Research Article

Constraints on Heavy Neutrino and SUSY Parameters Derived from the Study of Neutrinoless Double Beta Decay

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New constraints on the lepton number violating (LNV) parameters are derived from the analysis of the neutrinoless double beta ($0\nu\beta\beta$) decay in the hypothesis that this process would occur through the exchange of heavy neutrinos and/or SUSY particles. For derivation, we use new values of both phase space factors (PSFs) and nuclear matrix elements (NMEs) calculated with numerical codes developed recently, as well as the most recent experimental lifetimes. The NMEs are computed with a shell model (ShM) code for ^{48}Ca, ^{76}Ge, and ^{82}Se nuclei, while at present similar ShM results are available only for the first nucleus. We compare our results with similar ones from literature, obtained with ShM, QRPA, and IBM-2 methods, and conclude that more results are needed for a relevant analysis on the validity of NMEs associated with these decay mechanisms.

1. Introduction

Neutrinoless double beta ($0\nu\beta\beta$) decay is a beyond standard model (BSM) process by which an even-even nucleus transforms into another even-even nucleus with the emission of two electrons/positrons but no antineutrinos/neutrinos in the final states. Its study is important since it would clarify the question about the lepton number violation, decide on the neutrinos character (are they distinguished or not from their antiparticles?), and give a hint on the scale of their absolute masses. Moreover, the study of $0\nu\beta\beta$ decay has a broader potential to search for other BSM phenomena, such as new neutrino flavors and exotic particles. The great interest in understanding these fundamental issues has led to many theoretical and experimental investigations of this process. The reader can find up-to-date information on these studies in several recent reviews [1–6], which also contain therein a comprehensive list of references in the domain.

One of the open issues concerning the $0\nu\beta\beta$ decay is related to the possible mechanisms responsible for its occurrence. The exchange of a light Majorana neutrino in the presence of left handed (LH) weak interaction is still the most popular and studied mechanism. However, other mechanisms have also been considered, for example, the exchange of heavy neutrinos [7, 8] and SUSY particles [3, 9], which could also contribute to the total $0\nu\beta\beta$ decay rate. On the other hand, constraints on heavy neutrino and SUSY parameters can be now derived at hadron colliders, as well, by analyzing same sign dilepton decay channels, which are triggered by processes that violate the lepton number conservation by two units (like $0\nu\beta\beta$ decay). Indeed, the CMS, ATLAS, and LHCb experiments at LHC include now in their data analysis the search of such channels, and the first results were already reported [10–13]. Thus, complementary information that allows the constraint of various LNV parameters can also be obtained now from high-energy experiments.

For all mechanisms, the $0\nu\beta\beta$ lifetimes can be expressed in a good approximation as a product of a phase space factor, a nuclear matrix element related to the nuclear structure of the parent and daughter nuclei, and a LNV parameter related to the BSM mechanism considered. These three factors can be identified in (1) and (2) from the next section. Hence, to

extract reliable upper limits for the LNV parameters, we need accurate calculation of both PSFs and NMEs factors, as well as reliable measurements of the lifetimes.

The largest uncertainties in the theoretical calculations for double beta decay (DBD) arise from the calculated values of the NMEs. For the LH light neutrino exchange mechanism, the NMEs are currently computed by several methods, the present most employed ones being the proton-neutron quasi-random phase approximation (pnQRPA) [14–20], interacting shell model (ISM) [21–25], interacting boson model (IBM) [26–28], projected Hartree Fock Bogoliubov (PHFB) [29], and energy density functional (EDS) [30] methods. At present, there are still large discrepancies between the NMEs values computed with different methods and by different groups, which have been widely discussed in literature (see, e.g., [5, 6]) for the light neutrino exchange mechanism. At present, for heavy neutrino and SUSY exchange mechanisms, there are fewer NME calculations, performed with QRPA [31, 32] and IBA-2 [28] and ShM methods [33, 34]. The discrepancies between the existing NME values associated with heavy neutrino or SUSY mechanisms are even larger than those in the case of LH light neutrino exchange, so there is a need for new calculations.

