Left-Right Symmetric Model with Double Seesaw Mechanism: Its LNV imprints

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Based on the work

Neutrinoless double beta decay in Left-Right symmetric model with double seesaw mechanism

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Plan of the presentation

1. Neutrinoless Double Beta decay process
2. Left-right symmetric model and various aspect of seesaw
3. Double Seesaw effects to Neutrinoless Double Beta Decay in LRSM
4. Numerical Results
5. Conclusion

Standard Mechanism for $0\nu\beta\beta$ decay

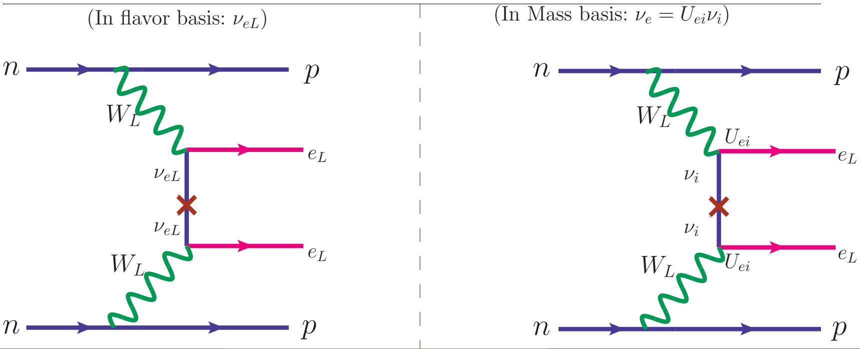
- Neutrino Oscillation experiments have revealed that neutrinos of different flavour mix with each other and have non-zero masses.

$$\nu_\alpha = U_{\alpha i}\nu_i \quad \text{with mass eigenvalues} \quad m_i\,.$$

- Charged current interaction in mass basis:

$$\mathcal{L}^{\ell}_{\rm CC} \;=\; \frac{g_L}{\sqrt{2}}\,\overline{e}_{Li}\,\gamma^\mu\,U_{\alpha i}\nu_i\,W_{\mu_L} + \text{h.c.}$$

$0\nu\beta\beta$ through standard mechanism



Half-life of Isotope: Measure of $0\nu\beta\beta$ decay process

If light Majorana neutrinos are the only contribution to the $0\nu\beta\beta$ transition, then the half-life can be expressed as,

$$\frac{1}{T^{0\nu}_{1/2}} = \left[T^{0\nu}_{1/2}\right]^{-1} = g_{\mathrm{A}}^4\, G^{0\nu}_{01}\, \left|\mathcal{M}^{0\nu}_{\nu}\right|^2 \left|\eta_\nu\right|^2 = G^{0\nu}_{01} \left|\frac{\mathcal{M}^{0\nu}_{\nu}}{m_e}\right|^2 \left|m_{\beta\beta}\right|^2$$

- $\mathcal{M}^{0\nu}_{\nu}$: Nuclear Matrix Elements (NME) for $0\nu\beta\beta$ transition.
- $G^{0\nu}_{01}$: Phase space factor
- η_ν: A dimensionless particle physics parameter – a measure of Lepton Number Violation involving neutrino masses and corresponding mixing. $\boxed{m_{\beta\beta} \equiv m^{\nu}_{ee} \equiv m_e \eta_\nu = \left|\sum_{i=1}^{3} U^2_{ei} m_i\right|}$
- g_{A}: axial coupling constant

Left-Right Symmetric Model

[Mohapatra:1974, Pati:1974, Senjanovic:1975,Senjanovic:1978,Mohapatra:1979,Mohapatra:1980]

- **Gauge Symmetry**

$$\mathcal{G}_{LR} \equiv SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$$

with electric charge relation

$$\mathbf{Q} = \mathbf{I_{3L}} + \mathbf{I_{3R}} + \frac{\mathbf{B} - \mathbf{L}}{\mathbf{2}}$$

