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THE SuperNEMO EXPERIMENT AND LIGHT NEUTRINO EXCHANGE MECHANISMS OF THE $0\nu\beta\beta$-DECAY*

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The left–right symmetric models provide different mechanisms of the neutrinoless double beta decay ($0\nu\beta\beta$-decay) with left-handed and right-handed currents, which might be of comparable importance. A new generation of the $0\nu\beta\beta$-decay experiments with improved sensitivity is currently under design and construction. From them practically only the SuperNEMO experiment, which will employ tracking and calorimetry approach, will be able to distinguish among these mechanisms. In this contribution, the single electron energy distribution associated with light neutrino exchange mechanisms of the $0\nu\beta\beta$-decay of ^{48}Ca and ^{82}Se is presented and the sensitivity of the SuperNEMO *Demonstrator* and SuperNEMO experiment to various lepton number violating parameters is calculated.

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1. Introduction

The search for the total lepton number violating neutrinoless double-beta decay ($0\nu\beta\beta$-decay),

$$(A, Z) \to (A, Z + 2) + 2e^- , \quad (1)$$

represents the new frontiers of neutrino physics, allowing to clarify if the neutrino is a Dirac or a Majorana particle (as the only one of all the fermions), to fix the neutrino mass scale, possible CP violation effects and to probe energy scales above TeV.

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Currently, there are three running $0\nu\beta\beta$-decay experiments (GERDA, EXO, KamLAND-ZEN) and many next generation $0\nu\beta\beta$-decay experiments (CUORE, SNO+, Majorana, SuperNEMO) are in preparation or under consideration (AMoRE, NEXT, CANDLES, COBRA). These experiments utilize a variety of isotopes and detection techniques suitable for observing the $0\nu\beta\beta$-decay.

The SuperNEMO tracking-and-calorimetry experiment, in contrast to other experiments, will detect not only the total energy deposition, but other parameters of the process, including the energy of the individual electrons, angle between them, and the coordinates of the event in the source plane. The SuperNEMO detector will house 100 kg of isotopes. ^{48}Ca, ^{82}Se and ^{150}Nd are under consideration. With 20 detection modules observing for 5 years 100 kg of ^{82}Se, the expected sensitivity should reach $T^{0\nu}_{1/2} > 10^{26}$ yr competitive with others experiments. Currently, the SuperNEMO *Demonstrator* module is constructed, which will accommodate 7 kg of enriched isotope ^{82}Se. The expected sensitivity is of $T^{0\nu}_{1/2} > 6.6\ 10^{24}$ yr [1].

The aim of this contribution is to discuss light neutrino exchange mechanisms of the $0\nu\beta\beta$-decay for ^{48}Ca and ^{82}Se isotopes being motivated by the SuperNEMO experiment.

2. The $0\nu\beta\beta$-decay rate in the case of light neutrino exchange

The new physics beyond the Standard Model is motivated by theoretical considerations. The left–right symmetric theories provide a natural framework to understand the origin of light neutrino masses [2]. An important prediction of the left–right symmetry is the existence of right-handed neutrinos, which are absent in the SM. In general, one cannot predict the scale where the left–right symmetry is realized, but it is natural to assume that it is as low as $\sim$ a few TeV [3].

Recently, the $0\nu\beta\beta$-decay with the inclusion of right-handed leptonic and hadronic currents has been revisited by considering the 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 [4]. The main interest to light neutrino exchange mechanisms is because they can give a dominant contribution to $0\nu\beta\beta$-decay amplitude [4] (and references therein). By considering only the exchange of light neutrinos, the $0\nu\beta\beta$-decay half-life takes the form

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 \left|M_{GT}\right|^2 \left\{ C_{mm} \frac{\left|m_{\beta\beta}\right|^2}{m_e^2} + C_{m\lambda} \frac{\left|m_{\beta\beta}\right|}{m_e} \left\langle\lambda\right\rangle \cos\psi_1 + C_{\lambda\lambda} \left\langle\lambda\right\rangle^2 \right.$$
$$\left. + C_{m\eta} \frac{\left|m_{\beta\beta}\right|}{m_e} \left\langle\eta\right\rangle \cos\psi_2 + C_{\eta\eta} \left\langle\eta\right\rangle^2 + C_{\lambda\eta} \left\langle\lambda\right\rangle \left\langle\eta\right\rangle \cos\left(\psi_1 - \psi_2\right) \right\} . \quad (2)$$