In this paper, we report new constraints on the heavy neutrino and SUSY parameters derived from the analysis of the neutrinoless double beta decay of three experimentally interested nuclei, ^{48}Ca, ^{76}Ge, and ^{82}Se, in the hypothesis that this process would occur through the exchange of such particle. The computation of the NMEs is performed with a ShM code developed recently and presented in detail in [35, 36]. Also, we estimate the uncertainties introduced in calculations by the use of different NN interactions and SRC parameterizations and found that the calculated NME values depend significantly on these nuclear ingredients. We compare our results with other previous ones from literature performed with ShM, QRPA, and IBM-2 approaches and discuss the discrepancies. We remark that, until now, large scale ShM calculations of NMEs corresponding to these mechanisms are available only for ^{48}Ca, and they differ significantly from the IBM-2 calculations. In order to understand these discrepancies, more ShM calculations of the NMEs for these (less discussed) $0\nu\beta\beta$ decay mechanisms, including other nuclei, are needed.

The values of the PSFs are taken from our recent work [37], which are very close to those reported in [38, 39]. We mention that PSFs for DBD have been calculated since long time [40, 41], but they were less discussed, being considered to be computed with enough precision. Recently, they were recalculated with improved approaches [38, 39, 42] and several discrepancies were revealed as compared to the old calculations, which should be taken into account for accurate predictions of $0\nu\beta\beta$ lifetimes and derivation of LNV parameters.

The paper is organized as follows. In the next section, we present the formulae for the $0\nu\beta\beta$ decay lifetimes together with the relevant expressions for the PSFs and NMEs which have to be computed for deriving the LNV parameters, for heavy neutrino and SUSY mechanisms. In Section 3, we

present and discuss our results, while in the last section we formulate the conclusions of our work.

2. Formalism

In this section, we give a short description of the heavy neutrino and SUSY formalisms, displaying the PSF and NME formulas that have to be computed. As we already mentioned, the expressions of the $0\nu\beta\beta$ lifetimes can be written as a product of three terms: a phase space, a nuclear matrix elements, and a term related to the corresponding LNV mechanism:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left(Q_{\beta\beta}, Z\right) \sum_k \left(\left|M_k^{0\nu}\right|^2\right)(\eta_k)^2, \quad (1)$$

where k is an index which denotes the mechanisms that can contribute to the $0\nu\beta\beta$ decay. In this work, we refer to the heavy neutrino and SUSY exchange mechanisms, so the lifetime reads

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left(Q_{\beta\beta}, Z\right)\left(\left|M_N^{0\nu}\right|\langle\eta_N\rangle + \left|M_{\lambda'}^{0\nu}\right|\langle\eta_{\lambda'}\rangle \right. \\ \left. + \left|M_q^{0\nu}\right|\langle\eta_q\rangle\right)^2, \quad (2)$$

where $G^{0\nu}$ is the phase space factor for this decay mode, depending on the energy decay $Q_{\beta\beta}$ and nuclear charge Z. $M_{N,\lambda',q}^{0\nu}$ are the NMEs associated with the heavy neutrino (N) exchange mechanism and with the gluino (λ') and squark-neutrino (q) exchange mechanisms. The last mechanisms may appear in SUSY theories with R-parity violation [3]. $\eta_{N,\lambda',q}$ are the corresponding coupling parameters associated with these mechanisms.

For the $0\nu\beta\beta$ decay, the expression of the PSFs reads

$$G_{0\nu} = \frac{2}{4g_A^4 R^2 \ln 2} \int_{m_ec^2}^{T_0-m_ec^2} f_{11}^{(0)} w_{0\nu} d\epsilon_1, \quad (3)$$

where $f_{11}^{(0)}$ are the solutions of the Dirac equation and

$$w_{0\nu} = \frac{g_A^4 (G\cos\theta_C)^4}{16\pi^5}\left(m_ec^2\right)^2 \left(\hbar c^2\right)(p_1c)(p_2c)\epsilon_1\epsilon_2, \quad (4)$$

where g_A ($g_A = 1.25$) is the axial-vector coupling constant, $G = 1.16637 \times 10^{-5}$ GeV^{-2} is the Fermi constant, θ_C is the Cabbibo angle, m_e is the electron rest mass, while p_1, p_2 and ϵ_1, ϵ_2 are the electron momenta and energies, respectively. In (3), it is convenient to redefine the PSFs by a renormalization that eliminates the constant g_A and correlates (by dividing by $4R^2$, R the nuclear radius) the dimension of $G_{0\nu}$ with the NMEs which are dimensionless, such that the PSFs are expressed in [yr^{-1}].

