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Sterile neutrinos in a left-right mirror model

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In this work, we investigate the possibility that one neutrino mirror plays the role of sterile neutrinos with mass on the scale of a few eV's, that is, $\hat{m}_1 \sim O$(1 eV). We consider the extension of the Standard Model with gauge symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$ and additional exotic fermions known as mirror fermions. A double application of the seesaw type I approximation to the most general Majorana-type neutrino mass matrix and diagonalization is performed to study neutrino masses and mixing.

Keywords: Seesaw approximation; neutrino mass matrix; diagonalization; mirror model.

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1. Introduction

Neutrino oscillation experiments on atmospheric, solar, reactor and accelerators neutrinos reveal that neutrinos have nonzero masses. The tiny neutrino masses may be the first clear evidence of physics beyond the standard model. The sterile neutrinos are believed to interact only via gravity and not through the other fundamental interactions of the Standard Model (SM). The term refers to neutrinos with right-handed chirality and is used to distinguish them from the known, active neutrinos in the SM. A sterile neutrino is a neutral, spin 1/2 particle which is a singlet under $SU(3) \otimes SU(2) \otimes U(1)$ group. Such singlets appear naturally in supersymmetry models, grand unified theories (GUT) and superstring. The experimental information on neutrino masses and mixing implies new physics beyond the SM, which have generated great activity on theoretical implications of these results. Cosmology and Short Baseline Oscillation experiments lead to the possible existence of light sterile neutrinos. In the Neutrino-4 experiment the effect of oscillations of reactor antineutrinos into a sterile neutrino was observed [1,2]. Here, we study neutrino masses within the context of the "Left Right Mirror Model" (LRMM) [3-6]. Applying a double seesaw approximation to the most general Majorana-type neutrino mass matrix, we perform an approximate analytical diagonalization, where one of the mirror neutrinos may get a mass of a few eV's.

2. The model

The LRMM formulation is based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$. With the fermion content:

$$l^0_{i\,L} = \begin{pmatrix} \nu^0_i \\ e^0_i \end{pmatrix}_L, e^0_{i\,R}, \nu^0_{i\,R}, \hat{l}^0_{i\,R} = \begin{pmatrix} \hat{\nu}^0_i \\ \hat{e}^0_i \end{pmatrix}_R, \hat{e}^0_{i\,R}, \hat{\nu}^0_{i\,R},$$

$$Q^0_{i\,L} = \begin{pmatrix} u^0_i \\ d^0_i \end{pmatrix}_L, u^0_{i\,R}, d^0_{i\,R}, \hat{Q}^0_{i\,R} = \begin{pmatrix} \hat{u}^0_i \\ \hat{d}^0_i \end{pmatrix}_R, \hat{u}^0_{i\,R}, \hat{d}^0_{i\,R},$$

where the last entry corresponds to the hypercharge (Y') with the electric charge $Q = T_{3L} + T_{3R} + (Y'/2)$.

We assume the "Spontaneous Symmetry Breaking" (SSB) stages

$$\mathrm{G} \xrightarrow{\langle\hat{\Phi}\rangle} \mathrm{G}^{SM} \xrightarrow{\langle\Phi\rangle} SU(3)_C \otimes U(1)_Q, \qquad (1)$$

where $G_{SM} = SU(2)_L \otimes SU(3)_C \otimes U(1)_Y$ is the SM gauge group and $Y/2 = T_{3R} + (Y'/2)$. The Higgs sector to induce this SSB, Eq. (1), involves two doublets of scalar fields:

$$\Phi = (1, 2, 1, 1), \quad \hat{\Phi} = (1, 1, 2, 1), \qquad (2)$$

with the "Vacuum Expectation Values" (VEV's)

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle\hat{\Phi}\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \hat{v} \end{pmatrix}, \qquad (3)$$

The most general potential that we can write with the above scalars, Eq. (2), which develops the pattern of VEV's, Eq. (3), and then the SSB, Eq. (1), is

$$V = -(\mu\Phi^\dagger\Phi + \hat{\mu}\hat{\Phi}^\dagger\hat{\Phi}) + \frac{\lambda_1}{2}[(\Phi^\dagger\Phi)^2 + (\hat{\Phi}^\dagger\hat{\Phi})^2] + \lambda_2(\Phi^\dagger\Phi)(\hat{\Phi}^\dagger\hat{\Phi}), \qquad (4)$$

and the scalar Lagrangian for the model is written as

$$\mathcal{L}_{sc} = (D_\mu\Phi)^\dagger(D^\mu\Phi) + (\hat{D}_\mu\hat{\Phi})^\dagger(\hat{D}^\mu\hat{\Phi}), \qquad (5)$$

where D_μ and $\hat{D}_\mu$ are the covariant derivatives for the SM and the mirror part, respectively.

