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Dark matter and neutrinos in Left-Right Mirror Model with Z_2 symmetry

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We discussed the feasibility of including dark matter in the Left-Right Mirror Model with an additional discrete Z_2 symmetry. The Z_2 symmetry helps to prevent any decay of the possible dark matter candidate, that is, guarantees the stability of the dark matter. The dark matter candidate is proposed as the lightest mirror neutrino. This Z_2 discrete symmetry not only guarantees the stability of the dark matter but also controls the free parameters of the model such that they are significantly reduced. Then, mass spectrum of neutrinos is also discussed in two possible scenarios obtained by assigning charge under Z_2 symmetry. For one of the scenarios we obtain the relic density for the dark matter candidate and the spin independent scattering cross section between dark matter and proton (neutron).

Keywords: Dark matter; models beyond the standard model; neutrino mass and mixing; non-standard neutrinos.

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1. Introduction

Models with Left-Right (LR) symmetry are based on increasing the gauge symmetry by including a $SU(2)$ symmetry group analogous to the $SU(2)_L$ symmetry group [1, 2]. This group named as $SU(2)_R$ will assign the chiral right fermion fields in representation of doublets while the chiral left fermion fields will be assigned as singlets, that is, an inverse assignment for the chiral projections in $SU(2)_L$. We consider the LR model which includes the same amount of left fermions as right fermions [3–5]. New fermions are included such that the right (left) projections are doublets (singlets) under $SU(2)_R$. These fermions are named as mirror fermions and the model is known as Left-Right Mirror Model (LRMM). Note that mirror and ordinary fermions will share new hypercharge (Y') and color interactions. The Table I shows the field content of the LRMM that we will study in this work. The circumflex notation ($\wedge$ symbol) will be used to identify the mirror fermions and the latin indices run for the three generations. The Table I not only shows the fermions but also shows the content of scalar fields of the model. For the scalar sector, only two doublets are considered, one ($\hat{\Phi}$) is responsible to break the $SU(2)_R$ while the other one (Φ) breaks the $SU(2)_L$.

TABLE I. The bold numbers denote the dimensions of representations of $SU(3)_C$, $SU(2)_L$ and $SU(2)_R$. The hypercharge Y is related with Y' as $Y/2 = T_{3R} + Y'/2$.

Field	$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$
ℓ_{iL}	$(\mathbf{1},\ \mathbf{2},\ \mathbf{1},\ -1)$
ν_{iR}	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ 0)$
e_{iR}	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ -2)$
$\hat{\nu}_{iL}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ 0)$
$\hat{e}_{iL}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{1},\ -2)$
$\hat{l}_{iR}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{2},\ -1)$
u_{iR}	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 4/3)$
d_{iR}	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 2/3)$
$\hat{u}_{iL}$	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 4/3)$
$\hat{d}_{iL}$	$(\mathbf{3},\ \mathbf{1},\ \mathbf{1},\ 2/3)$
q^o_{iL}	$(\mathbf{3},\ \mathbf{2},\ \mathbf{1},\ 1/3)$
$\hat{q}_{iR}$	$(\mathbf{3},\ \mathbf{1},\ \mathbf{2},\ 1/3)$
Φ	$(\mathbf{1},\ \mathbf{2},\ \mathbf{1},\ -1)$
$\hat{\Phi}$	$(\mathbf{1},\ \mathbf{1},\ \mathbf{2},\ -1)$

2. Masses and mixing

In this section we will present how neutrinos acquire masses as well as it is for neutral scalars and gauge bosons. The importance of introducing neutral scalars and gauge bosons lies in the fact that they will be the main channels for the study of the annihilation of Dark Matter (DM) and Spin Independent (SI) nucleon cross section. We also present the mixing between neutral fields, for the neutrinos, scalar and gauge sector. We closely follow the notation and model presented in Refs. [1–4].