Concerning the NMEs, their expressions can be written, in general, as a sum of three components:

$$M^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 \cdot M_F^{0\nu} - M_T^{0\nu}, \quad (5)$$

where $M_{GT}^{0\nu}$, $M_F^{0\nu}$, and $M_T^{0\nu}$ are the Gamow-Teller (GT), Fermi (F), and Tensor (T) components, respectively.

Due to the two-body nature of the transition operator, the NMEs can be expressed as a sum of products of two-body transition densities (TBTDs) and matrix elements of the two-body transition operators for two-particle states, shortly, two-body matrix elements (TBMEs) [35, 36]. Consider

$$M_\alpha^{0\nu} = \sum_{j_p j_{p'} j_n j_{n'} J_\pi} \text{TBTD}\left(j_p j_{p'}, j_n j_{n'}; J_\pi\right)$$

$$\times \left\langle j_p j_{p'}; J_\pi \left\| \tau_{-1} \tau_{-2} O_{12}^\alpha \right\| j_n j_{n'}; J_\pi \right\rangle, \tag{6}$$

where $|jj'; J^\pi\rangle$ represent the antisymmetrized two-particle states and O_{mn}^α are DBD transition operators ($\alpha = \text{GT}, F, T$). Since the NN effective interaction can be treated by means of a central (single-particle) potential, the NMEs can be conveniently calculated using Moshinsky's transformations between the relative and center of mass (CM) coordinates and the proper use of nuclear states in different coupling notations. The calculation of the matrix elements of these operators can be decomposed into products of reduced matrix elements within the spin and relative coordinates subspaces [21, 35]. The expressions of the two-body transition operators are

$$O_{12}^{\text{GT}} = \sigma_1 \cdot \sigma_2 H(r), \qquad O_{12}^F = H(r),$$

$$O_{12}^T = \sqrt{\frac{2}{3}} [\sigma_1 \times \sigma_2]^2 \cdot \frac{r}{R} H(r) C^{(2)}(\hat{r}), \tag{7}$$

where σ are the Pauli spin operators and $C^{(2)}(\hat{r})$ is the center of mass operator. The expressions for the neutrino potentials H_α in the case of heavy neutrino mechanisms are

$$H_\alpha(r) = \frac{2R}{\pi m_e m_p} \int_0^\infty j_k(qr) h_\alpha(q^2) q^2 dq, \tag{8}$$

where m_p is the proton mass and j_k ($k = 0$ for $\alpha = \text{GT}, F$, and $k = 2$ for $\alpha = T$) are the Bessel spherical functions. The expressions of h_α ($\alpha = \text{GT}, F, T$) are

$$h_F(q^2) = G_V^2(q^2), \tag{9}$$

$$h_{\text{GT}}(q^2) = \frac{G_A^2(q^2)}{g_A^2} \left[1 - \frac{2}{3} \frac{q^2}{q^2 + m_\pi^2} + \frac{1}{3} \left(\frac{q^2}{q^2 + m_\pi^2}\right)^2\right]$$

$$+ \frac{2}{3} \frac{G_M^2(q^2)}{g_A^2} \frac{q^2}{4m_p^2}, \tag{10}$$

$$h_T(q^2) = \frac{G_A^2(q^2)}{g_A^2} \left[\frac{2}{3} \frac{q^2}{q^2 + m_\pi^2} - \frac{1}{3} \left(\frac{q^2}{q^2 + m_\pi^2}\right)^2\right]$$

$$+ \frac{1}{3} \frac{G_M^2(q^2)}{g_A^2} \frac{q^2}{4m_p^2}, \tag{11}$$

where m_π is the pion mass and

$$G_M(q^2) = (\mu_p - \mu_n) G_V(q^2), \tag{12}$$

with $(\mu_p - \mu_n) = 4.71$. The expressions (9)–(11) include the following nuclear effects: (i) finite nucleon size (FNS) effects through the nucleon form factors G_A, G_V and (ii) higher order current (HOC) effects by the second and third terms in the h_{GT} expression and by the appearance of the h_T contribution.

