28th International Scientific Conference of Young Scientists and Specialists (AYSS-2024)

October 27, 2024 to November 1, 2024
Europe/Moscow timezone

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Sterile neutrinos of the left-right symmetric model as dark matter

Oct 28, 2024, 4:30 PM
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Oral | Theoretical Physics | Theoretical Physics

Speaker

Dmitrii Kazarkin (Lomonosov Moscow State University)

Description

The observation of neutrino oscillations provides convincing evidence for non-zero neutrino masses, indicating the existence of a New Physics beyond the Standard Model (SM). A natural generalization on the high-energy scale, theoretically motivated by the idea of Grand Unification, is the left-right symmetry (LR symmetry), in which left- and right- chiral fermions are treated in the same way. Such extension of the SM has several attractive consequences: (1) it provides sources of parity violation that could explain the baryon asymmetry of the Universe, (2) implements the seesaw mechanism that explains the small neutrino masses and neutrino oscillations, (3) predicts the existence of sterile neutrinos, the lightest one is a candidate for the role of a dark matter particle. In our work, we focused on the Minimal Left-Right Symmetric Model (MLRM) with a gauge group $SU(3)_c \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ that is broken down to $SU(3)_c \times U(1)_{em}$ due to the non-trivial vacuum structure of the extended Higgs sector. Within this framework, we fixed a set of parameters in the extended Higgs potential by "tuning" them to match the observed Higgs boson mass of 125 GeV, while taking into account existing experimental constraints on the masses of additional non-standard Higgs bosons and massive vector bosons $W_R^\pm$ and Z_R. We also considered the parameterization of mixing in the lepton sector in detail, investigated the possibility of sterile neutrinos as a warm dark matter, taking into account astrophysical, cosmological, and accelerator constraints.

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Presentation materials

Kazarkin_LRSM_AYSS_2024.pdf

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Sterile neutrinos of the left-right symmetric model as dark matter

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Problems of the Standard Model

- **Presence of dark matter** $\rightarrow$ hint to new elementary particles beyond the SM.

$$\Omega_{DM,0}h^2 = 0.120 \pm 0.001 \quad [\textit{Planck}\ 2018\ \text{results}]$$

- **Neutrino oscillation phenomenon** $\rightarrow$ there is no mechanism for small neutrino mass generation in the SM

$$m_\nu \lesssim 0.2\ \text{eV}$$

- **Baryon asymmetry of the Universe** $\rightarrow$ 3 Sakharov's conditions (We need a source of B-violation, C and CP-violation, no thermal equilibrium)

$$Y_{B,0} = \frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10} - 10^{-11}$$

Theoretical motivation: Grand Unification

Gauge group of Left-Right Symmetric Model (LRSM) can occur as a chain link of SO(10) Grand Unified Theory symmetry breaking. $\mathcal{G}_{3221}$ corresponds to so-called Minimal Left Right symmetric model (MLRM).

Notations:

$$\mathcal{G}_{51} = SU(5)\times U(1)$$
$$\mathcal{G}_{5} = SU(5)$$
$$\mathcal{G}_{PS} = SU(4)_C\times SU(2)_L\times SU(2)_R$$
$$\mathcal{G}_{421} = SU(4)_C\times SU(2)_L\times U(1)_{B-L}$$
$$\mathcal{G}_{3221} = SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$$
$$\mathcal{G}_{3211} = SU(3)_C\times SU(2)_L\times U(1)_R\times U(1)_{B-L}$$

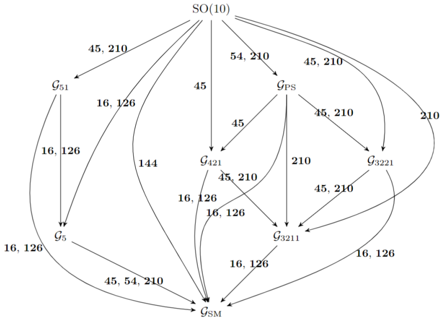


Figure: Possible breaking chains of SO(10) to $\mathcal{G}_{SM}$. [Fig. from M.Pernow,"Models of SO(10) Grand Unified Theories", 2021, Doctoral thesis]

LRSM: Fermion fields

LR-model gauge group:

$$G_{LR} = SU(3)_c \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \times \mathcal{P},$$

where $\mathcal{P}$ is $L \longleftrightarrow R$ discrete symmetry.

