Brief Review of the Results Regarding the Possible Underlying Mechanisms Driving the Neutrinoless Double Beta Decay

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Since the experimental discovery of neutrino oscillations, the search for the neutrinoless double beta (0νββ) decay has intensified greatly, as this particular decay mode, if experimentally discovered, could offer a testing ground for Beyond Standard Model (BSM) theories related to the yet hidden fundamental properties of neutrinos and the possibility of violating of some fundamental symmetries. In this work we make a brief review of the nuclear matrix elements and phase space factors calculations performed mainly by our group. Next, using these calculations and the most recent experimental half-life limits, we revise the constraints on the BSM parameters violating the lepton number corresponding to four mechanisms that could contribute to 0νββ decay. Finally, using the values obtained for the BSM parameters from one of the most sensitive double-beta decay experiments, we provide a comparison with the sensitivities of other experiments.

Keywords: double beta decay, nuclear matrix elements, phase-space factors, shell model, beyond standard model, neutrino

1. INTRODUCTION

Two decades ago, the successful experimental measurement of neutrino oscillations [1, 2] established that neutrinos have a mass different from zero. Although this discovery was a significant one, many of the neutrino properties still remain unknown to this day. Because in neutrino oscillation experiments only squared mass differences can be measured, we still have unanswered questions regarding their absolute masses, the mass hierarchy, the underlying mechanism that gives neutrinos mass, and even the very nature of the neutrinos (whether they are Dirac or Majorana particles). While there are many experimental and theoretical endeavors to bring clear answers to some of these questions, like high-precision calculations, measurements of different single-β decays, cosmological observations, the double-beta decay (DBD) and particularly the 0νββ decay mode are still considered the most appealing approaches to study the yet unknown properties of neutrinos. However, even if one 0νββ transition event would be experimentally observed, not all of the desired information about neutrinos would be immediately revealed. Recording such an event would demonstrate that the lepton number conservation is violated by two units, but cannot indicate the mechanism that dominates this process. Many large-scale experiments dedicated to the discovery of this lepton number violating (LNV) decay are already collecting data, with up-dates and new ones planned for the future, but so far there is...
no experimental proof of $0\nu\beta\beta$ transitions, only reports of lower limits for the corresponding half-lives. Experimentally, DBD of the isotopes $^{76}\text{Ge}$ and $^{136}\text{Xe}$ are currently the most accurately measured, but others like $^{48}\text{Ca}$, $^{82}\text{Se}$, and $^{130}\text{Te}$ are also investigated, with $^{134}\text{Sn}$ being considered for the future. There are advantages and disadvantages to studying each of these isotopes (costs, purity, $Q$-value, background signals, etc.), but the fact that different ones are being investigated is of great importance if an experimental confirmation is obtained for any of them. Theoretical studies of $0\nu\beta\beta$ involve the computation of nuclear matrix elements (NME) and phase space factors (PSF) appearing in the half-life expressions, whose precise calculation is essential for predicting the neutrino properties and interpretation of the DBD experimental data. Particularly, the NME computation is the subject of the largest uncertainties, so much effort is devoted to their accurate estimation. The most commonly used nuclear structure approaches for the NME calculation are proton-neutron Quasi Random Phase Approximation (pnQRPA) [3–11], Interacting Shell Model (ISM) [12–30], Interacting Boson Model (IBM-2) [31–35], Projected Hartree Fock Bogoliubov method (PHFB) [36], Energy Density Functional method (EDF) [37], and the Relativistic Energy Density Functional method (REDF) [38]. Each of these methods presents various advantages and disadvantages when compared to each other, especially when dealing with the nuclear structure of particular isotopes. Once experimentally confirmed, it is also important to establish the underlying mechanism(s) that may contribute to the $0\nu\beta\beta$ decay, as to properly extend the Standard Model. For the longest time, studies only addressed the so called “mass mechanism” that involves the exchange of light left-handed (LH) Majorana neutrinos. Presently, more scenarios are being considered and their investigation consists of calculating of the NME associated to each mechanism and the corresponding PSF. Other contributions from possible RH components of the weak currents has also been discussed (for example in [40, 51]), but very few papers presented theoretical results considering these contributions. However, any mechanism/scenario that violates with two units the lepton number conservation may, in principle, contribute to the decay rate. Considering several mechanisms, the $0\nu\beta\beta$ decay half-life can be written in a factorized compact form, as a sum of products of PSF, NME, and the BSM parameters, corresponding to each mechanism [52], as follows:

$$\left[ T_{1/2}^{0\nu\beta\beta} \right]^{-1} = g_A^4 \sum_{i} \left| E_i \right|^2 \mathcal{M}_i^2 + Re \sum_{i \neq j} E_i E_j \mathcal{M}_{ij}. $$ \hspace{1cm} (1)

