Right-handed Currents in $0\nu\beta\beta$ Decays and Ton-Scale $\beta\beta$ Detectors

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1. Right-handed currents (RHC) as BSM physics by Fukuyama
2. RHC DBD Nuclear Matrix Elements (NMEs) for the ground 0^+ and excited 2^+ states by Sato
3. Nuclear and Detector Sensitivities For DBD RHCs by Ejiri

Right handed weak currents (RHCs) in the left-right (L-R) symmetric model are examined in neutrinoless double beta decays of both $0^+ \rightarrow 0^+$ and $0^+ \rightarrow 2^+$ transitions. The structures of the nuclear matrix elements (NMEs) of $< m >, \ < \lambda >$ and $< \eta >$ -terms are studied in detail for these two transitions. In case of $0^+ \rightarrow 0^+$ transition, the enhancement mechanisms of the $< \eta >$ term over the $< \lambda >$ term are shown. The Δ isobar contribution to the NME for the transition to the 2^+ state is evaluated to be of the order of $10 - 20\%$ of the NME. Measurements of both $\beta\beta$ and γ rays associated with 0ν DBDs by means of the ton-scale DBD detectors under construction are used to study the effective RHCs around $< \lambda > \approx 10^{-7}$ and $< \eta > \approx 10^{-10}$. These values depend on the phase space and the NME with the effective weak coupling of g_{A}^{eff}.
Refs. H. Ejiri, J. Suhonen, and K. Zuber, Phys. Rep. **797**, 1, 2019.
H. Ejiri, T. Fukuyama and H. Sato, arXiv:2501.03454 v1

Definition

$$< m >= |\sum_i U_{ei}^2 m_i|, \quad < \lambda >= \lambda |\sum_j U_{ej} V_{ej}|, \quad < \eta >= \eta |\sum_j U_{ej} V_{ej}|$$

$$\left(\begin{array}{c} \nu \\ (N_R)^c \end{array} \right)_L = \left(\begin{array}{cc} U & X \\ V^* & Y \end{array} \right) \left(\begin{array}{c} \nu' \\ N' \end{array} \right)_L$$

The Hadronic Currents are

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

Theoretical Aspects of RHC DBDs

We know from the neutrino oscillation experiments that at least two speicies of neutrinos have masses. Then, where does the neutrino mass come from ? Naively we can consider type II seesaw as usual as the Higgs mechanism of usual matters. However, it does not explain why the neutrino mass is so tiny compared with the other matters. So we may consider type I (seesaw mechanism) with right-handed currents or radiative generation of neutrino masses. In this talk we adopt the former case since it has also the origin of baryogenesis via leptogenesis and dark matter (DM) candidate (lightest right-handed neutrinos or neutral triplet scalar).

Radiative neutrino mass

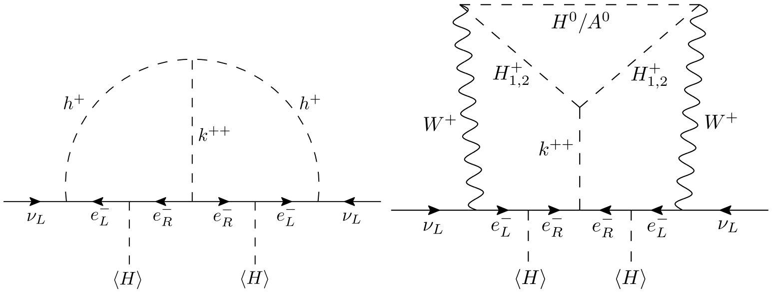


Figure: The diagram to induce the neutrino masses. Left: Zee-Babu model, where the symbol $\langle H \rangle$ stands for the vev of the SM Higgs boson. Right: Cocktail model, where the charged scalar in the inert doublet η and the $SU(2)_L$ singlet scalar S^+ are mixed to be $H^+_{1,2}$. By splitting the masses of the real and imaginary parts (H^0, A^0) of the neutral scalar in η, neutrino masses are generated. The symbol $\langle H \rangle$ stands for the vev of the SM Higgs boson.

L-R symmetric Model in GUT

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

where

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

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

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:

$$M_W = \frac{g^2}{4}\left(\begin{array}{cc} v_u^2 + v_d^2 + 2v_L^2 & 2v_u v_d \\ 2v_u v_d & v_u^2 + v_d^2 + 2v_R^2 \end{array} \right),$$

$$\left(\begin{array}{c} W_1 \\ W_2 \end{array} \right) = \left(\begin{array}{cc} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{array} \right) \left(\begin{array}{c} W_L \\ W_R \end{array} \right)$$

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

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

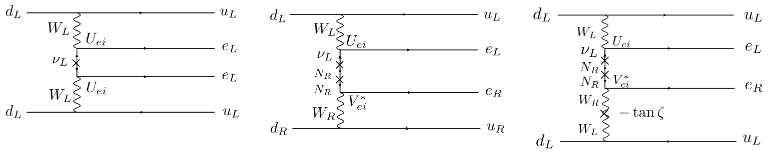
and $\nu_{lL}(N_{lR})$ are L-handed (R-handed) weak eigenstates of the neutrinos,
The Hadronic Currents are

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

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

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

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



(a) (b) (c)

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

Further simplification

However, the quark mixing angle is almost diagonal and if we assume

$$\kappa \gg \kappa' \quad Y_{ij} \gg Y'_{ij},$$

then they are related with more familiar quantities,

$$\kappa \approx v_u, \quad \kappa' \approx v_d, \quad \frac{1}{\sqrt{2}}(\kappa^2 + \kappa'^2) = v_{ew}^2$$

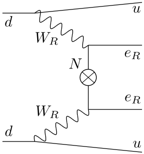
and the L-R weak boson mixing angle becomes

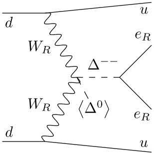
$$\tan 2\zeta = -\frac{2\kappa\kappa'}{v_R^2} \approx \frac{2v_u v_d}{v_R^2} = -4\xi \left(\frac{M_{WL}}{M_{WR}}\right)^2$$

with

$$\xi \equiv \kappa'/\kappa \approx v_d/v_u \equiv 1/\tan\beta$$

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





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

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

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))

Summaries

We have overviewed 0νDBD based on the minimal L-R symmetric model, which gives possibilities to give the chance to get non-null result in ton-scale DBD experiments even in the normal hierarchy. The details are discussed in the continueing talks by Professor Sato and Professor Ejiri.

Thank you.