- **Particle Content**

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [2, 1, \frac{1}{3}, 3], \quad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [1, 2, \frac{1}{3}, 3],$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \equiv [2, 1, -1, 1], \quad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \equiv [1, 2, -1, 1],$$

Minimal LRSM

- Neutral components of the scalar bidoublet Φ generate masses for charged leptons and Dirac mass for the light neutrinos.
- Light neutrino mass: purely Dirac
- **NO LNV** in theory

LRSM with scalar triplets: *Manifest LRSM*

- Scalar triplets Δ_L and Δ_R (carrying $B-L$ charge 2) generate **Majorana masses** for **light** and **heavy** neutrinos.
- Mass matrix for neutral leptons in the basis (ν_L, N_R^c)

$$\mathcal{M}_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}, \; M_R \gg M_D$$

- Type-(I+II) contribution to light neutrino masses,

$$m_\nu^I = -M_D\, M_R^{-1}\, M_D^T, \qquad m_\nu^{II} = f\, v_L = f\, \langle \Delta_L^0 \rangle \,.$$

- $m_N \simeq M_R$, puerly **Majorana**
- $\Theta \simeq \frac{M_D}{M_R}$ light-heavy neutrino mixing: neglegible.

LRSM with sterile neutrinos: *Low Scale Seesaw*

- Usual quarks and leptons, plus one sterile neutrino $S_L \equiv [1, 1, 0]$ per generation
- The neutral lepton mass matrix in the basis (ν_L, N_R^c, S_L) is,

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & \mu_L \\ M_D^T & 0 & M_{RS} \\ \mu_L^T & M_{RS}^T & M_S \end{pmatrix}$$

- M_D is the Dirac mass matrix connecting left-handed and right-handed neutrino fields $\nu_L - N_R$
- M_{RS} and μ_L are Dirac mass terms connecting N_R-S_L and ν_L-S_L respectively,
- M_S is the bare Majorana mass matrix for sterile neutrinos S_L

Inverse seesaw in LRSM

Inverse Seesaw:- Mass hierarchy assumed $M_{RS} > M_D \gg M_S$ and taking $\mu_L \to 0$, the resulting inverse seesaw mass formula for neutrinos

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_{RS}^T \\ 0 & M_{RS} & M_S \end{pmatrix} \tag{1}$$

- light neutrino mass formula $m_\nu = \left(\frac{M_D}{M_{RS}}\right) M_S \left(\frac{M_D}{M_{RS}}\right)^T$

$$\left(\frac{m_\nu}{0.1\ \text{eV}}\right) = \left(\frac{M_D}{100\ \text{GeV}}\right)^2 \left(\frac{M_S}{\text{keV}}\right) \left(\frac{M_{RS}}{10^4\,\text{GeV}}\right)^{-2} .$$

- light-heavy neutrino mixing: **large** $\Theta \simeq \frac{M_D}{M_{RS}}$
- heavy neutrino masses: **pseudo-Dirac** $m_{N/S} \simeq M_{RS}$

Linear seesaw in LRSM

Linear Seesaw:- Mass hierarchy assumed $M_{RS} > M_D \gg \mu_L$ and taking $M_S \to 0$, the resulting linear seesaw mass matrix structure

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & \mu_L \\ M_D^T & 0 & M_{RS}^T \\ \mu_L^T & M_{RS} & 0 \end{pmatrix} \quad (2)$$

- light neutrino mass formula $m_\nu = M_D^T M_{RS}^{-1} \mu_L +$ transpose
- light-heavy neutrino mixing: **large** $\Theta \simeq \frac{M_D}{M_{RS}}$
- heavy neutrino masses: **pseudo-Dirac** $m_{N/S} \simeq M_{RS}$