The effective lepton number violating parameters and their relative phases are given by

$$|m_{\beta\beta}| = \left|\sum_{j=1}^{3} U_{ej}^2 m_j\right|, \ \langle\lambda\rangle = \lambda\left|\sum_{j=1}^{3} U_{ej} T_{ej}^* \left(g'_V/g_V\right)\right|, \ \langle\eta\rangle = \eta\left|\sum_{j=1}^{3} U_{ej} T_{ej}^*\right|,$$

$$\psi_1 = \arg\left[\sum_{i,j=1}^{3}\left(m_i U_{ei}^2\right)\left(U_{ej} T_{ej}^* \frac{g'_V}{g_V}\right)^*\right], \ \psi_2 = \arg\left[\sum_{i,j=1}^{3}\left(m_j U_{ej}^2\right)\left(U_{ej} T_{ej}^*\right)^*\right].$$

Here, $\lambda \simeq (M_{W_1}/M_{W_2})^2$ and $\eta \simeq -\tan\zeta$ (M_{W_1}, M_{W_2} and ζ are masses of light and heavy vector boson and W_L–W_R mixing parameter, respectively). U and T are the 3×3 matrices describing the mixing between light neutrinos and between light and heavy neutrinos, respectively.

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

$$\begin{aligned}
C_{mm} &= (1-\chi_F+\chi_T)^2 G_{01}\,,\\
C_{m\lambda} &= (\chi_F-\chi_T-1)\left[\chi_{2-}G_{03}-\chi_{1+}G_{04}\right],\\
C_{m\eta} &= (1-\chi_F+\chi_T)\left[\chi_{2+}G_{03}-\chi_{1-}G_{04}-\chi_P G_{05}+\chi_R G_{06}\right],\\
C_{\lambda\lambda} &= \chi_{2-}^2 G_{02}+\tfrac{1}{9}\chi_{1+}^2 G_{011}-\tfrac{2}{9}\chi_{1+}\chi_{2-}G_{010}\,,\\
C_{\eta\eta} &= \chi_{2+}^2 G_{02}+\tfrac{1}{9}\chi_{1-}^2 G_{011}-\tfrac{2}{9}\chi_{1-}\chi_{2+}G_{010}\\
&\quad +\chi_P^2 G_{08}-\chi_P\chi_R G_{07}+\chi_R^2 G_{09}\,,\\
C_{\lambda\eta} &= -2\left[\chi_{2-}\chi_{2+}G_{02}-\tfrac{1}{9}\left(\chi_{1+}\chi_{2+}+\chi_{2-}\chi_{1-}\right)G_{010}+\tfrac{1}{9}\chi_{1+}\chi_{1-}G_{011}\right].
\end{aligned} \quad (3)$$

The explicit form of phase-space factors G_{0k}, matrix element M_{GT} and ratios of matrix elements χ_I is given in [4].

3. Constraints on the effective lepton number violating parameters

The $0\nu\beta\beta$-decay half-life in Eq. (2) is exploited to constrain the three unknown total lepton number violating parameters ($m_{\beta\beta}$, $\langle\lambda\rangle$ and $\langle\eta\rangle$) for the case of half-life limits expected to be achieved by the SuperNEMO *Demonstrator* ($T_{1/2}^{0\nu} \geq 6.6\times 10^{24}$ yr) and SuperNEMO experiment ($T_{1/2}^{0\nu} \geq 10^{26}$ yr) [1] (see Table I). Two types of phase space factors are considered, namely those calculated with approximated (w.f. A, the lowest terms in expansion in coordinate r are considered) and exact electron wave functions (w.f. D) [4]. Nuclear matrix elements calculated within interacting shell-model ISM [6] and quasiparticle random phase approximation (QRPA) [7] are taken into account (see Table II). We note that the effect of the induced pseudoscalar term of hadron current has been not considered in any calculation of nuclear matrix elements associated with right-handed current mechanisms yet.