The G_V and G_A form factors which take into account the finite size of the nucleons effect are

$$G_A(q^2) = g_A \left(\frac{\Lambda_A^2}{\Lambda_A^2 + q^2}\right)^2,$$

$$G_V(q^2) = g_V \left(\frac{\Lambda_V^2}{\Lambda_V^2 + q^2}\right)^2. \tag{13}$$

For the vector and axial coupling constants, the majority of calculations take $g_V = 1$ and the unquenched value $g_A = 1.25$, while the values of the vector and axial vector form factors are $\Lambda_V = 850$ MeV and $\Lambda_A = 1086$ MeV [1], respectively.

For the SUSY mechanisms, only the GT and T components of the $M^{0\nu}$ are contributing. For the gluino exchange mechanism (SUSY1), the radial neutrino potentials H_α have a similar form as that for the heavy neutrino mechanism (9), but with different h_α factors [3, 14]:

$$\mathcal{M}_{\lambda'}^{0\nu} = c^{1\pi} \left(M_{\text{GT}}^{1\pi} - M_T^{1\pi}\right) + c^{2\pi} \left(M_{\text{GT}}^{2\pi} - M_T^{2\pi}\right), \tag{14}$$

with

$$c^{1\pi} = -\frac{2}{9} \frac{\sqrt{2} f_\pi m_\pi^4}{m_p^3 m_e (m_u + m_d)} \frac{g_s F_P}{g_A^2},$$

$$c^{2\pi} = \frac{1}{18} \frac{f_\pi^2 m_\pi^4}{m_p^3 m_e (m_u + m_d)^2} \frac{g_s^2}{g_A^2}, \tag{15}$$

where m_π is the charged-pion mass, 139.6 MeV, $f_\pi = 0.668 m_\pi$ MeV, m_u and m_d are the up and down quark masses $(m_u + m_d) = 11.6$ MeV, $m_p = 938.27$ MeV, $m_e = 0.511$ MeV, $g_s = 13.4$, and $F_P \approx 4.41$ [3]. Computing the expressions from (15), we obtain $c^{1\pi} = -85.33$ and $c^{2\pi} = 365.72$. Consider

$$H_\alpha^{1\pi}(r) = -\frac{2R}{\pi} \int_0^\infty j_k(qr) h_\alpha^{1\pi}(q^2) dq,$$

$$H_\alpha^{2\pi}(r) = -\frac{4R}{\pi} \int_0^\infty j_k(qr) h_\alpha^{2\pi}(q^2) dq, \tag{16}$$

with

$$h_\alpha^{1\pi}(q^2) = \frac{G_A^2(q^2)}{g_A^2} \frac{q^4/m_\pi^4}{1 + q^2/m_\pi^2},$$

$$h_\alpha^{2\pi}(q^2) = \frac{G_A^2(q^2)}{g_A^2} \frac{q^4/m_\pi^4}{(1 + q^2/m_\pi^2)^2}. \tag{17}$$

For the squark-neutrino mechanism (SUSY2), H_α has an expression similar to the light neutrino mechanism:

$$H_\alpha(r) = \frac{2R}{\pi} \int_0^\infty j_k(qr) \frac{h_\alpha(q^2)}{q + \langle E \rangle} G_\alpha(q^2) q \, dq, \tag{18}$$

TABLE 1: $0\nu\beta\beta$ NMEs values for heavy neutrino mechanism and comparison to other results in the literature.

	No SRC	Jastrow	AV-18	CD-BONN
^{48}Ca (GXPF1A)	91.5	23.7	47.5	70.3
^{48}Ca (KB3G)	106.8	29.7	56.8	82.8
^{48}Ca [34]			52.9	75.5
^{48}Ca [28]		16.3	46.3	76.0
^{76}Ge (JUN45)	255.7	73.1	137.8	199.2
^{76}Ge [31][a], [32][b]		32.6[a]	233[b]	351[b]
^{76}Ge [28]		48.1	107	163
^{82}Se (JUN45)	237.3	66.1	126.9	184.5
^{82}Se [31][a], [32][b]		30.0[a]	226[b]	340[b]
^{82}Se [28]		35.6	84.4	132

The indices a and b are used to indicate different calculations performed by the Tubingen group.

