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The λ Mechanism of the $0\nu\beta\beta$-Decay

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The λ mechanism ($W_L - W_R$ exchange) of the neutrinoless double beta decay ($0\nu\beta\beta$-decay), which has origin in left-right symmetric model with right-handed gauge boson at TeV scale, is investigated. The revisited formalism of the $0\nu\beta\beta$-decay, which includes higher order terms of nucleon current, is exploited. The corresponding nuclear matrix elements are calculated within quasiparticle random phase approximation with partial restoration of the isospin symmetry for nuclei of experimental interest. A possibility to distinguish between the conventional light neutrino mass ($W_L - W_L$ exchange) and λ mechanisms by observation of the $0\nu\beta\beta$-decay in several nuclei is discussed. A qualitative comparison of effective lepton number violating couplings associated with these two mechanisms is performed. By making viable assumption about the seesaw type mixing of light and heavy neutrinos with the value of Dirac mass m_D within the range $1\ \mathrm{MeV} < m_D < 1\ \mathrm{GeV}$, it is concluded that there is a dominance of the conventional light neutrino mass mechanism in the decay rate.

Keywords: majorana neutrinos, neutrinoless double beta decay, right-handed current, left-right symmetric models, nuclear matrix elements, quasiparticle random phase approximation

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1. INTRODUCTION

The Majorana nature of neutrinos, as favored by many theoretical models, is a key for understanding of tiny neutrino masses observed in neutrino oscillation experiments. A golden process for answering this open question of particle physics is the neutrinoless double beta decay ($0\nu\beta\beta$-decay) [1–3],

$$(A, Z) \rightarrow (A, Z+2) + 2e^-, \tag{1}$$

in which an atomic nucleus with Z protons decays to another one with two more protons and the same mass number A, by emitting two electrons and nothing else. The observation of this process, which violates total lepton number conservation and is forbidden in the Standard Model, guaranties that neutrinos are Majorana particles, i.e., their own antiparticles [4].

The searches for the $0\nu\beta\beta$-decay have not yielded any evidence for Majorana neutrinos yet. This could be because neutrinos are Dirac particles, i.e., not their own antiparticles. In this case we will never observe the decay. However, it is assumed that the reason for it is not sufficient sensitivity of previous and current $0\nu\beta\beta$-decay experiments to the occurrence of this rare process.

Due to the evidence for neutrino oscillations and therefore for 3 neutrino mixing and masses the $0\nu\beta\beta$-decay mechanism of primary interest is the exchange of 3 light Majorana neutrinos interacting through the left-handed V-A weak currents ($m_{\beta\beta}$ mechanism). In this case, the inverse $0\nu\beta\beta$-decay half-life is given by Vergados et al. [1], DellOro et al. [2] and Vergados et al. [3]

$$\left[T^{0\nu}_{1/2}\right]^{-1} = \left(\frac{m_{\beta\beta}}{m_e}\right)^2 g_A^4\, M_\nu^2\, G_{01}, \tag{2}$$

where G_{01}, g_A and M_ν represent an exactly calculable phase space factor, the axial-vector coupling constant and the nuclear matrix element (whose calculation represents a severe challenge for nuclear theorists), respectively. m_e is the mass of an electron. The effective neutrino mass,

$$m_{\beta\beta} = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3 \right| , \tag{3}$$

is a linear combination of the three neutrino masses m_i, weighted with the square of the elements U_{ei} of the first row of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix. The measured value of $m_{\beta\beta}$ would be a source of important information about the neutrino mass spectrum (normal or inverted spectrum), absolute neutrino mass scale and the CP violation in the neutrino sector. However, that is not the only possibility.

There are several different theoretical frameworks that provide various $0\nu\beta\beta$-decay mechanisms, which generate masses of light Majorana neutrinos and violate the total lepton number conservation. One of those theories is the left-right symmetric model (LRSM) [5–9], in which corresponding to the left-handed neutrino, there is a parity symmetric right-handed neutrino. The parity between left and right is restored at high energies and neutrinos acquire mass through the see-saw mechanism, what requires presence of additional heavy neutrinos. In general one cannot predict the scale where the left-right symmetry is realized, which might be as low as a few TeV—accessible at Large Hadron Collider, or as large as GUT scale of 10^{15} GeV.

The LRSM, one of the most elegant theories beyond the Standard Model, offers a number of new physics contributions to $0\nu\beta\beta$-decay, either from right-handed neutrinos or Higgs triplets. The main question is whether these additional $0\nu\beta\beta$-mechanisms can compete with the $m_{\beta\beta}$ mechanism and affect the $0\nu\beta\beta$-decay rate significantly. This issue is a subject of intense theoretical investigation within the TeV-scale left-right symmetry theories [10–14]. In analysis of heavy neutrino mass mechanisms of the $0\nu\beta\beta$-decay an important role plays a study of related lepton number and lepton flavor violation processes in experiments at Large Hadron Collider [2, 15–19].

The goal of this article is to discuss in details the $W_L - W_R$ exchange mechanism of the $0\nu\beta\beta$-decay mediated by light neutrinos (λ mechanism) and its coexistence with the standard $m_{\beta\beta}$ mechanism. For that purpose the corresponding nuclear matrix elements (NMEs) will be calculated within the quasiparticle random phase approximation with a partial restoration of the isospin symmetry [20] by taking the advantage of improved formalism for this mechanism of the $0\nu\beta\beta$-decay of Štefánik [21]. A possibility to distinguish $m_{\beta\beta}$ and λ mechanisms in the case of observation of the $0\nu\beta\beta$-decay on several isotopes will be analyzed. Further, the dominance of any of these two mechanisms in the $0\nu\beta\beta$-decay rate will be studied within seesaw model with right-handed gauge boson at TeV scale. We note that a similar analysis was performed by exploiting a simplified $0\nu\beta\beta$-decay rate formula and different viable particle physics scenarios in Tello et al. [10], Barry and Reodejohann [11], Bhupal Dev et al. [12], Deppisch et al. [13] and Borah et al. [14].

