Neutrinoless Double Beta Decay and $< \eta >$ Mechanism in the Left-Right Symmetric Model

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based on T. Fukuyama and T. Sato
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Possibility to extract signal of right-handed current from 0ν double beta decay

- Right handec current $\tilde{J}^{\mu}_{R} = \eta J^{\mu}_{L} + \lambda J^{\mu}_{R}$: η and λ term

$$\lambda \sim \frac{M^2_{WL}}{M^2_{WR}}, \quad \eta \sim -\tan\zeta, \text{with} \quad \tan 2\zeta = \frac{2}{\tan\beta}(\frac{M_{WL}}{M_{WR}})^2$$

- 0ν double beta decay amplitude:$< \eta >\sim UV\eta, < \lambda >\sim UV\lambda$
  U, V and m_ν from type I seesaw or Inverse seesaw mechanism

$$\begin{aligned}\frac{1}{T_{1/2}} &= C^{(0)}_{mm}(\frac{< m_\nu >}{m_e})^2 + C^{(0)}_{m\lambda}\frac{< m_\nu >}{m_e} < \lambda > \cos\psi \\ &+ C^{(0)}_{m\eta}\frac{< m_\nu >}{m_e} < \eta > \cos\psi + C^{(0)}_{\lambda\lambda} < \lambda >^2 + C^{(0)}_{\eta\eta} < \eta >^2 \\ &+ C^{(0)}_{\lambda\eta} < \lambda >< \eta > .\end{aligned}$$

Here $\sqrt{|C_{\eta,\eta}|/|C_{mm}|} \geq 100$

- Nuclear enhancement of $< \eta >$-term may provide us an opprtunity to search RHC from 0ν DBD

Contents

1. What is L-R symmetric Model ?
2. How to make the seesaw mechanism of low energy scale $O(\text{TeV})$.
3. Why does η mechanism work ?
4. How to find New Physics beyond the Standard Model.

The condition that the neutrinoless double beta decay occurs

1. ν_e should be the same as its anti-particle

$$\nu_e = \overline{\nu_e}$$

2. the connecting neutrinos should have the same helicity. The latter condition is satisfied if neutrinos are massive or if the R-handed current coexists with the L-handed current. The first case of 2. is described as the well known effective neutrino mass,

$$< m_\nu >= | \sum_j U_{ej}^2 m_j |.$$

Here $U_{\alpha i}$ is the PMNS mixing matrix in L-handed current. Substituting the observed values,

$$|U_{11}|^2 / |U_{13}|^2 \approx 30$$

and the Inverted Hierarchy enhances $0\nu\beta\beta$. We consider the second case of 2 in this talk.

L-R symmetric Model in GUT

$$\begin{aligned} SO(10) &\supset SU(4)_{PS} \times SU(2)_L \times SU(2)_R \\ &\supset SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\supset SU(3)_c \times SU(2)_L \times U(1)_Y \end{aligned}$$

where

$$\mathbf{16} = (\mathbf{4},\mathbf{2},\mathbf{1}) + (\overline{\mathbf{4}},\mathbf{2},\mathbf{1})$$

$$(\mathbf{4},\mathbf{2},\mathbf{1}) = \begin{pmatrix} u_r & u_y & u_b & \nu_e \\ d_r & d_y & d_b & e \end{pmatrix}_L \equiv F_{L1}$$

Likewise

$$(\overline{\mathbf{4}},\mathbf{2},\mathbf{1}) = F_{R1}$$

Yukawa interaction in L-R symmetric model

The interaction is

$$
\begin{aligned}
-\mathcal{L} &= Y_{ij}\overline{\Psi}_{L,i}\Phi\Psi_{R,j} + \tilde{Y}_{ij}\overline{\Psi}_{L,i}\tilde{\Phi}\Psi_{R,j} \\
&+ f_{L,ij}\Psi^T_{L,i}Ci\tau_2\Delta_L\Psi_{L,j} + f_{R,ij}\Psi^T_{R,i}Ci\tau_2\Delta_R\Psi_{R,j}
\end{aligned}
$$

$$
\Psi_{L,i} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i \quad \Psi_{R,i} = \begin{pmatrix} u_R \\ d_R \end{pmatrix}_i
$$

$$
\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix},
$$

$$
\tilde{\Phi} = \tau_2\Phi^*\tau_2, \quad <\phi_1^0>= v_u, \quad <\phi_2^0>= v_d, \quad <\Delta^0_{L,R}>= v_{L,R}
$$

$$
\Delta_{L,R} = \begin{pmatrix} \Delta^+_{L,R}/\sqrt{2} & \Delta^{++}_{L,R} \\ \Delta^0_{L,R} & -\Delta^+_{L,R}/\sqrt{2} \end{pmatrix}
$$

