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# Connecting Radiative Neutrino Mass, Neutron-Antineutron Oscillation, Proton Decay, and Leptogenesis through Dark Matter

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**Abstract**

The scotogenic mechanism for radiative neutrino mass is generalized to include neutron-antineutron oscillation as well as proton decay. Dark matter is stabilized by extending the notion of lepton parity to matter parity. Leptogenesis is also a possible byproduct. This framework unifies the description of all these important topics in physics beyond the standard model of particle interactions.

*Introduction* :

The standard model (SM) of quarks and leptons is based on the well-tested $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. It admits two well-known accidental symmetries, baryon number $B$ and lepton number $L$, which are known to be conserved as far as present experimental limits are concerned. Of course, if neutrino masses are confirmed as Majorana from neutrinoless double beta decay in the near future, then $L$ should be downgraded to just $(-1)^L$, i.e. lepton parity $P_L$. This is actually an important concept, because dark matter may be stabilized by the proper extension of $P_L$ to physics beyond the SM [1]. It would also tell us that $P_L$ may be the true symmetry of a complete theory, whereas the conservation of $L$ only holds in the absence of neutrino masses.

Let us now consider $B$. Is there a possible clue that it is not the true symmetry of a complete theory? The analog to Majorana neutrino mass is then neutron-antineutron $(n-\bar{n})$ oscillation. If proven to exist, $B$ would be downgraded to $(-1)^{3B}$, i.e. baryon parity $P_B$. What about proton decay? If it exists, then the final product must contain a lepton, e.g. $p \to \pi^0 e^+$ or $p \to \pi^+ \nu(\bar{\nu})$. This would violate both lepton parity and baryon parity. It may however be accommodated by combining lepton parity with baryon parity to form matter parity, i.e. $P_M = (-1)^{3B+L}$.

In this paper, we assume that the true symmetry of a complete theory beyond the SM is $P_M$. However, $P_L$ and $P_B$ are respected by all dimension-four and dimension-three terms of the Lagrangian, broken only to $P_M$ by a unique dimension-two term. With the present available experimental accuracy, the separate conservation of $B$ and $L$ holds. To allow for neutrinoless double beta decay (for $P_L$), neutron-antineutron oscillation (for $P_B$), and proton decay (for $P_M$) in a comprehensive framework, we adopt here the scotogenic mechanism (from the Greek *scotos* meaning darkness), invented 10 years ago [2].

*Scotogenic neutrino mass* :

The scotogenic mechanism was applied to obtaining one-loop Majorana neutrino masses as shown in Fig. 1. The scalar doublet $(\eta^+, \eta^0)$ is odd under $P_L$ to distinguish it from the SM

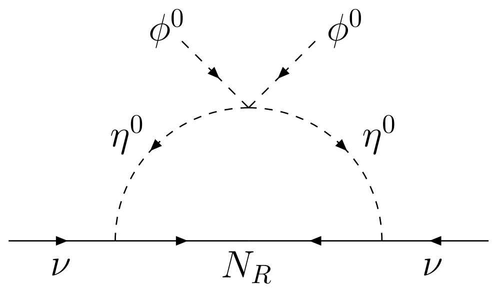


Figure 1: One-loop $Z_2$ scotogenic neutrino mass.

Higgs doublet $(\phi^+, \phi^0)$ which is even. The three neutrinos $\nu_L$ are odd under $P_L$, and the three singlet neutral fermions $N_R$ are even. The latter have allowed Majorana masses $m_N$, forming thus three Majorana fermions $N = N_R + N_R^c$. Note that $N_R$ are not the right-handed neutrinos which would be odd under $P_L$. This assignment is equivalent [1] to having odd dark parity for $\eta$ and $N_R$, and even dark parity for $\nu_L$ and $\phi$, using the conserved product $P_L(-1)^{2j}$, where $j$ is the spin angular momentum of the particle.