2. DECAY RATE FOR THE NEUTRINOLESS DOUBLE-BETA DECAY

Recently, the $0\nu\beta\beta$-decay with the inclusion of right-handed leptonic and hadronic currents has been revisited by considering exact Dirac wave function with finite nuclear size and electron screening of emitted electrons and the induced pseudoscalar term of hadron current, resulting in additional nuclear matrix elements [21]. In this section we present the main elements of the revisited formalism of the λ mechanism of the $0\nu\beta\beta$-decay briefly. Unlike in Štefánik et al. [21] the effect the weak-magnetism term of the hadron current on leading NMEs is taken into account.

If the mixing between left and right vector bosons is neglected, for the effective weak interaction hamiltonian density generated within the LRSM we obtain

$$H^\beta = \frac{G_\beta}{\sqrt{2}} \left[j_L^{\rho} J_{L\rho}^{\dagger} + \lambda j_R^{\rho} J_{R\rho}^{\dagger} + h.c. \right]. \tag{4}$$

Here, $G_\beta = G_F \cos\theta_C$, where G_F and θ_C are Fermi constant and Cabbibo angle, respectively. The coupling constant λ is defined as

$$\lambda = (M_{W_L}/M_{W_R})^2. \tag{5}$$

Here, M_{W_L} and M_{W_R} are masses of the Standard Model left-handed W_L and right-handed W_R gauge bosons, respectively. The left- and right-handed leptonic currents are given by

$$j_L^{\rho} = \bar{e}\gamma_\rho(1-\gamma_5)\nu_{eL}, \qquad j_R^{\rho} = \bar{e}\gamma_\rho(1+\gamma_5)\nu_{eR}. \tag{6}$$

The weak eigenstate electron neutrinos ν_{eL} and ν_{eR} are superpositions of the light and heavy mass eigenstate Majorana neutrinos ν_j and N_j, respectively. We have

$$\nu_{eL} = \sum_{j=1}^{3} \left(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C \right), \; \nu_{eR} = \sum_{j=1}^{3} \left(T_{ej}^{*}(\nu_{jL})^C + V_{ej}^{*} N_{jR} \right) \tag{7}$$

Here, U, S, T, and V are the 3×3 block matrices in flavor space, which constitute a generalization of the Pontecorvo-Maki-Nakagawa-Sakata matrix, namely the 6×6 unitary neutrino mixing matrix [22]

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}. \tag{8}$$

The nuclear currents are, in the non-relativistic approximation, [23]

$$J_{L,R}^{\rho}(\mathbf{x}) = \sum_n \tau_n^+ \delta(\mathbf{x}-\mathbf{r}_n) \left[\left(g_V \mp g_A C_n\right) g^{\rho 0} + g^{\rho k} \left(\pm g_A \sigma_n^k - g_V D_n^k \mp g_P\, q_n^k \, \frac{\vec{\sigma}_n \cdot \mathbf{q}_n}{2m_N} \right) \right]. \tag{9}$$

Here, m_N is the nucleon mass. $q_V \equiv q_V(q^2)$, $q_A \equiv q_A(q^2)$, $q_M \equiv q_M(q^2)$ and $q_P \equiv q_P(q^2)$ are, respectively, the vector, axial-vector, weak-magnetism and induced pseudoscalar form-factors. The nucleon recoil terms are given by

$$\begin{aligned} C_n &= \frac{\vec{\sigma}\cdot(\mathbf{p}_n+\mathbf{p}'_n)}{2m_N} - \frac{g_P}{g_A}\left(E_n - E'_n\right)\frac{\vec{\sigma}\cdot\mathbf{q}_n}{2m_N}, \\ \mathbf{D}_n &= \frac{(\mathbf{p}_n+\mathbf{p}'_n)}{2m_N} - i\left(1+\frac{g_M}{g_V}\right)\frac{\vec{\sigma}\times\mathbf{q}_n}{2m_N}, \end{aligned} \quad (10)$$

where $\mathbf{q}_n = \mathbf{p}_n - \mathbf{p}'_n$ is the momentum transfer between the nucleons. The initial neutron (final proton) possesses energy E'_n (E_n) and momentum $\mathbf{p}'_n$ ($\mathbf{p}_n$). $\mathbf{r}_n$, τ_n^+ and $\vec{\sigma}_n$, which act on the n-th nucleon, are the position operator, the isospin raising operator and the Pauli matrix, respectively.

By assuming standard approximations [21] for the $0\nu\beta\beta$-decay half-life we get

$$\left[T_{1/2}^{0\nu}\right]^{-1} = \eta_\nu^2\, C_{mm} + \eta_\lambda^2\, C_{\lambda\lambda} + \eta_\nu\, \eta_\lambda\, \cos\psi\, C_{m\lambda}. \quad (11)$$

The effective lepton number violating parameters η_ν ($W_L - W_L$ exchange), η_λ ($W_L - W_R$ exchange) and their relative phase Ψ are given by

$$\begin{aligned} \eta_\nu &= \frac{m_{\beta\beta}}{m_e}, \quad \eta_\lambda = \lambda|\sum_{j=1}^{3} U_{ej}T_{ej}^*|, \\ \psi &= \mathrm{argj}\left[\left(\sum_{j=1}^{3} m_j U_{ej}^2\right)\left(\sum_{j=1}^{3} U_{ej}T_{ej}^*\right)^*\right]. \end{aligned} \quad (12)$$

The coefficients C_I (I $= mm$, $m\lambda$ and $\lambda\lambda$) are linear combinations of products of nuclear matrix elements and phase-space factors:

$$\begin{aligned} C_{mm} &= g_A^4 M_\nu^2\, G_{01}, \\ C_{m\lambda} &= -g_A^4 M_\nu\left(M_{2-}G_{03} - M_{1+}G_{04}\right), \\ C_{\lambda\lambda} &= g_A^4\left(M_{2-}^2 G_{02} + \frac{1}{9}M_{1+}^2 G_{011} - \frac{2}{9}M_{1+}M_{2-}G_{010}\right), \end{aligned} \quad (13)$$

