Neutrino Masses, Leptogenesis and Decaying Dark Matter

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(Dated: June 10, 2009)

Abstract

We study a simple extension of the standard model to simultaneously explain neutrino masses, dark matter and the matter-antimatter asymmetry of the Universe. In our model, the baryon asymmetry is achieved by the leptogenesis mechanism, while the decaying dark matter with the lifetime of \(O(10^{26}\text{ s})\) provides a natural solution to the electron and positron excesses in Fermi and PAMELA satellite experiments. In particular, we emphasize that our model is sensitive to the structure at the endpoint around 1 TeV of the Fermi data. In addition, some of new particles proposed in the model are within the reach at the near future colliders, such as the Large Hadron Collider.
The observed neutrino oscillations and matter-antimatter asymmetry as well as the evidence for dark matter (DM) [1] clearly imply physics beyond the standard model (SM). Recently, PAMELA [2] and ATIC [3] cosmic-ray measurements show the positron/electron excesses above the calculated backgrounds for the energy of $\mathcal{O}(100)$ GeV. These data are consistent with the measurements of the high energy electrons and positrons fluxes in the cosmic ray spectra by PPB-BETS [4], HEAT [5], AMS [6] and HESS [7, 8]. Very recently, a more precise data by the Fermi LAT collaboration [9] also indicates some enhancements in the electrons + positrons flux in the 100 − 1000 GeV energy range. However, the Fermi’s result is in conflict with the large excess in flux around 500 GeV range by ATIC. Similar conclusion has also been given by HESS based on the low energy data [8]. In this study, we will concentrate on the combined data of PAMELA and Fermi (PF) without fitting that of ATIC.

To explain the PAMELA/ATIC data, there have been many possible mechanisms, such as DM decays [10, 11], DM annihilations [12] and astrophysical sources [13], while recent studies related to the PF data without the ATIC one can be found in Refs. [14, 15]. In this paper, we would like to explore the possibility of connecting the neutrino masses to the dark matter problem as well as the baryon asymmetry of the Universe (BAU). In particular, we would like to pay attentions to models which can be tested directly by the future high energy colliders, such as the Large Hadron Collider [16] and Linear Collider (LC) [17].

We introduce three new neutral leptons $N_i$ ($i = 1, 2$) and $N$ with the masses of $M_i$ and $M$, and two new doublet scalars $\zeta$ and $\eta$ with zero VEVs and the masses of $M_\zeta$ and $M_\eta$, respectively, in the SM. These new particles have non-trivial transformation properties under the two discrete symmetries $Z_2$ and $Z_2'$ as listed in Table I, whereas the corresponding SM particles are trivial.

| Particle | $\zeta$ | $\eta$ | $N_i$ | $N$ |
|----------|---------|---------|-------|-----|
| $Z_2$    | $-$     | $+$     | $-$   | $+$ |
| $Z_2'$   | $+$     | $-$     | $+$   | $-$ |

The relevant Majorana mass terms and Yukawa couplings as well as the soft breaking
A term involving the new particles can be written as
\[
\frac{M_{ij}}{2} N_i^T C N_j + \frac{M}{2} N^T C N + y_{ij} \bar{L}_i \zeta N_j + y'_{ij} \bar{L}_i \eta N + \mu^2 \eta^\dagger \zeta + \text{H.c.},
\]
where \(i\) and \(j\) are the flavor indexes and \(L_i\) are the lepton doublets in the SM. We note that the soft breaking term in Eq. (1) breaks the two discrete symmetries to a diagonal one. In our study, we will assume the mass hierarchies of \(M_\phi < M_\zeta < M_1 < M_2\) and \(M_\zeta < M < M_\eta\). We will demonstrate that the leptogenesis is achieved by \(N_1\) decays, while \(N\) is the decaying dark matter.

The neutrino masses are generated by the one-loop diagram in Fig. 1 as proposed in Ref. [18] due to the quartic scalar interaction of
\[
\frac{\lambda}{2} (\phi^\dagger \zeta)^2 + \text{H.c.},
\]
where \(\phi\) is the SM Higgs boson. A simple formula for the neutrino masses is found to
\[
(m_\nu)_{ij} = \frac{O(\lambda)}{16\pi^2} \sum_{k=1}^2 \frac{y_{ik} y_{jk}}{M_k} v^2
\]
with the SM Higgs VEV of \(v \simeq 174\) GeV. For the parameter set of \(\lambda = O(10^{-4})\), \(y_{ij} = O(10^{-3})\) and \(M_i = O(100\) GeV \(- 10\) TeV), we obtain \(m_\nu = O(0.01 - 0.1\) eV), consistent with the current neutrino data. Similarly to the minimal seesaw model with two right-handed neutrinos [20], our model contains one massless neutrino with only normal or inverted hierarchy of the neutrino masses. However, the extended model with three \(N_i\) could still has the possibility of the quasi-degenerate neutrino masses.

