Verifiable radiative seesaw mechanism of neutrino mass and dark matter

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Neutrino oscillations have established that neutrinos ν_i have very small masses. Theoretically, they are believed to arise through the famous seesaw mechanism from their very heavy and unobservable Dirac mass partners N_i. It is proposed here in a new minimal extension of the standard model with a second scalar doublet (η^+, η^0) that the seesaw mechanism is actually radiative, and that N_i and (η^+, η^0) are experimentally observable at the forthcoming Large Hadron Collider, with the bonus that the lightest of them is also an excellent candidate for the dark matter of the Universe.

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In the well-known canonical seesaw mechanism [1], three heavy singlet Majorana neutrinos N_i $(i = 1)$, 2, 3 are added to the standard model (SM) of elementary particles, so that

$$\mathcal{M}_\nu^{(e,\mu,\tau)} = -\mathcal{M}_D \mathcal{M}_N^{-1} \mathcal{M}_D^T, \tag{1}$$

where $\mathcal{M}_D$ is the 3×3 Dirac mass matrix linking the observed neutrinos ν_α $(\alpha = e, \mu, \tau)$ to N_i, and $\mathcal{M}_N$ is the Majorana mass matrix of N_i. More generally [2], $\mathcal{M}_\nu$ comes from the unique dimension-five operator

$$\mathcal{L}_\Lambda = \frac{f_{ij}}{\Lambda}(\nu_i\phi^0 - l_i\phi^+)(\nu_j\phi^0 - l_j\phi^+) + \text{H.c.}, \tag{2}$$

where (ν_i, l_i) are the usual left-handed lepton doublets transforming as $(2, -1/2)$ under the standard electroweak $SU(2)_L \times U(1)_Y$ gauge group and $(\phi^+, \phi^0) \sim (2, 1/2)$ is the usual Higgs doublet of the SM. There are three and only three tree-level realizations [3] of this operator, one of which is of course the canonical seesaw mechanism. There are also three generic mechanisms for obtaining this operator in one loop [3]. Whereas the new particles required in the three tree-level realizations are most likely too heavy to be observed experimentally in the near future, those involved in the one-loop realizations may in fact be light enough to be detected, in forthcoming experiments at the Large Hadron Collider (LHC), for example.

Consider the following minimal extension of the SM. Under $SU(2)_L \times U(1)_Y \times Z_2$, the particle content is given by

$$(\nu_i, l_i) \sim (2, -1/2; +), \quad l_i^c \sim (1, 1; +), \quad N_i \sim (1, 0; -), \tag{3}$$

$$(\phi^+, \phi^0) \sim (2, 1/2; +), \qquad (\eta^+, \eta^0) \sim (2, 1/2; -). \tag{4}$$

Note that the new particles, i.e. N_i and the scalar doublet (η^+, η^0), are odd under Z_2. A previously proposed model [4] of neutrino mass shares the same particle content of this model, but the extra symmetry assumed there is global lepton number, which is broken explicitly but softly by the unique bilinear term $\mu^2\Phi^\dagger\eta$ + H.c. in the Higgs potential. Here, Z_2 is an exact symmetry, in analogy with the well-known R-parity of the minimal supersymmetric standard model (MSSM), hence this term is strictly forbidden. As a result, η^0 has zero vacuum expectation value and there is no Dirac mass linking ν_i with N_j. Neutrinos remain massless at tree level as in the SM.

The Yukawa interactions of this model are given by

$$\mathcal{L}_Y = f_{ij}(\phi^-\nu_i + \bar{\phi}^0 l_i)l_j^c + h_{ij}(\nu_i\eta^0 - l_j\eta^+)N_j + \text{H.c.} \tag{5}$$

In addition, the Majorana mass term

$$\tfrac{1}{2}M_i N_i N_i + \text{H.c.}$$

and the quartic scalar term

$$\tfrac{1}{2}\lambda_5(\Phi^\dagger\eta)^2 + \text{H.c.}$$

are allowed. Hence the one-loop radiative generation of $\mathcal{M}_\nu$ is possible, as depicted in Fig. 1. This diagram was discussed in Ref. [3], but without recognizing the crucial role of the exact Z_2 symmetry being considered here.

The immediate consequence of the exact Z_2 symmetry of this model is the appearance of a lightest stable particle (LSP). This can be either bosonic, i.e. the lighter of the two mass eigenstates of Reη^0 and Imη^0, or fermionic, i.e. the lightest mass eigenstate of $N_{1,2,3}$. The latter possibility was first proposed in a different model [5], where neutrino masses are radiatively generated in three loops with the addition of two charged scalar singlets.

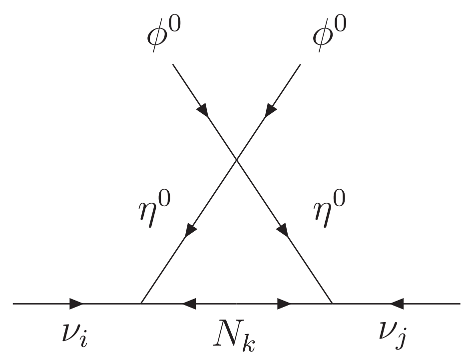

FIG. 1. One-loop generation of neutrino mass.