The explicit form and calculated values of phase-space factors G_{0i} ($i = 1, 2, 3, 4, 10$ and 11) of the $0\nu\beta\beta$-decaying nuclei of experimental interest are given in Štefánik et al. [21]. The NMES, which constitute the coefficients C_I in Equation (13), are defined as follows:

$$\begin{aligned} M_\nu &= M_{GT} - \frac{M_F}{g_A^2} + M_T, \qquad M_{\nu\omega} = M_{GT\omega} - \frac{M_{F\omega}}{g_A^2} + M_{T\omega} \\ M_{1+} &= M_{qGT} + 3\frac{M_{qF}}{g_A^2} - 6M_{qT}, \qquad M_{2-} = M_{\nu\omega} - \frac{1}{9}M_{1+}. \end{aligned} \quad (14)$$

The partial nuclear matrix elements M_I, where I = GT, F, T, ωF, ωGT, ωT, qF, qGT, and qT are given by

$$\begin{aligned} M_{F,GT,T} &= \sum_{rs}\langle A_f|h_{F,GT,T}(r_-)O_{F,GT,T}|A_i\rangle \\ M_{\omega F,\omega GT,\omega T} &= \sum_{rs}\langle A_f|h_{\omega F,\omega GT,\omega T}(r_-)O_{F,GT,T}|A_i\rangle \\ M_{qF,qGT,qT} &= \sum_{rs}\langle A_f|h_{qF,qGT,qT}(r_-)O_{F,GT,T}|A_i\rangle. \end{aligned} \quad (15)$$

Here, $O_{F,GT,T}$ are the Fermi, Gamow-Teller and tensor operators $1, \vec{\sigma}_1\cdot\vec{\sigma}_2$ and $3(\vec{\sigma}_1\cdot\hat{r}_{12})(\vec{\sigma}_2\cdot\hat{r}_{12})$. The two-nucleon exchange potentials $h_I(r)$ with I = F, GT, T, ωF, ωGT, ωT, qF, qGT, and qT can be written as

$$h_I(r) = \frac{2R}{\pi}\int f_I(q,r)\frac{q\, dq}{q + \bar{E}_n - (E_i+E_f)/2}, \quad (16)$$

where

$$\begin{aligned} f_{GT} &= \frac{j_0(q,r)}{g_A^2}\left(g_A^2(q^2) - \frac{g_A(q^2)g_P(q^2)}{m_N}\frac{q^2}{3} + \frac{g_P^2(q^2)}{4m_N^2}\frac{q^4}{3}\right. \\ &\qquad \left. + 2\frac{g_M^2(q^2)}{4m_N^2}\frac{q^2}{3}\right), \\ f_F &= g_V^2(q^2)j_0(qr), \\ f_T &= \frac{j_2(q,r)}{g_A^2}\left(\frac{g_A(q^2)g_P(q^2)}{m_N}\frac{q^2}{3} - \frac{g_P^2(q^2)}{4m_N^2}\frac{q^4}{3} + \frac{g_M^2(q^2)}{4m_N^2}\frac{q^2}{3}\right), \\ f_{qF} &= r g_V^2(q^2)j_1(qr)q, \\ f_{qGT} &= \left(\frac{g_A^2(q^2)}{g_A^2}q + 3\frac{g_P^2(q^2)}{g_A^2}\frac{q^5}{4m_N^2} + \frac{g_A(q^2)g_P(q^2)}{g_A^2}\frac{q^3}{m_N}\right) r j_1(qr), \\ f_{qT} &= \frac{r}{3}\left(\left(\frac{g_A^2(q^2)}{g_A^2}q - \frac{g_P(q^2)g_A(q^2)}{2g_A^2}\frac{q^3}{m_N}\right) j_1(qr)\right. \\ &\qquad \left. - 9\frac{g_P^2(q^2)}{2g_A^2}\frac{q^5}{20m_N^2}\left[2j_1(qr)/3 - j_3(qr)\right]\right), \end{aligned} \quad (17)$$

and

$$h_{\omega GT,F,T} = \frac{q}{(q + \bar{E}_n - (E_i+E_f)/2)} h_{GT,F,T}. \quad (18)$$

Here, E_i, E_f and $\bar{E}_n$ are energies of the initial and final nucleus and averaged energy of intermediate nuclear states, respectively. $\mathbf{r} = (\mathbf{r}_r - \mathbf{r}_s)$, $\mathbf{r}_{r,s}$ is the coordinate of decaying nucleon and $j_i(qr)$ ($i = 1, 2, 3$) denote the spherical Bessel functions. $\mathbf{p}_r + \mathbf{p}'_r \simeq 0$, $E_r - E'_r \simeq 0$ and $\mathbf{p}_r - \mathbf{p}'_r \simeq \mathbf{q}$, where $\mathbf{q}$ is the momentum exchange. The form factors $g_V(q^2)$, $g_A(q^2)$, $g_M(q^2)$ and $g_P(q^2)$ are defined in Simkovic et al. [24]. We note that factor 4 in definition of the two-nucleon exchange potentials $h_I(r)$ with I = ωF, ωGT, and ωT in Equation (48) of Štefánik et al. [21] needs to be replaced by factor 2.

3. RESULTS AND DISCUSSION

The nuclear matrix elements are calculated in proton-neutron quasiparticle random phase approximation with partial restoration of the isospin symmetry for ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{116}Cd, ^{124}Sn, ^{130}Te and ^{136}Xe, which are of experimental interest. In the calculation the same set of nuclear structure parameters is used as in Simkovic et al. [20]. The pairing and residual interactions as well as the two-nucleon short-range correlations derived from the realistic nucleon-nucleon Argonne V18 potential are considered [26]. The closure approximation for intermediate nuclear states is assumed with $(\bar{E}_n - (E_i + E_f)/2) = 8$ MeV. The free nucleon value of axial-vector coupling constant ($g_A = 1.25 - 1.27$) is considered.

TABLE 1 | The nuclear matrix elements of the $0\nu\beta\beta$-decay associated with $m_{\beta\beta}$ and λ mechanisms and the coefficients C_{mm}, $C_{m\lambda}$ and $C_{\lambda\lambda}$ (in 10^{-14} years^{-1}) of the decay rate formula (see Equation 11).