Here, the $E_i$ contain the BSM parameters associated with the following mechanisms: $E_1 = E_{0\nu} = \sum_{k}^{\text{light}} U_{ek}^2 m_k^2 m_w^2 \eta_k$ the exchange of light LH neutrinos, $E_2 = E_{\lambda} = \left( m_{\text{WLR}} \right)^2 \sum_{k}^{\text{RH}} U_{ek} V_{ek}$ corresponds to the “$\lambda$ mechanism” with RH leptonic and LH hadronic currents, $E_3 = E_{\eta} = \left( m_{\text{WLR}} \right)^2 \sum_{k}^{\text{heavy}} U_{ek} V_{ek}$ is associated to the “$\eta$ mechanism” with RH leptonic and RH hadronic currents, and $E_4 = E_{0\eta} = \left( m_{\text{WLR}} \right)^4 \sum_{k}^{\text{heavy}} V_{ek}^2 m_p m_k m_w \sum_{j}^{\text{heavy}} \mathcal{M}_{kj}$ comes from the exchange of heavy RH neutrinos, with $m_w$ being the electron mass and $m_p$ the proton mass. $M_{WLR}$ and $M_{WBR}$ denote the masses of the LH and the RH W bosons, respectively. We assume that the neutrino mass eigenstates are separated as light, $m_{\text{LR}}(m_{\text{LR}} \ll 1 \text{ eV})$, and heavy, $M_{\text{LR}}(M_{\text{LR}} \gg 1 \text{ GeV})$. $U_{ek}$ and $V_{ek}$ are electron neutrino mixing matrices for the light LH and heavy RH neutrino, respectively [14, 44]. Following [4–6, 39, 46], $\mathcal{M}_i^2$ are factors expressed in a standardized form as combinations of NME described in Equation (2) and integrated PSF denoted with $G_{01} - G_{09}$. Values for the PSF used in this paper can be seen in Table 1, together with our ShM values for the individual NME $M_{\alpha}$ (with $\alpha = GTq, Fq, Tq, GT\omega, F\omega, P, R, M_{\text{GTN}}, M_{\text{EN}}, \text{and } M_{\text{TAY}}$). Assuming that only one mechanism dominates the $0\nu\beta\beta$ transition, we can perform a so called “on-axis” analysis where the interference terms $E_i E_j \mathcal{M}_{ij}$ are no longer taken into account.

$$\mathcal{M}_{0\nu}^2 = G_{01} \left[ M_{\text{GT}} - \left( \frac{g_{\nu}}{g_A} \right)^2 M_{E} + M_{T} \right]^2, \hspace{1cm} (2a)$$

$$\mathcal{M}_{0\eta}^2 = G_{01} \left[ M_{\text{GTN}} - \left( \frac{g_{\nu}}{g_A} \right)^2 M_{F} + M_{T} \right]^2, \hspace{1cm} (2b)$$

$$\mathcal{M}_{\lambda}^2 = \frac{2}{9} G_{03} M_{1-} M_{2+} + \frac{1}{9} G_{04} M_{1-}^2 - G_{07} M_{p} M_{R} + G_{08} M_{p}^2 + G_{09} M_{R}^2, \hspace{1cm} (2c)$$

Table 1
TABLE 1 | In the upper part we present the $Q_{\beta\beta}$ values and the calculated PSF ($G_{11}$ – $G_{00}$) in years$^{-1}$ for all five isotopes currently under investigation.