*Scotogenic neutron-antineutron oscillation* :

The scotogenic analog for $n - \bar{n}$ oscillation is actually very simple. Add to the SM two color scalar triplets, one with even $P_B$ and the other with odd $P_B$ as follows:

$$\delta \sim (3, 1, -1/3; +), \quad \xi \sim (3, 1, -1/3; -). \tag{1}$$

The resulting allowed interactions are $d_R N_R \xi^*$, $(\delta^* \xi)^2$, and $u_{L,R} d_{L,R} \delta$. Hence $\delta$ is a scalar diquark, and $n - \bar{n}$ oscillation is generated as shown in Fig. 2, by converting each outgoing $\delta$ to an incoming $ud$ pair. Note that $N_R$ is again used because it has even $P_B$ as well as $P_L$, and the scalar $\xi$ inside the loop has odd dark parity. The new particles of this model are listed in Table 1, together with two other real scalar singlets $\chi_{1,2}$ to be discussed later. The dark parity $P_D$ is simply defined as $P_M(-1)^{2j}$. This connection between radiative neutrino

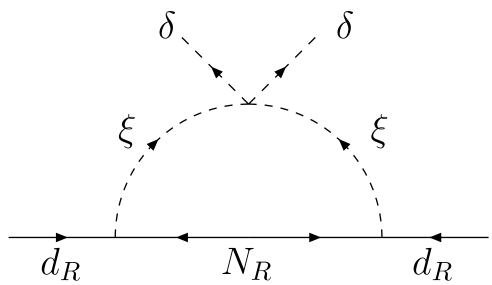


Figure 2: One-loop $Z_2$ scotogenic $n - \bar{n}$ oscillation.

mass and $n - \bar{n}$ oscillation in a much more nonminimal scheme has also been suggested [3].

<u>*Scotogenic proton decay*</u> :

Let us now bisect Figs. 1 and 2 and try to join the two different halves. The quartic couplings $(\delta^* \xi)(\bar{\phi}^0 \eta^0)$ and $(\delta^* \xi)(\phi^0 \bar{\eta}^0)$ are forbidden by $P_L$ and by $P_B$. However they may be induced by the trilinear couplings $\delta^* \xi \chi_1$, $\bar{\phi}^0 \eta^0 \chi_2$, and $\phi^0 \bar{\eta}^0 \chi_2$, which respect both $P_L$ and $P_B$. The dimension-two mass-squared term $m_{12}^2 \chi_1 \chi_2$ is then inserted to break $P_L$ and $P_B$ softly to $P_M = P_L P_B$. Since no discrete symmetry is spontaneously broken, this model has no domain wall. The resulting diagrams are shown in Figs. 3 and 4. Both processes conserve

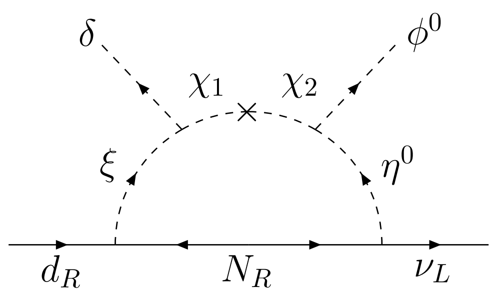


Figure 3: One-loop $Z_2$ scotogenic $n \to \nu$ transition.

$P_M$, whereas $n \to \nu$ conserves $B + L$ in Fig. 3, and $n \to \bar{\nu}$ conserves $B - L$ in Fig. 4. It will be shown later that the integral associated with Fig. 4 is negligible compared to that of

Table 1: Particle content of proposed model.