	^{48}Ca	^{76}Ge	^{82}Se	^{96}Zr	^{100}Mo	^{110}Pd	^{116}Cd	^{124}Sn	^{130}Te	^{136}Xe
PNQRPA NMEs OF MUTO ET AL. [25]										
M_{GT}		3.014	2.847		0.763				2.493	1.120
M_F		−1.173	−1.071		−1.356				−0.977	−0.461
$M_{\omega GT}$		2.912	2.744		1.330				2.442	1.172
$M_{\omega F}$		−1.025	−0.939		−1.218				−0.867	−0.411
M_{qGT}		1.945	1.886		−1.145				1.526	0.480
M_{qF}		−1.058	−0.966		−1.161				−0.860	−0.389
PRESENT WORK										
M_{GT}	0.569	4.513	4.005	2.104	4.293	4.670	3.178	2.056	3.192	1.808
M_F	−0.312	−1.577	−1.496	−1.189	−2.214	−2.152	−1.573	−0.907	−1.489	−0.779
M_T	−0.162	−0.571	−0.525	−0.397	−0.650	−0.558	−0.262	−0.350	−0.561	−0.288
$M_{\omega GT}$	0.568	4.238	3.784	2.088	4.159	4.436	2.979	2.108	3.091	1.758
$M_{\omega F}$	−0.295	−1.487	−1.409	−1.117	−2.076	−2.015	−1.466	−0.955	−1.410	−0.745
$M_{\omega T}$	−0.156	−0.547	−0.502	−0.379	−0.623	−0.535	−0.251	−0.368	−0.536	−0.275
M_{qGT}	0.245	2.919	2.533	1.026	2.389	2.878	2.105	1.109	1.746	0.975
M_{qF}	−0.203	−1.071	−1.031	−0.804	−1.588	−1.565	−1.208	−0.617	−0.995	−0.492
M_{qT}	−0.107	−0.294	−0.262	−0.200	−0.329	−0.281	−0.142	−0.156	−0.252	−0.125
M_ν	0.601	4.921	4.410	2.446	5.018	5.449	3.894	2.333	3.554	2.004
$M_{\nu\omega}$	0.595	4.615	4.157	2.402	4.826	5.153	3.638	2.269	3.430	1.946
M_{1+}	0.506	2.689	2.183	0.729	1.402	1.646	0.705	0.894	1.407	0.807
M_{2-}	0.497	4.549	4.096	2.364	4.790	5.114	3.613	2.222	3.381	1.897
C_{mm}	2.33	14.9	51.3	32.0	104.0	37.2	65.8	12.8	46.7	15.2
$C_{m\lambda}$	−1.04	−5.96	−27.0	−20.1	−62.2	−17.0	−38.1	−6.24	−24.0	−7.62
$C_{\lambda\lambda}$	10.1	20.1	150.0	128.0	339.0	53.8	179.0	24.5	109.0	33.4
$Q_{\beta\beta}$	4.272	2.039	2.995	3.350	3.034	2.017	2.814	2.287	2.527	2.457
$f_{\lambda m}$	4.344	1.349	2.917	4.002	3.256	1.446	2.723	1.913	2.324	2.191
$f^G_{\lambda m}$	6.536	1.650	3.467	4.345	3.628	1.685	3.197	2.171	2.639	2.516

The nuclear matrix elements are calculated within the quasiparticle random phase approximation with partial restoration of the isospin symmetry. The G-matrix elements of a realistic Argonne V18 nucleon-nucleon potential are considered [20]. The phase-space factors are taken from Štefánik et al. [21]. $f_{\lambda m} = C_{\lambda\lambda}/C_{mm}$, $f^G_{\lambda m} = G_{02}/G_{01}$ *and* $g_A = 1.269$ *is assumed.* $Q_{\beta\beta}$ *is the Q-value of the double beta decay in MeV.*

In **Table 1** the calculated NMEs are presented. The values of $M_{F,GT,T}$ and M_ν differ slightly (within 10%) with those given in Simkovic et al. [20], which were obtained without consideration of the closure approximation. By glancing **Table 1** we see that $M_{F\omega,GT\omega,T\omega} \simeq M_{F,GT,T}$ and $M_{\nu\omega} \simeq M_\nu$ as for the average neutrino momentum q = 100 MeV and used average energy of intermediate nuclear states we have $q/\left(q + \bar{E}_n - (E_i + E_f)/2\right) \simeq 1$. The absolute value of $M_{Fq,GTq,Tq}$ is smaller in comparison with $M_{F,GT,T}$ by about 50% for Fermi NMEs and by about factor two in the case of Gamow-Teller and tensor NMEs. From **Table 1** it follows that there is a significant difference between results of this work and the QRPA NMEs of Muto et al. [25], especially in the case of ^{100}Mo. This difference can be attributed to the progress achieved in the $0\nu\beta\beta$-decay formalism due to inclusion of higher order terms of nucleon currents [21, 24], the way of adjusting the parameters of nuclear Hamiltonian [27], description of short-range correlations [26] and restoration of the isospin symmetry [20].

Nuclear matrix elements M_{2^-}, M_{1^+} (λ mechanism) and M_ν ($m_{\beta\beta}$ mechanism) for 10 nuclei under consideration are given in **Table 1** and displayed in **Figure 1**. We note a rather good agreement between M_{2^-} and M_ν for all calculated nuclear systems. It is because the contribution of M_{1+} to M_{2-} is suppressed by factor 9 and as a result M_{2-} is governed by the $M_{\nu\omega}$ contribution (see Equation 14). Values of M_{1^+} exhibit similar systematic behavior in respect to considered nuclei as values of M_ν and M_{2^-}, but they are suppressed by about factor 2–3 (with exception of ^{48}Ca).