TABLE 2: $0\nu\beta\beta$ NMEs values for SUSY1 mechanism and comparison to other results in the literature.

	No SRC	Jastrow	AV-18	CD-BONN
^{48}Ca (GXPF1A)	643.7.2	242.4	417.2	548.2
^{48}Ca (KB3G)	750.1	293.3	492.47	641.7
^{48}Ca [34]			453	618
^{48}Ca [43]	392	147		
^{76}Ge (JUN45)	1762.1	678.3	1156.2	1509.4
^{76}Ge [43][a], [32][b]	1831[a]	625[a]	587[b]	515[b]
^{82}Se (JUN45)	1628.0	612.8	1062.5	1393.5
^{82}Se [43][a], [32][b]	1667[a]	583[a]	574[b]	504[b]

The indices a and b are used to indicate different calculations performed by the Tubingen group.

where $\langle E \rangle$ is the energy used in the closure approximation and represents the average excitation energy of the states in the intermediate odd-odd nucleus that contribute to the decay. The h_α factors have in this case the following expressions [3, 14]:

$$h_{\text{GT},T} = -\frac{1}{6}\frac{m_\pi^2}{m_e(m_u + m_d)}\frac{q^2/m_\pi^2}{(1 + q^2/m_\pi^2)^2}. \qquad (19)$$

For computing the radial matrix elements $\langle nl|H_\alpha|n'l'\rangle$, we use the harmonic oscillator wave functions $\psi_{nl}(lr)$ and $\psi_{n'l'}(r)$ corrected by a factor $[1 + f(r)]$, which takes into account the SRCs induced by the nuclear interaction:

$$\psi_{nl}(r) \longrightarrow [1 + f(r)]\psi_{nl}(r). \qquad (20)$$

For the correlation function, we take the functional form

$$f(r) = -c \cdot e^{-ar^2}\left(1 - br^2\right), \qquad (21)$$

where a, b, and c are constants which have particular values in different parameterizations. In this work, we consider the Miller-Spencer (MS) [44], AV18 [45], and CD-Bonn [46, 47] parameterizations.

TABLE 3: $0\nu\beta\beta$ NMEs values for SUSY2 mechanism and comparison to other results in the literature.

$M^{0\nu}$	No SRC	Jastrow	AV-18	CD-BONN
^{48}Ca (GXPF1A)	65.1	46.4	65.0	70.0
^{48}Ca (KB3G)	72.9	51.8	72.9	78.6
^{48}Ca [34]			81.8	86.7
^{76}Ge (JUN45)	281.7	233.4	283.5	296.8
^{76}Ge [32]			594	612
^{82}Se (JUN45)	253.6	208.6	255.7	268.1
^{82}Se [32]			578	595

3. Numerical Results and Discussions

We calculate first the NMEs for the three nuclei, that is, ^{48}Ca, ^{76}Ge, and ^{82}Se, and the three mechanisms mentioned above, using the code described in detail in [35, 36]. For ^{48}Ca, we performed calculations with two different NN interactions, GXPF1A [51] and KB3G [52] interactions, while for the other two isotopes we used the JUN45 [53] NN interaction. In the case of ^{48}Ca, our model space includes the whole fp shell $f_{7/2}$, $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$, while, for ^{76}Ge and ^{82}Se, the model space is jj44, including the following orbitals $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$. For the nuclear parameters involved in calculations, we used the values mentioned in the previous section and, for the nuclear radius, $R = r_0 A^{1/3}$, we used $r_0 = 1.2\,fm$. The results are presented in Tables 1, 2, and 3. One can see that there are significant differences between the results when using different NN interactions and different SRC parameterizations. Indeed, especially for the short-range exchange mechanisms, as the heavy neutrino and gluino (SUSY1) ones, one expects the results to be sensitive to the NN interaction and to the type of SRC parameterizations. The uncertainties in the NME calculated values due to the use of different NN interactions are in the range of (10–16)%. The uncertainties due to the use of different SRC parameterizations are larger; sometimes differences between results are larger than 100%, especially when comparing the NME values obtained with MS [44] parameterizations with those obtained with softer parameterizations, such as AV18 [45] and CD-Bonn [46, 47]. Further, we compare our results with other similar ones found in literature. To the best of our knowledge, explicit values of NMEs calculated with large scale ShM approaches are reported only in [34] and for one nucleus, ^{48}Ca. Our results agree within ~10% with those from [34], for all three mechanisms. At this point, it is worth mentioning that the GT and tensor contributions in (5) must have a relative opposite sign, such that the adding of the tensor contribution decreases the $M^{0\nu}$ total value. Hence, one has to pay attention when applying formula (5) because the GT and tensor contributions can come out from numerical calculations with opposite signs. In this respect, we suspect that our NME values agree even better with those from [34]. For the other two isotopes, that is, ^{76}Ge and ^{82}Se, we compare our (ShM) results with QRPA [31, 32, 43] and IBM-2 [28] results. For the heavy neutrino and SUSY2 mechanisms, the differences between our NME values and NME values