Fermions	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$L_{\alpha_L} = \begin{pmatrix} \nu_{\alpha_L} \\ l_{\alpha_L} \end{pmatrix}$	**1**	**2**	**1**	-1
$L_{\alpha_R} = \begin{pmatrix} \nu_{\alpha_R} \\ l_{\alpha_R} \end{pmatrix}$	**1**	**1**	**2**	-1
$Q_{a_L} = \begin{pmatrix} u_{a_L} \\ d_{a_L} \end{pmatrix}$	**1**	**2**	**1**	$\frac{1}{3}$
$Q_{a_R} = \begin{pmatrix} u_{a_R} \\ d_{a_R} \end{pmatrix}$	**1**	**1**	**2**	$\frac{1}{3}$

Table: Representations of the fermion fileds in LRSM

LRSM: Higgs fields

Higgs fields	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$\Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$	**1**	**3**	**1**	2
$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$	**1**	**1**	**3**	2
$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$	**1**	**2**	**2**	0
η	**1**	**1**	**1**	0

Table: Representations of the Higgs fileds in LRSM

$$\mathcal{L}_{Higgs} = tr|D_\mu \Phi|^2 + tr|D_\mu \Delta_R|^2 + tr|D_\mu \Delta_L|^2 - V(\Phi, \Delta_L, \Delta_R)$$

Spontaneous symmetry breaking

Steps of SSB:

1. $\mathcal{P}$ broke at scale $M_{\mathcal{P}} \sim M_{GUT} \sim 10^{15}$ GeV due to non-zero vacuum expectation value (VEV) of Higgs singlet scalar field $\eta = (1, 1, 1, 0)$

$$\mathcal{P}: \quad l_L \leftrightarrow l_R, \quad q_L \leftrightarrow q_R, \quad \Delta_L \leftrightarrow \Delta_R, \quad \Phi \leftrightarrow \Phi^\dagger$$

2. $$\boxed{SU(2)_R \times U(1)_{B-L} \xrightarrow[M_R \sim \mathcal{O}(1\ \text{TeV})]{\langle \Delta_R \rangle} U(1)_Y \times \mathbb{Z}_2}$$

   with VEV of Higgs right triplet Δ_R

3. Electroweak SSB at the $M_{W,Z}$-scale due to non-zero VEVs of the Higgs bi-doublet Φ and the left triplet Δ_L:

$$\boxed{SU(2)_L \times U(1)_Y \xrightarrow{\langle \Phi \rangle, \langle \Delta_L \rangle} U(1)_{em}}, \quad Q_{\rm em} = T_{3R} + T_{3L} + \frac{B-L}{2}$$

$$\langle \Delta_{L,R} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix} \quad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \quad \sqrt{k_1^2 + k_2^2} = 246\ \text{GeV}$$

Seesaw for VEVs

β-sector of the Higgs potential:

$$V_\beta(\Phi,\Delta_L,\Delta_R) = \beta_1\Big(Tr[\phi\Delta_R\phi^\dagger\Delta_L^\dagger]+Tr[\phi^\dagger\Delta_L\phi\Delta_R^\dagger]\Big)+\beta_2\Big(Tr[\tilde\phi\Delta_R\phi^\dagger\Delta_L^\dagger]+Tr[\tilde\phi^\dagger\Delta_L\phi\Delta_R^\dagger]\Big)+ \beta_3\Big(Tr[\phi\Delta_R\tilde\phi^\dagger\Delta_L^\dagger]+Tr[\phi^\dagger\Delta_L\tilde\phi\Delta_R^\dagger]\Big),$$

Additional GUT and/or SUSY assumptions $\rightarrow \beta_i = 0$ or $\beta_i \simeq 0$

Seesaw relation between v_L and v_R

$$v_L = \gamma\,\frac{(246\ \text{GeV})^2}{v_R}, \qquad \text{where}\ \ \gamma \equiv \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1-\rho_3)(246\ \text{GeV})^2}\ ,$$

$\beta_i = 0$

$$(2\rho_1-\rho_3)v_R v_L = 0$$
$$v_L = 0\ \ \big(v_R\neq 0 \text{ and } (2\rho_1-\rho_3)\neq 0\big)$$