The importance of the $m_{\beta\beta}$ and λ mechanisms depends, respectively, not only on values of η_ν and η_λ parameters, which are unknown, but also on values of coefficients C_I (I = mm, $m\lambda$, $\lambda\lambda$), which are listed for all studied nuclei in **Table 1**. They have been obtained by using improved values of phase-space factors G_{0k} (k = 1, 2, 10 and 11) from Štefánik et al. [21]. We note that the squared value of M_{GT} and fourth power of axial-vector coupling constant g_A are included in the definition of coefficient C_I unlike

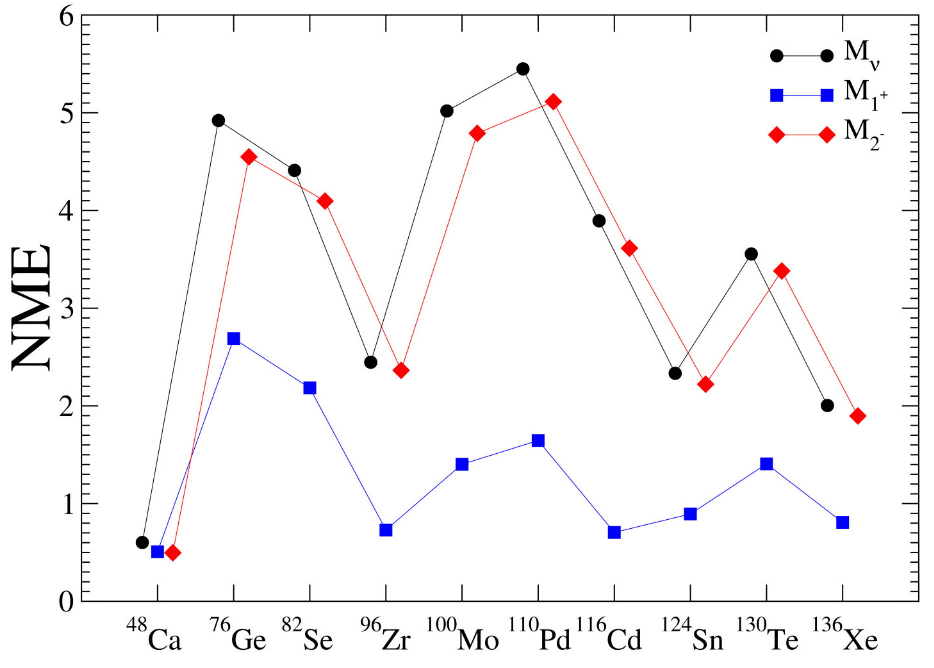

FIGURE 1 | A comparison of the nuclear matrix elements M_{1+}, M_{2-} (λ mechanism) and M_ν ($m_{\beta\beta}$ mechanism) of the $0\nu\beta\beta$-decay.

in Štefánik et al. [21]. We see that $C_{\lambda\lambda}$ is always larger when compared with C_{mm}. The absolute value of $C_{m\lambda}$ is significantly smaller than C_{mm} and $C_{\lambda\lambda}$. This fact points out on less important contribution to the $0\nu\beta\beta$-decay rate from the interference of $m_{\beta\beta}$ and λ mechanisms.

For 10 nuclei of experimental interest the decomposition of coefficient $C_{\lambda\lambda}$ (see Equation 11) on partial contributions C_I^{0k} associated with phase-space factors G_{0k} (k = 2, 10, and 11) is shown in **Figure 2**. By glancing the plotted ratio C_I^{0k}/C_I we see that $C_{\lambda\lambda}$ is dominated by a single contribution associated with the phase-space factor G_{02}. From this and above analysis it follows that $0\nu\beta\beta$-decay half-life to a good accuracy can be written as

$$\left[T_{1/2}^{0\nu}\right]^{-1} = \left(\eta_\nu^2 + \eta_\lambda^2 f_{\lambda m}\right) C_{mm} \simeq \left(\eta_\nu^2 + \eta_\lambda^2 f_{\lambda m}^G\right) g_A^4 M_\nu^2 G_{01} \quad (19)$$

with

$$f_{\lambda m} = \frac{C_{\lambda\lambda}}{C_{mm}} \simeq f_{\lambda m}^G = \frac{G_{02}}{G_{01}}. \quad (20)$$

For a given isotope the factor $f_{\lambda m}$ reflects relative sensitivity to the $m_{\beta\beta}$ and λ mechanisms and $f_{\lambda m}^G$ is its approximation, which does not depend on NMEs. The values $f_{\lambda m}$ and $f_{\lambda m}^G$ are tabulated in **Table 1** and plotted as function of $Q_{\beta\beta}$ in **Figure 3**. We see that $f_{\lambda m}$ depends only weakly on involved nuclear matrix elements (apart for the case of ^{48}Ca) what follows from a comparison of $f_{\lambda m}$ with $f_{\lambda m}^G$. The value of $f_{\lambda m}$ is mainly determined by the Q-value of double beta decay process. From 10 analyzed nuclei the largest value of $f_{m\lambda}$ is found for ^{48}Ca and the smallest value for ^{76}Ge. A larger value of $f_{\lambda m}$ means increased sensitivity to $m_{\beta\beta}$ mechanism in comparison to λ mechanism and vice versa.

Upper bounds on the effective neutrino mass $m_{\beta\beta}$ and right-handed current coupling strength η_λ are deduced from experimental half-lives of the $0\nu\beta\beta$-decay by using the coefficients C_{mm}, $C_{m\lambda}$ and $C_{\lambda\lambda}$ of **Table 1**. The maximum and the value on axis ($m_{\beta\beta} = 0$ or $\eta_\lambda = 0$) are listed in **Table 2**. The decays of ^{136}Xe and ^{76}Ge set the sharpest limit $m_{\beta\beta} \leq 0.13$ eV and 0.18 eV, and $\eta_\lambda \leq 1.7\ 10^{-7}$ and $3.1\ 10^{-7}$, respectively. These are more stringent than those deduced from other experimental sources.

It is well known that by measuring different characteristics, namely energy and angular distributions of two emitted electrons, it is possible to identify which of $m_{\beta\beta}$ and λ mechanisms is responsible for $0\nu\beta\beta$-decay [21, 23]. It might be achieved only by some of future $0\nu\beta\beta$-decay experiments, e.g., the SuperNEMO [37] or NEXT [38]. A relevant question is whether the underlying $m_{\beta\beta}$ or λ mechanism can be revealed by observation of the $0\nu\beta\beta$-decay in a series of different isotopes. In **Figure 4** this issue is addressed by an illustrative case of observation of the $0\nu\beta\beta$-decay of ^{136}Xe with half-life $T_{1/2}^{0\nu} = 6.86\ 10^{26}$ years, which can be associated with $m_{\beta\beta} = 50$ meV or $\eta_\lambda = 9.8\ 10^{-8}$. The $0\nu\beta\beta$-decay half-life predictions associated with a dominance of $m_{\beta\beta}$ and λ mechanisms exhibit significant difference for some nuclear systems. We see that by observing, e.g., the $0\nu\beta\beta$-decay of ^{100}Ge and ^{100}Mo with sufficient accuracy and having calculated relevant NMEs with uncertainty below 30%, it might be possible to conclude, whether the $0\nu\beta\beta$-decay is due to $m_{\beta\beta}$ or λ mechanism.

