Non-standard $0\nu\beta\beta$ decay study of ^{48}Ca with nuclear shell model

S. Sarkar* and R. Chatterjee
Department of Physics, Indian Institute of Technology Roorkee, Roorkee - 247667, Uttarakhand, India

Introduction

The neutrinoless double beta decay ($0\nu\beta\beta$) is a lepton number-violating process where two neutrons in certain even-even nuclei convert into two protons without emitting neutrinos [1]. Detecting this would confirm the Majorana nature of neutrinos, with implications for physics beyond the Standard Model, such as establishing the neutrino mass hierarchy. A key focus in studying $0\nu\beta\beta$ is accurately calculating nuclear matrix elements (NME) using models like the interacting shell model and quasi-particle random phase approximation, as the NME connects the decay half-life with lepton number-violating parameters, like absolute neutrino mass.

Although forbidden in the Standard Model, several beyond Standard Model (BSM) theories predict $0\nu\beta\beta$, including the standard light neutrino exchange and left-right symmetric mechanisms. This study calculates NMEs for $0\nu\beta\beta$ decay of ^{48}Ca, an experimentally important nucleus in projects like CANDLES in Japan [1]. We explore the coexistence of the standard light neutrino-exchange and the non-standard λ mechanism from left-right symmetric theory, using the interacting shell model and a spin-dependent approach to short-range correlations (SRC) from Ref. [2], rather than the more common Jastrow approach [3, 4].

Formalism of NME calculations

The inverse of the half-life for $0\nu\beta\beta$ decay, when both the light neutrino-exchange and λ mechanisms coexist, is expressed as [4]:

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

where the parameters η_ν, η_λ, and ψ are defined in Ref. [4]. The coefficients C_I (with $I = mm, m\lambda, \lambda\lambda$) are linear combinations of NME and phase-space factors [3]. The expression for the required matrix element is given by [5]:

$$M_\alpha = \langle f \left| f_{\mathrm{SD}}(r) O_{12}^{\alpha} f_{\mathrm{SD}}\,(r) \right| i \rangle\,, \tag{2}$$

where $f_{\mathrm{SD}}(r) = f(r) + g(r), \sigma_1 \cdot \sigma_2$ is the spin-dependent short-range correlation (SRC) function. The parameters for $f(r)$ and $g(r)$ are provided in Refs. [2, 5]. Here, $|i\rangle$ represents the 0^+ ground state of the initial nucleus ^{48}Ca, while $|f\rangle$ denotes the 0^+ ground state of the final nucleus ^{48}Ti. The index α corresponds to various Fermi (F), Gamow-Teller (GT), tensor (T), and total matrix elements, with specific types being $\alpha = (GT, F, T, \nu, \omega GT, \omega F, \omega T, v\omega, qGT, qF, qT)$. The operator O_{12}^{α} represents the transition operator for $0\nu\beta\beta$ decay [3]. Finally, the NMEs in Eq. (2) are computed by first evaluating the initial and final nuclear states using the interacting shell model, followed by calculating a large number of intermediate states of ^{46}Ca with different spin-parity configurations. These intermediate states are crucial for determining the two-nucleon transfer amplitude (TNA) as described in Ref. [3].

Results and Discussion

The nuclear states of ^{48}Ca, ^{48}Ti, and ^{46}Ca were calculated using the interacting shell model with the KSHELL code [6]. For each allowed spin-parity of the intermediate nucleus ^{46}Ca, 100 energy states were computed

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*Electronic address: `shahariar.ph@sric.iitr.ac.in`

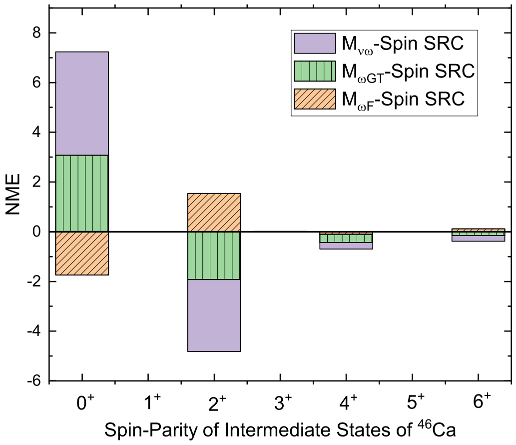

FIG. 1: Contributions of individual spin-parity of intermediate nucleus ^{46}Ca on $M_{\omega F}$, $M_{\omega GT}$, and $M_{\nu\omega}$ type NMEs for $0\nu\beta\beta$ decay of ^{48}Ca.

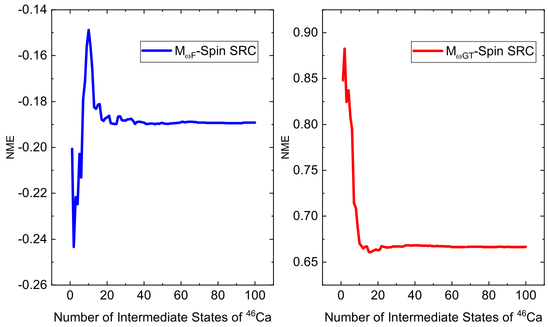

FIG. 2: Dependence of $M_{\omega F}$ and $M_{\omega GT}$ type NMEs for $0\nu\beta\beta$ decay of ^{48}Ca on the number of intermediate states for each spin-parity of ^{46}Ca.

to evaluate the TNA required for NME calculations of $0\nu\beta\beta$ decay in ^{48}Ca. A portion of the results is discussed below.

Figure 1 shows the contributions of individual spin-parity states of ^{46}Ca to the $M_{\omega F}$, $M_{\omega GT}$, and $M_{\nu\omega}$ types of NMEs for the $0\nu\beta\beta$ decay of ^{48}Ca. These NMEs are part of the Fermi, Gamow-Teller, and total contributions required for both the light neutrino-exchange and λ mechanisms in $0\nu\beta\beta$ decay. The results indicate that the 0^+ and 2^+ states of ^{46}Ca contribute the most, but with opposite signs. Negligible contributions arise from states with odd spin-parities.

Additionally, the impact of the number of excitation states in the virtual intermediate nucleus ^{46}Ca on the $M_{\omega F}$ and $M_{\omega GT}$ NMEs is examined in Figure 2. The variations are shown for up to 100 states for each allowed spin-parity of ^{46}Ca. It was observed that after about 40 states, the NMEs reach a saturation point, confirming the reliability of the calculated values. Similar saturation behavior is observed for other type of NMEs.

Summary

In summary, we have investigated the $0\nu\beta\beta$ decay of ^{48}Ca under the coexistence of the standard light neutrino-exchange and non-standard λ mechanisms using the interacting shell model. Our primary objective was to incorporate the effects of SRC by employing a non-conventional spin-dependent approach rather than the standard Jastrow-type method. We demonstrated the contributions of various allowed spin-parity states of the intermediate nucleus ^{46}Ca and analyzed the saturation behavior of the NMEs as the number of states considered for each spin-parity of ^{46}Ca.

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