$\beta_i \rightarrow 0$

$$v_L \simeq \frac{(246\ \text{GeV})^2}{v_R}$$
$$v_L \simeq 0\ \ (v_R \gg 246\ \text{GeV} \ \ \text{or}\ \gamma \ll 1)$$

LRSM: Gauge sector

- New $SU(2)_R$-gauge field $V^j_{R,\mu}$, $(j = \overline{1,3})$
- SM gauge fields G^a_μ, $V^i_{L,\mu}$ and B_μ, $(a = \overline{1,8},\ i = \overline{1,3})$

Basis of mass states:

$$\begin{pmatrix} V^3_L \\ V^3_R \\ B \end{pmatrix} = \begin{pmatrix} c_W c_\phi & c_W s_\phi & s_W \\ -s_W s_M c_\phi - c_M s_\phi & -s_W s_M s_\phi + c_M c_\phi & c_W s_M \\ -s_W c_M c_\phi + s_M s_\phi & -s_W c_M s_\phi - s_M c_\phi & c_W c_M \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \\ A \end{pmatrix},$$

$$\begin{pmatrix} W^\pm_L \\ W^\pm_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W^\pm_1 \\ W^\pm_2 \end{pmatrix}, \qquad W^\pm_{L,R} = \frac{1}{\sqrt{2}} \left(V^1_{L,R} \mp V^2_{L,R} \right)$$

$$M^2_{W_{1,2}} = \frac{g^2}{4} \left[k^2_+ + v^2_R \mp \sqrt{v^4_R + 4\, k^2_1\, k^2_2} \right], \quad (1)$$

$$M^2_{Z_{1,2}} = \frac{1}{4} \left[g^2 k^2_+ + 2 v^2_R (g^2 + g'^2) \right] \mp \frac{1}{4} \sqrt{\left[g^2 k^2_+ + 2 v^2_R (g^2 + g'^2) \right]^2 - 4 g^2 (g^2 + 2 g'^2)\, k^2_+ v^2_R}. \quad (2)$$

Masses of Higgs and gauge bosons

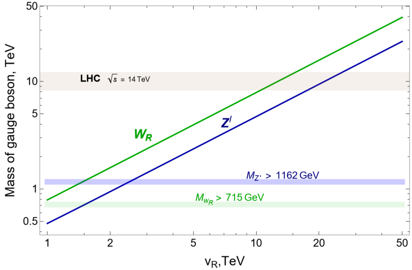


Figure: Masses of new vector gauge bosons Z_2 and W_2

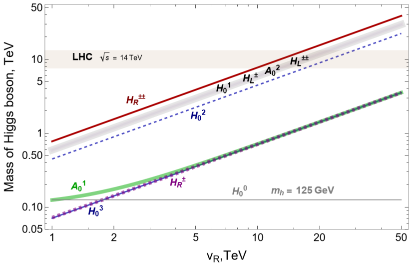


Figure: Masses of all 14 Higgs bosons in LRSM with tuning of self-interaction constants:

$\alpha_3 = 0.01$ $\rho_1 = 0.1,$ $\rho_2 = 0.3,$ $\rho_3 = 0.9,$

$\lambda_1 = \lambda_{SM} = 0.118,$

$\lambda_2 = 0.01,$ $\lambda_3 = 0.1$

Neutrino mixing: seesaw II

In flavor basis:

$$\mathcal{L} \supset (\overline{\nu_L}, \quad \overline{\nu_R^c}) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}, \qquad \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = P_L\, \mathcal{U} \begin{pmatrix} \nu \\ N \end{pmatrix} \quad (3)$$

$$M_D = \frac{1}{\sqrt{2}}(h_L k_1 + \tilde{h}_L k_2), \qquad M_L = \sqrt{2} h_M v_L, \qquad M_R = \sqrt{2} h_M v_R,$$

where $h_L, \ \tilde{h}_L, \ h_M$ are the Yukawa constants
Move to mass basis with unitary transformation $\mathcal{U}$:

$$\mathcal{L} \supset (\overline{\nu}, \quad \overline{N}) \begin{pmatrix} \hat{m} & 0 \\ 0 & \hat{M} \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}, \quad (4)$$

Form of $\mathcal{U}$ choose as a generalization of *Casas-Ibarra* approach
[Casas J., Ibarra A., Nucl.Phys.B 618 (2001) 171.]