| Isotope | $Q_{\beta\beta}$ (MeV) | $G_{11}$ | $G_{00}$ |
|---------|------------------------|----------|----------|
| $^{48}$Ca | 4.272/4.271 | 2.039/2.041 | 2.995/3.005 |
| $^{76}$Ge | 10.14 | 0.24/0.26 | 1.01/1.15 |
| $^{82}$Se | 16.2/17.1 | 0.39/0.43 | 3.53/4.04 |
| $^{130}$Te | 18.9/19.8 | 1.30/1.44 | 6.91/7.82 |
| $^{136}$Xe | 5.33/5.55 | 0.47/0.51 | 2.14/2.39 |

The $s$-wave electron PSF ($G_{11}$) are from [40] and the $p$-wave electron PSF ($G_{00}$ – $G_{00}$) are from [49] on the left side of each column, while the older, less rigorous values with the point-like formalism of [40] are on the right side for comparison. The lower part shows the $M_n$ NME calculated by our group.

$$M_n^2 = G_{02}M_{2-}^2 - \frac{2}{9} G_{03}M_{1+}M_{2-} + \frac{1}{9} G_{04}M_{2+}^2, \quad (2d)$$

with $M_{1\pm} = M_{GTq} \pm \left( \frac{4\nu}{\xi A} \right)^2 M_{Eq} - 6M_{Tq}$,

and $M_{2\pm} = M_{GT\omega} \pm \left( \frac{4\nu}{\xi A} \right)^2 M_{F\omega} - \frac{1}{9} M_{1\pm}$.

Detailed equations of individual NME $M_n$ can be found in the Appendix of [46], where they have been expressed in a consistent form. The expressions for the PSF can be found in [47, 49]. We note that Equations (2a, 2b) contain combinations of NME and PSF coming from contributions of only $s$-wave electron wave functions, while Equations (2c, 2d) present combinations of NME and PSF with contributions only from $p$-wave electron wave functions.

To use the expressions in Equation (2), we need accurate calculations of both the PSF that embed the distortion of the motion of outgoing electrons by the electric field of the daughter nucleus, and of the NME that depend on the nuclear structure of the parent and the daughter nuclei. Thus, the theoretical investigation of $0\nu\beta\beta$ transitions is a complex task that involves knowledge of physics at the atomic level for the PSF, nuclear level when calculating the NME, and at the fundamental particle level dealing with the LNV couplings.

### 2.1. Phase Space Factors

For a long time, PSF that enter the $\beta\beta$ half-life equations were considered to be calculated accurately enough [40, 53]. However, more recent reevaluations of their values using methods that use improved Fermi functions and more accurate integration routines have shown relevant differences in several cases, when compared to the previous results. Within these new methods of PSF calculation, the Fermi functions are constructed with “exact” electron wave functions (w.f.) obtained by solving the Dirac equation and consider finite nuclear size (FNS) and screening effects [47–49, 54]. In addition, in [47, 48] a Coulomb potential built from a realistic proton distribution in the daughter nucleus is used and the most recent $Q$-values [55] are taken into account.

In the upper part of Table 1, we present our choice of values for the nine PSF that enter Equation (2) for the five nuclei of interest. The PSF values obtained with $s$-electron w.f. ($G_{11}$) are taken from [48], while the PSF values obtained with the $p$-electron w.f. ($G_{00}$ – $G_{00}$) are from [49]. Both references provide consistently very similar values for the PSF needed in this study. Also, these current PSF values are compared to the previous calculations of [40] that relied on older $Q_{\beta\beta}$ values and where the proton distribution in the daughter nucleus, FNS, or electron screening effects were not considered. This comparison is meant to emphasize the need to use the results of newer calculations for more reliable analyzes.
### Table 2 | The first line shows the experimental lower half-life limits $T_{1/2}$ in years.