Minimal Coupling and Weak Boson Masses

$$D_\mu \phi = \partial_\mu \phi - i\frac{g_L}{2}\vec{W}_{L\mu}\cdot\vec{\tau}\phi - i\frac{g_R}{2}\vec{W}_{R\mu}\cdot\vec{\tau}\phi$$

$$D_\mu \Delta_{(L,R)} = \partial_\mu \Delta_{(L,R)} - i\frac{g_{(L,R)}}{2}\vec{W}_{(L,R)\mu}\cdot\vec{\tau}\Delta_{(L,R)} - ig' B_\mu \Delta_{(L,R)}$$

Inserting vevs,we obtain weak bosn masses:

$$M_W = \frac{g^2}{4}\begin{pmatrix} v_u^2 + v_d^2 + 2v_L^2 & 2v_u v_d \\ 2v_u v_d & v_u^2 + v_d^2 + 2v_R^2 \end{pmatrix},$$

$$\begin{pmatrix} W_1 \\ W_2 \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix}\begin{pmatrix} W_L \\ W_R \end{pmatrix}$$

If we have R-handed current, H_W is enlarged as

$$H_W = \frac{G_F \cos\theta_c}{\sqrt{2}} \left[j_L^\mu \tilde{J}_{L\mu}^\dagger + j_R^\mu \tilde{J}_{R\mu}^\dagger \right] + H.c.$$

Here the Leptonic Currents are

$$\begin{aligned} j_{L\alpha} &= \sum_{l=e,\mu,\tau} \overline{l(x)}\gamma_\alpha(1-\gamma_5)\nu_{lL}(x) \equiv \sum \overline{l(x)}\gamma_\alpha 2P_L \nu_{lL}(x), \\ j_{R\alpha} &= \sum_{l=e,\mu,\tau} \overline{l(x)}\gamma_\alpha(1+\gamma_5)N_{lR}(x) \equiv \sum \overline{l(x)}\gamma_\alpha 2P_R N_{lR}(x), \end{aligned}$$

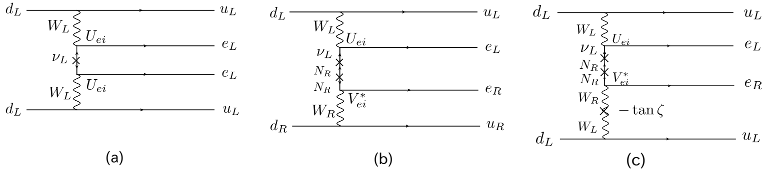
and $\nu_{lL}(N_{lR})$ are L-handed (R-handed) weak eigenstates of the neutrinos,
The Hadronic Currents are

$$\begin{aligned} \tilde{J}_L^\mu(\boldsymbol{x}) &= J_L^\mu(\boldsymbol{x}) + \kappa J_R^\mu(\boldsymbol{x}), \\ \tilde{J}_R^\mu(\boldsymbol{x}) &= \eta J_L^\mu(\boldsymbol{x}) + \lambda J_R^\mu(\boldsymbol{x}). \end{aligned}$$

λ and η are related to the mass eigenvalues of the weak bosons in the L and $R-$ handed gauge sectors.

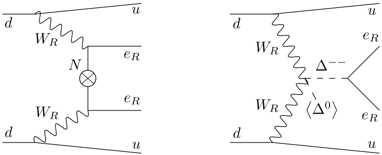
$$\lambda \equiv \frac{M_{W1}^2 + M_{W2}^2 \tan^2\zeta}{M_{W1}^2 \tan^2\zeta + M_{W2}^2}, \quad \eta \equiv -\frac{(M_{W2}^2 - M_{W1}^2)\tan\zeta}{M_{W1}^2 \tan^2\zeta + M_{W2}^2}.$$

$$\tan 2\zeta = \frac{2v_u v_d}{v_R^2 - v_L^2} = 2\frac{v_d}{v_u}\left(\frac{M_{WL}}{M_{WR}}\right)^2$$



(a), (b), and (c) are $< m_\nu >$, $< \lambda >$, and $< \eta >$-mechanisms, respectively.