TABLE 4: Upper limits for Majorana neutrino mass parameters together with the other components of the $0\nu\beta\beta$ decay halftimes: the experimental lifetimes lower limits, the phase space factors, and the nuclear matrix elements.

	$T_{exp}^{0\nu}$ [yr]	$G^{0\nu}$ [yr^{-1}]	$M_N^{0\nu}$	$M_{\lambda'}^{0\nu}$	$M_q^{0\nu}$	$\langle\eta_N\rangle$	$\langle\eta_{\lambda'}\rangle$	$\langle\eta_q\rangle$
^{48}Ca*	$5.8 \cdot 10^{22}$ [48]	$2.46E-14$	70.3	548.2	70	$2.42 \cdot 10^{-7}$	$3.10 \cdot 10^{-8}$	$2.42 \cdot 10^{-7}$
^{48}Ca†	$5.8 \cdot 10^{22}$ [48]	$2.46E-14$	82.8	641.7	78.6	$2.05 \cdot 10^{-7}$	$2.64 \cdot 10^{-8}$	$2.16 \cdot 10^{-7}$
^{76}Ge	$2.1 \cdot 10^{25}$ [49]	$2.37E-15$	199.2	1509.4	296.8	$0.14 \cdot 10^{-7}$	$0.19 \cdot 10^{-8}$	$0.10 \cdot 10^{-7}$
^{82}Se	$3.6 \cdot 10^{23}$ [50]	$1.01E-14$	184.5	1393.5	268.1	$0.58 \cdot 10^{-7}$	$0.76 \cdot 10^{-8}$	$0.40 \cdot 10^{-7}$

*Denotes GXPF1A [51] effective interaction and †KB3G [52] effective interaction.

calculated with QRPA and IBM-2 methods are significant, but they are similar (in magnitude) to those encountered usually in the case of light neutrino exchange mechanism. For the SUSY1 mechanism, our results compare differently with the QRPA results reported by Tuebingen group in [32, 43], the only ones found in literature. We note that the agreement is good when comparing with the results of [43], where the MS parameterizations of the SRCs are employed, and it is bad when comparing with those of [32], where AV18 and CD-Bonn parameterizations for SRCs are used. As a conclusion, it turns out that more results for the NMEs associated with heavy neutrino and SUSY mechanisms, performed with different methods and including more nuclei, are needed for a relevant analysis of their validity.