The Higgs potential of this model is given by

$$V = m_1^2\Phi^\dagger\Phi + m_2^2\eta^\dagger\eta + \tfrac{1}{2}\lambda_1(\Phi^\dagger\Phi)^2 + \tfrac{1}{2}\lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi) + \tfrac{1}{2}\lambda_5[(\Phi^\dagger\eta)^2 + \text{H.c.}], \tag{6}$$

where λ_5 has been chosen real without any loss of generality. For $m_1^2 < 0$ and $m_2^2 > 0$, only ϕ^0 acquires a nonzero vacuum expectation value v. The masses of the resulting physical scalar bosons are given by

$$m^2(\sqrt{2}\,\mathrm{Re}\phi^0) = 2\lambda_1 v^2, \tag{7}$$

$$m^2(\eta^\pm) = m_2^2 + \lambda_3 v^2, \tag{8}$$

$$m^2(\sqrt{2}\,\mathrm{Re}\eta^0) = m_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2, \tag{9}$$

$$m^2(\sqrt{2}\,\mathrm{Im}\eta^0) = m_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2. \tag{10}$$

The diagram of Fig. 1 is exactly calculable from the exchange of $\mathrm{Re}\eta^0$ and $\mathrm{Im}\eta^0$ and is given by

$$(\mathcal{M}_\nu)_{ij} = \sum_k \frac{h_{ik}h_{jk}M_k}{16\pi^2}\left[\frac{m_R^2}{m_R^2 - M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2}\ln\frac{m_I^2}{M_k^2}\right], \tag{11}$$

where m_R and m_I are the masses of $\sqrt{2}\,\mathrm{Re}\eta^0$ and $\sqrt{2}\,\mathrm{Im}\eta^0$, respectively. If $m_R^2 - m_I^2 = 2\lambda_5 v^2$ is assumed to be small compared to $m_0^2 = (m_R^2 + m_I^2)/2$, then

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2}\sum_k \frac{h_{ik}h_{jk}M_k}{m_0^2 - M_k^2}\left[1 - \frac{M_k^2}{m_0^2 - M_k^2}\ln\frac{m_0^2}{M_k^2}\right]. \tag{12}$$

If $M_k^2 \gg m_0^2$, then

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2}\sum_k \frac{h_{ik}h_{jk}}{M_k}\left[\ln\frac{M_k^2}{m_0^2} - 1\right]. \tag{13}$$

If $m_0^2 \gg M_k^2$, then

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2 m_0^2}\sum_k h_{ik}h_{jk}M_k. \tag{14}$$

If $m_0^2 \simeq M_k^2$, then

$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_5 v^2}{16\pi^2}\sum_k \frac{h_{ik}h_{jk}}{M_k}. \tag{15}$$

From the above, it is clear that the seesaw scale is reduced by roughly the factor $\lambda_5/16\pi^2$. Assuming $\lambda_5 \sim h^2 \sim 10^{-4}$, the corresponding canonical seesaw scale of 10^9 GeV (with $m_\nu \sim h^2v^2/M \sim 1$ eV) is then reduced to just 1 TeV, which is amenable to experimental verification in forthcoming experiments at the LHC, for example.

This radiative seesaw mechanism of neutrino mass also predicts the existence of dark matter, either in the form of N_1 (assuming $M_1 < M_2 < M_3$) or $\sqrt{2}\,\mathrm{Re}\eta^0$ (assuming that it is the lightest scalar particle odd under Z_2). In the former case, if the η masses are all greater than M_k, there will be observable decays

$$\eta^\pm \to l^\pm N_{1,2,3}, \tag{16}$$

then

$$N_2 \to l^\pm l^\mp N_1 \tag{17}$$

and

$$N_3 \to l^\pm l^\mp N_{1,2} \tag{18}$$

through $\eta^\pm$ exchange. The Yukawa couplings h_{ij} may then be extracted and compared against the neutrino mass matrix as a means of verifying the seesaw mechanism [4].

In the latter case, with $\sqrt{2}\,\mathrm{Re}\eta^0$ as a bosonic dark-matter candidate [6], the fact that $\sqrt{2}\,\mathrm{Im}\eta^0$ must be just slightly heavier is a natural condition for their coannihilation in the early Universe [7]. This is better than the usual supersymmetric scenario for dark matter, where coannihilation requires the accidental degeneracy of two unrelated particles.

If M_k are all greater than the η masses, there will be observable decays

$$N_{1,2,3} \to l^\pm \eta^\mp, \tag{19}$$

then

$$\eta^\mp \to \eta^0 + \{W^\mp\}, \tag{20}$$

where the real or virtual $W^\mp$ becomes a quark or lepton pair. Again the Yukawa couplings h_{ij} may be extracted.

The η particles can be produced in pairs directly by the SM gauge bosons $W^\pm$, Z, or γ. Their subsequent decays will produce N_i if kinematically allowed. In the case where $N_{1,2,3}$ are all heavier than the η particles, pair production by e^+e^- annihilation through $\eta^\pm$ exchange appears to be the only realistic possibility.

This model is also a very suitable framework for considering lepton family symmetry. It has the flexibility of having the neutrino mass matrix proportional to the inverse mass matrix of N_i as in the canonical seesaw mechanism [8], or to the mass matrix of N_i itself. For example, using the tetrahedral symmetry A_4 [9], many recent ideas [10] of implementing tribimaximal mixing [11] can be easily incorporated.

In conclusion, with a minimal addition to the standard model, i.e. a second scalar doublet and three heavy neutral fermion singlets transforming as -1 under an exact Z_2 symmetry, realistic radiative neutrino masses can be obtained together with candidates for the dark matter of the Universe. This framework parallels that of the SM in family structure and the new particles are very likely to be observable in forthcoming experiments at the Large Hadron Collider, or at a future Linear Collider.

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