nu_R = -M^{-1}_R M'_D \nu'_R - M'_R M^{' T} \nu'_R. \quad (21)$$

The effective Lagrangian is written as

$$- \mathcal{L}_\nu = \frac{1}{2} \left( \bar{\nu}_L \bar{\nu}'_L \left( M_{LL} \ M^{' LR} \ M^{' TR} \ M'_R \right) \left( \nu'_R \ \nu_R \right) + h.c., \quad (22)$$

where

$$M_{LL} \simeq -M_D M^{-1}_R M^{' T}_D, \quad M^{' LR} \simeq M'_D - M_D M^{-1}_R M^{' T}$$

The mass matrix of Eq. (22) is diagonalized by the approximately unitary matrix

$$U^\dagger \sim \begin{pmatrix} V^\dagger_L & 0 \\ 0 & V^\dagger_R \end{pmatrix} \begin{pmatrix} 1/\sqrt{2} I + W^\dagger_{LL} & -1/\sqrt{2} I + W^\dagger_{LL} \\ 1/\sqrt{2} I - W^\dagger_{RR} & 1/\sqrt{2} I + W^\dagger_{RR} \end{pmatrix}, \quad (24)$$

such that

$$U^\dagger \mathcal{M} U^* = \begin{pmatrix} D_L & 0 \\ 0 & D'_R \end{pmatrix}, \quad (25)$$

where $W^\dagger_{LL}$ and $W^\dagger_{RR}$, $D_L$ and $D'_R$ have the expressions given in Eqs. (11) and (12) with $M'_R = 0$. 
5. Phenomenological Remarks

We have considered an scenario where each LH neutrino $\nu_L$ has two RH partners: $\nu_R$ and $\nu'_R$. A seesaw mechanism of type-I has been applied in which the Majorana mass $m_R$ of $\nu_R$ is assumed to be much larger than the Dirac mass $m_D$ coupling $\nu_L$ to $\nu_R$. The state $\nu_R$ is decoupled at low energies leaving $\nu'_R$ as the main partner of $\nu_L$. The mass $m_D$ is assumed to be of order the charged lepton mass. In the approximation of one generation, $m_D \sim m_e \sim 1$ MeV, while the mass term $m_R$ may be as large as the scale of Grand Unification Theories, say $m_R \sim 10^{14}$ GeV, and in principle even up to the Planck mass. This would leads to an effective LH Majorana mass of order

$$m_{LL} = \frac{m_D^2}{m_R} \sim 10^{-11} \text{eV}. \quad (26)$$

On the other hand, it is found that oscillations of solar neutrinos set an upper bound for $m'_{RR}$:

$$m'_{RR} = m'_R - \frac{\mu'^2 m_D}{m_R} \lesssim 10^{-9} \text{eV}. \quad (27)$$

Next, taking from the neutrino data

$$m'_{LR} = m'_D - \frac{\mu' m_D}{m_R} \sim 10^{-1} \text{eV}, \quad (28)$$

we have the following benchmark values for the parameters in the model,

$$m_R \sim 10^{14} \text{GeV}, \quad m_D \sim 1 \text{ MeV}, \quad \mu' \lesssim 10 \text{ MeV}, \quad m'_R \lesssim 10^{-9} \text{eV}, \quad m'_D \sim 10^{-1} \text{eV}, \quad (29)$$

with the expected hierarchy of masses

$$m_{LL}, m'_{RR} \ll m'_LR \ll m_D \ll m_R, \quad (30)$$

so realizing the approximations used in the model, where in the end light neutrinos appear to have a Dirac character.

The phenomenological implications at low energies are essentially those of the usual Dirac approach, while at high energies the model maintains the expectations of the high scale type-I seesaw mechanism. The parameter region we have considered is consistent with experimental bounds which exclude the pseudo-Dirac limit, but not a Dirac nature for light neutrinos. And their masses or Yukawa couplings may have exceptionally small values because of the adulterant character of RH partners. Besides, there is consistency between this Dirac picture and the vanishing of the Majorana mass $m'_R$ assumed above. Also, the Dirac nature of lighter neutrinos, as effectively implied in this work, refuses to allow the neutrinoless double-beta decay, in accordance with recent precision experiments.
6. Conclusions

We have constructed an extension of the SM by incorporating two RH neutrinos per generation of leptons and quarks, but considering the hypothesis of the symmetry of fermionic content in order to deprive the number of RH neutrinos of freedom, generate Dirac neutrinos and accommodate naturally their tiny masses. One of these is the ordinary RH neutrino which restores the correspondence between leptons and quarks at high energies with weak couplings having order of magnitudes as those of its weak charged partner and a Majorana mass term whose coupling is assumed to be large, as in the canonical high scale type-I seesaw scenario. The other, adulterant, RH neutrino, which breaks the lepton–quark symmetry established with the first one, is regarded to have relatively small mass and couplings, as the ’t Hooft’s naturalness criterion applied to this symmetry of lepton and quark contents provides a ready explanation. The first RH neutrino is decoupled at the high scale, but the second RH neutrino survives down to the low scale to pair off in a Dirac-like fashion with the corresponding LH neutrino, imposing its own form of the symmetry of fermionic content.

We have emphasized, however, that the correspondence of lepton and quark contents is not an actual symmetry in the Lagrangian because one cannot write a symmetry transformation between leptons and quarks to keep the Lagrangian invariant. As it is well-known, the ’t Hooft’s argument for small parameters in a Lagrangian relies on the symmetry, which guarantees the quantum corrections of such numbers to be proportional to the parameters themselves. Its application to the lepton–quark correspondence therefore demands the attachment of a proper symmetry in a Lagrangian somehow associated with the SM extended with RH neutrinos, which surpasses the aims of this work. Yet, we have considered that it serves as a guideline to the natural choice of parameters of small values.

Thus, a low scale Dirac scenario with lepton–quark symmetry of content and small neutrino masses appears to be natural with extra RH neutrinos via the high scale type-I seesaw mechanism. The parameter region considered in this approach makes irrelevant to low energy processes the perturbation of the seesaw mechanism on a description given in terms of light Dirac neutrinos, foreseeing that experiments will not have sensitiveness to the Majorana character of neutrinos predicted by the seesaw mechanism, as in the case of the neutrinoless double-beta decay.

The usual Dirac scenario deals with the same chiral neutrino included in the alternative seesaw mechanism, which generates problems to explain naturally the smallness of Dirac neutrino mass terms relative to those of charged leptons. Our key result making the difference with this approach is that the symmetry of fermionic content at low energies is achieved only with the additional RH neutrinos and not with the ordinary ones which are decoupled, may carry $B - L$ charge and form RH doublets with RH leptons as in models of left–right symmetry. In other words, light pseudo-Dirac neutrinos obtained by replacing the regular factor $m_D$ by the new and independent, naturally small parameter $m_D'$, giving an understanding why observed
neutrinos are ultralight and at the same time Dirac-like. While there are no hard predictions for the light neutrino masses and mixings, let alone the mass hierarchy, this new framework opens up a new line for future exploration.

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