TABLE I

Upper bounds on the effective neutrino mass $m_{\beta\beta}$ and parameters $\langle\eta\rangle$ and $\langle\lambda\rangle$ associated with right-handed currents mechanisms imposed by the constraints on the $0\nu\beta\beta$-decay of ^{82}Se expected by the SuperNEMO *Demonstrator* ($T^{0\nu}_{1/2} \geq 6.6 \times 10^{24}$ yr) and SuperNEMO experiment $T^{0\nu}_{1/2} \geq 10^{26}$ yr) [1]. Nuclear matrix elements of interacting shell-model (ISM) and quasiparticle random phase approximation (QRPA) are considered (see Table II). CP conservation is assumed ($\psi_1 = \psi_2 = 0$). The previously commonly used approximated electron wave functions (w.f. A) [5] and screened exact finite-size Coulomb wave functions (w.f. D) are considered.

$T^{0\nu}_{1/2}$	6.6×10^{24} yr		1.0×10^{26} yr	
w.f.	A	D	A	D
		QRPA		
$\|m_{\beta\beta}\|$ [eV]	0.325	0.343	0.084	0.088
$\|m_{\beta\beta}\|$ [eV] (for $\langle\eta\rangle = \langle\lambda\rangle = 0$)	0.294	0.312	0.076	0.080
$10^9\langle\eta\rangle$	3.332	3.535	0.856	0.908
$10^9\langle\eta\rangle$ (for $\|m_{\beta\beta}\| = \langle\lambda\rangle = 0$)	3.040	3.249	0.781	0.835
$10^7\langle\lambda\rangle$	3.836	4.070	0.986	1.046
$10^7\langle\lambda\rangle$ (for $\|m_{\beta\beta}\| = \langle\eta\rangle = 0$)	3.799	4.035	0.976	1.037
		ISM		
$\|m_{\beta\beta}\|$ [eV]	0.512	0.539	0.132	0.138
$\|m_{\beta\beta}\|$ [eV] (for $\langle\eta\rangle = \langle\lambda\rangle = 0$)	0.461	0.488	0.118	0.126
$10^9\langle\eta\rangle$	8.308	8.605	2.134	2.211
$10^9\langle\eta\rangle$ (for $\|m_{\beta\beta}\| = \langle\lambda\rangle = 0$)	7.563	7.892	1.943	2.028
$10^7\langle\lambda\rangle$	6.037	6.395	1.551	1.643
$10^7\langle\lambda\rangle$ (for $\|m_{\beta\beta}\| = \langle\eta\rangle = 0$)	5.954	6.317	1.529	1.623

Different contributions to the $0\nu\beta\beta$-decay rate (2) are associated with different products of effective lepton number violating parameters $m_{\beta\beta}$, $\langle\lambda\rangle$ and $\langle\eta\rangle$, which values are unknown. The importance of these contributions depends also on values of C_{mm}, $C_{m\lambda}$, $C_{m\eta}$, $C_{\lambda\lambda}$, $C_{\eta\eta}$ and $C_{\lambda\eta}$ coefficients, which are a superposition of contributions C^{0k}_I associated with phase-space factors G_{0k} ($k = 1, \ldots, 11$). In Fig. 1, we show ratios C^{0k}_I/C_I for the $0\nu\beta\beta$-decay of ^{48}Ca and ^{82}Se and both sets of nuclear matrix elements. We note that coefficients C_{mm}, $C_{\lambda\lambda}$, $C_{\eta\eta}$, and $C_{m\eta}$ are dominated by a single contribution associated with a different phase-space factor. In the case of $C_{m\lambda}$ and $C_{\lambda\eta}$, there is a competition of mostly two contributions.

TABLE II

Nuclear matrix elements associated with light neutrino exchange mechanisms of the $0\nu\beta\beta$-decay of ^{48}Ca and ^{82}Se and calculated within interacting shell-model (ISM) [6] (the value of M_{GT} is taken from Ref. [8]) and the quasiparticle random phase approximation (QRPA) [7].