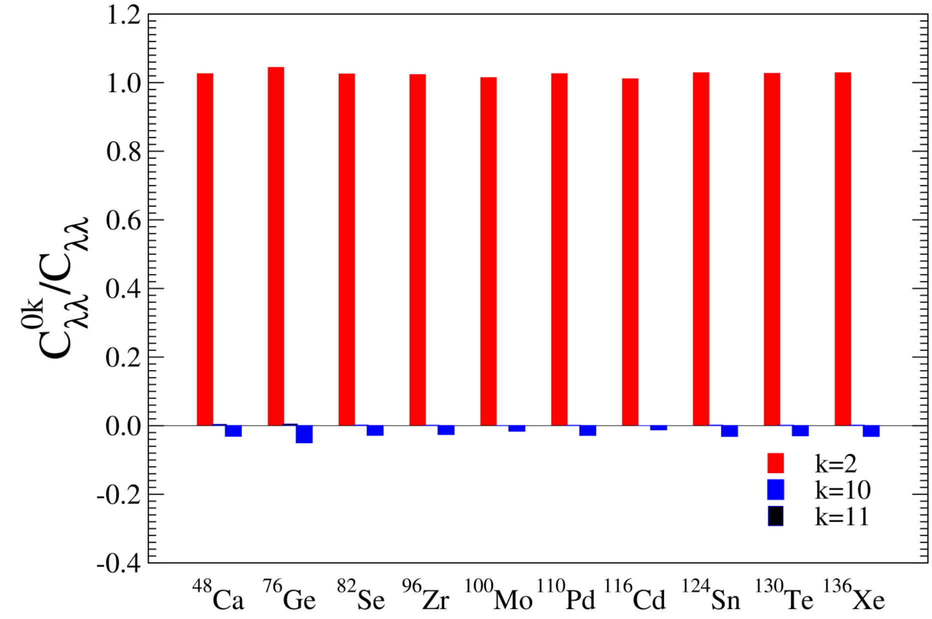

FIGURE 2 | The decomposition of coefficient $C_{\lambda\lambda}$ (see Equation 11) on partial contributions C_l^{0k} associated with phase-space factors G_{0k} (k = 2, 10 and 11) for nuclei of experimental interest. The partial contributions are identified by index k. The contributions from largest to the smallest are displayed in red, blue and black colors, respectively.

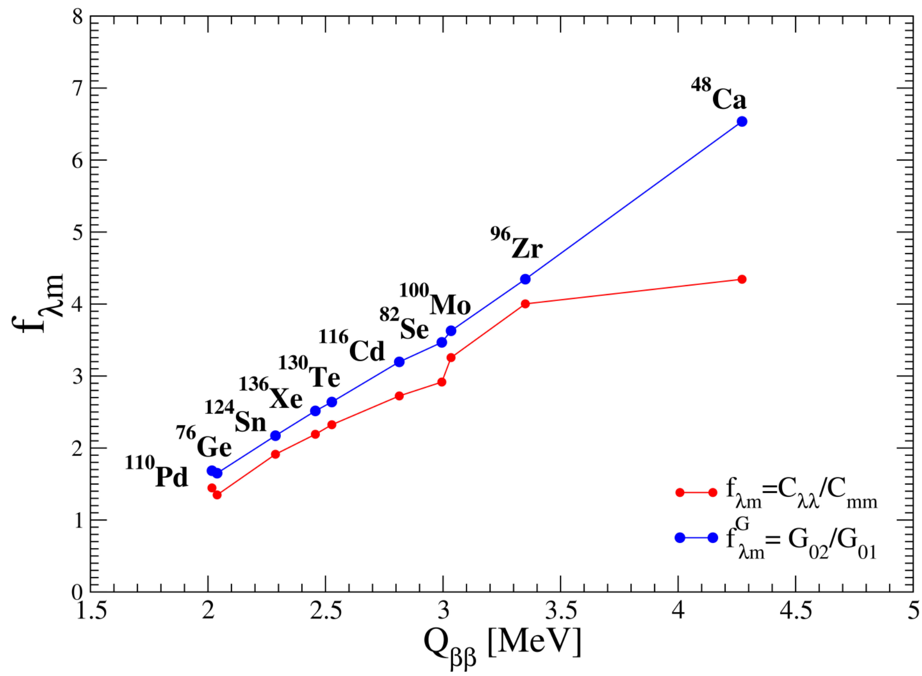

FIGURE 3 | The factor $f_{\lambda m}$ (see Equation 19) as function of Q-value of the double beta decay process ($Q_{\beta\beta}$) plotted from the numbers of **Table 1**.

Currently, the uncertainty in calculated $0\nu\beta\beta$-decay NMEs can be estimated up to factor of 2 or 3 depending on the considered isotope as it follows from a comparison of results of different nuclear structure approaches [3]. The improvement of the calculation of double beta decay NMEs is a very important and challenging problem. There is a hope that due to a recent progress in nuclear structure theory (e.g., ab initio methods) and increasing computing power the calculation of the $0\nu\beta\beta$-decay

TABLE 2 | Upper bounds on the effective Majorana neutrino mass $m_{\beta\beta}$ and parameter η_λ associated with right-handed currents mechanism imposed by current constraints on the $0\nu\beta\beta$-decay half-life for nuclei of experimental interest.