The other diagrams for $0\nu\beta\beta$ decay



$$\frac{A^{\text{left}}}{A^{Xe}} = 0.15 \times \frac{g_R^4}{g_L^4}\left(\frac{5\text{TeV}}{M_{WR}}\right)^4 \frac{100\text{TeV}}{m_N}$$

$$\frac{A^{\text{right}}}{A^{Xe}} = 0.15 \times \frac{g_R^4}{g_L^4}\left(\frac{5\text{TeV}}{M_{WR}}\right)^4 \frac{< \Delta^0 >}{8\text{TeV}}\left(\frac{1\text{TeV}}{m_{\Delta^{++}}}\right)^2 \frac{g_{ee}}{0.3}$$

where A^{Xe} is the current experimental bound for Xe by using NME Deppisch et al. J. Phys. G**39** (2012). (T.F, Mimura and Uesaka, Phys. Rev, D**106** (2022))

Nuclear matrix element and role of $<\eta>$ mechanism

$$R_{0\nu} = 4\sqrt{\frac{1}{2}}\left(\frac{G\cos\theta_c}{\sqrt{2}}\right)^2 \sum_i \sum_{\alpha,\beta} \int d\boldsymbol{x} d\boldsymbol{y} \int \frac{d\boldsymbol{k}}{(2\pi)^3} e^{i\boldsymbol{k}\cdot(\boldsymbol{y}-\boldsymbol{x})} H^{\nu\mu} L_{\nu\mu},$$

where the lepton tensor $L^{\nu\mu}$ is

$$L_{\nu\mu} = \overline{e}_{p_2,s_2'}(\boldsymbol{y})\gamma_\nu P_\beta \frac{1}{2\omega}\left[\frac{\omega\gamma^0 - \boldsymbol{k}\cdot\boldsymbol{\gamma} + m_i}{\omega + A_1} + \frac{-\omega\gamma^0 - \boldsymbol{k}\cdot\boldsymbol{\gamma} + m_i}{\omega + A_2}\right] P_\alpha \gamma_\mu e^c_{p_1,}$$

The nuclear tensor $H^{\nu\mu}$ is given by the matrix element of the nuclear weak current as

$$H^{\nu\mu} = \langle F | \tilde{J}^{\nu +}_{\beta i}(\boldsymbol{y}) \tilde{J}^{\mu +}_{\alpha i}(\boldsymbol{x}) | I \rangle ,$$

where $\tilde{J}^{\mu}_{L,R}$ are given in the previous page.

The neutrino propagator becomes,

$$P_\alpha(\pm\omega\gamma^0 - \mathbf{k}\cdot\gamma + m_i)P_\beta = \begin{cases} m_i P_\alpha & (\alpha=\beta) \\ (\pm\omega\gamma^0 - \mathbf{k}\cdot\gamma)P_\beta & (\alpha\neq\beta) \end{cases}.$$

In the presence of the R-handed current, we have $(\pm\omega\gamma^0 - \boldsymbol{k}\cdot\boldsymbol{\gamma})P_\beta$ in addition to $< m_\nu >= |\sum_j U_{ej}^2 m_j|$. The half life $T_{1/2}$ in this case is given as

$$\frac{1}{T_{1/2}} = C_{mm}^{(0)}(\frac{< m_\nu >}{m_e})^2 + C_{m\lambda}^{(0)}\frac{< m_\nu >}{m_e} < \lambda > \cos\psi$$
$$+C_{m\eta}^{(0)}\frac{< m_\nu >}{m_e} < \eta > \cos\psi + C_{\lambda\lambda}^{(0)} < \lambda >^2 + C_{\eta\eta}^{(0)} < \eta >^2$$
$$+C_{\lambda\eta}^{(0)} < \lambda >< \eta > .$$

Here $C_{ab}^{(0)}$ includes NME and phase space integral.