| Particle | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $P_L$ | $P_B$ | $P_M$ | $P_D$ |
|---|---|---|---|---|---|---|---|
| $(u,d)_L$ | 3 | 2 | 1/6 | + | − | − | + |
| $u_R$ | 3 | 1 | 2/3 | + | − | − | + |
| $d_R$ | 3 | 1 | −1/3 | + | − | − | + |
| $(\nu,l)_L$ | 1 | 2 | −1/2 | − | + | − | + |
| $l_R$ | 1 | 1 | −1 | − | + | − | + |
| $N_R$ | 1 | 1 | 0 | + | + | + | − |
| $(\phi^+,\phi^0)$ | 1 | 2 | 1/2 | + | + | + | + |
| $(\eta^+,\eta^0)$ | 1 | 2 | 1/2 | − | + | − | − |
| $\delta$ | 3 | 1 | −1/3 | + | + | + | + |
| $\xi$ | 3 | 1 | −1/3 | + | − | − | − |
| $\chi_1$ | 1 | 1 | 0 | + | − | − | − |
| $\chi_2$ | 1 | 1 | 0 | − | + | − | − |

Fig. 3. Hence proton decay proceeds mainly via $p \to \pi^+\nu$, thereby conserving $B+L$ [4, 5], instead of the usual $B-L$. However, since $\nu$ cannot be distinguished from $\bar{\nu}$ in practice, this prediction cannot be tested. In this scenario, we assume $\xi$ to be heavier than $N$, so $\xi$ decays to $N+d$. We also assume that the lightest $N$ is heavier than $\eta$, so that its decay to $\eta^+l^-$ and $\eta^-l^+$ may generate a lepton asymmetry [6], which gets converted to a baryon asymmetry through the sphalerons [7] before the electroweak phase transition is over. The

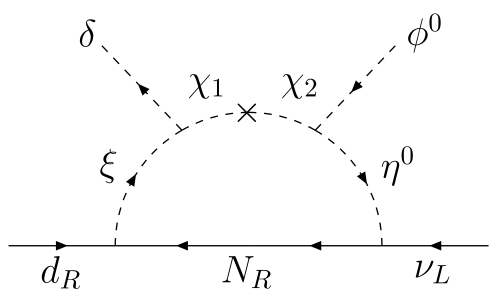


Figure 4: One-loop $Z_2$ scotogenic $n \to \bar{\nu}$ transition.

dark-matter candidate is thus either the real or imaginary component of $\eta^0$ [8]. For some recent studies on this possibility, see for example Refs. [9, 10, 11].

*Evoution of $B$ and $L$ symmetries* :

In our scenario the heaviest particle is $\xi$. For convenience we also assume $\chi_{1,2}$ to be at this mass scale. They may however be much lighter and not affect our following discussion. As the Universe cools below $m_\xi$, the effective theory (minus $\xi$ and possibly $\chi_{1,2}$) gains the symmetry $B$ in all its dimension-four terms, whereas the dimension-five term $(\delta^* d_R)^2$ breaks $B$ to $P_B$. The $(\delta^* d_R)(\phi^0\nu - \phi^+ l^-)$ and $(\delta^* d_R)(\bar{\phi}^0\bar{\nu} - \phi^- l^+)$ terms break $P_L$ and $P_B$ to $P_M$. The next heaviest particles are $N_{1,2,3}$. As the Universe further cools below their masses, the effective theory gains also the symmetry $L$ in all its dimension-four terms, whereas the dimension-five term $(\phi^0\nu - \phi^+ l^-)^2$ breaks $L$ to $P_L$. Meanwhile, the decay $N \to l^\pm \eta^\mp$ has created a lepton asymmetry and is being converted by sphalerons to the observed baryon asymmetry of the Universe. Finally at the electroweak scale, the particle content of our proposal is that of the SM plus the dark scalar doublet $(\eta^+, \eta^0)$, and perhaps also the scalar diquark $\delta$. If $m_\delta$ is much heavier, then the $n - \bar{n}$ oscillation effective operators $(u_R d_R) d_R d_R (u_R d_R)$, $(u_L d_L) d_R d_R (u_L d_L)$, $(u_R d_R) d_R d_R (u_L d_L)$ are dimension-nine, and the proton decay effective operators $(u_R d_R) d_R (\bar{\phi}^0 \bar{\nu} - \phi^- l^+)$, $(u_L d_L) d_R (\bar{\phi}^0 \bar{\nu} - \phi^- l^+)$ are dimension-seven [12, 13, 14]. Note that the decay of $n$ to $l^-$ is possible, but it requires the insertion of $W^+$ to change $\phi^0$ to $\phi^+$ and $\nu$ to $l^-$, so it is very much suppressed compared to any decay of $n$ to $\nu$.