Our model framework: double seesaw in LRSM

Double Seesaw:-mass hierarchy $M_S \gg M_{RS} > M_D$ and $M_R \gg M_D$

$$\left[\begin{array}{c|cc} \mathbf{0} & M_D & \mathbf{0} \\ \hline M_D^T & 0 & M_{RS} \\ \mathbf{0} & M_{RS}^T & M_S \end{array}\right] \xrightarrow[\text{1st seesaw}]{M_S \gg M_{RS} \gg M_D} \left[\begin{array}{c|cc} \mathbf{0} & M_D & \mathbf{0} \\ \hline M_D^T & -M_{RS} M_S^{-1} M_{RS}^T & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & M_S \end{array}\right] \qquad (3)$$

$$\left[\begin{array}{cc|c} \mathbf{0} & M_D & \mathbf{0} \\ M_D^T & M_R & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{0} & M_S \end{array}\right] \xrightarrow[\text{2nd seesaw}]{M_R \gg M_D} \left[\begin{array}{c|c|c} -M_D M_R^{-1} M_D^T & 0 & 0 \\ \hline 0 & M_R & 0 \\ \hline 0 & 0 & M_S \end{array}\right] \qquad (4)$$

$$\begin{aligned} m_\nu &= -M_D \left(-M_{RS} M_S^{-1} M_{RS}^T\right)^{-1} M_D^T = \frac{M_D}{M_{RS}^T} M_S \frac{M_D^T}{M_{RS}} \\ m_N &= M_R = -M_{RS} M_S^{-1} M_{RS}^T, \\ m_S &= M_S \,. \end{aligned} \qquad (5)$$

- Different choice of M_D and M_{RS} are possible [A. Y. Smirnov:1993,M. Lindner, M. A. Schmidt, and A. Y. Smirnov 2005,P. O. Ludl and A. Y. Smirnov 2015, **B. Bajc and A. Y. Smirnov 2016**, A. Y. Smirnov and X.-J. Xu 2018]
- we have considered $M_D = k_d I$ and $M_{RS} = k_{rs} I$, where k_d and k_{rs} are real constants with $|k_d| < |k_{rs}|$. This means, $\boxed{M_D M_{RS}^{-1} = \frac{k_d}{k_{rs}} I}$.[V. Brdar and A. Y. Smirnov 2019]
- the equality and simultaneous diagonal structures of M_D and M_{RS} may arise as a consequence of $Z_2 \times Z_2$ symmetry.
- mass matrices relations, m_ν,m_N and m_S $\rightarrow$ $\boxed{m_\nu = \frac{k_d^2}{k_{rs}^2} m_S}$ and $\boxed{m_N = -k_d^2 \frac{1}{m_\nu}}$.
- physical masses m_i are related to the mass matrix m_ν in the flavor basis as $\boxed{m_\nu = U_{\rm PMNS}\, m_\nu^{\rm diag}\, U_{\rm PMNS}^T\,.}$
- It proves convenient to work with positive masses of N_j, $m_{N_j} > 0$, implies that the unitary transformation matrices diagonalizing mass matrices m_ν and m_N are related as $\boxed{U_N = i\, U_\nu^* \equiv i\, U_{PMNS}^*\,.}$
- the diagonalization m_S, $\widehat{m_S} = {U_S}^\dagger m_S {U_S}^*$, where $\widehat{m_S} = \text{diag}(m_{S_1}, m_{S_2}, m_{S_3})$, $m_{S_k} > 0$, $k = 1, 2, 3$, can be performed with the help of the same mixing matrix U_{PMNS} : $\boxed{U_S = U_\nu \equiv U_{PMNS}\,.}$
- Thus, in the considered scenario the the light neutrino masses m_i, the heavy RH neutrino masses m_{N_j} and the sterile neutrino masses (m_{S_k}) are related as follows:

$$\boxed{m_i = \frac{k_d^2}{m_{N_j}} = \frac{k_d^2}{k_{rs}^2}\, m_{S_k}\,, \quad i, j, k = 1, 2, 3\,.} \tag{6}$$