|        | $^{48}$Ca | $^{76}$Ge | $^{82}$Se | $^{130}$Te | $^{136}$Xe |
|--------|-----------|-----------|-----------|-----------|-----------|
| $T_{1/2}$ | 2.0 · $10^{22}$ [61] | 1.8 · $10^{26}$ [50] | 2.5 · $10^{23}$ [62] | 4.0 · $10^{24}$ [63] | 1.07 · $10^{26}$ [64] |
| $\mathcal{M}_{0
u}^2$ | 2.62 | 3.13 | 11.8 | 5.29 | 4.43 |
| $\mathcal{M}_{0
nu}^2$ | 1.14 | 0.44 | 3.74 | 1.29 | 1.04 |
| $\mathcal{M}_{0\nu}^2$ | 1.57 | 1.55 | 5.56 | 4.09 | 3.45 |
| $\mathcal{M}_{0\nu\nu}^2$ | 1.79 | 0.96 | 3.53 | 2.44 | 1.99 |
| $\mathcal{E}_0$ | 2.71 · $10^{-6}$ | 2.61 · $10^{-7}$ | 3.61 · $10^{-6}$ | 1.35 · $10^{-6}$ | 2.85 · $10^{-7}$ |
| $\mathcal{E}_e$ | 1.3 · $10^{-6}$ | 2.21 · $10^{-7}$ | 2.03 · $10^{-6}$ | 8.62 · $10^{-7}$ | 1.86 · $10^{-7}$ |
| $\mathcal{E}_g$ | 1.11 · $10^{-7}$ | 1.18 · $10^{-9}$ | 1.66 · $10^{-8}$ | 4.85 · $10^{-9}$ | 1.02 · $10^{-9}$ |
| $\mathcal{E}_{2N}$ | 3.28 · $10^{-7}$ | 4.71 · $10^{-9}$ | 6.6 · $10^{-8}$ | 1.99 · $10^{-8}$ | 4.24 · $10^{-9}$ |
| $m_{0
nu}$ (in units of keV) | 13.85 | 0.133 | 1.845 | 0.69 | 0.146 |
| $T_{0
nu} \cdot 10^{-26}$ | 2.15 | 1.0 | 0.48 | 1.07 | 1.27 |
| $T_{0\nu} \cdot 10^{-26}$ | 0.69 | 1.80 | 0.21 | 0.61 | 0.75 |
| $T_{0\nu\nu} \cdot 10^{-26}$ | 1.78 | 1.80 | 0.50 | 0.68 | 0.81 |
| $T_{0\nu\nu\nu} \cdot 10^{-26}$ | 0.97 | 1.80 | 0.49 | 0.71 | 0.87 |

In the upper part, we present the $\mathcal{M}_{0\nu}^2$ factors of Equation (2) using the NME and PSF from Table 1. Displayed in the middle section are the values of the LNV parameters $\mathcal{E}_\nu$ that can be extracted and the corresponding light left-handed Majorana neutrino mass $m_{0\nu}$. In units of eV. In the lower part, we estimate the $\mathcal{E}_{2N}$ that are expected for all the 5 isotopes when the LNV parameters of $^{76}$Ge are used in Equation (1).

### 2.2. Nuclear Matrix Elements

We choose our NME values from [46]. These were calculated using ShM techniques in the closure approximation with optimal closure energies ($\mathcal{E}$) taken from [21, 23, 26]. These values were found to reproduce the NME results obtained in non-closure calculations. The Hamiltonians specific for each model space are chosen such that good agreements with experimental spectroscopic observables is achieved. The testing of these Hamiltonians can be found in [27, 28], where we performed calculations of $\nu\nu\beta\beta$ NME, the energy spectra for the first $[0^+ - 6^+]$ states, $B(2\nu\beta\nu)$ transition probabilities, occupation probabilities and the Gamow-Teller strengths, which were compared to the experimental data available. For $^{48}$Ca in the $pf$ model space ($0f_{7/2}, 1p_{3/2}, 0j_{5/2}, 1p_{1/2}$) we use the GXPF1A [56] effective Hamiltonian and ($\mathcal{E}$) 0.5 MeV, for $^{76}$Ge and $^{82}$Se in the $jj44$ model space ($0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2}$) we choose the JUN45 [57] effective Hamiltonian and ($\mathcal{E}$) 3.4 MeV, and for $^{130}$Te and $^{136}$Xe in the $jj55$ model space ($0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 1s_{1/2}, 0h_{11/2}$) we use the SVD [58] effective Hamiltonian and ($\mathcal{E}$) 3.5 MeV. For the calculation of our two-body NME, we use finite size effects and higher order corrections of the nucleon current (with the vector and axial-vector form factors $\Lambda_V = 850$ MeV and $\Lambda_A = 1086$ MeV, respectively), and we include short-range correlations by multiplying the harmonic oscillator wave functions $\psi_n(r)$ and the Jastrow correlation function $\psi_\eta(r) \rightarrow [1 + f(r)] \psi_\eta(r)$ with the CD-Bonn parametrization ($f(r) = -c \cdot e^{-a r^2}$, with $a = 1.59, b = 1.45, c = 0.46$ [19, 27–29]).