*Relevant interactions* :

The Lagrangian involving the interactions of the new particles $N, (\eta^+, \eta^0), \delta, \xi, \chi_{1,2}$ is given by

$$\begin{aligned} \mathcal{L}_{int} &= h\bar{N}(\nu\eta^0 - l\eta^+) + \frac{1}{2}\lambda_5(\Phi^\dagger\eta)^2 + f_\xi d N \xi^* + f_\delta u d \delta + \frac{1}{2}\lambda'_5(\delta^*\xi)^2 \\ &+ \mu_1 \delta^* \xi \chi_1 + \mu_2 \Phi^\dagger \eta \chi_2 + m_{12}^2 \chi_1 \chi_2 + H.c., \end{aligned} \tag{2}$$

where the family indices of the leptons and quarks and $N$ have been suppressed. This

Lagrangian has the symmetry $P_M$ and by implication also $P_D$ as listed in Table 1, which is always conserved. In the limit that $\chi_{1,2}$ become much heavier than the other particles, the symmetry becomes larger, i.e. $P_B$ and $P_L$, for most terms. Of course, the effect of $\chi_{1,2}$ remains in the induced term $\delta^* \xi \Phi^\dagger \eta$, but it is very much suppressed by the factor $m_{12}^2 \mu_1 \mu_2 / m_1^2 m_2^2$. If $\xi$ is the next heaviest particle, then the symmetry becomes larger again, i.e. $B$ and $P_L$, at energies much below $m_\xi$, meaning again that terms breaking $B$ to $P_B$ are small. If the next heaviest particles are $N$, the symmetry becomes that of the SM, i.e. $B$ and $L$, with odd $P_D$ for dark matter which is $\eta^0$ in this case. Of course, our ultraviolet-complete scheme also generates small higher-dimensional operators, namely dimension-five for Majorana neutrino mass (which conserves $P_L$), dimension-nine for $n-\bar{n}$ oscillation (which conserves $P_B$), and dimension-seven for proton decay (which conserves $P_M$). Note that if we remove $N$, then Figs. 1 to 4 all collapse, showing thus that all the mentioned phenomena are related.

*Evaluations of the loop integrals* :

The evaluation of the integral involved in the one-loop diagram of Fig. 1 is well-known. The $(\lambda_5/2)(\Phi^\dagger \eta)^2 + H.c.$ interaction splits the complex scalar $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ into two mass eigenstates with different eigenvalues $m_{R,I}$, i.e.

$$m_R^2 - m_I^2 = 2\lambda_5 v^2, \tag{3}$$

with $v = \langle \phi^0 \rangle = 174$ GeV. For a given $N$ with mass $m_N$, their contribution is given by

$$I_1(m_N, m_R, m_I) = \frac{m_N}{16\pi^2} \left[ \frac{m_R^2 \ln(m_N^2/m_R^2)}{m_N^2 - m_R^2} - \frac{m_I^2 \ln(m_N^2/m_I^2)}{m_N^2 - m_I^2} \right]. \tag{4}$$

The analog integral for Fig. 2 is

$$I_2(m_N, m_\xi) = \frac{m_N}{16\pi^2} \left[ \frac{1}{m_\xi^2 - m_N^2} - \frac{m_N^2 \ln(m_\xi^2/m_N^2)}{(m_\xi^2 - m_N^2)^2} \right]. \tag{5}$$