	^{48}Ca		^{82}Se	
	ISM	QRPA	ISM	QRPA
M_{GT}	0.670	1.000	2.260	2.847
χ_F	−0.148	−0.620	−0.108	−0.376
χ_{1+}	1.786	1.150	0.616	1.307
χ_{1-}	2.728	4.870	1.288	3.343
χ_{2+}	0.433	−0.121	0.633	0.263
χ_{2-}	0.820	1.332	0.916	1.148
χ_R	0.940	1.020	0.680	1.174
χ_P	0.085	−0.150	0.494	−0.176

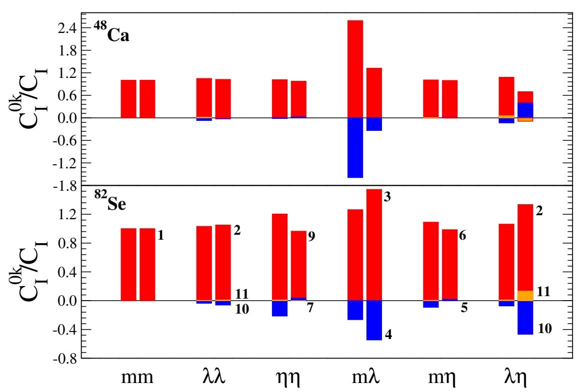

Fig. 1. (Color on-line) The decomposition of coefficients C_I ($I = mm$, $m\lambda$, $m\eta$, $\lambda\lambda$, $\eta\eta$ and $\lambda\eta$, see Eqs. (2) and (3)) on partial contributions C_I^{0k} associated with phase-space factors G_{0k} ($k = 1, \ldots, 11$). The symbols standing for index I are shown on the horizontal axis. The partial contributions are identified by index k, whose value is shown by the corresponding bar. The contributions from largest to the third largest are displayed in dark gray/red, black/blue and medium gray/orange colors, respectively. Ratios C_I^{0k}/C_I calculated with the ISM and QRPA matrix elements are presented with left and right bars for each value of index I, respectively. Results for ^{40}Ca and ^{82}Se are presented in the upper and lower panel, respectively. Phase factors calculated with w.f. D are considered [4].

4. Differential decay rates for limiting cases

The subject of interest is the single electron energy spectrum for the three limiting cases of lepton number violating mechanism since with the sufficient experimental accuracy one could distinguish between decays due to coupling to the left-handed and right-handed hadronic currents.

In Fig. 2, we present the single electron energy distribution for the $0\nu\beta\beta$-decay of ^{48}Ca and ^{82}Se normalized to the total decay rate. Three limiting cases are considered:

(i) Case $m_{\beta\beta} \neq 0(\langle\lambda\rangle = 0$ and $\langle\eta\rangle = 0)$;

(ii) Case $\langle\lambda\rangle \neq 0(m_{\beta\beta} = 0$ and $\langle\eta\rangle = 0)$;

(iii) Case $\langle\eta\rangle \neq 0$ $(m_{\beta\beta} = 0$ and $\langle\lambda\rangle = 0)$.

