SU(5) Completion of the Dark Scalar Doublet Model of Radiative Neutrino Mass

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Abstract

Adding a second scalar doublet \((\eta^+, \eta^0)\) and three neutral singlet fermions \(N_{1,2,3}\) to the Standard Model of particle interactions with a new \(Z_2\) symmetry, it has been shown that \(\eta^0_R\) or \(\eta^0_I\) is a good dark-matter candidate and seesaw neutrino masses are generated radiatively. A minimal extension of this new idea is proposed to allow for its SU(5) completion. Supersymmetric unification is then possible, and leptoquarks of a special kind are predicted at the TeV scale.
A new idea has recently been proposed that without dark matter, neutrinos would be massless. This is minimally implemented [1, 2, 3] by the addition of a second scalar doublet \((\eta^+, \eta^0)\) and three neutral singlet Majorana fermions \(N_{1,2,3}\) to the Standard Model (SM) of particle interactions, together with a new \(Z_2\) discrete symmetry [4], under which \((\eta^+, \eta^0)\) and \(N_{1,2,3}\) are odd, and all SM particles are even. Using the allowed term \((\lambda_5/2)(\Phi^\dagger\eta)^2 + H.c.,\) where \(\Phi = (\phi^+, \phi^0)\) is the SM Higgs doublet, seesaw neutrino masses are generated in one loop, as shown in Fig. 1.

![Diagram of one-loop generation of neutrino mass.](image)

At the same time, \(\eta_R^0\) and \(\eta_I^0\) are split in mass, and either is a good dark-matter candidate [5, 6, 7] with mass between 45 and 75 GeV, with reasonable prognosis [5, 8] for detection at the Large Hadron Collider (LHC). Variants of this basic idea have also been discussed [9, 10, 11, 12, 13, 14, 15, 16].

In this note, the SU(5) completion of this simplest model is proposed, leading to its possible supersymmetric unification. (It has been shown [17] that the string-inspired \(E_6/U(1)_N\) model may also be used, but gauge-coupling unification in this case is not as straightforward [18].) As a consequence, there are two kinds of dark matter, and leptoquarks are predicted which always decay into one or both, and may well be observable at the LHC.
Under SU(5), the SM quarks and leptons are organized into

\[ \begin{align*}
\mathbf{5}^* &= d^c \ (3^*, 1, 1/3) + (\nu, e) \ (1, 2, -1/2), \\
\mathbf{10} &= (u, d) \ (3, 2, 1/6) + u^c \ (3^*, 1, -2/3) + e^c \ (1, 1, 1),
\end{align*} \tag{1, 2} \]

where their SU(3)C × SU(2)L × U(1)Y decompositions are also indicated. If the SM is supersymmetrized and two Higgs superfields transforming as

\[ \Phi_{1,2} \sim (1, 2, \mp 1/2) \tag{3} \]

are added, then it is well-known [19] that the three SM gauge couplings unify at an energy scale of order \(10^{16}\) GeV. This may be taken to be an indication of the validity of SU(5) unification. Note in particular that the unification of gauge couplings is insensitive to the addition or subtraction of complete SU(5) multiplets, such as in split supersymmetry [20]. In one-loop order, each complete multiplet contributes equally to the slopes of \(\alpha_i^{-1} = 4\pi/g_i^2\) as a function of energy scale. Hence the three gauge couplings \(g_i\) still converge at around \(10^{16}\) GeV; the only change is their numerical value.

In the dark scalar doublet model [11] of seesaw radiative neutrino mass, the obvious thing to do is to consider \((\eta^+, \eta^0)\) as part of a \(\mathbf{5}\) representation of SU(5), together with its conjugate \(\mathbf{5}^*\), i.e.

\[ \begin{align*}
\mathbf{5} &= h \ (3, 1, -1/3) + (\eta_2^+, \eta_2^0) \ (1, 2, 1/2), \\
\mathbf{5}^* &= h^c \ (3^*, 1, 1/3) + (\eta_1^0, \eta_1^-) \ (1, 2, -1/2),
\end{align*} \tag{4, 5} \]

both of which are of course odd under the new \(Z_2\). In that case, gauge-coupling unification is again possible, provided that \(m_h\) and \(m_\eta\) are comparable within an order of magnitude. For \(\eta_{1,2}^0\) to be considered as components of dark matter, the energy scale of \(m_h\) is then likely to be TeV or less. Conventionally, the existence of \(h(h^c)\) in the \(\mathbf{5} (\mathbf{5}^*)\) representation of SU(5) is considered dangerous because it would mediate rapid proton decay. However, the new \(Z_2\)
symmetry used here for dark matter and radiative neutrino mass also serves the purpose of conserving baryon number and preventing proton decay.