For Fig. 3, we assume

$$m_{12}^2, m_{R,I}^2 << m_N^2 << m_\xi^2 \simeq m_{1,2}^2, \tag{6}$$

then the integral is proportional to $\mu_1\mu_2 m_N m_{12}^2$, where $\mu_{1,2}$ are the trilinear couplings of $\chi_1\delta^*\xi$ and $\chi_2\bar{\phi}^0\eta^0$, and the contribution of $m_{R,I}^2$ is negligible. We obtain

$$\begin{aligned} I_3(m_N, m_\xi) &= \frac{\mu_1\mu_2 m_N m_{12}^2}{16\pi^2}\left[\frac{-2m_\xi^2+m_N^2}{2m_\xi^4(m_\xi^2-m_N^2)^2}+\frac{\ln(m_\xi^2/m_N^2)}{(m_\xi^2-m_N^2)^3}\right] \\ &\simeq \frac{\mu_1\mu_2 m_N m_{12}^2[-1+\ln(m_\xi^2/m_N^2)]}{16\pi^2 m_\xi^6}. \end{aligned} \tag{7}$$

Using the same assumption of Eq. (6), we obtain also

$$I_1 \simeq \frac{1}{16\pi^2}\left[\frac{m_R^2}{m_N}\ln\left(\frac{m_N^2}{m_R^2}\right)-\frac{m_I^2}{m_N}\ln\left(\frac{m_N^2}{m_I^2}\right)\right], \quad I_2 \simeq \frac{m_N}{16\pi^2 m_\xi^2}. \tag{8}$$

The integral $I_4$ for Fig. 4 is helicity suppressed, so that $m_N$ has to be replaced by $m_d$, hence it is negligible compared to $I_3$ and will not be considered further. There are also contributions to $I_{1,2}$ from $\chi_{2,1}$, but they are suppressed by $\mu_{2,1}^2/m_{2,1}^2$.

*Phenomenological details* :

The $3\times 3$ neutrino mass matrix is given by

$$(\mathcal{M}_\nu)_{ij} = \sum_k h_{ik}h_{jk}I_1(m_{N_k}, m_R, m_I), \tag{9}$$

where $h$ are the Yukawa $\bar{N}_R\nu\eta^0$ couplings. The applicability of this formula has been studied extensively. For example, if $h\sim 10^{-3}$, $m_{R,I}\sim 100$ GeV, and $m_N \sim 10^6$ GeV, then neutrino masses are of order 0.1 eV. For this set of parameters, i.e. small $h$ and large $m_N$, this model's contributions to radiative processes such as $\mu\to e\gamma$ are also very much below their experimental bounds,

The above mechanism has also the built-in possibility [15] of leptogenesis [6] from the decay of $N\to l^\pm\eta^\mp$. In particular, the required CP asymmetry can obtain a resonantly enhanced contribution from self-energy corrections [16, 17] since the decaying singlet fermions may have a quasi-degenerate mass spectrum, i.e.

$$\varepsilon_{N_i} = \frac{1}{8\pi}\sum_{j\neq i}\frac{\mathrm{Im}\{[(h^\dagger h)_{ij}]^2\}}{(h^\dagger h)_{ii}}\frac{m_{N_j}m_{N_i}}{m_{N_j}^2-m_{N_i}^2}\,. \tag{10}$$

Consider as usual the quantity

$$K_i = \frac{\Gamma_{N_i}}{2H(T)}\Big|_{T=m_{N_i}} \quad \text{with} \quad \Gamma_{N_i} = \frac{1}{8\pi}(h^\dagger h)_{ii} m_{N_i}\,, \quad H(T) = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}} \frac{T^2}{M_{Pl}}\,. \tag{11}$$