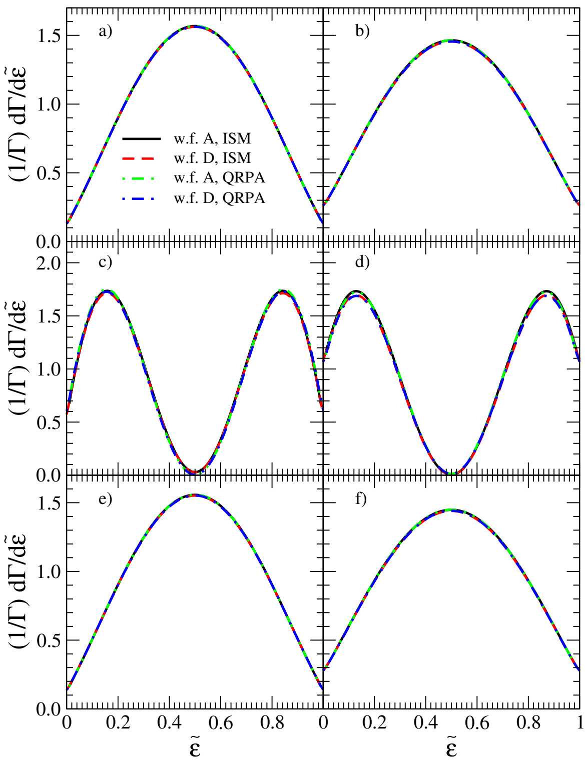

Fig. 2. The single electron differential decay rate normalized to the total decay rate *vs.* the electron energy $\tilde{\varepsilon}$ ($\tilde{\varepsilon} = (\varepsilon - m_e)/Q_{\beta\beta}$) for $0\nu\beta\beta$-decay of ^{48}Ca (left panels (a), (c) and (e)) and ^{82}Se (right panels (b), (d) and (f)). Results are presented for $|m_{\beta\beta}|^2$ (panels (a) and (b)); $\langle\lambda\rangle = \langle\eta\rangle = 0$), $|\langle\lambda\rangle|^2$ (panels (c) and (d)); $m_{\beta\beta} = \langle\eta\rangle = 0$), $|\langle\eta\rangle|^2$ (panels (e) and (f)); $m_{\beta\beta} = \langle\lambda\rangle = 0$) terms.

We see that the energy distribution of single electron for the $\langle\lambda\rangle$ mechanism differs significantly from those for $m_{\beta\beta}$ and $\langle\eta\rangle$ mechanisms. In addition, results depend only weakly on the type of electron wave function and considered nuclear matrix elements.

5. Conclusions

In summary, the light neutrino exchange contributions to the $0\nu\beta\beta$-decay of ^{48}Ca and ^{82}Se due to TeV-scale left–right symmetric model for type-I seesaw dominance were analyzed. The single electron differential decay rate normalized to the total decay rate was presented for a dominance of a single mechanism associated with $m_{\beta\beta}$, $\langle\lambda\rangle$ and $\langle\eta\rangle$ total lepton number violating parameters. It was shown that this quantity depends only weakly on the choice of electron wave functions and nuclear matrix elements (ISM or QRPA). By using the expected half-life limits to be achieved by the SuperNEMO *Demonstrator* and SuperNEMO experiment for the $0\nu\beta\beta$-decay of ^{82}Se and assuming a coexistence of all three mechanisms, we derived upper limits on $m_{\beta\beta}$, $\langle\lambda\rangle$ and $\langle\eta\rangle$, which are less stringent as those derived for the case of dominance of a single mechanism. Further, the importance of different phase-space factors in evaluation of six main contributions (mm, $\lambda\lambda$, $\eta\eta$, $m\lambda$, $m\eta$ and $\lambda\eta$) the $0\nu\beta\beta$-decay of ^{48}Ca and ^{82}Se was analyzed.

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REFERENCES

[1] A. Remoto, *Nucl. Part. Phys. Proc.* **265–266**, 67 (2015).

[2] J.C. Pati, A. Salam, *Phys. Rev. D* **10**, 275 (1974); R. Mohapatra, J.C. Pati, *Phys. Rev. D* **11**, 2558 (1975).

[3] G. Senjanovic, R.N. Mohapatra, *Phys. Rev. D* **12**, 1502 (1975).

[4] D. Štefánik, R. Dvornický, F. Šimkovic, P. Vogel, *Phys. Rev. C* **92**, 055502 (2015).

[5] M. Doi, T. Kotani, E. Takasugi, *Prog. Theor. Phys. Suppl.* **83**, 1 (1985).

[6] J. Retamosa, E. Caurier, F. Novacky, *Phys. Rev. C* **51**, 371 (1995); E. Caurier *et al.*, *Phys. Rev. Lett.* **77**, 1954 (1996).

[7] K. Muto, E. Bender, H.V. Klapdor, *Z. Phys. A* **334**, 187 (1989); K. Muto, E. Bender, H.V. Klapdor-Kleingrothaus, *Z. Phys. A* **339**, 435 (1991).

[8] E. Caurier, F. Nowacki, A. Poves, J. Retamosa, *Eur. Phys. J. A* **36**, 195 (2008).