$$\mathcal{U} \equiv \exp \begin{pmatrix} 0 & \theta \\ -\theta^\dagger & 0 \end{pmatrix} \cdot \begin{pmatrix} U_\nu & 0 \\ 0 & U_N^* \end{pmatrix} \simeq \begin{pmatrix} \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_\nu & \theta U_N^* \\ -\theta^\dagger U_\nu & \left(1 - \frac{1}{2}\theta^\dagger\theta\right) U_N^* \end{pmatrix},$$

$$\boxed{\Theta \equiv \theta U_N^*}$$

$$U_{PMNS} \equiv \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_\nu$$

Neutrino mixing: parametrization

Matrix equation system for transformation $\mathcal{U}$: (leading order accuracy)

$$\begin{cases} \theta \simeq M_D M_R^{-1}, \\ m_\nu = M_L - \theta M_R \theta^T, \\ M_N \simeq M_R \end{cases} \Rightarrow$$

seesaw II equation

$$\boxed{m_\nu = M_L - M_D M_N^{-1} M_D^T}$$

.

Orthogonality condition: (where $\hat{m} = diag(m_1, m_2, m_3)$, $\hat{M} = diag(M_1, M_2, M_3)$)

$$I = \Omega\Omega^T = \left[i\sqrt{\tilde{m}^{-1}} U_\nu^\dagger M_D U_N \sqrt{\hat{M}^{-1}} \right]^T \left[-i\sqrt{\tilde{m}^{-1}} U_\nu^\dagger M_D U_N \sqrt{\hat{M}^{-1}} \right],$$

$$\Theta = iU_\nu \left(\sqrt{\tilde{m}} \right) \Omega \sqrt{\hat{M}^{-1}}, \qquad \sqrt{\tilde{m}} = \sqrt{\hat{m} - U_{\mathrm{PMNS}}^\dagger M_L U_{\mathrm{PMNS}}^*}$$

Using approximation: $U_N = I$, $\theta^2 \ll 1$ we can write

$$h_M \simeq \frac{1}{\sqrt{2} v_R} (\theta^\dagger U_\nu \hat{m} U_\nu^T \theta^* + U_N^* \hat{M} U_N^\dagger) \simeq \frac{\hat{M}}{\sqrt{2} v_R} \Rightarrow \boxed{\tilde{m} = \hat{m} - \frac{v_L}{v_R} U_{\mathrm{PMNS}}^\dagger \hat{M} U_{\mathrm{PMNS}}^*}$$

Charged and Neutral currents

$$\mathcal{L}_{CC}^{\nu} = \frac{g}{\sqrt{2}}(U_{\text{PMNS}})_{\alpha i}\,\bar{l}_\alpha\,\hat{W}_1\,(\cos\zeta P_L - \sin\zeta P_R)\,\nu_i + \frac{g}{\sqrt{2}}(U_{\text{PMNS}})_{\alpha i}\,\bar{l}_\alpha\,\hat{W}_2\,(\sin\zeta P_L + \cos\zeta P_R)\,\nu_i + h.c. \quad (5a)$$

$$\mathcal{L}_{NC}^{\nu} = \frac{g}{2c_W}\left(U_{\text{PMNS}}^{\dagger}U_{\text{PMNS}}\right)_{ij}\bar{\nu}_i\sum_{X=Z_1,Z_2}\hat{X}\left(a_X^{(L)}P_L - a_X^{(R)}P_R\right)\nu_j \quad (5b)$$

$$\mathcal{L}_{CC}^{N} = -\frac{g}{\sqrt{2}}\Theta_{\alpha J}\,\bar{l}_\alpha\,\hat{W}_1\,(\cos\zeta P_L - \sin\zeta P_R)\,N_J - \frac{g}{\sqrt{2}}\Theta_{\alpha J}\,\bar{l}_\alpha\,\hat{W}_2\,(\sin\zeta P_L + \cos\zeta P_R)\,N_J + h.c. \quad (5c)$$

$$\mathcal{L}_{NC}^{N} = \frac{g}{2c_W}(\Theta^{\dagger}\Theta)_{IJ}\,\bar{N}_I\sum_{X=Z_1,Z_2}\hat{X}\left(a_X^{(L)}P_L - a_X^{(R)}P_R\right)N_J + \quad (5d)$$

$$+ \left(\frac{g}{2c_W}\left(U_{\text{PMNS}}^{\dagger}\Theta\right)_{iJ}\,\bar{\nu}_i\sum_{X=Z_1,Z_2}\hat{X}\left(a_X^{(L)}P_L - a_X^{(R)}P_R\right)N_J + h.c.\right)$$

Sterile neutrino as warm DM

Warm Dark Matter: The lightest sterile neutrino with mass $\sim 1-10$ keV.