The leptogenesis mechanism in our paper is the same as that in Ref. [19], provided by \(N_i\) and \(\zeta\). The relevant diagrams for the leptogenesis are shown in Fig. 2. The decay width of
\[ \Gamma(N_1 \rightarrow e^\mp \zeta^\pm) = \frac{(y^\dagger y)_{11}}{16\pi} M_1 r^2 \]  

(4)

with \( r = 1 - M_2^2/M_1^2 \). The out-of-equilibrium condition requires \( r \sim 10^{-4} \). We remark that this small value of \( r \) implies some degeneracy between \( M_1 \) and \( M_\zeta \). However, it may be avoided by including another new doublet with a soft breaking term similar to the discussion on the decaying dark matter discussed later.

In the case of \( 3M_1 < M_2 \), the \( CP \) violating parameter in the leptogenesis is given by

\[ \varepsilon \sim -\frac{3}{16\pi} \frac{1}{(y^\dagger y)_{11}} \text{Im} \left[(y^\dagger y)_{12}\right] \frac{M_1}{M_2}. \]  

(5)

By using \( y_{ij} = \mathcal{O}(10^{-3}) \) and \( M_i = \mathcal{O}(100 \text{ GeV} - 1 \text{ TeV}) \) and assuming a maximal CP phase, the net BAU can be obtained as

\[ \frac{n_B}{s} \sim -\frac{1}{15} \frac{\varepsilon}{g_*} \sim 10^{-10}, \]  

(6)

where \( g_* \simeq 100 \) is the relativistic degrees of freedom. The decays of \( \zeta^+ \rightarrow \zeta^0 \ell^+\nu \) and \( \zeta^- \rightarrow \zeta^0 \ell^-\bar{\nu} \) help to avoid the dangerous relics from the singly-charged component of \( \zeta \), while \( \zeta^0 \) may provide only a sub-dominant component of the DM due to the annihilation into gauge bosons [21].

The diagram for the DM decay is shown in Fig. 3. The decay width of \( N \) is given by

\[ \Gamma_i = \frac{|y'_{ij}|^2}{4\pi} \left( \frac{\mu}{M_\eta} \right)^4 \frac{M_\eta^2}{M}, \]  

(7)

where we have used the definition of

\[ M_\pm = \frac{M_2^2 \pm M_1^2}{2M}. \]  

(8)

By neglecting the effects of the off-shell \( \zeta^\pm \), the lifetime of \( N \) is

\[ \tau_N = \frac{1}{4 \sum_i \Gamma_i} = \frac{\pi A^4 M}{M^2}, \]  

(9)
FIG. 3: Diagram for the DM decay.

with

$$A = \frac{M_\eta}{|\mu| (\sum |y'_i|^2)^{1/4}}, \quad (10)$$

where we have included both charged and neutral modes. By taking $y'_i = \mathcal{O}(10^{-4})$, $\mu = \mathcal{O}(1 \text{ keV})$ and $M_\eta = \mathcal{O}(100 \text{ TeV})$, one gets $A \sim 10^{13}$, leading to $\tau_N \sim 10^{26}$ s with $M_\zeta \sim 0.5 \text{ TeV}$ and $M \sim 2 \text{ TeV}$.

The normalized energy spectrum of the electron/positron for $N \rightarrow e^\mp \zeta^\pm$ can be written as

$$\frac{dN_e}{dE} = 2\delta(M_- - E), \quad (11)$$

while that for the decaying chain of $N \rightarrow \zeta^\pm \mu^\mp (\rightarrow e^\mp 2\nu)$ is [14]

$$\frac{dN_{\mu e}}{dE} = \frac{4}{3M_-} \left[ (x^3 - 1) - \frac{9}{4} (x^2 - 1) \right], \quad (12)$$

with $x = E/M_-$ and $0 < E < M_-$. For the electron/positron produced in the $\zeta^\mp \rightarrow e^\mp \nu \zeta^0$ subprocesses via exchanges of $W^\mp$ bosons, we have