As an example, let $h \sim 10^{-3}$ and $m_{N_3} \gg m_{N_{1,2}} \sim 10^6\,\text{GeV}$. We then obtain the CP asymmetries $\varepsilon_{N_{1,2}} = \mathcal{O}(0.01 - 0.1)$ for $m_{N_2} - m_{N_1} = \mathcal{O}(1 - 10\,\text{GeV})$. Using $g_* \simeq 100$ and $M_{Pl} \simeq 10^{19}\,\text{GeV}$, we find $K_{1,2} = \mathcal{O}(10^5)$, hence $z_{1,2} \simeq 4.2(\ln K_{1,2})^{0.6} \simeq \mathcal{O}(18)$ [18]. This means that the lighter singlet fermions $N_{1,2}$ can efficiently decay to generate a lepton asymmetry at a temperature around $T_{1,2} \simeq m_{N_{1,2}}/z_{1,2} = \mathcal{O}(10^5\,\text{GeV})$ where the sphaleron processes are still active. Note that during this epoch, because the temperature of the Universe is much below $m_\xi$, the $B$ violating process $qq \to \bar{q}\bar{q}\bar{q}\bar{q}$ is very much suppressed, and will not affect the conversion of a lepton asymmetry to a $B-L$ asymmetry through sphalerons. The final baryon asymmetry, which is conveniently described by the ratio of the baryon number density $n_B$ over the entropy density $s$, is then $n_B/s \simeq \varepsilon_{N_1}/(g_* K_1 z_1) + \varepsilon_{N_2}/(g_* K_2 z_2) = \mathcal{O}(10^{-10})$ as desired [18]. This is a rough estimate without taking into account flavor effects, but it serves to show the viability of our overall framework.

As for the topic of $n - \bar{n}$ oscillation, there has been a recent resurgence of interest [19]. Let the effective Hamiltonian density be given by

$$\mathcal{H}_{eff} = \sum_i c_i \mathcal{O}_i \tag{12}$$

where $\mathcal{O}_i$ are the dimension-nine operators responsible for this transition. Then

$$\langle \bar{n}|\mathcal{H}_{eff}|n\rangle = \sum_i c_i \langle \bar{n}|\mathcal{O}_i|n\rangle \simeq \sum_i c_i \Lambda_{QCD}^6 \simeq \sum_i c_i (180~\text{MeV})^6. \tag{13}$$

Let the $d_R N_R \xi^*$ coupling be $f_\xi$, the $u_{L,R} d_{L,R} \delta$ couplings be $f_\delta^{L,R}$, and the $(\delta^*\xi)^2$ coupling be $\lambda_5'/2$, then

$$\sum_i c_i = \frac{(f_\delta^L + f_\delta^R)^2 \lambda_5' f_\xi^2 m_N}{16\pi^2 m_\xi^2 m_\delta^4}. \tag{14}$$

For $\tau_{n-\bar{n}} = 2 \times 10^8$ s, this translates to [19]

$$\sum_i c_i = 10^{-28} \text{ GeV}^{-5}. \tag{15}$$

Inside a nucleus, the $n - \bar{n}$ transition is exponentially suppressed. Hence the present experimental limit [20] $\tau_{n-\bar{n}} > 0.86 \times 10^8$ s yields a deuteron stability lifetime $> 10^{31}$ y. To match Eq. (14) with Eq. (15), we may for example take again $m_N \sim 10^6$ GeV, then choose $m_\xi \sim 10^7$ GeV, $m_\delta \sim 10^4$ GeV, and $f_\delta^{L,R} \sim \sqrt{\lambda'_5} \sim f_\xi \sim 0.4$.

For proton decay, the dominant decay $p \to \pi^+ \nu$ has an effective coupling given by

$$\begin{aligned} G_{eff} &= \frac{\sqrt{(f_\delta^L)^2 + (f_\delta^R)^2} f_\xi h v I_3 \Lambda_{QCD}^3}{f_\pi m_\delta^2} \\ &= \left( \frac{\sqrt{(f_\delta^L)^2 + (f_\delta^R)^2} f_\xi h v \Lambda_{QCD}^3}{f_\pi m_\delta^2} \right) \frac{\mu_1 \mu_2 m_N m_{12}^2 [-1 + \ln(m_\xi^2/m_N^2)]}{16\pi^2 m_\xi^6}. \end{aligned} \tag{16}$$

