Variation of NMEs of $0\nu\beta\beta$ for ^{48}Ca with different components of NN interaction

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Abstract. We examine the sensitivity of nuclear matrix elements (NMEs) for light-neutrino exchange mechanism of neutrinoless double beta decay ($0\nu\beta\beta$) for ^{48}Ca to the various components of two-nucleon interaction, GXPF1A, in *fp* model space. It is found that the contribution in NMEs coming from the central component is close to contribution from total interaction. The spin-orbit and tensor components are found canceling the contribution of each other.

1 Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a rare weak process, known mainly for determining the nature of neutrino and neutrino mass [1]. The decay rate of this process depends on nuclear matrix elements (NMEs), which are calculated using theoretical nuclear many-body models. In the literature, the nuclear shell model (NSM) has been widely used to calculate NMEs [1].

It is well known that the total two-nucleon interaction is the sum of central (C), spin-orbit (SO), and tensor (T) interaction. The earlier calculations of NMEs in NSM have been done using total two-nucleon interaction [2–5]. In the present work, we examine the variation of NMEs for light neutrino exchange mechanism of $0\nu\beta\beta$ of ^{48}Ca with different components of two-nucleon interaction-GXPF1A [6] of *fp*-model space using closure approximation. The employed interaction is decomposed into its central, spin-orbit, and tensor components using spin-tensor decomposition (STD) method [7–10].

This article is organized as follows. In section 2, the theoretical formalism for NMEs for light neutrino exchange mechanism of $0\nu\beta\beta$ is given. The STD is discussed in section 3. Results and discussion are presented in section 4. The summary of this work is given in section 5.

2 Nuclear Matrix Elements of $0\nu\beta\beta$

The NMEs for light neutrino exchange mechanism of $0\nu\beta\beta$ can be presented as a sum of Gamow-Teller (M_{GT}), Fermi (M_F), and tensor (M_T) matrix elements [4];

$$M^{0\nu} = M_{GT} - \left(\frac{g_V}{g_A}\right)^2 M_F + M_T \tag{1}$$

where, $g_V = 1$ and $g_A = 1.27$. $M_\alpha = \langle f|\tau_{-1}\tau_{-2}O^\alpha_{12}|i\rangle$ with $\alpha = GT, F, T$ can be written in terms of two-body transition density (TBTD) and two-body matrix elements ($\langle k_1', k_2', J|\tau_{-1}\tau_{-2}O^\alpha_{12}|k_1, k_2, J\rangle$) [4];

$$M_\alpha = \sum_{J,k_1'\leq k_2',k_1\leq k_2} TBTD(f,i,k,J) \langle k_1', k_2', J|\tau_{-1}\tau_{-2}O^\alpha_{12}|k_1, k_2, J\rangle \tag{2}$$

where, τ_- is isospin lowering operator, O^α_{12} is transition operator of $0\nu\beta\beta$ defined with spin (σ) and neutrino potential operator ($H_\alpha(r, E_\kappa)$) [2]; $O_{GT} = (\boldsymbol{\sigma_1}.\boldsymbol{\sigma_2})H_{GT}(r, E_\kappa)$, $O_F = H_F(r, E_\kappa)$ and $O_T = (3(\boldsymbol{\sigma_1}.\hat{\mathbf{r}})(\boldsymbol{\sigma_2}.\hat{\mathbf{r}}) - (\boldsymbol{\sigma_1}.\boldsymbol{\sigma_2}))H_T(r, E_\kappa)$. In Eq.(2), k stands for the set of quantum numbers $(n; l; j)$, $|i\rangle$ and $|f\rangle$ refer to the ground state (0^+) of ^{48}Ca and ^{48}Ti, respectively. Neutrino potential is defined as [3];

$$H_\alpha(r, E_\kappa) = \frac{2R}{\pi}\int_0^\infty \frac{j_p(qr)h_\alpha(q^2)qdq}{q + E_\kappa - (E_i + E_f)/2} \tag{3}$$

Where, E_κ , E_i and E_f are the energies of ^{48}Sc, ^{48}Ca and ^{48}Ti respectively. q is the momentum of the virtual Majorana neutrino and r is the distance between the nucleons. $j_p(qr)$ is the spherical Bessel function with p =0 and 2. In closure approximation one replaces $E_\kappa - (E_i + E_f)/2 \longrightarrow \langle E\rangle$, where, $\langle E\rangle$ is the closure energy which takes care the effects of large number of excitation energy of states of intermediate nuclei (^{48}Sc). Closure approximation removes the complications of calculating large number of states of ^{48}Sc. As neutrino momentum (q) in the decay is high (~100-200 MeV), NMEs are not much sensitive with the excitation energy of ^{48}Sc. So by replacing all excitation energy with a constant closure energy $\langle E\rangle$ gives NME with around 90% accuracy [3].