First of all, let us introduce gauge symmetry breaking, which takes place in two stages. In the first stage the $SU(2)_R$ symmetry is broken through the $\hat{\Phi}$. For the second stage the symmetry breaking is achieved by the Φ, as it happens in the Standard Model (SM). The spontaneous breaking of symmetry can be represented as

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'} \xrightarrow{\langle\hat{\Phi}\rangle} SU(2)_L \otimes U(1)_Y \xrightarrow{\langle\Phi\rangle} U(1)_{\text{EM}}, \quad (1)$$

where the vacuum expectation values (VEV's) of the Higgs field are $\langle\Phi\rangle^T = \left(0,\ v/\sqrt{2}\right)$ and $\langle\hat{\Phi}\rangle^T = \left(0,\ \hat{v}/\sqrt{2}\right)$ for $v = 246$ GeV and the value for $\hat{v}$ must satisfy $\hat{v} > v$.

The masses of the scalars are obtained from the scalar potential. If we impose the invariance under gauge and parity symmetries, then scalar potential can be written as simple as

$$V = -\left(\mu_1^2\Phi^\dagger\Phi + \mu_2^2\hat{\Phi}^\dagger\hat{\Phi}\right) + \frac{\lambda_1}{2}\left[\left(\Phi^\dagger\Phi\right)^2 + \left(\hat{\Phi}^\dagger\hat{\Phi}\right)^2\right] + \lambda_2\left(\Phi^\dagger\Phi\right)\left(\hat{\Phi}^\dagger\hat{\Phi}\right).$$

In order to respect the parity symmetry we assume $\mu_1 = \mu_2$.

After the symmetry breaking, the neutral Higgs boson squared masses are

$$m^2_{H,\hat{H}} = \lambda_1\left(v^2+\hat{v}^2\right) \mp \sqrt{\lambda_1\left(v^2+\hat{v}^2\right)^2 + 4\lambda_2 v^2\hat{v}^2}. \quad (2)$$

For neutral scalars their weak and mass eigenstates are related with the mixing angle, denoted by α, which is given by $\tan(2\alpha) = 2\lambda_2 v\hat{v}/\lambda_1(v^2 - \hat{v}^2)$.

The masses for the gauge bosons are obtained from the kinetic terms for scalars in the Lagrangian

$$\mathcal{L}_{\text{scalar}} = \left(\mathrm{D}^\mu\Phi\right)^\dagger\left(\mathrm{D}_\mu\Phi\right) + \left(\hat{\mathrm{D}}^\mu\hat{\Phi}\right)^\dagger\left(\hat{\mathrm{D}}_\mu\hat{\Phi}\right), \quad (3)$$

where D_μ and $\hat{D}_\mu$ denote the covariant derivatives associated with g_2 and $\hat{g}_2$ gauge coupling constants, respectively. After substituting the VEV's in the Lagrangian given by Eq. (3) and change to physical basis with rotation matrix, the expressions for Z and Z' masses are

$$M_{Z,Z'} = \frac{1}{2}\left[v^2\left(g_2^2+g_1^2\right) + \hat{v}^2\left(\hat{g}_2^2+g_1^2\right)\right] \mp \frac{1}{2}\sqrt{\left[v^2\left(g_2^2+g_1^2\right)+\hat{v}^2\left(\hat{g}_2^2+g_1^2\right)\right]^2 - 4v^2\hat{v}^2\left(g_2^2g_1^2 + g_2^2\hat{g}_2^2 + \hat{g}_2^2 g_1^2\right)}. \quad (4)$$

For the neutral gauge bosons there are three mixing parameters in the orthogonal matrix that diagonalizes the mass matrix. The orthogonal matrix can be written by $R = R_{ZZ'}R_{AZ'}R_{ZA}$, where R_{XY}, for $X,Y = A,Z,Z'$ is a rotation matrix for two different gauge bosons between gauge and physical states. The details for the diagonalization method can be found in Refs. [1, 2]. For the charged gauge bosons their masses are $M_W = (1/2)vg_2$ and $M_{W'} = (1/2)\hat{v}\hat{g}_2$.

