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Radiative inverse seesaw mechanism for nonzero neutrino mass

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If the canonical seesaw mechanism alone is responsible for neutrino mass, i.e. $m_\nu \simeq -m_D^2/m_N$, it would be difficult to prove at the TeV energy scale. A new verifiable mechanism of neutrino mass is proposed, using the *inverse* seesaw, with new physics at the TeV scale, such that $m_\nu \simeq m_D^2 \epsilon_L / m_N^2$, where ϵ_L is a two-loop effect. Dark-matter candidates also appear naturally.

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I. INTRODUCTION

Neutrinos have mass, but the mechanism for it to occur remains a topic of theoretical study. The reason is that, unlike other charged fermions such as the electron or the quarks, the neutrinos are electrically neutral and could have either Dirac or Majorana masses or both. The prevalent thinking is that in addition to the left-handed neutrino ν_L in the electroweak lepton doublet $(\nu, l)_L$ of the standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge model of particle interactions, there is also a right-handed neutrino N_R (for each of the three families of quarks and leptons), which is a singlet. Thus it has no gauge interactions and couples only to the Higgs doublet $\Phi = (\phi^+, \phi^0)$, i.e. $f\bar{N}_R(\nu_L\phi^0 - l_L\phi^+)$, so that a Dirac mass is obtained as ϕ^0 acquires a vacuum expectation value $v = \langle\phi^0\rangle$, linking ν_L with N_R. If this is the only allowed additional term, then N_R is simply ν_R, i.e. ν is a four-component Dirac spinor with mass $m_D = fv$, and additive lepton number L is conserved. However, since N_R is a singlet, it should be allowed a Majorana mass m_N. Hence the 2×2 mass matrix spanning $\bar{\nu}_L$ and N_R is given by

$$\mathcal{M}_{\nu N} = \begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix}, \tag{1}$$

with eigenvalues $m_{1,2} = m_N/2 \mp \sqrt{(m_N/2)^2 + m_D^2}$. It is customarily assumed that $m_D << m_N$, in which case $m_1 \simeq -m_D^2/m_N$ and $m_2 \simeq m_N$. [It is usually stated that L is now broken at a large scale. A more proper viewpoint is that L is never a symmetry of the Lagrangian, but that $(-)^L$ is.] This is the famous canonical seesaw mechanism [1] and explains why m_1 (which is then renamed m_ν) is so small. However, the mixing between ν_L and N_R is $|m_D/m_N| \simeq \sqrt{|m_\nu/m_N|}$ which is at most 10^{-6} (for $m_\nu = 1$ eV and $m_N = 1$ TeV) and precludes any observable effect in support of this hypothesis. If this is the correct mechanism of neutrino mass, it would be difficult to prove [2]. On the other hand, it has been argued [3,4] that large cancellations may occur to keep m_ν small in the case of two or three N's, which would then allow large $\nu - N$ mixing, but that really corresponds to using the inverse seesaw, as recently pointed out [5].

II. INVERSE SEESAW

There are other mechanisms of neutrino mass [6], and some may be verifiable at the TeV scale [7,8]. In this paper, a new mechanism is proposed, where the origin of neutrino mass is radiative and suppressed by the inverse seesaw [9–14] due to new physics at the TeV scale. The basic framework of the inverse seesaw is to extend Eq. (1) to include one additional singlet N_L, so that the resulting 3×3 mass matrix spanning $\bar{\nu}_L$, N_R, and $\bar{N}_L$ becomes [14]

$$\mathcal{M}_{\nu N} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & m_R & m_N \\ 0 & m_N & m_L \end{pmatrix}. \tag{2}$$

Thus m_D is the usual Dirac mass linking ν_L with N_R through $\langle\phi^0\rangle$, and m_N is an invariant Dirac mass, whereas m_R and m_L are Majorana mass terms. If $m_{R,L} = 0$, then the linear combination $(m_D\nu_L + m_N N_L)/\sqrt{m_D^2 + m_N^2}$ will combine with N_R to form a Dirac fermion of mass $\sqrt{m_D^2 + m_N^2}$ and the orthogonal combination

$$\nu_1 = \frac{m_N\nu_L - m_D N_L}{\sqrt{m_D^2 + m_N^2}} \tag{3}$$

remains massless. Additive lepton number L is conserved in this case. This limit allows one to argue that $m_{R,L}$ should be small, because in their absence, the symmetry of the resulting theory is enlarged, i.e. from $(-)^L$ to L. [Note that in contrast to the case of the canonical seesaw, it is assumed here that L is a valid symmetry at high energies.] In all previous applications, these small parameters are simply put in by hand. Here it will be shown how they may only be radiatively generated and must therefore be small.

