Double Beta Decay Half Lives for A=60-90 Nuclei in DSM

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Introduction

Double-β decay (DBD) is a rare weak-interaction process in which two identical nucleons inside the nucleus undergo decay with or without emission of neutrinos and they are denoted by $2\nu\beta^-\beta^-$ and $0\nu\beta^-\beta^-$ respectively. In addition, nuclei can also decay by positron DBD and here three modes $\beta^+\beta^+$, β^+EC and ECEC are possible (hereafter, these three are called e^+DBD). Observation of $0\nu\beta^-\beta^-$ (also $0\nu e^+$DBD) is important as this gives neutrino mass [provided the nuclear matrix elements defined in Eq. (1) ahead are known]. Except for a claim by Heidelberg-Moscow group for ^{76}Ge [1], this process is not yet observed experimentally. On the other hand, $2\nu\beta^-\beta^-$ has been observed in several nuclei (also there are some claims for $2\nu e^+$DBD) [2]. Nuclear transition matrix elements (NTME), defined ahead, are needed for calculating DBD half lives. For 2ν, they provide tests of the nuclear models and predictions for unknown half-lives while for 0ν, they will give neutrino mass if half-lives are measured experimentally. We have initiated a project to calculate NTME using the so called deformed shell model (DSM) and spectral distribution methods (SDM) [3]. Here our focus is on DSM.

Deformed shell model (DSM) based on Hartree-Fock states with band mixing has been established to be very successful in describing various spectroscopic properties [band structures, shapes, band crossings, $B(E2)$'s and so on] of nuclei in the A=60-90 mass region (also in A=44-60); see [4] for details. Following this, we have focused on NTME calculations for DBD candidates with Z=30-40, N $\leq$ 48 and A=60-90. These nuclei are listed in Table 1. The current status of DSM results is presented here.

Formalism

Half-life for $0\nu\beta^-\beta^-$ for the 0_i^+ ground state (gs) of a initial even-even nucleus decay to the 0_f^+ gs of the final even-even nucleus, with a few approximations [5], is given by

$$\begin{aligned}
&[T_{1/2}^{0\nu}(0_i^+ \to 0_f^+)]^{-1} = G^{0\nu}|M^{0\nu}|^2 \frac{\langle m_\nu\rangle^2}{m_e^2}\;; \\
&M^{0\nu} = M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \\
&\qquad = \left\langle 0_f^+ \mid\mid \mathcal{O}(2:0\nu) \mid\mid 0_i^+ \right\rangle\;, \\
&\mathcal{O}(2:0\nu) = \sum_{a,b} \mathcal{H}(r_{ab},\overline{E})\tau_a^+\tau_b^+ \left(\sigma_a\cdot\sigma_b - \frac{g_V^2}{g_A^2}\right), \\
&\mathcal{H}(r_{ab},\overline{E}) \to \mathcal{H}_{eff}(r_{ab},\overline{E}) \\
&\qquad = \frac{R}{r_{ab}} \exp\left(-\frac{3}{2}\frac{\overline{E}}{\hbar c} r_{ab}\right) \\
&\qquad \times \left[1-\exp(-\gamma_1 r_{ab}^2)\left(1-\gamma_2 r_{ab}^2\right)\right]^2\;. \qquad (1)
\end{aligned}$$

In (1), $M^{0\nu}$ is NTME and $\langle m_\nu\rangle$ is the average neutrino mass. The $G^{0\nu}$ are phase space integrals and tabulations for them are available in Ref. [6]. The g_A and g_V are the weak axial-vector and vector coupling constants (we use g_A/g_V=1). The $\mathcal{H}_{eff}(r_{ab},\overline{E})$ is the 'neutrino potential' with short range correlations incorporated. The parameters $\gamma_1 = 1.1$ fm^{-2}, $\gamma_2 = 0.68$ fm^{-2}, $R = 1.2A^{1/3}$ fm, $\overline{E} = 1.12A^{1/2}$ MeV, r_{ab} in fm and $\hbar c = 197.327$ MeV fm. Calculation of the two-body matrix elements of the 0ν transition operator $\mathcal{O}(2:0\nu)$ involves Talmi integrals and Brody-Moshnisky brackets. Here we also need the oscillator length parameter $b = \sqrt{\hbar/m\omega} \sim 0.9A^{1/6}$ fm. Half-life for the $2\nu\beta^-\beta^-$ for $0^+ \to 0^+$ transi-

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$$[T^{2\nu}_{1/2}(0^+_i \rightarrow 0^+_f)]^{-1} = G^{2\nu}|M^{2\nu}|^2$$

$$M^{2\nu} = \sum_N \frac{\left\langle 0^+_f \mid\mid \sigma\tau^+ \mid\mid 1^+_N \right\rangle \left\langle 1^+_N \mid\mid \sigma\tau^+ \mid\mid 0^+_i \right\rangle}{[E_N - (E_i + E_f)/2]/m_e} \qquad (2)$$

In (2), $M^{2\nu}$ are NTME and $G^{2\nu}$ are phase space integrals [6]. Similarly E_i and E_f are the energies of the initial and final nuclei and E_N are the energies of the intermediate 1^+ levels. For e^+DBD, $\tau^+ \longrightarrow \tau^-$ in Eqs. (1) and (2). See [6] for further details.

Results and Discussion

Calculations of NTME using DSM in $f_{5/2}pg_{9/2}$ space with a modified Kuo interaction have been carried out for several of the nuclei in Table 1. The results are as follows.

DSM results for $2\nu\beta^-\beta^-$ in ^{76}Ge were reported in [7]. We made a first DSM calculation using $\sim$ 10 intrinsic states in band mixing for ^{82}Se decay and we have obtained $M^{2\nu} = 0.23$ while QRPA gives $0.13 - 0.16$ and expt'l value is 0.06. At present we are making calculations using much larger number of intrinsic states and changing $1g_{9/2}$ energy. We also plan to use the new interaction JUN45 [8].

For $2\nu e^+$DBD, the DSM results for ^{78}Kr were published in [9] and the calculated half-lives are close to those from QRPA. Similarly the DSM half-lives for ^{74}Se were published in [10] and there no results from other models for this nucleus. The half-life for the ECEC mode is $\sim 10^{26}$ yr and it should be possible to observe this in future experiments. We have recently performed calculations for ^{84}Sr (here also there no published results) [11] and the calculated half-lives for the β^+EC and ECEC modes are 10^{26} yr and $\sim 4 \times 10^{24}$ yr respectively. Here $1g_{9/2}$ has to be lowered close to $2p_{1/2}$ orbit. In [3], a first attempt has been made to calculate half-lives for ^{64}Zn.

For $0\nu\beta^-\beta^-$ decay we have performed first calculations using DSM (with $\sim$ 10 intrinsic states for band mixing) for ^{76}Ge and ^{82}Se and also $0\nu e^+$DBD for ^{84}Sr. Our results for ^{76}Ge and ^{82}Se differ by a factor of 2 to 3 in comparison to shell model and QRPA results. More detailed (with much larger number of intrinsic states) calculations are under way by relaxing the various approximations that gave Eq. (1) and also using JUN45 interaction. After testing the success of these calculations, we will consider the other nuclei in Table 1.

TABLE I: DBD candidates with A=60-90, $30 \leq Z \leq 40$ and $N \leq 48$.

$(0+2\nu)\beta^-\beta^-$	$(0+2\nu)e^+$DBD
^{70}Zn	^{64}Zn
^{76}Ge	^{74}Se
^{80}Se	^{78}Kr
^{82}Se	^{84}Sr

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