Now, for fermion fields, the gauge invariant Yukawa couplings for neutral lepton sector are given by

$$\begin{aligned}\mathcal{L}_\nu &= h_{ij}\overline{\hat{\nu}}_{iL}\nu_{jR} + \chi_{ij}\overline{\nu}_{iR}\left(\nu_{jR}\right)^c + \hat{\chi}_{ij}\overline{\hat{\nu}}_{iL}\left(\hat{\nu}_{jL}\right)^c \\ &+ \sigma_{ij}\bar{l}_{iL}\tilde{\Phi}\left(\hat{\nu}_{jL}\right)^c + \hat{\sigma}_{ij}\bar{\hat{l}}_{iR}\tilde{\hat{\Phi}}\left(\nu_{jR}\right)^c \\ &+ \lambda_{ij}\bar{l}_{iL}\tilde{\Phi}\nu_{jR} + \hat{\lambda}_{ij}\bar{\hat{l}}_{iR}\tilde{\hat{\Phi}}\hat{\nu}_{jL} + \text{h.c.}\end{aligned} \quad (5)$$

When Φ and $\hat{\Phi}$ acquire VEV's the neutrino masses are written in the generic Majorana matrix

$$\begin{pmatrix} \overline{\Psi}_{\nu L}, & \overline{\Psi^c}_{\nu L}\end{pmatrix}\begin{pmatrix} M_L & M_D \\ M_D & M_R\end{pmatrix}\begin{pmatrix}\Psi_{\nu R} \\ \Psi^c_{\nu R}\end{pmatrix}, \quad (6)$$

where

$$\Psi_{\nu(L,R)} = \begin{pmatrix}\nu_i \\ \hat{\nu}_i\end{pmatrix}_{(L,R)}, \quad (7)$$

$$M_L = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\sigma_{ij} \\ \frac{v}{\sqrt{2}}\sigma^T_{ij} & \hat{\chi}_{ij}\end{pmatrix}, \quad (8)$$

$$M_R = \begin{pmatrix} \chi_{ij} & \frac{\hat{v}}{\sqrt{2}}\hat{\sigma}_{ij} \\ \frac{\hat{v}}{\sqrt{2}}\hat{\sigma}^T_{ij} & 0\end{pmatrix}, \quad (9)$$

and

$$M_D = \begin{pmatrix} \frac{v}{\sqrt{2}}\lambda_{ij} & 0 \\ h_{ij} & \frac{\hat{v}}{\sqrt{2}}\hat{\lambda}_{ij}\end{pmatrix}. \quad (10)$$

Until now, the charge assignment under Z_2 discrete symmetry for both fermions and scalars has not yet been defined. In the next section a convenient assignment will be proposed to allow that a DM candidate emerges from mirror neutrinos.

3. Neutrinos and dark matter

In general the Yukawa couplings do not guarantee the stability of a candidate for DM, in the case that one of the mirror neutrinos is assumed to play the role of DM. One way to achieve stability for DM candidate is by including an additional discrete symmetry, for sake of simplicity, we consider Z_2 symmetry. Naturally, under Z_2 symmetry all ordinary leptons are assigned with an even charge (+1) while mirror leptons are assigned with an odd charge (-1). The selection of the charge under Z_2 symmetry for the doublet scalar fields can generate different scenarios, for instance, one in which both doublets are assigned as even and the second one in which they are assigned with different charges. Let us define the following scenarios:

- Φ and $\hat{\Phi}$ even. The Yukawa interactions are invariant under Z_2 if $h_{ij} = \sigma_{ij} = \hat{\sigma}_{ij} = 0$.
- Φ is even and $\hat{\Phi}$ odd. The Yukawa interactions are invariant under Z_2 if $h_{ij} = \sigma_{ij} = \hat{\lambda}_{ij} = 0$.

We first consider the scenario in which both doublets are even. In this case the ordinary neutrinos can be written separately from for mirror neutrinos in the matrix (6) as follows

$$\begin{pmatrix}\overline{\nu}_{iL}, & \overline{\nu^c}_{\nu R}\end{pmatrix}\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\lambda_{ij} \\ \frac{v}{\sqrt{2}}\lambda^T_{ij} & \chi_{ij}\end{pmatrix}\begin{pmatrix}\nu^c_{iL} \\ \nu_{jR}\end{pmatrix}, \quad (11)$$

$$\begin{pmatrix}\overline{\hat{\nu}}_{iL}, & \overline{\hat{\nu}^c}_{\nu R}\end{pmatrix}\begin{pmatrix} \hat{\chi}_{ij} & \frac{\hat{v}}{\sqrt{2}}\hat{\lambda}_{ij} \\ \frac{\hat{v}}{\sqrt{2}}\hat{\lambda}^T_{ij} & 0\end{pmatrix}\begin{pmatrix}\hat{\nu}^c_{iL} \\ \hat{\nu}_{jR}\end{pmatrix}. \quad (12)$$