In Table 4, we present new upper limits for the LNV parameters associated with the studied $0\nu\beta\beta$ decay mechanisms, in the hypothesis of a single dominance mechanism. The PSFs values are taken from [37] and we mention that they are very close to PSF values reported in [38, 39]. The PSFs have been calculated since long time [40, 41] but they were less discussed, being considered to be computed with enough precision. Recently, they were recalculated with improved approaches, by using exact electron Dirac wave functions, taking into account the finite nuclear size and electron screening effects [38] and, in addition, a realistic Coulomb potential [39, 42], and differences/discrepancies were found in several cases between the old and the recent PSF values. For the three isotopes considered in this work, the new PSF values differ from older calculations (e.g., from those reported in [41, 54–56]) up to 10%, justifying hence their use in a precise derivation of LNV parameters. The uncertainties in NME values reflect on the precision of derivation the LNV parameters. According to the consensus agreed upon in literature that softer SRC parameterizations are indicated, we adopt the NME values calculated with the CD-Bonn parameterization and derive the LNV parameters for the three nuclei and the three mechanisms considered. These results are presented in Table 4. For derivation, we used the most recent results for the experimental lifetimes, reported in references indicated in parenthesis. For ^{48}Ca, our limits for the LNV parameters are close to those reported in [34], while for the other two nuclei they differ from other results from literature [28, 32, 34, 43], derived with NMEs values calculated with QRPA and IBM-2 methods. As we already mentioned, information on LNV parameters for the heavy neutrino mechanism can be now extracted, as well, from the data analysis of the same sign dilepton channels at the LHC experiments. Thus, we expect that complementary information from both low- and high-energy experiments could be used in the future for better constraining of the LNV parameters.

4. Conclusions

We report new constraints for the heavy neutrino and SUSY parameters derived from an analysis of $0\nu\beta\beta$ decay of three experimentally interesting nuclei, ^{48}Ca, ^{76}Ge, and ^{82}Se. To the best of our knowledge, for the last two isotopes, no other large scale ShM results for these mechanisms are available so far. For deduction of these parameters, precise values of the NMEs and PSFs which enter the lifetime formulae are needed, as well as accurate experimental measurements of the lifetimes. The NME calculations are performed with a recent ShM code described widely in [35, 36]. The PSFs are taken from our most recent calculations reported in [37]. For SUSY mechanisms, we discuss two mechanisms associated with possible R-parity breaking in SUSY theories, a short-range one with exchange of heavy Majorana neutrino and scalar SUSY particles (gluinos and squarks and/or neutralinos and selectrons) and a long-range one involving exchange of both heavy squarks and light Majorana neutrinos—"squark-neutrino" mechanism. First, we calculated the NMEs using different nuclear ingredients. For ^{48}Ca, we use two different NN interactions, GXPF1A and KB3G, and found differences between the results within 10%. Also, we performed the calculations using three different parameterizations for the SRCs and found a significant dependence of the results on the way the SRCs are introduced in calculations. Further, we compare our (ShM) results with similar results from literature. For ^{48}Ca, our results are in good agreement with the results from [34], for all three mechanisms. For the other two isotopes, ^{76}Ge and ^{82}Se, we compare our (ShM) NMEs with those computed by QRPA [31, 32, 43] and IBM-2 [28] methods. For the heavy neutrino and SUSY2 mechanisms, the differences between our results and the results from those references are significant but similar (up to a factor of two) to those encountered usually in literature in the case of light neutrino exchange mechanism. For the SUSY1 mechanism, our results compare differently with QRPA results, reported by Tuebingen group. There is a good agreement with the results from [43], when the MS SRC parameterization is employed, but the agreement is bad when comparing with the values from [32], when softer SRC parameterizations are employed. As a conclusion, it turns out that more results for the NMEs associated with these $0\nu\beta\beta$ decay mechanisms, alternative to the light neutrino exchange one, performed with different nuclear methods and including more nuclei,

are needed for a relevant analysis of their validity. Then, we derived upper limits of the LNV parameters associated with the three mechanisms, in the hypothesis of one single dominance mechanism, using NMEs values computed with CD-Bonn parameterization. Finally, it is worth noting that information on LNV parameters can now be provided by LHC experiments at CERN from the analysis of the same sign dilepton channels. Thus, there is now the possibility to gather complementary information from both low- and high-energy experiments and use it to better constrain LNV parameters.

Conflict of Interests

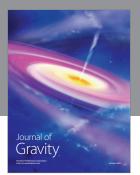The authors declare that there is no conflict of interests regarding the publication of this paper.

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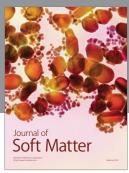
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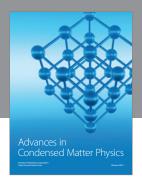
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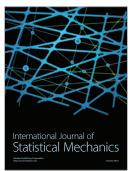[56] M. Doi and T. Kotani, "Neutrinoless modes of double beta decay," *Progress of Theoretical Physics*, vol. 89, pp. 139–159, 1993.