$< \eta >$ and $< \lambda >$ are given as

$$< \lambda >= \lambda |\sum_j{}' U_{ej} V_{ej}^*|, \quad < \eta >= \eta |\sum_j{}' U_{ej} V_{ej}^*|.$$

ψ is the relative phase between $< m_\nu >$ and $< \lambda >$ and $< \eta >$,

$$\psi = \text{arg}\left[\left(\sum{}' m_j U_{ej}^2\right)\left(\sum{}' U_{ej} V_{ej}^*\right)^*\right],$$

where $\sum'$ indicates the summation over only the light neutrinos.
λ and η are related to the mass eigenvalues of the weak bosons in the L and $R-$ handed gauge sectors.

$$\begin{aligned} \lambda &\equiv \frac{M_{W1}^2 + M_{W2}^2 \tan^2\zeta}{M_{W1}^2 \tan^2\zeta + M_{W2}^2}, \\ \eta &\equiv -\frac{(M_{W2}^2 - M_{W1}^2)\tan\zeta}{M_{W1}^2 \tan^2\zeta + M_{W2}^2}. \end{aligned}$$

$$M_\nu = \begin{pmatrix} 0 & M_D^T & 0 \\ M_D & 0 & M^T \\ 0 & M & \mu \end{pmatrix} \equiv \begin{pmatrix} 0_{3\times 3} & \mathcal{M}_{D3\times 6}^T \\ \mathcal{M}_{D6\times 3} & \mathcal{M}_{R6\times 6} \end{pmatrix}$$

$$\mathcal{U} = \begin{pmatrix} U & X \\ V & Y \\ W & Z \end{pmatrix} \approx \qquad m_\nu = M_D^T M^{-1} \mu (M^T)^{-1} M_D$$

$$\begin{pmatrix} 1 - \frac{1}{2}\mathcal{M_D}^\dagger [\mathcal{M_R}(\mathcal{M_R})^\dagger]^{-1} \mathcal{M_D} & \mathcal{M_D}^\dagger (\mathcal{M_R}^\dagger)^{-1} \\ -\mathcal{M_R}^{-1}\mathcal{M_D} & 1 - \frac{1}{2}\mathcal{M_R}^{-1}\mathcal{M_D}\mathcal{M_D}^\dagger (\mathcal{M_R}^\dagger)^{-1} \end{pmatrix}$$

$$\begin{pmatrix} V \\ W \end{pmatrix} = -\mathcal{M}_R^{-1}\mathcal{M}_D = -\begin{pmatrix} 0 & M \\ M & \mu \end{pmatrix}^{-1} \begin{pmatrix} m_D \\ 0 \end{pmatrix} = \begin{pmatrix} -m_\nu / M_D \\ M_D / M \end{pmatrix}$$

$$
\begin{aligned}
<\lambda> &= \left(U_{ei}V_{ei}^* + X_{ei}Y_{ei}^*\frac{k^2}{k^2-M_I^2}\right)\frac{M_{WL}^2}{M_{WR}^2} \\
<\eta> &= \left(U_{ei}V_{ei}^* + X_{ei}Y_{ei}^*\frac{k^2}{k^2-M_I^2}\right)\frac{M_{WL}^2}{M_{WR}^2}(-\tan\zeta)
\end{aligned}
$$

So far we have assumed $M > M_D > \mu$. There is a possibility of $M > \mu > M_D$. Then a rather large $|V|$ is possible, within the upper bound of the experiment. Compatibitities with the other LNV processes are on going.

$$R_{0\nu} = 4\sqrt{\frac{1}{2}}\left(\frac{G\cos\theta_c}{\sqrt{2}}\right)^2 \sum_i \sum_{\alpha,\beta} \int d\boldsymbol{x} d\boldsymbol{y} \int \frac{d\boldsymbol{k}}{(2\pi)^3} e^{i\boldsymbol{k}\cdot(\boldsymbol{y}-\boldsymbol{x})} \frac{1}{2\omega}\left[\frac{1}{\omega+A_1}+\frac{1}{\omega+A_2}\right]$$
$$\overline{e}_{p_2,s_2'}(\boldsymbol{y})\mathcal{O}(\boldsymbol{x},\boldsymbol{y})e^c_{p_1,s_1'}(\boldsymbol{x}),$$