By assuming the natural hierarchy $|\lambda_{ij}| \ll |\chi_{ij}|$ among the mass terms, the mass matrix in Eq. (11) can approximately be diagonalized, yielding

$$\left(\overline{\nu}_{iL}, \quad \overline{\nu^c}_{\nu R} \right) \begin{pmatrix} M_\nu^{\text{light}} & 0 \\ 0 & M_\nu^{\text{heavy}} \end{pmatrix} \begin{pmatrix} \nu_{iL}^c \\ \nu_{jR} \end{pmatrix}, \quad (13)$$

where $M_\nu^{\text{light}} \approx (v^2/2)\lambda\chi^{-1}\lambda^T$ and $M_\nu^{\text{heavy}} \approx \chi$. In general, the M_ν^{light} matrix is not diagonal and it is not written in the base of physical states. Taking advantage of the fact that all λ_{ij} and χ_{ij} are free parameters, we parameterize these matrices through the matrix S, such that $S = S^T$, and by the parameters m, y, y_i, such as

$$\lambda_{ij} = yS_{ij}, \quad (14)$$

and

$$\chi_{ij} = mD_{ik}^{-1}S_{kj}, \quad (15)$$

where $D = \text{Diagonal}[y_1, y_2, y_3]$. Details for the parametrization method can be reviewed in Refs. [3–5]. The inverse matriz for χ can be found as

$$\chi^{-1} = \frac{1}{m}S^{-1}D\,. \quad (16)$$

We substitute Eqs. (14) and (16) to write the M_ν^{light} matrix in terms of the S and D matrices. Then, the matrix for light neutrinos is written as

$$M_\nu^{\text{light}} = \frac{v^2y^2}{2m}SD. \quad (17)$$

In order to diagonalize M_ν^{light} we use the PNMS matrix U_ν to obtain the

$$\text{Diagonal}\left[m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\right] = \frac{v^2y^2}{2m}D, \quad (18)$$

where m_{ν_i} are the neutrino masses related with the reported values for neutrino experiment [6]. In Eq. (18) we must assume $U_\nu^T S U_\nu = I$, which allows us to find the values of the elements of the S matrix. After solving the system, the numerical values for elements of the S matrix are $S_{11} = 56.837$, $S_{12} = 723.087$, $S_{13} = -760.42$, $S_{22} = 9560.53$, $S_{23} = -10031.1$ and $S_{33} = 10527.7$.

Now, the order of magnitude for the m, y, y_i parameters can be set with previous assumption $|\lambda_{ij}| \ll |\chi_{ij}|$ and from Eqs. (14), (15) and (18). If the order of parameters is written as $\mathcal{O}(x) \sim 10^{n_x}$ for $x = m, y, y_i, S$, we obtain the following relations for the orders of the ordinary and mirror neutrino masses

$$n_\nu = 18 + 2n_y + n_{y_i} - n_m, \quad (19)$$

and

$$n_{\hat{\nu}} = n_m + n_S - n_{y_i}, \quad (20)$$

respectively. The $n_y + n_{y_i} < n_m$ inequality must hold for $n_{y,y_i,m}$ in $\mathbb{Z}$. Based on this analysis, we fixed the numerical values as $m = 1$ MeV, $y = 2.0 \times 10^{-6}$ and by taking into account the reported values for $\Delta m^2_{\text{sol}} \sim 7.5 \times 10^{-5}$ eV^2 and $|\Delta m^2_{\text{atm}}| \sim 2.5 \times 10^{-5}$ eV^2, the masses of the ordinary neutrinos are $m_1 = 0.1207$ eV, $m_2 = 0.1210$ eV and $m_3 = 0.1307$ eV for normal hierarchy, meanwhile $m_3 = 0.1104$ eV for the inverted hierarchy. The heavy neutrinos are directly proportional to the χ matrix, whose elements were fixed as parameters of the order of $10 \sim 10^3$ TeV. In the case of mirror neutrinos, we have the mass matrix given in Eq. (12). This matrix has a structure similar to the structure of the matrix Eq. (11) but with the difference that the zero matrix is in the lower part of the diagonal. In this work, for the sake of simplicity, we consider only one generation of mirror neutrinos which could play the role of DM candidate.