Let $m_\xi \sim 10^7$ GeV, $m_N \sim 10^6$ GeV, $m_\delta \sim 10^4$ GeV, $\Lambda_{QCD} = 180$ MeV, $f_\delta^{L,R} \sim f_\xi \sim 0.4$, and $h \sim 10^{-3}$ as before. Using $f_\pi = 130$ MeV, and choosing $\mu_{1,2} \sim 10^5$ GeV, $m_{12}^2 \sim 10^7$ GeV$^2$ in addition, then $G_{eff} \sim 4.0 \times 10^{-32}$ which yields a proton decay lifetime $\sim 1.4 \times 10^{33}$ y, using

$$\Gamma_p = \frac{G_{eff}^2 (m_p^2 - m_\pi^2)^2}{32\pi m_p^3}. \tag{17}$$

The numerical values of the various parameters are of course for illustration only. They are chosen to demonstrate that realistic solutions exist for neutrino mass, neutron-antineutron oscillation, and proton decay, all in the scotogenic context. Again our framework assumes the validity of matter parity $P_M$ which translates to dark parity $P_D = P_M(-1)^{2j}$, and is derivable from lepton parity $P_L$ and baryon parity $P_B$, both of which are respected by all dimension-four and dimension-three terms of our renormalizable Lagrangian. A unique dimension-two term breaks both $P_L$ and $P_B$, but preserves the product $P_M = P_L P_B$. In the illustrative example shown, the heaviest particles are the scalar $\xi$ and perhaps also the scalars $\chi_{1,2}$ at $\sim 10^7$ GeV. They decay to the singlet fermions $N$ with mass $\sim 10^6$ GeV, which also couple to leptons and are responsible for generating a lepton asymmetry of the Universe. Leaving aside these very heavy particles, our proposal also predicts a scalar diquark $\delta$ of mass $\sim 10$ TeV, as compared with the present experimental lower limit [21] of about 6 TeV. Finally, we also have the dark scalar doublet $(\eta^+, \eta^0)$ which should be observable at the electroweak scale.

*Concluding remarks* :

In this scotogenic worldview, new physics phenomena beyond the standard model are all interconnected through dark matter and dictated by the extension of the discrete symmetries lepton parity $P_L$ and baryon parity $P_B$, both of which are respected by the dimension-four and dimension-three terms of our complete renormalizable Lagrangian. A unique dimension-two term breaks $P_L$ and $P_B$, but preserves matter parity $P_M = P_L P_B$. Dark parity is then simply $P_M(-1)^{2j}$.

The new particles of this scenario are three dark singlet neutral Majorana fermions $N$, a dark scalar doublet $(\eta^+, \eta^0)$, a scalar diquark $\delta$, a dark scalar leptoquark $\xi$, and two dark real scalar singlets $\chi_{1,2}$. Scotogenic radiative neutrino masses are obtained through $N$ and $\eta^0$ as shown in Fig. 1. Leptogenesis is facilitated by the decay $N \to l^\pm \eta^\mp$. Neutron-antineutron oscillation is obtained through $N$, $\xi$, and $\delta$ as shown in Fig. 2. Slicing the two diagrams and joining them together with $\chi_{1,2}$, proton decay is obtained as shown in Fig. 3. This new notion of physics beyond the standard model connects all four fundamental processes through dark matter. Possible experimental verfication includes the discovery of the dark scalar doublet $(\eta^+, \eta^0)$, the crucial heavy scalar diquark $\delta$ if kinematically possible, and the prediction that proton decay should be $p \to \pi^+ \nu$, and not $p \to \pi^0 e^+$ or $p \to \pi^+ \bar{\nu}$.

To summarize, in our new proposal for going beyond the SM, new heavy particles are added to change the symmetries $L$ to $P_L$, $B$ to $P_B$, then $P_L$ and $P_B$ are combined to form $P_M = P_L P_B$. As the Universe cools, these new heavy particles are frozen out, and the SM conserves both $L$ and $B$, but the memory of $P_L$, $P_B$, and $P_M$ is encoded in the rare processes of Majorana neutrino mass, neutron-antineutron oscillation, and proton decay, with the addition of $P_D = P_M(-1)^{2j}$ as dark parity.

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