As studied already in Ref. [3], the $\lambda_5$ term needed for Fig. 1 is not available in a supersymmetric context. Hence one additional singlet superfield $\chi$ is needed, as shown in Table 1.

Table 1: Particle content of proposed model.

| Superfield                          | $Z_2$ | $Z'_2$ |
|------------------------------------|-------|--------|
| $d^c, (\nu, e)$                    | $-$   | $+$    |
| $(u, d), u^c, e^c$                 | $-$   | $+$    |
| $(\phi_0^0, \phi_1^{-}), (\phi_2^+, \phi_2^0)$ | $+$   | $+$    |
| $N$                                | $-$   | $-$    |
| $h^c, (\eta_1^0, \eta_1^-)$       | $+$   | $-$    |
| $h, (\eta_2^+, \eta_2^0)$         | $+$   | $-$    |
| $\chi$                            | $+$   | $-$    |

The imposition of $Z_2$ amounts to the usual $R$ parity of the Minimal Supersymmetric Standard Model (MSSM). The additional exactly conserved $Z'_2$ forbids the coupling $(\nu\phi_2^0 - e\phi_2^+)N$ but allow [3]

$$f_{ij}(\nu_i\eta_2^0 - e_i\eta_2^+)N_j + \lambda_1\Phi_1\eta_2\chi + \lambda_2\Phi_2\eta\chi + \mu_\phi\Phi_1\Phi_2 + \mu_\eta\eta\eta_2 + \frac{1}{2}\mu_\chi\chi\chi + \frac{1}{2}M_{ij}N_iN_j, \quad (6)$$

thereby generating radiative neutrino masses in one loop, as shown in Fig. 2.

Because of the two separately conserved discrete symmetries, there are now at least two absolutely stable particles: the lightest particle with $R = -1$ as in the MSSM, and the lightest particle which is odd under $Z'_2$. Consider in particular the three lightest particles with $(R, Z'_2) = (-, +), (+, -)$, and $(-, -)$ respectively. If one is heavier than the other two combined, then the latter are the two components of dark matter. If not, then all three contribute.
The new prediction of the proposed supersymmetric SU(5) completion of the dark scalar doublet model is of course the leptoquark $h(h^c)$ and its associated scalar partners $\tilde{h}$ and $\tilde{h}^c$. Because they are odd under $Z_2'$, they must decay into one or both of the dark-matter candidates with $(R, Z_2') = (+, -)$ or $(-, -)$. If kinematically allowed, the $(\pm, -)$ particle may also decay into $(\mp, -)$ and $(-, +)$. Specifically, the only allowed trilinear coupling involving $h$ or $h^c$ is $hd^cN$. Assuming that $N$ is much heavier than $h$, then from Eq. (6) it is clear that $h$ always decays into a quark and a lepton plus a particle which is odd under $Z_2'$.

Since $m_h$ should be at the TeV scale or below (from the argument that the gauge couplings should be unified), strong production of $h\bar{h}$ at the LHC is expected. Note however that $h$ is different from the usual leptoquark which conserves both additive baryon number $B$ and lepton number $L$. Here $h$ has $B = 1/3$, but only odd $(-)^L$. This means that it can decay into either $d e^- \eta_2^+$ or $d e^+ \eta_2^-$. Thus $h\bar{h}$ production will result in same-sign dileptons plus quark jets plus missing energy, which is a possible unique signature of this exotic particle.

In conclusion, by adding the new exotic leptoquark superfields $h$ and $h^c$ to a supersymmetric version of the dark scalar doublet model of radiative seesaw neutrino mass, the SU(5) completion of the model is accomplished, allowing the gauge couplings to be unified as in the MSSM. The pair production of these leptoquarks will result in same-sign dilepton events with missing energy, which may be observable at the LHC.
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