Renaming $m_{R,L}$ as $\epsilon_{R,L}$, and using $\epsilon_{R,L} << m_D, m_N$, the eigenvalues of Eq. (2) are

$$m_1 = \frac{m_D^2\epsilon_L}{m_N^2 + m_D^2}, \tag{4}$$

$$m_2 = \sqrt{m_N^2 + m_D^2} + \frac{\epsilon_R}{2} + \frac{m_N^2\epsilon_L}{2(m_N^2 + m_D^2)}, \tag{5}$$

$$m_3 = -\sqrt{m_N^2 + m_D^2} + \frac{\epsilon_R}{2} + \frac{m_N^2 \epsilon_L}{2(m_N^2 + m_D^2)}, \quad (6)$$

where m_1 is now an inverse seesaw neutrino mass. It is small because ϵ_L is small, without requiring m_N to be excessively large. For example, let $m_D \sim 10$ GeV, $m_N \sim 1$ TeV, and $\epsilon_L \sim 10$ keV, then $m_1 \sim 1$ eV. Note that ν_1 is again given by Eq. (3) to a very good approximation. The mixing of ν_L with N_R remains very small, i.e. $m_D\epsilon_L/(m_N^2 + m_D^2)$, but the mixing of ν_L with N_L is m_D/m_N, which may be large enough to be observed, as unitarity violation in future neutrino experiments [15–20], as well as lepton flavor violation.

III. $U(1)_\chi$ EXTENSION OF THE STANDARD MODEL

To enforce the form of Eq. (2) where $m_{R,L}$ are necessarily radiative, a gauge extension of the standard model (SM) is recommended. As a concrete example, consider the breaking of

$$SO(10) \to SU(5) \times U(1)_\chi \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi. \quad (7)$$

This is simply achieved with a Higgs scalar multiplet $\underline{45}$ which decomposes as

$$\underline{45} = (\underline{1}, 0) + (\underline{10}, -4) + (\underline{10}^*, 4) + (\underline{24}, 0), \quad (8)$$

where

$$(\underline{1}, 0) = (1, 1, 0, 0), \quad (9)$$

$$(\underline{10}, -4) = (3, 2, 1/6, -4) + (3^*, 1, -2/3, -4) + (1, 1, 1, -4), \quad (10)$$

$$(\underline{10}^*, 4) = (3^*, 2, -1/6, 4) + (3, 1, 2/3, 4) + (1, 1, -1, 4), \quad (11)$$

$$(\underline{24}, 0) = (1, 1, 0, 0) + (8, 1, 0, 0) + (1, 3, 0, 0) + (3, 2, -5/6, 0) + (3^*, 2, 5/6, 0). \quad (12)$$

As the (1, 1, 0, 0) component of the $(\underline{24}, 0)$ acquires a vacuum expectation value at the grand-unification scale, the 45 generators of $SO(10)$ are reduced to the 12 + 1 generators of the SM plus $U(1)_\chi$, with exactly 32 would-be Goldstone bosons provided by the $(\underline{10}, -4) + (\underline{10}^*, 4)$ components of the $\underline{45}$ and the $(3, 2, -5/6, 0) + (3^*, 2, 5/6, 0)$ components of the $(\underline{24}, 0)$. This means that $U(1)_\chi$ may survive to near the electroweak symmetry breaking scale. It is also orthogonal to $U(1)_Y$, unlike recent proposals where $U(1)_{B-L}$ is used [21–27]. In fact, the $U(1)_\chi$ charge is given by

$$Q_\chi = 5(B - L) - 4Y = 5(B - L) + 4T_{3L} - 4Q. \quad (13)$$

The neutral fermion singlet N^c in the $\underline{16}$ of $SO(10)$, often referred to as the right-handed neutrino, has $B = 0$, $L = -1$, and $Y = 0$, so it has $Q_\chi = 5$. Similarly, (u, d), u^c, e^c have $Q_\chi = 1$ and (ν, e), d^c have $Q_\chi = -3$.

To allow for quark and lepton masses, a Higgs scalar doublet

$$\Phi = (\phi^+, \phi^0) \sim (1, 2, 1/2, -2) \quad (14)$$

under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$ is needed, with the Yukawa interactions

$$(u\phi^0 - d\phi^+)u^c, \quad (d\bar{\phi}^0 + u\phi^-)d^c, \quad (e\bar{\phi}^0 + \nu\phi^-)e^c, \quad (\nu\phi^0 - e\phi^+)N^c. \quad (15)$$

To break $U(1)_\chi$ and not the SM gauge group, a Higgs scalar η transforming under only $U(1)_\chi$ is needed. If η has $Q_\chi = \pm 10$, then N^c gets a Majorana mass and the usual seesaw mechanism is operable. However, another more interesting choice is available, as shown below.