	^{48}Ca	^{76}Ge	^{82}Se	^{100}Mo	^{116}Cd	^{130}Te	^{136}Xe
$T_{1/2}^{0\nu-exp}$ [years]	$2.0\ 10^{22}$	$5.3\ 10^{25}$	$2.5\ 10^{23}$	$1.1\ 10^{24}$	$1.7\ 10^{23}$	$4.0\ 10^{24}$	$1.07\ 10^{26}$
Reference	[28]	[29]	[30]	[31]	[32, 33]	[34]	[35, 36]
$m_{\beta\beta}$ [eV]	23.8	0.185	1.45	0.484	1.55	0.379	0.128
η_λ	$2.24\ 10^{-5}$	$3.11\ 10^{-7}$	$1.65\ 10^{-6}$	$5.25\ 10^{-7}$	$1.84\ 10^{-6}$	$4.87\ 10^{-7}$	$1.70\ 10^{-7}$
				for $\eta_\lambda = 0$			
$m_{\beta\beta}$ [eV]	23.7	0.182	1.43	0.477	1.53	0.374	0.126
				for $m_{\beta\beta} = 0$			
η_λ	$2.23\ 10^{-5}$	$3.07\ 10^{-7}$	$1.63\ 10^{-6}$	$5.18\ 10^{-7}$	$1.81\ 10^{-6}$	$4.80\ 10^{-7}$	$1.67\ 10^{-7}$

The calculation is performed with NMEs obtained within the QRPA with partial restoration of the isospin symmetry (see ***Table 1****). The upper limits on $m_{\beta\beta}$ and η_λ are deduced for a coexistence of the $m_{\beta\beta}$ and λ mechanisms (Maximum) and for the case $\eta_\lambda = 0$ or $\eta_\nu = 0$ (On axis). $g_A = 1.269$ and CP conservation ($\psi = 0$) are assumed.*

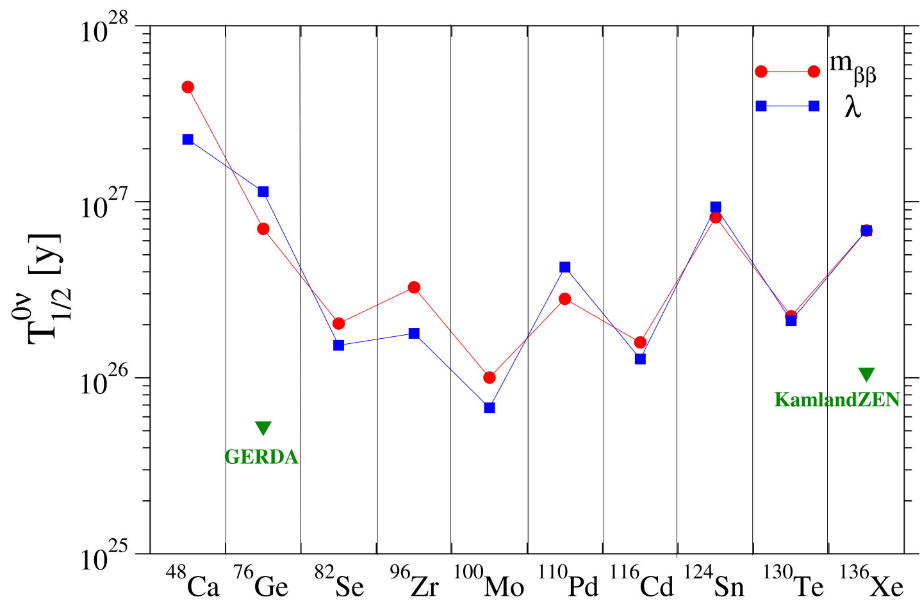

FIGURE 4 | The $0\nu\beta\beta$-decay half-lives of nuclei of experimental interest calculated for $m_{\beta\beta}$ (red circle) and λ (blue square) mechanisms by assuming an illustrative case of observation $0\nu\beta\beta$-decay of ^{136}Xe with half-life $T_{1/2}^{0\nu} = 6.86\ 10^{26}$ years ($m_{\beta\beta} = 50$ meV or $\eta_\lambda = 9.8\ 10^{-8}$). The current experimental limits on $0\nu\beta\beta$-decay half-life of ^{76}Ge (the GERDA experiment) and ^{136}Xe (the Kamland-Zen experiment) are displayed with green triangles.

NMEs with uncertainty of about 30 % might be achieved in future.

4. THE LEPTON NUMBER VIOLATING PARAMETERS WITHIN THE SEESAW AND NORMAL HIERARCHY

The 6 × 6 unitary neutrino mixing matrix $\mathcal{U}$ (see Equation 8) can be parametrized with 15 rotational angles and 10 Dirac and 5 Majorana CP violating phases. For the purpose of study different LRSM contributions to the $0\nu\beta\beta$-decay the mixing matrix $\mathcal{U}$ is usually decomposed as follows [22]

$$\mathcal{U} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix} \begin{pmatrix} A & R \\ S & B \end{pmatrix} \begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}. \quad (21)$$

Here, **0** and **1** are the 3×3 zero and identity matrices, respectively. The parametrization of matrices A, B, R and S and corresponding orthogonality relations are given in Xing [22].

If A = **1**, B = **1**, R = **0** and S = **0**, there would be a separate mixing of light and heavy neutrinos, which would participate only in left and right-handed currents, respectively. In this case we get $\eta_\lambda = 0$, i.e., the λ mechanism is forbidden.

If masses of heavy neutrinos are above the TeV scale, the mixing angles responsible for mixing of light and heavy neutrinos are small. By neglecting the mixing between different generations of light and heavy neutrinos, the unitary mixing matrix $\mathcal{U}$ takes the form

$$\mathcal{U} = \begin{pmatrix} U_0 & \frac{m_D}{m_{LNV}}\mathbf{1} \\ -\frac{m_D}{m_{LNV}}\mathbf{1} & V_0 \end{pmatrix}. \quad (22)$$