We obtain the relic abundance density and the SI scattering cross section to compare with the reported experimental values. We implement a routine in micrOMEGAs package [7] to obtain the relic density for several values of Z' and $\hat{H}$ masses, shown in Fig. 1. The LanHEP package [8] generates the necessary files associated with LRMM. For the relic abundance density the reported value is given by PLANCK

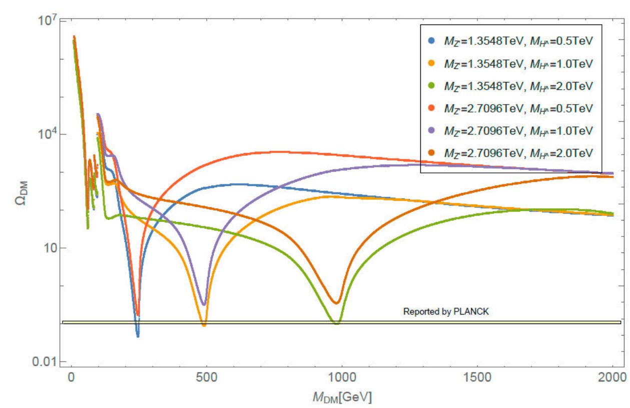

FIGURE 1. Relic density for lightest mirror neutrino as dark matter. The horizontal blue line represents the current reported value from PLANCK collaboration, $\Omega_c h^2 = 0.1200 \pm 0.00121$ (68 %, Planck TT,TE,EE+lowE+lensing).

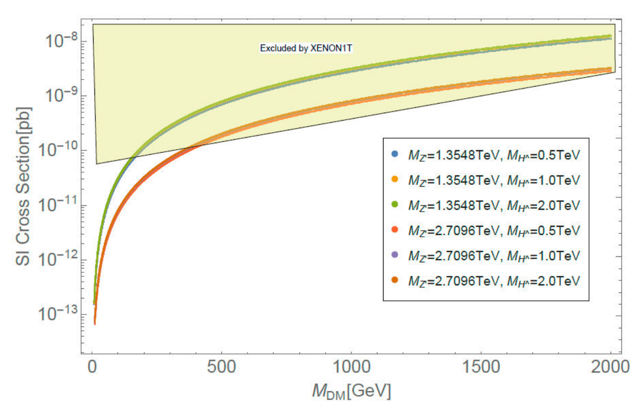

FIGURE 2. Spin independent cross section for the scattering between dark matter and some nucleon. Yellow region represents the excluded region reported by XENON1T collaboration.

collaboration, $\Omega_c h^2 = 0.1200 \pm 0.00121$ [9]. We also take into account the current reported values from XENON1T collaboration [10] in order to find allowed regions by SI scattering cross section. These reported limits depend on the DM mass, thus we take in good agreement an approximation shown in Fig. 2. The minimum value for Z' mass in the LR models is of the order of 1.3 TeV [6]. We explore mass values above the minimum value. For the $\hat{H}$ mass, a range of representative values is considered in Figs. 1 and 2.

4. Conclusions

We research the viability to include both neutrino masses and DM in LRMM. The masses for neutrino are introduced through See-Saw mechanism of the type I. The model parameters are constrained to explore a benchmark for DM relic density and SI cross section. The collider constraints for this model can be review in Ref. [11]. We consider the value for no baryonic relic density reported by Planck collaboration and XENON1T collaboration limit for SI cross section to obtain allowed values for the DM candidate mass. We assume that a DM candidate arise from the mirror neutrinos, in this work only consider one generation. Under reported values from PLANCK and XENON1T collaborations, we find that DM masses are viable for $m_{Z'} = 1.35$ TeV and $m_{\hat{H}} = 0.5, 1.0$ TeV. When $m_{\hat{H}} = 0.5$ TeV we obtain two possible values for the mass of dark matter ~ 230 GeV or ~ 260 GeV, while for $m_{\hat{H}} = 1.0$ TeV the mass of dark matter are ~ 480 GeV or ~ 500 GeV, as Fig. 1 shows. The value for the DM mass of the order of ~ 1000 GeV is excluded by the Fig. 2.

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