IV. ADDITIONAL SINGLETS

Instead of one scalar with $Q_\chi = \pm 10$, two scalars transforming under $U(1)_\chi$, namely

$$\eta_1 \sim 1, \quad \eta_2 \sim 2, \quad (16)$$

will be used. In addition, neutral fermion singlets

$$S_3 \sim -3, \quad S_2 \sim 2, \quad S_1 \sim -1, \quad (17)$$

are added. [These neutral singlets do not come from just $SO(10)$. They may be remnants of larger symmetries such as E_6 which contain $SO(10)$.] Note that the set of one S_3, four S_2, and five S_1 is anomaly free, because $(-3) + 4(2) + 5(-1) = 0$ and $(-27) + 4(8) + 5(-1) = 0$. As a result, the Yukawa couplings

$$N^c S_3 \eta_2^\dagger, \quad S_3 S_2 \eta_1, \quad S_2 S_1 \eta_1^\dagger, \quad S_1 S_1 \eta_2 \quad (18)$$

are allowed, as well as the scalar interaction terms

$$\eta_1^2 \eta_2^\dagger, \quad (\eta_1^\dagger \eta_1)^2, \quad (\eta_2^\dagger \eta_2)^2, \quad (\eta_1^\dagger \eta_1)(\eta_2^\dagger \eta_2). \quad (19)$$

Altogether, it is clear that the choice of particle content allows a multiplicatively conserved lepton parity to be defined, so that ν, e, e^c, N^c, S_3, S_1, η_1 are odd and S_2, η_2 are even. The $U(1)_\chi$ gauge symmetry is broken by $\langle \eta_2 \rangle \neq 0$, whereas $\langle \eta_1 \rangle = 0$.

In the basis spanned by ν, N^c, S_3, S_1, the 4×4 mass matrix is then given at tree level by

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 & 0 \\ m_D & 0 & m_N & 0 \\ 0 & m_N & 0 & 0 \\ 0 & 0 & 0 & M_1 \end{pmatrix}. \quad (20)$$

In the above, S_1 gets a Majorana mass at the $U(1)_\chi$ breaking scale, but it decouples from the other three fields. The remaining 3×3 submatrix is exactly of the form of Eq. (2) without $m_{R,L}$. The next step is to show that the latter are not zero but small, because they will be generated radiatively.

V. DARK MATTER

Before showing the specific radiative mechanisms responsible for $\epsilon_{R,L}$, i.e. $m_{R,L}$ renamed, an important bonus of this proposal is the occurrence of dark-matter candidates, i.e. S_2 and η_1. They have odd R parity, i.e. $R = (-)^{3B+5L+2j}$, whereas all other particles have even R parity. This is another example of the possibility of generalized lepton number [28,29].

VI. RADIATIVE MASSES

At tree level, S_3 links with N^c to form a Dirac fermion with mass m_N, and S_1 gets a Majorana mass M_1, both at the scale of $U(1)_\chi$ breaking due to $\langle \eta_2 \rangle$. This leaves S_2 massless, but it picks up a radiative Majorana mass in one loop, as shown in Fig. 1. This is exactly analogous to the one-loop mechanism for neutrino mass first proposed in Ref. [30]. It is easily calculable from the exchange of $\mathrm{Re}(\eta_1)$ and $\mathrm{Im}(\eta_1)$ and is given by

$$m_2 = \frac{f_{12}^2 M_1}{16\pi^2}\left[\frac{m_R^2}{m_R^2 - M_1^2} \ln\frac{m_R^2}{M_1^2} - \frac{m_I^2}{m_I^2 - M_1^2} \ln\frac{m_I^2}{M_1^2}\right]. \quad (21)$$

This means that S_2 is lighter than either $\mathrm{Re}(\eta_1)$ or $\mathrm{Im}(\eta_1)$, so the lightest S_2 should be a dark-matter candidate.

Once S_2 gets a mass, S_3 also gets a Majorana mass, as shown in Fig. 2.

This is the ϵ_L term being sought after, and since it is a two-loop effect (m_2 itself being a one-loop effect), it is guaranteed to be small, as promised. It is also a scotogenic

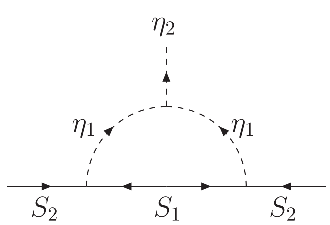

FIG. 1. One-loop S_2 mass.

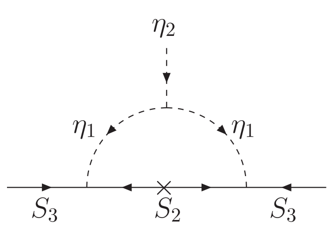

FIG. 2. Two-loop scotogenic S_3 mass.

