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

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based on
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二重ベータ崩壊核行列要素に関する実験理論合同研究会

Summary

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

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

$$| < \lambda > | \leq 5.7 \times 10^{-7}$$
$$| < \eta > | \leq 5.7 \times 10^{-7}/\tan\beta.$$

In $0^+ \to 0^+$ transition, $< \eta >$ mechanism may dominate $0\nu\beta\beta$.

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

L and R-handed leptonic currents

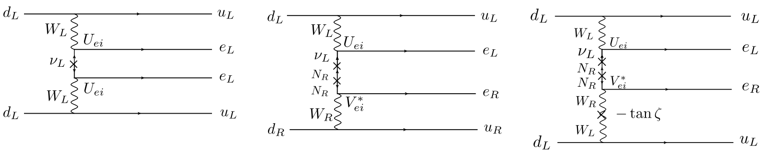
$$\begin{aligned} j_{L\alpha} &= \sum_{l=e,\mu,\tau} \overline{l(x)}\gamma_\alpha(1-\gamma_5)\nu_{lL}(x) \equiv \sum \overline{l(x)}\gamma_\alpha 2P_L \nu_{lL}(x), \\ j_{R\alpha} &= \sum_{l=e,\mu,\tau} \overline{l(x)}\gamma_\alpha(1+\gamma_5)N_{lR}(x) \equiv \sum \overline{l(x)}\gamma_\alpha 2P_R N_{lR}(x),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

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

Hadronic Currents:

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

Diagrams of $0\nu\beta\beta$ decay



(a) (b) (c)

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

The half life $T_{1/2}$ in this case (Takasugi85, Simkovic2010, Engel2017, Pantis92, Suhonen98) is given as

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

Here $C^{(0)}_{ab}$ include NME and phase space integral.

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

$$\begin{aligned}
\lambda &\equiv \frac{M_{W1}^2 + M_{W2}^2 \tan^2\zeta}{M_{W1}^2 \tan^2\zeta + M_{W2}^2}, \\
\eta &\equiv -\frac{(M_{W2}^2 - M_{W1}^2)\tan\zeta}{M_{W1}^2 \tan^2\zeta + M_{W2}^2}, \\
\tan 2\zeta &= \frac{2v_u v_d}{v_R^2 - v_L^2} \approx \frac{2v_u v_d}{v_R^2} = \frac{2}{\tan\beta}\left(\frac{M_{WL}}{M_{WR}}\right)^2
\end{aligned}$$

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

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

$$\mathcal{M}_R^{-1}\mathcal{M}_D = \begin{pmatrix} 0 & M \\ M & \mu \end{pmatrix}^{-1} \begin{pmatrix} m_D \\ 0 \end{pmatrix} = -\frac{1}{M^2} \begin{pmatrix} -\mu m_D \\ M m_D \end{pmatrix}$$

$$m_{light} = M_D^T M^{-1} \mu (M^T)^{-1} M_D$$

$$\mathcal{U} = \begin{pmatrix} U & X \\ V & Y \\ W & Z \end{pmatrix},$$

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

$$\begin{aligned} | < \lambda > | &\leq 5.7 \times 10^{-7} \\ | < \eta > | &\leq 5.7 \times 10^{-7} / \tan\beta. \end{aligned}$$

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

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

$$L_{\nu\mu} = \overline{e}_{p_2,s_2'}(\boldsymbol{y})\gamma_\nu P_\beta \frac{1}{2\omega}\left[\frac{\omega\gamma^0 - \boldsymbol{k}\cdot\boldsymbol{\gamma} + m_i}{\omega + A_1} + \frac{-\omega\gamma^0 - \boldsymbol{k}\cdot\boldsymbol{\gamma} + m_i}{\omega + A_2}\right] P_\alpha \gamma_\mu e^c_{p_1,s_1'}(\boldsymbol{x}).$$

The nuclear tensor $H^{\nu\mu}$

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

$0^+ \to 0^+$ transition

$$R_{0\nu} = 4\sqrt{\frac{1}{2}}\left(\frac{G\cos\theta_c}{\sqrt{2}}\right)^2 \sum_i \sum_{\alpha,\beta} \int d\boldsymbol{x} d\boldsymbol{y} \int \frac{d\boldsymbol{k}}{(2\pi)^3} e^{i\boldsymbol{k}\cdot(\boldsymbol{y}-\boldsymbol{x})} \frac{1}{2\omega}\left[\frac{1}{\omega + A_1} + \frac{1}{\omega + A_2}\right] \bar{e}_{p_2,s'_2}(\boldsymbol{y})\mathcal{O}(\boldsymbol{x},\boldsymbol{y})e^c_{p_1,s'_1}(\boldsymbol{x}),$$

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

Non-relativistic limit:

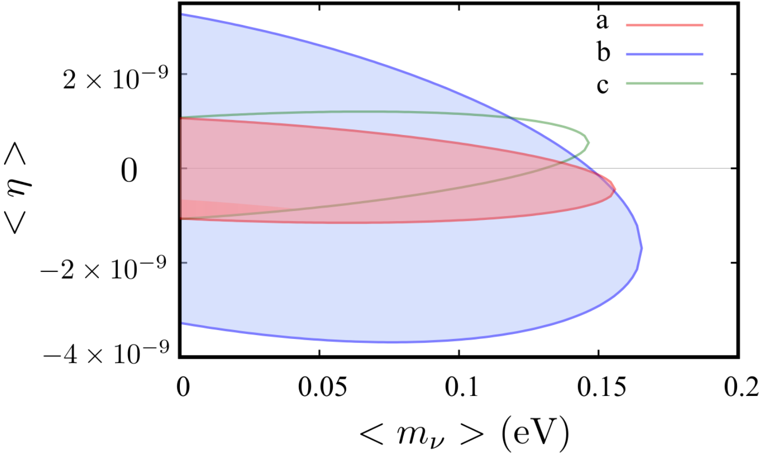
$$J^\mu_L = \left(g_V\tau, \; -g_A\boldsymbol{\sigma}\tau + i\frac{g_V + g_M}{2M}\boldsymbol{\sigma}\times\boldsymbol{q}\tau\right)$$

$$J^\mu_R = \left(g_V\tau, \; +g_A\boldsymbol{\sigma}\tau + i\frac{g_V + g_M}{2M}\boldsymbol{\sigma}\times\boldsymbol{q}\tau\right)$$

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

$$
\begin{aligned}
= \; & \langle F| <\lambda> (\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{x}) - \boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{x}))(-\gamma_0) \\
& + <\eta> (\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{x}) + \boldsymbol{k}\times\boldsymbol{A}(\boldsymbol{y})\cdot\boldsymbol{k}\times\boldsymbol{\mu}(\boldsymbol{x}))(\gamma_5\gamma_0)\,|I\rangle\,.
\end{aligned}
$$

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



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.