$$\frac{dN_{\zeta e}}{dE} = \left[ \int_{0}^{E_{\text{max}}} dE_d \frac{d\tilde{N}_{\zeta e}}{dE} \right]^{-1} \frac{d\tilde{N}_{\zeta e}}{dE} \quad (13)$$

where

$$E_{\text{max}} = \frac{M \left( M_\zeta^2 - M_{\zeta^0}^2 \right)}{2M_\zeta^2}, \quad (14)$$

$$\frac{d\tilde{N}_{\zeta e}}{dE} = (m_{\nu e}^2)^2 - (m_{\nu e}^2)^2 \quad (15)$$
with
\[ (m_{\nu_e}^2)_\pm = (E_1^* + E_3^*)^2 - (|E_1^*| \mp |E_3^*|)^2, \]  \hspace{1cm} (16)
\[ E_1^* = \frac{m_{\nu_0}^2 - M_\zeta^2}{2m_{\nu_0}}, \quad E_3^* = \frac{M_\zeta^2 - m_{\nu_0}^2}{2m_{\nu_0}}, \]  \hspace{1cm} (17)
\[ m_{\nu_0}^2 = M_\zeta^2 \left( 1 - 2E/M_\zeta \right). \]  \hspace{1cm} (18)

Note that we will concentrate on the case in which \( \Delta M_\zeta \equiv M_\zeta - M_\zeta^0 \) is small to forbid the hadronic decay modes of \( W \) bosons. The normalized resultant energy spectrum of the electron/positron from the DM decays can be written as
\[ \frac{dN}{dE} = \frac{1}{2 + \varepsilon} \left[ \frac{dN_e}{dE} + \varepsilon \frac{dN_{\mu e}}{dE} + \frac{dN_{\zeta e}}{dE} \theta(E_{\text{max}} - E) \right], \]  \hspace{1cm} (19)
where \( \varepsilon = |y_\mu'|^2/|y_e'|^2 \) and we have assumed 100% rate for the electron channel of the \( \zeta \) decay. We remark that we have neglected the tau-lepton effect in this study, but it can be included straightforwardly.

The DM component of the primary electron/positron flux is given by \[10, 22\]
\[ \Phi_{e}^{DM}(E) = \frac{c}{4\pi M_\tau T_\odot} \int_{0}^{E_\text{max}} dE' G(E, E') \frac{dN}{dE'}, \]  \hspace{1cm} (20)
where \( E \) is in units of GeV and \( c \) is the speed of light. All the information about astrophysics is encoded in the Green function of \( G(E, E') \), given by
\[ G(E, E') \simeq \frac{10^{16}}{E^2} \exp[a + b(E^\delta - 1 - E'^{\delta - 1})] \theta(E' - E) \quad [\text{cm}^{-3}\text{s}], \]  \hspace{1cm} (21)
where the normalization is adjusted to yield a local halo density \( \rho_\odot \sim 1 \text{ GeV cm}^{-3} \) \[23\]. We use the coefficients of \( a = -1.0203 \) and \( b = -1.4493 \) \[22\] for the spherically symmetric Navarro, Frenk and White density profile of the DM in our Galaxy \[24\] and the diffusion parameter \( \delta = 0.70 \) for the MED propagation model \[25\], which is consistent with the observed Boron-to-Carbon ratio \[26\]. Here, we have not taken account of the charge-sign dependent solar modulation \[27\] as well as other astrophysical uncertainties \[25\], which could be significant in the energies below 10 GeV. The total electron and positron fluxes are
\[ \Phi_{e-} = \kappa \Phi_{e-}^{\text{prim}} + \Phi_{e-}^{\text{DM}} + \Phi_{e-}^{\text{sec}}, \]
\[ \Phi_{e+} = \Phi_{e+}^{\text{DM}} + \Phi_{e+}^{\text{sec}}. \]  \hspace{1cm} (22)
respectively, where $\Phi^{\text{prim}}_{e^-}$ is a primary astrophysical component, presumably originated from supernova remnants, $\Phi^{DM}_{e^-}$ is an exotic primary component from the DM decays, $\Phi^{\text{sec}}_{e^-}$ is a secondary component from the spallation of cosmic rays on the interstellar medium, and $\kappa$ is a free parameter about 1 to fit the data when there is no DM primary source. We choose $\kappa = 0.7$ to insure the flux calculation to be consistent with the data. For the background fluxes, we will use the parameterizations obtained in Refs. [27, 28], given by