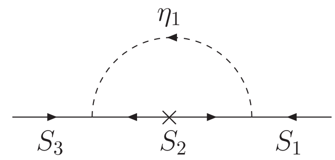

FIG. 3. Two-loop mass linking S_3 with S_1.

mass, i.e. induced by darkness, because S_2 and η_1 have odd R, as pointed out previously.

There is also a mass term linking S_3 with S_1, as shown in Fig. 3.

Together with M_1, this gives a seesaw contribution to ϵ_L as well, but its magnitude is clearly much smaller than the S_3S_3 term. As for ϵ_R, i.e. the N^cN^c term, it is a three-loop effect and safely negligible.

VII. $U(1)_\chi$ PHENOMENOLOGY

With $\langle \phi^0 \rangle = v$ and $\langle \eta_2 \rangle = u$, both the Z of the SM and Z'_χ become massive, but there is also $Z - Z'_\chi$ mixing which is of order $v/u \sim M_Z/M_{Z'_\chi}$. Precision electroweak measurements at the Z resonance constrain this mixing to be very small. To satisfy it without making u very large, a second Higgs scalar doublet may be added, i.e. $\Phi' \sim (1, 2, 1/2, 2)$ with $v' = v$, in which case $Z - Z'_\chi$ mixing is zero, and $M_{Z'_\chi}$ is not constrained except by the direct production of Z'_χ. The present experimental limit [31] is 822 GeV at 95% CL.

Note that because of its $U(1)_\chi$ charge, Φ' does not couple to quarks or leptons, thus avoiding the appearance of flavor-changing neutral currents. It also does not link ν with S_3 or S_1 in Eq. (20). Note further that the quartic $\eta_2^\dagger \eta_2^\dagger \Phi^\dagger \Phi'$ term is allowed, so that the introduction of Φ' does not create an extra global $U(1)$ symmetry, thus avoiding the appearance of an unwanted massless Goldstone boson in the presence of v'.

If Z'_χ is not much heavier than 1 TeV, it will be discovered at the LHC, due to start taking data soon in 2009. The key to verifying the radiative inverse seesaw mechanism is that N^c must combine with S_3 to form a pseudo-Dirac fermion N with lepton number $L = 1$, as shown in Eqs. (5) and (6). If $M_{Z'_\chi} > 2m_N$, then Z'_χ will decay into $N\bar{N}$ with subsequent decays $N \to e^- W^+$, νZ and $\bar{N} \to e^+ W^-$, $\bar{\nu} Z$, etc. This differs from the usual $U(1)_\chi$ expectation for $Z'_\chi \to N^c \bar{N}^c$, because N^c is Majorana in that case. Hence there would be both $e^\mp e^\mp W^\pm W^\pm$ and $e^\pm e^\mp W^\pm W^\mp$ final states. The absence of the former would be the first indication of the inverse seesaw. In addition, the branching-fraction ratio $B(Z'_\chi \to N\bar{N})/B(Z'_\chi \to e^+e^-)$ is 17/5, whereas $B(Z'_\chi \to N^c\bar{N}^c)/B(Z'_\chi \to e^+e^-)$ is 5/2.

The smoking gun of the scotogenic origin of ϵ_L, i.e. the S_3S_3 term, is the decay $N \to \bar{S}_2 \eta_1^\dagger$, which is invisible. This would be very difficult to ascertain at the LHC, but in a future possible linear e^+e^- collider, Z'_χ may be produced at resonance. In that case, $Z'_\chi \to N\bar{N}$ with $N \to \bar{S}_2 \eta_1^\dagger$ and $\bar{N} \to e^+ W^-$ or $\bar{\nu} Z$ would provide the proof necessary.

VIII. CONCLUSION

The origin of neutrino mass may well be the inverse seesaw mechanism, i.e. $m_\nu \simeq m_D^2 \epsilon_L / m_N^2$. To understand the possibility of $m_N \sim 1$ TeV and $\epsilon_L \sim 10$ keV, an extra $U(1)_\chi$ gauge symmetry is proposed, from the simple breaking of $SO(10) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$ by a single Higgs multiplet transforming as $\underline{45}$ of $SO(10)$. With the addition of fermion and scalar singlets, m_N comes from the breaking of $U(1)_\chi$. As a bonus, dark-matter candidates emerge which are responsible for generating ϵ_L in two loops. This is the first example of a radiative inverse seesaw mechanism, which is verifiable at the TeV scale. It allows for observable unitarity violation of the 3×3 neutrino mixing matrix, as well as lepton flavor violation.

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