Neutrino Mixing

The diagonalization of $\mathcal{M}_{\mathrm{LRDSM}}$ after changing it from flavor (weak interaction eigenstate) basis to mass basis is done by a generalized unitary transformation as,

$$|\,\Psi\rangle_{\mathrm{flavor}} = V\,|\,\Psi\rangle_{\mathrm{mass}} \tag{7}$$

$$\begin{pmatrix} \nu_{\alpha L} \\ N^c_{\beta L} \\ S_{\gamma L} \end{pmatrix} = \begin{pmatrix} V^{\nu\nu}_{\alpha i} & V^{\nu N}_{\alpha j} & V^{\nu S}_{\alpha k} \\ V^{N\nu}_{\beta i} & V^{NN}_{\beta j} & V^{NS}_{\beta k} \\ V^{S\nu}_{\gamma i} & V^{SN}_{\gamma j} & V^{SS}_{\gamma k} \end{pmatrix} \begin{pmatrix} \nu_{iL} \\ N^c_{jL} \\ S_{kL} \end{pmatrix} . \tag{8}$$

- The mixing between the right-handed neutrinos and sterile neutrinos ($N^c_L - S_L$) is given by the term, $V^{NS} \propto M_{RS} M_S^{-1}$
- the mixing between the fields of the left-handed flavor neutrinos and the heavy right-handed neutrinos ($\nu_L - N^c_L$) is: $V^{\nu N} \propto M_D M_R^{-1} = -M_D {M_{RS}^T}^{-1} M_S M_{RS}^{-1}$
- The mixing between sterile and light neutrinos ($\nu_L - S_L$) is vanishing, $V^{\nu S}_{\alpha k} \cong 0$ and $V^{S\nu}_{\gamma i} \cong 0$.

Dominant contributions to the $0\nu\beta\beta$ decay amplitude are given by:

- the standard mechanism due to the exchange of light neutrino ν_i, mediated by left-handed gauge boson W_L, i.e. due to purely left-handed (LH) CC interaction;
- new contributions due to the exchange of heavy neutrinos $N_{1,2,3}$ and sterile neutrinos $S_{1,2,3}$, mediated by right-handed gauge boson W_R, i.e. due to purely right-handed (RH) CC interaction. **The contribution due to exchange of virtual $S_{1,2,3}$ is possible due to the mixing between N_L^c and S_L.**

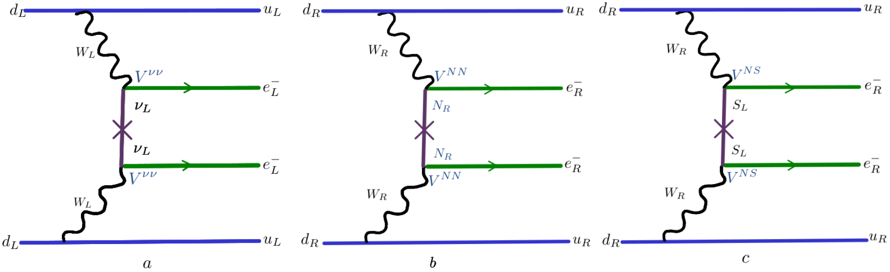


Figure: $0\nu\beta\beta$ mediated by (a) light neutrino which is called the standard mechanism, (b) heavy right-handed neutrino N_R and (c) heavy sterile neutrino S_L.

- Considering both the **standard mechanism** and the **new contributions** to this decay process in our model, the inverse half life can be written as:

$$\left[T_{1/2}^{0\nu}\right]^{-1} = g_{\rm A}^4\, G_{01}^{0\nu}\left[\left|\mathcal{M}_\nu^{0\nu}\cdot\eta_\nu\right|^2 + \left|\mathcal{M}_N^{0\nu}\cdot(\eta_N+\eta_S)\right|^2\right], \quad (9)$$

where $\mathcal{M}_N^{0\nu}$ is the Nuclear Matrix Elements (NME) for the heavy neutrino exchange and η_N and η_S are lepton number violating parameters associated with the exchange of the heavy neutrinos $N_{1,2,3}$ and $S_{1,2,3}$.