3. Majorana neutrino mass matrix

After symmetry breaking, we may write the most general neutrino Majorana mass matrix

$$(\bar{\Psi}_{\nu L}, \bar{\Psi^c}_{\nu L}) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} (\Psi_\nu^c)_R \\ (\Psi_\nu)_R \end{pmatrix}, \qquad (6)$$

with

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

$$(\Psi_\nu^c)_{L,R} = \begin{pmatrix} (\nu_i^c) \\ (\hat{\nu}_i^c) \end{pmatrix}_{L,R}, \qquad (8)$$

$$M_L = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}}\sigma \\ \frac{v}{\sqrt{2}}\sigma^T & \hat{M} \end{pmatrix}, \qquad (9)$$

$$M_R = \begin{pmatrix} \chi & \frac{\hat{v}}{\sqrt{2}}\pi \\ \frac{\hat{v}}{\sqrt{2}}\pi^T & 0 \end{pmatrix}, \qquad (10)$$

$$M_D = \begin{pmatrix} \frac{v}{\sqrt{2}}\lambda & 0 \\ h & \frac{\hat{v}}{\sqrt{2}}\eta \end{pmatrix}, \qquad (11)$$

where σ, $\hat{M}$, χ, π, λ, h and η in Eqs. (9), (10), (11) are unknown matrices of 3×3 dimension.

4. Double Seesaw approximation

By assuming the natural hierarchy $|(M_L)_{ij}| \ll |(M_D)_{ij}| \ll |(M_R)_{ij}|$ for the mass terms, the mass matrix

$$\begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix},$$

Eq. (6), can be diagonalized in the Seesaw approximation [7,8], yielding

$$(\bar{\Psi}'_{\nu L}, \bar{\Psi}'^c_{\nu L}) \begin{pmatrix} M_\nu & 0 \\ 0 & M_R \end{pmatrix} \begin{pmatrix} (\Psi'^c_\nu)_R \\ (\Psi'_\nu)_R \end{pmatrix}, \qquad (12)$$

where, neglecting $O(M_D M_R^{-1})$ terms, we may write with good approximation $\Psi'_{\nu L,R} \approx \Psi_{\nu L,R}$, and $\Psi'^c_{\nu L,R} \approx \Psi^c_{\nu L,R}$.

The Majorana mass matrix for the left-handed neutrinos may be written in this seesaw approximation as

$$M_\nu \approx M_l - M_D M_R^{-1} M_D^T. \qquad (13)$$

We assume a scenario where the dominant contribution, for the active known neutrinos, comes from the M_L matrix, Eq. (13), with a Type I seesaw structure. We can explicitly write

$$M_\nu \approx M_L = \begin{pmatrix} m & \mu \\ \mu^T & \bar{m} \end{pmatrix}, \qquad (14)$$

where

$$m = \begin{pmatrix} 0 & 0 & 0 & \sigma'_{11} \\ 0 & 0 & 0 & \sigma'_{21} \\ 0 & 0 & 0 & \sigma'_{31} \\ \sigma'_{11} & \sigma'_{21} & \sigma'_{31} & \bar{M}_{11} \end{pmatrix}, \qquad (15)$$

$$\mu = \begin{pmatrix} \sigma'_{12} & \sigma'_{13} \\ \sigma'_{22} & \sigma'_{23} \\ \sigma'_{32} & \sigma'_{33} \\ \bar{M}_{12} & \bar{M}_{13} \end{pmatrix} \qquad (16)$$

$$\bar{m} = \begin{pmatrix} \bar{M}_{22} & \bar{M}_{23} \\ \bar{M}_{23} & \bar{M}_{33} \end{pmatrix}, \qquad (17)$$

and $\sigma'_{ij} = v/\sqrt{2}\sigma_{ij}$. In this way we explore the possibility that one of the mirror neutrinos may acquire a mass of the order of a few eV's. Therefore, applying the seesaw approximation again to M_L, Eq. (14), we obtain