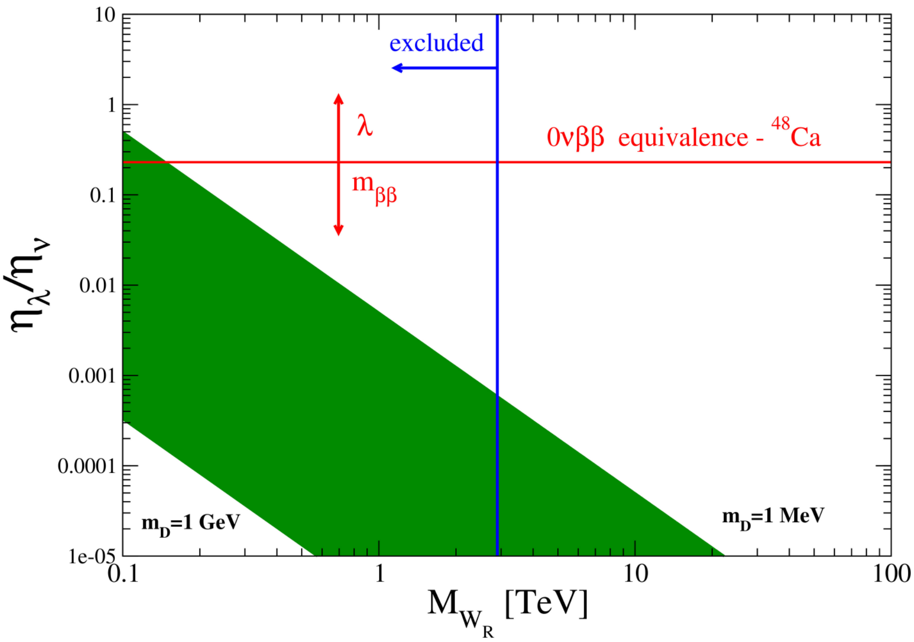

FIGURE 5 | The allowed range of values for the ratio η_λ/η_ν (in green) as a function of the mass of the heavy vector boson M_{W_R}. The line of the $0\nu\beta\beta$ equivalence corresponds to the case of equal importance of both $m_{\beta\beta}$ and λ mechanisms in the $0\nu\beta\beta$-decay rate.

Here, m_D represents energy scale of charged leptons and m_{LNV} is the total lepton number violating scale, which corresponds to masses of heavy neutrinos. We see that $U = U_0$ can be identified to a good approximation with the PMNS matrix and V_0 is its analogue for heavy neutrino sector. Due to unitarity condition we find $V_0 = U_0^\dagger$. Within this scenario of neutrino mixing the effective lepton number violating parameters η_ν ($m_{\beta\beta}$ mechanism) and η_λ (λ mechanism) are given by

$$\eta_\nu = \frac{m_D}{m_e}\frac{m_D}{m_{LNV}}\zeta_m, \quad \eta_\lambda = \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \frac{m_D}{m_{LNV}}\zeta_\lambda \tag{23}$$

with

$$\zeta_m = \left|\sum_{j=1}^{3} U_{ej}^2 \frac{m_j m_{LNV}}{m_D^2}\right|, \quad \zeta_\lambda = \left|\sum_{j=1}^{3} U_{ej}\right| = 0.14 - 1.5. \tag{24}$$

The importance of $m_{\beta\beta}$ or λ-mechanism can be judged from the ratio

$$\frac{\eta_\lambda}{\eta_\nu} = \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \frac{m_e}{m_D}\frac{\zeta_\lambda}{\zeta_m}. \tag{25}$$

It is naturally to assume that $\zeta_m \approx 1$ and to consider the upper bound for the factor ζ_λ, i.e., there is no anomaly cancellation among terms, which constitute these factors. Within this approximation η_λ/η_ν does not depend on scale of the lepton number violation m_{LNV} and is plotted in **Figure 5**. The Dirac mass m_D is assumed to be within the range 1 MeV $< m_D <$ 1 GeV. The flavor and CP-violating processes of kaons and B-mesons make it possible to deduce lower bound on the mass of the heavy vector boson $M_{W_2} > 2.9$ TeV [12]. From **Figure 5** it follows that within accepted assumptions the λ mechanism is practically excluded as the dominant mechanism of the $0\nu\beta\beta$-decay.

In this section the light-heavy neutrino mixing of the strength m_D/m_{LNV} is considered. However, we note that there are models with heavy neutrinos mixings where strength of the mixing decouples from neutrino masses [39–44]. This subject goes beyond the scope of this paper.

5. SUMMARY AND CONCLUSIONS

The left-right symmetric model of weak interaction is an attractive extension of the Standard Model, which may manifest itself in the TeV scale. In such case the Large Hadron Collider can determine the right-handed neutrino mixings and heavy neutrino masses of the seesaw model. The LRSM predicts new physics contributions to the $0\nu\beta\beta$ half-life due to exchange of light and heavy neutrinos, which can be sizable.

In this work the attention was paid to the λ mechanism of the $0\nu\beta\beta$-decay, which involves left-right neutrino mixing through mediation of light neutrinos. The recently improved formalism of the $0\nu\beta\beta$-decay concerning this mechanism was considered. For 10 nuclei of experimental interest NMEs were calculated within the QRPA with a partial restoration of the isospin symmetry. It was found that matrix elements governing the conventional $m_{\beta\beta}$ and λ mechanisms are comparable and that the λ contribution to the decay rate can be associated with a single phase-space factor. A simplified formula for the $0\nu\beta\beta$-decay half-life is presented (see Equation 19), which neglects the suppressed contribution from the interference of both mechanisms. In this expression the λ contribution to decay rate is weighted by the factor $f_{\lambda m}$, which reflects relative sensitivity to the $m_{\beta\beta}$ and λ mechanisms for a given isotope and depends only weakly on nuclear physics input. It is manifested that measurements of $0\nu\beta\beta$-decay half-life on multiple isotopes with largest deviation in the factor $f_{\lambda m}$ might allow to distinguish both considered mechanisms, if involved NMEs are known with sufficient accuracy.

Further, upper bounds on effective lepton number violating parameters $m_{\beta\beta}$ (η_ν) and η_λ were deduced from current lower limits on experimental half-lives of the $0\nu\beta\beta$-decay. The ratio η_λ/η_ν was studied as function of the mass of heavy vector boson M_{W_R} assuming that there is no mixing among different generations of light and heavy neutrinos. It was found that if the value of Dirac mass m_D is within the range 1 MeV $< m_D <$ 1 GeV, the current constraint on M_{W_R} excludes the dominance of the λ mechanism in the $0\nu\beta\beta$-decay rate for the assumed neutrino mixing scenario.

AUTHOR CONTRIBUTIONS

FŠ: calculation of nuclear matrix elements and preparation of manuscript; RD: analysis of lepton number violating parameters and preparation of manuscript; DŠ: derivation of the formalism of neutrinoless double beta decay, and analysis of obtained results.

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