The lower part of Table 1 shows the ShM individual NME that enter Equation (2) which were calculated by our group using the effective Hamiltonians and ingredients listed above. In the values presented, the sign convention is that the Gamow-Teller NME $M_{GT}$ is taken positive, with the other contributions having their sign listed as relative to that of $M_{GT}$.

### 3. DISCUSSIONS

This brief review summarizes our recent calculations of the PSF and NME involved in $0\nu\beta\beta$ decay for four possible decay mechanisms, namely the light LH neutrino exchange, heavy RH neutrino exchange, $\lambda-$mechanism involving RH leptonic and RH hadronic currents, and the $\eta-$mechanism involving RH leptonic and LH hadronic currents. The PSF are calculated with Fermi functions built with exact electron w.f. solutions of the Dirac equation with a Coulomb-type potential obtained from a realistic distribution of protons in the daughter nucleus. FNS and screening effects were taken into account, as well. $G_{0\nu}$ that include s-w.f. are taken from [48], while $G_{0\nu-0\nu}$ that include p-w.f. are taken from [49]. Between the newer and the older PSF values, one can observe numerous differences in the range of 5–30%, with some rising of up to 90% (see $G_{0\nu}$ of $^{136}$Xe in Table 1). Such differences would impact the LNV values and the conclusions regarding the sensitivity of the experiments with various isotopes to the possible $0\nu\beta\beta$ mechanisms. In passing, we mention that in addition to the development of the new PSF codes, our group has also developed a very fast effective method [59] that is still based on the formalism of [40], but is fitted and tweaked to replicate the current results obtained with the most rigorous methods. Within reasonable precision, this method can be used for rapid PSF estimations and for plotting the un-integrated angular and energy electron distributions.

The NME are calculated within a ShM approach with the ingredients presented in section 2.2. ShM calculations are attractive because they consider all the correlations around the Fermi surface, respect all symmetries, and take into account consistently the effects of the missing single particle space via many-body perturbation theory (the effects were shown to be small, about 20%, for $^{82}$Se [60]). In the case of closed-shell nuclei, ShM calculations using optimized Hamiltonians...
for nucleon-nucleon interactions are very reliable and compare well with the spectroscopic data available from experiments. Another advantage of this approach, important for reliable calculations, is that the calculated nucleon occupancies are close to the experimental ones. ShM calculations were successful in predicting the $\nu\nu\beta\beta$ decay half-life of $^{48}$Ca [12] before experimental measurements. Calculations of different groups largely agree with each other without the need to adjust model parameters.

From Equation (2), using the NME and PSF in Table 1, we calculate the $M^2_i$ factors that enter the half-life in Equation (1). Using these factors and the most recent experimental half-life limits, we re-evaluate the LNV parameters corresponding to the four mechanisms. These results are presented in Table 2.

Table 2 first presents in the top section the experimental lower half-life limits $T_{1/2}$ in years. The next rows list the $M^2_i$ factors that contain combinations of PSF and NME for the five nuclei of current experimental interest, in the case of four possible $\nu\nu\beta\beta$ decay mechanisms described in Equation (2). In the middle section are found the values of the LNV parameters $E_\nu$ deduced from the experimental $T_{1/2}$ and the $M^2_i$ factors. For the mass mechanism, we also show the electron neutrino mass parameters $\langle m_0 \rangle_i$ in units of eV that are obtained by the multiplication of $E_\nu$ with the electron mass $m_e$. This extracted $\langle m_0 \rangle_i$ is what is most commonly reported in the literature and is presented here for the convenience of the reader and an easier comparison with other references.

Lastly, we perform predictions of the half-lives for each isotope that would correspond to the LNV parameters extracted from one experiments of the highest sensitivity. Choosing the $E_\nu$ LNV deduced from the $^{76}$Ge experiment [50], we estimate the half-lives of the other four isotopes. These values are displayed in the lower section of Table 2 and offer an indication about the relative sensitivity between DBD experiments.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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