Here the interference terms of R-handed and L-handed current from the neutrino momentum $(\boldsymbol{k})$ dependent term of the neutrino propagator are given as

$$\mathcal{O}(\boldsymbol{x},\boldsymbol{y}) = -\langle F|\tilde{\mathcal{J}}^{\dagger}_R(\boldsymbol{y})\boldsymbol{k}\cdot\boldsymbol{\gamma}P_L\tilde{\mathcal{J}}^{\dagger}_L(\boldsymbol{x}) + \tilde{\mathcal{J}}^{\dagger}_L(\boldsymbol{y})\boldsymbol{k}\cdot\boldsymbol{\gamma}P_R\tilde{\mathcal{J}}^{\dagger}_R(\boldsymbol{x})|I\rangle\,.$$

$$\tilde{J}^{\mu}_R(\boldsymbol{x}) = \eta J^{\mu}_L(\boldsymbol{x}) + \lambda J^{\mu}_R(\boldsymbol{x}).$$

$$C_{\eta\eta}^{(0)} = \Big[\chi_{2+}^2 G_{02} + \frac{1}{9}\chi_{1-}^2 G_{04} - \frac{2}{9}\chi_{1-}\chi_{2+} G_{03} + \chi_P'^2 G_{08} - \chi_P'\chi_R' G_{07} + \chi_R'^2 G_{09}\Big]$$

Here

$$\chi_R' =< 0_f || h_+ \left(\frac{R}{2r_{nm}}\right) [\hat{\mathbf{r}}_{nm} \cdot (\sigma_n \times \mathbf{D}_m + \mathbf{D}_n \times \sigma_m)] || 0_i >,$$

where

$$\mathbf{D}_n = \left[\mathbf{p}_n + \mathbf{p}_n' - i\mu_B \sigma_n \times (\mathbf{p}_n - \mathbf{p}_n')\right] / 2M$$

(Doi-Kotani-Takasugi (1985)). This implies that the cross term of GT and weak magnetism dominates $R_{0\nu}$.

$$\not{J}\not{k}\not{J}' = -\vec{J}\cdot\vec{k}\not{J}' + \not{J}(-\vec{J'}\cdot\vec{k}) - (J_0J_0' - \vec{J}\cdot\vec{J'}) - i\epsilon^{\alpha i\gamma\delta}J_\alpha k_i J_\gamma'\gamma_5\gamma_\delta$$

The weak magnetism term appears in the last term. So we remark this term,

$$\begin{aligned}
&\vec{J}_L \times \vec{k}\cdot(\eta\vec{J}_L + \lambda\vec{J}_R) \\
&= \left(-g_A\vec{\sigma}_1 + \frac{g_V+g_M}{2M}i\vec{\sigma}_1\times(\vec{k}-\vec{p}_1)\right)\times\vec{k} \\
&\cdot\left[\eta\left(-g_A\vec{\sigma}_2 + \frac{g_V+g_M}{2M}i\vec{\sigma}_2\times(-\vec{k}-\vec{p}_2)\right)\right. \\
&\left.+\lambda\left(+g_A\vec{\sigma}_2 + \frac{g_V+g_M}{2M}i\vec{\sigma}_2\times(-\vec{k}-\vec{p}_2)\right)\right]
\end{aligned}$$

$$\left.\begin{matrix}\eta\\ \lambda\end{matrix}\right\} = \vec{\sigma}_1\times\vec{k}\cdot\vec{\sigma}_2\times\vec{k}\mp(\vec{\sigma}_1\times\vec{k})\times\vec{k}\cdot\vec{\sigma}_2$$

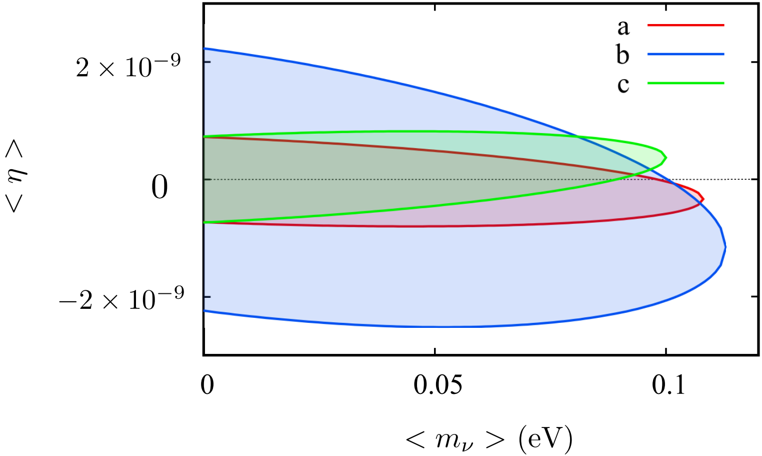
Using $J^\mu_{L/R} = V^\mu \pm A^\mu$, $\mathcal{O}(\boldsymbol{x},\boldsymbol{y})$ responsible to the enhancement of η term is given as