$$
\Phi^{\text{prim}}_{e^-}(E) = \frac{0.16 E^{-1.1}}{1 + 11 E^{0.9} + 3.2 E^{2.15}} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}], \quad (23)
$$

$$
\Phi^{\text{sec}}_{e^-}(E) = \frac{0.7 E^0.7}{1 + 110 E^{1.5} + 600 E^{2.9} + 580 E^{4.2}} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}], \quad (24)
$$

$$
\Phi^{\text{sec}}_{e^+}(E) = \frac{4.5 E^0.7}{1 + 650 E^{2.3} + 1500 E^{4.2}} \text{[GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}], \quad (25)
$$

where $E$ is in units of GeV.

FIG. 4: Electron + positron energy spectrum (left) and positron fraction (right) of the DM decays with $\tau_N = 2.5 \times 10^{26}$ s, $M = 2$ TeV, $M_\zeta = 500$ GeV and $\Delta M_\zeta = 1$ GeV, where $\varepsilon = 1$ (5) is represented by dashed (solid) lines, black points and blue rectangles stand for the observations of Fermi and HESS (left) and PAMELA and HEAT (right), and green triangles and dot-dashed lines correspond to the ATIC and backgrounds, respectively.

In Fig. 4, we show the electron plus positron energy spectrum (left) and the positron fraction (right) of the DM decays for $\tau_N = 2.5 \times 10^{26} [2 \times 10^{26}]$ s, $M = 2$ TeV, $M_\zeta = 500$ GeV, $\Delta M_\zeta = 1$ GeV and $\varepsilon = 1$ and 5, respectively, where the backgrounds are represented by dot-dashed lines. The electron + positron flux is multiplied by $E^3$ to compensate the roughly $E^{-3}$ falling of the flux. From the figures, we see that the model with the enhanced muon effects is in good agreement with the Fermi, HESS, PAMELA and HEAT data. In particular,
FIG. 5: Legend is the same as Fig. 4 but with $\tau_N = 2 \times 10^{26}$ s.

the energy spectrums in Figs. [H] (left) and [I] (left) with $\varepsilon = 5$ perfectly matches the Fermi’s result. It is worth to mention that the results for the energy spectrum and positron fraction are not significantly dependent on the $\zeta$ mass in the wide range of $100 \text{ GeV} - 1 \text{ TeV}$ besides the end point moving to a higher energy for a smaller $M_\zeta$. We remark that for a lighter DM particle, the drop in the electron flux occurs at a lower energy compared to the Fermi data.

As for the collider signatures from the new particles in the model, there are possible pair productions of $\zeta$ directly by the SM gauge bosons [18]. However, the pair productions of $N_i$ by the $e^+ e^-$ annihilations through the $\zeta$ exchanges [19] are hard to be observed at the near future LC due to the small values of $y_{ij} = \mathcal{O}(10^{-3})$. In addition, although $N$ and $\eta$ will escape the detection in the next generation of colliders due to their weak couplings and heavy masses, their properties can be tested by precise measurements of the electron spectrum and positron fraction since the signals are not sensitive to the propagation models at the energies higher than $400 \text{ GeV}$. In particular, future measurements of the positron fraction at energies higher than $100 \text{ GeV}$ can be crucial in testing the same origin of the Fermi and PAMELA electron and positron excesses.

Finally, we remark that the neutral lepton $N$ could be produced copiously after the big bang to become a typical unwanted relic. However, the inflation dilutes $N$ away since its number density reduces exponentially. The present abundance of $N$ may be generated by the $e^+ e^-$ annihilation.

In conclusion, we have investigated a relatively simple extension of the SM to generate the small neutrino masses at one-loop level and the observed BAU by the leptogenesis mechanism. Our model also contains the decaying dark matter with the lifetime of $\mathcal{O}(10^{26} \text{ s})$, 

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which provides a natural solution to the electron and positron excesses in cosmic rays in the energy range of $100 - 1000$ GeV by Fermi and PAMELA. It should be emphasized that the structure at the endpoint around $1000$ GeV of the Fermi data is crucial to determine the muon effects in the dark matter decays. More precise cosmic ray measurements around this energy range are clearly needed.

**Acknowledgements**

We would like to thank Dr. Takeshi Araki for useful discussions. This work is supported in part by the Boost Program of NTHU and the National Science Council of R.O.C. under Grant Nos: NSC-97-2112-M-006-001-MY3 and NSC-95-2112-M-007-059-MY3.

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