- Since the dominant contributions to $0\nu\beta\beta$ decay arise from more than one contribution, **there might be intereference** between them in the decay rate of the process.

Effect of intereference

- ν_i with N_j or S_k interference is suppressed (being proportional to electron mass and due to helicity).
- However, the interference between the contributions of the heavy neutrinos N_j and S_k both involving RH currents, in general, can't be neglected.
- In the case when this interference is not taken into consideration,

$$\boxed{|m^{\rm eff}_{\beta\beta,L,R}| \equiv m^{\nu+N+S}_{ee} = \left(\left|m^{\nu}_{\beta\beta,L}\right|^2 + \left|m^{N}_{\beta\beta,R}\right|^2 + \left|m^{S}_{\beta\beta,R}\right|^2\right)^{\frac{1}{2}} .}$$

Numerical Analysis

- **Left-panel: Standard Mechanism**
- **Middle-panel: New physics without intereference**
- **Right-panel: New physics with intereference**

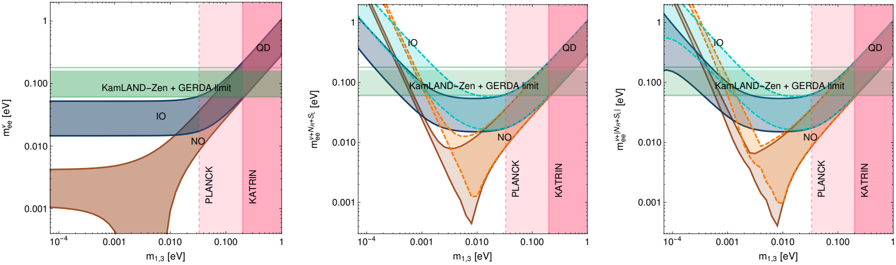


Figure: Plots showing effective Majorana mass parameter as a function of lightest neutrino mass, m_1 (NO), m_3(I0).

Bound on lightest neutrino mass

★ **In the NO case:**

- Contribution due to the $S_{1,2,3}$ exchange, $|m^S_{\beta\beta}|$, dominates over the light neutrino ν_i and $N_{1,2,3}$ exchange contributions for $10^{-4}\,\mathrm{eV} \leq m_1 \lesssim 1.5 \times 10^{-3}$ eV.
- At $m_1 \gtrsim 2 \times 10^{-3}$ eV, for $\alpha = \beta = 0$, the $S_{1,2,3}$ contribution is sub leading.
- For $\alpha = \pi$, $\beta = 0$, however, $|m^{\nu}_{\beta\beta,L}|$ is strongly suppressed in the interval $m_1 \cong (1.5 \times 10^{-3} - 9 \times 10^{-3})$ eV and goes through zero at $m_1 \cong 2.26 \times 10^{-3}$ eV.
- Therefore $|m^S_{\beta\beta}|$ gives significant contribution to $m_{ee}^{\nu+|N+S|}$ in the indicated interval and determines the minimal value of $m_{ee}^{\nu+|N+S|}$ at $m_1 \cong 2.26 \times 10^{-3}$ eV.
- Intereference effects giving sizable contribution to $0\nu\beta\beta$.

★ **In the IO case:**

- Contribution due to the $S_{1,2,3}$ exchange $|m^S_{\beta\beta,R}|$ and of the interference term $2\mathrm{Re}(m^N_{\beta\beta,R} \cdot m^{S^*}_{\beta\beta,R})$ in the interval of values of m_3 of interest are practically negligible.

Conclusion

- ★ New physics contributions to neutrinoless double beta decay induced by right-handed currents (left-right theories) can saturate the current experimental bound (GERDA, KamLAND-ZEN and EXO).
- ★ Interestingly, left-right theories with double seesaw framework induces large Majorana mass term N_R for right handed neutrinos even if there is no direct Majorana mass term to start with.
- ★ Intereference effects might play an important role in providing crucial information on absolute scale of lightest neutrino mass.