$$\begin{aligned}
\mathcal{O}(\boldsymbol{x},\boldsymbol{y}) &= \langle F| < \lambda > (\not{V}^\dagger(\boldsymbol{y})\boldsymbol{k}\cdot\boldsymbol{\gamma}\not{A}^\dagger(\boldsymbol{x}) - \not{A}^\dagger(\boldsymbol{y})\boldsymbol{k}\cdot\boldsymbol{\gamma}\not{V}^\dagger(\boldsymbol{x}))\gamma_5 \\
&+ < \eta > (\not{V}^\dagger(\boldsymbol{y})\boldsymbol{k}\cdot\boldsymbol{\gamma}\not{A}^\dagger(\boldsymbol{x}) + \not{A}^\dagger(\boldsymbol{y})\boldsymbol{k}\cdot\boldsymbol{\gamma}\not{V}^\dagger(\boldsymbol{x}))\,|I\rangle \\
&= \langle F| < \lambda > (\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{x}) - \boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{x}))(-\gamma_0) \\
&+ < \eta > (\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{x}) + \boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{x}))(\gamma_5\gamma_0)\,|I\rangle\,.
\end{aligned}$$

Here the magnetization current of the vector current is expressed as $\boldsymbol{V}(\boldsymbol{x}) = \boldsymbol{\nabla}\times\boldsymbol{\mu}(\boldsymbol{x})$. $\boldsymbol{\mu}(\boldsymbol{x})$ and $\boldsymbol{A}(\boldsymbol{x})$ are given by using the same spin-isospin flip operator $\sim \tau^+\boldsymbol{\sigma}$ as,

$$\begin{aligned}
\boldsymbol{A}(\boldsymbol{x}) &= \sum_i^A g_A(k^2)\tau_i^+\boldsymbol{\sigma}_i\delta(\boldsymbol{x}-\boldsymbol{r}_i), \\
\boldsymbol{\mu}(\boldsymbol{x}) &= \sum_i^A \frac{g_V(k^2)+g_M(k^2)}{2M}\tau_i^+\boldsymbol{\sigma}_i\delta(\boldsymbol{x}-\boldsymbol{r}_i).
\end{aligned}$$

Within this approximation, the $< \lambda >$ term vanishes and only the $< \eta >$ term remains.



Allowed region of $< \eta >$ and $< m_\nu >$ for ^{136}Xe. a,b,c are evaluated using C's of Refs. muto89, suhonen91, and Pantis96 (model without p-n pairing), respectively.

	^{48}Ca	^{76}Ge	^{82}Se	^{96}Zr	^{100}Mo	^{116}Cs	^{128}Te	^{130}Te
$R_A^{m_\nu}$	0.75	0.51	1.2	3.0	0.47	0.39	0.095	2.1
R_A^{η}	0.082	0.40	0.19	0.83	0.36	0.064	0.10	2.0
$R_A = R_A^{\eta}/R_A^{m_\nu}$	0.11	0.77	0.15	0.28	0.76	0.16	1.1	0.94

Ratio of decay rate R_A^α evaluated using C's of Pantis et.al.

$$R_A^\alpha = \frac{T_{1/2}^\alpha(Xe)}{T_{1/2}^\alpha(A)}$$

Here $\alpha =< m_\nu >, \;\; < \eta >$ and $R_A^{<m_\nu>}$ indicates that the decay occured only via $< m_\nu >$ etc.

Summaries

We have considered $0\nu\beta\beta$ decay in L-R symmetric Model and how to specify BSM physics if we found non-null results around the present experimental upper bound. We can narrow down the following two cases: (i) $< m >$ mechanism in the inverted neutrino hierarchy and/or (ii) $< \eta >$ mechanism. Then in order to specify BSM physics we need to study several experiments of different parent nuclei.

Thank you.