3 Spin Tensor Decomposition (STD)

Nucleons are intrinsic spin 1/2 fermions; therefore, the interaction between two-nucleon can be written as the linear sum of the scalar product of configuration space operator Q and spin space operator S of rank k [7, 8];

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$$V = \sum_{k=0}^{2} V(k) = \sum_{k=0}^{2} Q^k.S^k \tag{4}$$

where, rank $k = 0$, 1 and 2 represent central, spin-orbit and tensor force, respectively. Using the LS-coupled two-nucleon wave functions, the matrix element for each V^k can be calculated from matrix element for V [9];

$$\langle (ab), LS; JM|V(k)|(cd), L'S'; JM\rangle = (2k+1)(-1)^J \times \begin{Bmatrix} L & S & J \\ S' & L' & k \end{Bmatrix} \sum_{J'} (-1)^{J'}(2J'+1) \begin{Bmatrix} L & S & J' \\ S' & L' & k \end{Bmatrix} \times \langle (ab), LS; J'M|V|(cd), L'S'; J'M\rangle \tag{5}$$

here, a includes quantum numbers n_a and l_a.

4 Results and Discussion

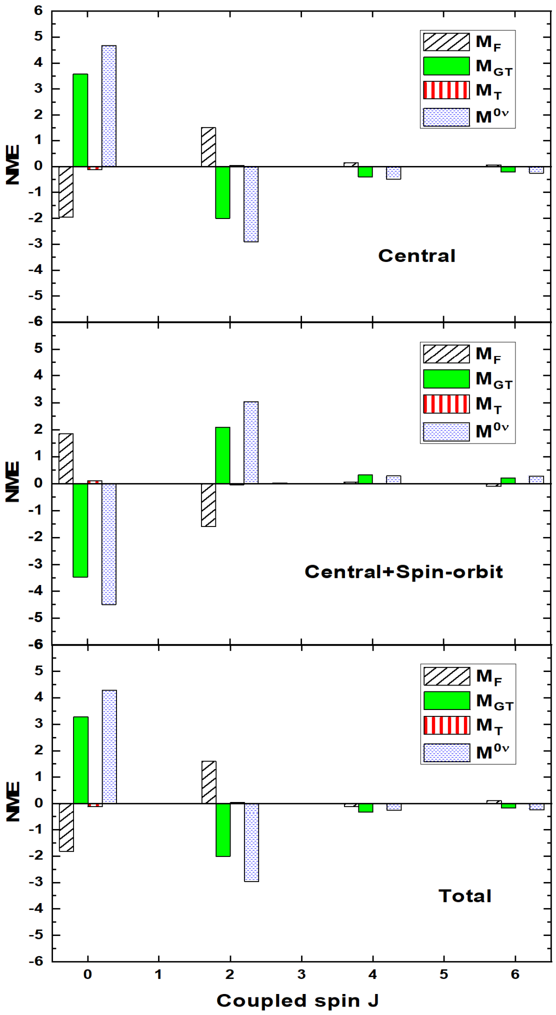

Figure 1. Contribution of various spin-parity (J^π) of decaying neutrons or final protons to the NMEs.

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We have calculated TBTD in terms of two-nucleon transfer amplitudes (TNA) with 50 states of ^{46}Ca using method described in Ref. [4]. The TBMEs have been calculated with closure energy $\langle E\rangle = 0.5$ MeV [3]. The effect of finite nucleon size (FNS), higher order currents (HOC) [2] have also been considered. The calculated NMEs are given in Table 1.

Table 1. NMEs for ^{48}Ca calculated with different components of two-nucleon interaction.

NME	Types	C	C+SO	C+SO+T
M_F	FNS+HOC	-0.273	0.234	-0.217
M_{GT}	FNS+HOC	0.933	-0.828	0.790
M_T	FNS+HOC	-0.081	0.070	-0.076
$M^{0\nu}$	FNS+HOC	1.021	-0.904	0.848

It is found that the NMEs calculated with C interaction are near to NMEs calculated with total interaction. On the addition of SO part to C part, the sign of NMEs gets change but in absolute value they remain almost same. Similar effects are also seen when we add T part to C+SO part of two-nucleon interaction. Thus, we infer that SO and T parts negate the effect of each other.

Results of NMEs as a function of coupled spin-parity of decaying nucleons are shown in Fig. 1. It is found that the dominant contribution in NMEs comes from $J^\pi = 0^+$ and 2^+. But, their contribution are present with the opposite effect resulting in a small value of NMEs. Negligible contributions comes from other J^π.

5 Summary

We have examined the sensitivity of NME for light-neutrino exchange mechanism of $0\nu\beta\beta$ for ^{48}Ca with various components we get using STD for GXPF1A interaction. It is found that the NMEs calculated with C part and total interaction are close to each other. SO and T parts negate the contribution of each other in the NMEs. Dominating contribution to NMEs comes from 0^+ and 2^+ spin-parity staes of decaying nucleons.

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