Further

- The LFV processes as like $\mu \to e + \gamma$, $\mu \to 3e$ decays and $\mu - e$ conversion in nuclei can be mediated by heavy RH and sterile neutrinos $N_{1,2,3}$ and $S_{1,2,3}$.

THANK YOU

Backups

Ratio $\mathcal{M}_N^{0\nu}/\mathcal{M}_\nu^{0\nu}$

- Using values of NMEs, the minimal and maximal values of the ratio $\mathcal{M}_N^{0\nu}/\mathcal{M}_\nu^{0\nu}$ for ^{76}Ge we get from Table 1:

$$22.2 \lesssim \frac{\mathcal{M}_N^{0\nu}}{\mathcal{M}_\nu^{0\nu}} \lesssim 76.3\,, \quad {}^{76}\mathrm{Ge}\,. \tag{10}$$

They correspond respectively to $\mathcal{M}_\nu^{0\nu} = 4.68$ and 5.26.

Methods	^{76}Ge $\mathcal{M}_\nu^{0\nu}$	^{76}Ge $\mathcal{M}_N^{0\nu}$	^{82}Se $\mathcal{M}_\nu^{0\nu}$	^{82}Se $\mathcal{M}_N^{0\nu}$	^{130}Te $\mathcal{M}_\nu^{0\nu}$	^{130}Te $\mathcal{M}_N^{0\nu}$	^{136}Xe $\mathcal{M}_\nu^{0\nu}$	^{136}Xe $\mathcal{M}_N^{0\nu}$
dQRPA	3.12	187.3	2.86	175.9	2.90	191.4	1.11	66.9
QRPA-Tu	5.16	287.0	4.64	262.0	3.89	264.0	2.18	152.0
QRPA-Jy	5.26	401.3	3.73	287.1	4.00	338.3	2.91	186.3
ISM	2.89	130	2.73	121	2.76	146	2.28	116
$G_{01}^{0\nu}$ [$10^{-14}\mathrm{yrs}^{-1}$]	0.22		1		1.4		1.5	

Table: Values of Nuclear Matrix Elements for various isotopes calculated by different methods for light and heavy neutrino exchange. Here QRPA-Jy uses CD-Bonn short range correlations (SRC) and the rest use Argonne SRC, with minimally quenched $g_A = 1$. The last row shows the phase space factor $G_{01}^{0\nu}$ for various isotopes.

Contribution of the interference term

- Accounting for the interference :

$$|m^{\rm eff}_{\beta\beta,L,R}| \equiv m_{ee}^{\nu+|N+S|} = \left(\left|m^{\nu}_{\beta\beta,L}\right|^2 + \left|m^{N}_{\beta\beta,R} + m^{S}_{\beta\beta,R}\right|^2\right)^{\frac{1}{2}}$$
$$= \left((m_{ee}^{\nu+N+S})^2 + 2\text{Re}(m^{N}_{\beta\beta,R} \cdot m^{S^*}_{\beta\beta,R})\right)^{\frac{1}{2}}$$
$$= m_{ee}^{\nu+N+S}\sqrt{1+R}\,. \tag{11}$$

The relative contribution of the interference term of interest is determined by the ratio:

$$\boxed{R \equiv \frac{2\text{Re}(m^{N}_{\beta\beta,R} \cdot m^{S^*}_{\beta\beta,R})}{|m^{\nu}_{\beta\beta,L}|^2 + |m^{N}_{\beta\beta,R}|^2 + |m^{S}_{\beta\beta,R}|^2}}\,.$$

- The contribution of the interference term $2\text{Re}(m^{N}_{\beta\beta,R} \cdot m^{S^*}_{\beta\beta,R})$ in the $0\nu\beta\beta$ decay rate may be non-negligible only in the interval of values of $m_{1(3)} = (10^{-4} - 10^{-2})$ eV, where the new non-standard contributions are significant.