We use notation

$m_D^{dm} \equiv \sum_\alpha |U_{\alpha i}(\sqrt{\tilde{m}})_{ij}\Omega_{j1}|^2 = M_1 \sum_\alpha |\Theta_{\alpha 1}|^2$, $\quad \Omega$ -3 $\times$ 3 orthogonal matrix

- **Lifetime:** quasi-stable because of very small mixing with active neutrino ($|\Theta_{\alpha 1}|^2 \ll 1$)

$$\tau_{N_1} = 10^{22} \left(\frac{M_1}{1\text{ keV}}\right)^{-4} \left(\frac{m_D^{dm}}{1\text{ eV}}\right)^{-1} \text{sec} \; > \; H_0^{-1} \simeq 10^{17} \text{ sec} \qquad (6)$$

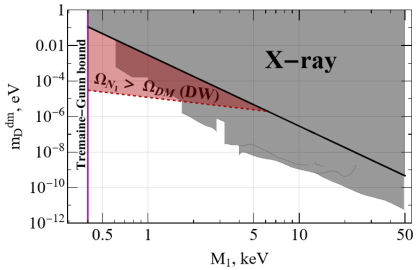
- **Non-observation of radiative one-loop decay** $N_1 \to \gamma, \nu$ with $E_\gamma = M_1/2$ lead to strong lifetime limit

$\tau_{N_1} > 10^{25} sec$ [Aliev, Vysotsky, Sov. Phys. Usp. 24 (1981)] [Boyarsky et al, arXiv:0811.2385v1]

.

DM mixing parameters

νMSM-**limit:** $v_L = 0 \to \sqrt{\tilde{m}} = \sqrt{\hat{m}}$



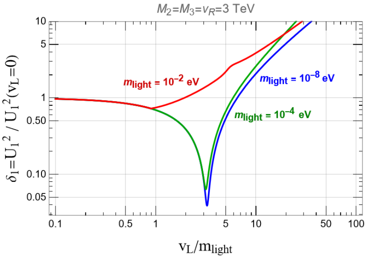
Strong constraints indicate an explicit form of Ω-matrix: (for normal/inverse hierarchy)

$$\Omega_{NH}: \quad \Omega_{j1} \to \delta_{j1} \qquad \Omega_{IH}: \quad \Omega_{j3} \to \delta_{j3}$$

$$m_D^{dm}(v_L = 0) = m_{\text{light}}$$

- if $\hat{m} \gg \frac{v_L}{v_R} \hat{M} \to \nu MSM$ limit;
- if $\hat{m} \ll \frac{v_L}{v_R} \hat{M} \to$ high increase of effective interaction between active and sterile neutrinos;
- if $\hat{m} \simeq U^\dagger_{\text{PMNS}} M_L U^*_{\text{PMNS}} \to$ mixing decrease for $v_L \sim m_{light}$.

We illustrate it for normal hierarchy, $M_2 = M_3 = v_R = 3$ TeV and $\Omega_{j1} = \delta_{j1}$



Conclusions

- We considered the lightest sterile neutrino as warm DM in the framework of the MLRM.
- We proposed a modified seesaw type II expression for the mixing matrix

$$\Theta = iU_{\text{PMNS}}\sqrt{\tilde{m}}\Omega\sqrt{\hat{M}^{-1}}, \qquad \sqrt{\tilde{m}} = \sqrt{\hat{m} - U^{\dagger}_{\text{PMNS}} M_L U^{*}_{\text{PMNS}}}$$

- We found out that the mixing parameter significantly depends on v_L in the regime of $M_1 \sim \mathcal{O}(\text{keV})$ and $M_{2,3} \sim v_R$
- At the scale of m_{light} fixed, the mixing extremely rapidly increases in range of $v_L = (2-5)m_{light}$.

The research was carried out within the framework of the scientific program of the National Center for Physics and Mathematics, project *"Particle Physics and Cosmology"*

Thank you for your attention