$$(M^{\text{light}})_{4\times4} = m - \mu\hat{m}^{-1}\mu^T. \qquad (18)$$

The matrix M_L in Eq. (14), may be diagonalized by using a unitary transformation

$$U^\dagger M_L U = Diag(m_1, m_2, m_3, \hat{m}_1, \hat{m}_2, \hat{m}_3), \qquad (19)$$

where the mixing matrix U compatible with our framework may be written as

$$U_{6\times6} \approx \begin{pmatrix} U_{4\times4} & \mu\hat{m}^{-1} \\ -(\mu\hat{m}^{-1})^T & I_{2\times2} \end{pmatrix}, \qquad (20)$$

where

$$U_{4\times4} \approx \begin{pmatrix} & & & U_{14} \\ & (U_{TB})_{3\times3} & & U_{24} \\ & & & U_{34} \\ U_{41} & U_{42} & U_{43} & O(\lesssim 1) \end{pmatrix}, \qquad (21)$$

for $|U_{i4}| \approx |U_{4i}| \lesssim 0.1$. The $U_{4\times4}$ in Eq. (21) being the neutrino mixing involving the three SM active neutrinos and one light neutrino mirror. To perform calculations, for the masses of the active neutrinos, we take the values: $m_1 \approx 0.0086$ eV, $m_2 \approx 0.0088$ eV, and $m_3 \approx 0.05$ eV [9]. We assume $\hat{m}_1 \ll \hat{m}_2, \hat{m}_3$.

5. Conclusions

In this work, we consider as framework a left-right model with mirror fermions to estimate the mass of the light sterile neutrino.

Applying a double seesaw approximation to the most general Majorana-type neutrino mass matrix, an approximate analytical diagonalization was performed for light neutrinos, Eqs. (18), (21), with the possibility that one neutrino mirror plays the role of a sterile neutrino with mass on the scale of a few eV's, that is, $\hat{m}_1 \sim O(1$ eV).

The estimation is based in a numerical fit of parameters to accommodate simultaneously the active neutrino masses and mixing consistent with the current neutrino oscillation data.

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1. A. P. Serebrov and R. M. Samoilov, Reply to Comment on Analysis of the Results of the Neutrino-4 Experiment on the Search for the Sterile Neutrino and Comparison with Results of Other Experiments. (*JETP Letters* **112** (2020) 199); *JETP Lett.* **112** (2020) 455, https://doi.org/10.1134/S0021364020190108.
2. A. P. Serebrov *et al*., Result of the Neutrino-4 Experiment and the Cosmological Constraints on the Sterile Neutrino (Brief Review), *JETP Lett.* **116** (2022) 669, https://doi.org/10.1134/S002136402260224X.
3. V. E. Cerón *et al*., Constraints on the parameters of the left-right mirror model, *Phys. Rev. D* **57** (1998) 1934, https://doi.org/10.1103/PhysRevD.57.1934.
4. U. Cotti *et al*., New Higgs signals induced by mirror fermion mixing effects, *Phys. Rev. D* **66** (2002) 015004, https://doi.org/10.1103/PhysRevD.66.015004.
5. R. Gaitán *et al*., Neutrino mixing and masses in a left-right model with mirror fermions, *Eur. Phys. J. C* **72** (2012) 1859, https://doi.org/10.1140/epjc/s10052-012-1859-7.
6. R. Gaitán *et al.*, Masses and mixings of neutrinos in extended models, *Nucl. Part. Phys. Proc*. **267-269** (2015) 101, https://doi.org/10.1016/j.nuclphysbps.2015.10.089.
7. S. Antusch and S. F. King, From hierarchical to partially degenerate neutrinos via type II upgrade of type I seesaw models, *Nucl. Phys. B* **705** (2005) 239, https://doi.org/10.1016/j.nuclphysb.2004.10.049.
8. S. Antusch, Models for Neutrino Masses and Mixings, *Nucl. Phys. B Proc. Suppl.* **235-236** (2013) 303, https://doi.org/10.1016/j.nuclphysbps.2013.04.026.
9. R. L. Workman *et al*., *Review of Particle Physics, PTEP* **2022** (2022) 083C01, https://doi.org/10.1093/ptep/ptac097.