Nuclear transition matrix elements calculation for $0\nu\beta\beta$ decay of ^{124}Sn in nuclear shell model

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Introduction

The neutrinoless double beta ($0\nu\beta\beta$) decay is an important lepton number violating nuclear decay that occurs when two neutrons inside some even-even nuclei are converted into two protons, and two electrons [1]. If this rare process is observed, one can conclude that neutrinos are their own anti-particle (Majorana particle), which is favored by many beyond the standard model physics theory. This process can also reveal the absolute masses of neutrinos. The nuclear transition matrix element (NTME) is an essential quantity to study $0\nu\beta\beta$ decay, as it connects the neutrino mass with the decay rate of the process. Hence, one of the objectives of this study is to calculate the reliable NTMEs for $0\nu\beta\beta$ decay within the large-scale nuclear shell model framework.

We have chosen ^{124}Sn as the decay candidate of $0\nu\beta\beta$ for its immense interest from the double beta decay community of India, including the TIFR and INO.

Earlier, the NTME of ^{124}Sn was calculated in the shell model in closure method [1] in which the effects of the excitation energies of a large number of intermediate states were approximated with constant closure energy to avoid the computational complexity of calculating a large number of intermediate states. Here, we are motivated to include the real effects of those excitation energies on the NTMEs of $0\nu\beta\beta$ decay of ^{124}Sn. This method is known as the nonclosure method [2].

Theoretical formalism of NTME calculation

The total NTME for light neutrino-exchange $0\nu\beta\beta$ decay can be written as [3]

$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F + M^{0\nu}_T, \quad (1)$$

where the Fermi ($M^{0\nu}_F$), Gamow-Teller ($M^{0\nu}_{GT}$), and Tensor ($M^{0\nu}_T$) type matrix element can be written as

$$M_\alpha = \langle f|\mathcal{O}^\alpha_{12}|i\rangle \quad (2)$$

with $|i\rangle$ is 0^+ ground state of initial nucleus ^{124}Sn and $|f\rangle$ is 0^+ ground state of final nucleus ^{124}Te. The α represents the type of NTME (F, GT or T). Expression to the calculate the NTME of Eq. (2) in terms of one body-transition density (OBTD) and two-body matrix elements can be found in Eq. (42) of Ref. [3]

Results and Discussion

First, we have calculated the initial, intermediate, and final nuclear states through large-scale shell model diagonalization with shell model code KSHELL [4]. These states are further used to calculate the OBTD that appears in the expression of NTME. The two-body matrix element part of the NTME is calculated by programming written by us.

Now we present some of the calculated results of NTME for $0\nu\beta\beta$ decay of ^{124}Sn. Total NTME is the sum of each partial NTME originating through the contribution of each spin-parity of the intermediate nucleus ^{124}Sb. De-

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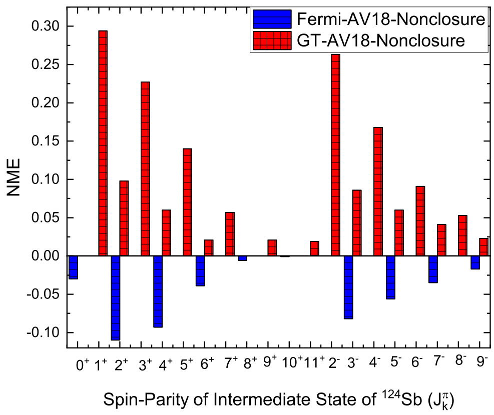

FIG. 1: (Color online) The dependence Fermi and Gamow-Teller nuclear transition matrix elements of $0\nu\beta\beta$ decay of ^{124}Sn on the spin-parity of intermediate states of ^{124}Sb.

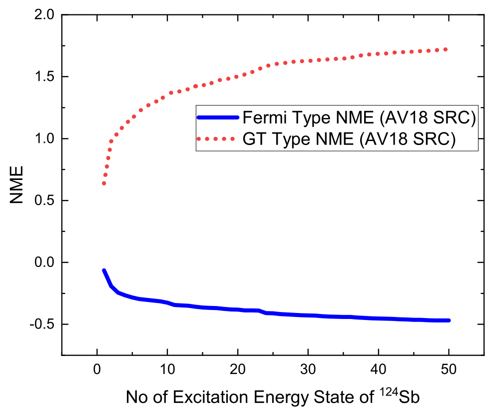

FIG. 2: (Color online) Variation of Fermi and Gamow-Teller nuclear transition matrix elements of $0\nu\beta\beta$ decay of ^{124}Sn on the number of intermediate states of ^{124}Sb.

pendence of Fermi and Gamow-Teller NTME with different J_k^π of ^{124}Sb are shown in FIG. 1. Here, NTMEs are calculated in nonclosure method with GCN5082 effective interaction [5] for AV18 SRC parametrization [3] by considering contribution from first fifty states of ^{124}Sb. It is found that for all Fermi type NTMEs, contribution through each J_k^π is negative, and for Gamow-Teller, all contribution is positive. The most dominating contribution comes through 1^+ state for GT type NTME.

Finally, the dependence of Fermi, Gamow-Teller NTMEs on the number of excitation energy of virtual intermediate nucleus ^{124}Sb is examined and shown in FIG. 2. Here, NTMEs are calculated with GCN5082 shell model Hamiltonian using nonclosure approximation for AV18 type SRC. Variation is shown for the first fifty states of ^{124}Sb. It is generally found from earlier studies [2, 3] that NTMEs attain a stable value by considering about 100 intermediate states which goes up to about 10 MeV in excitation energy. In the present case, we are able to examine the variation for a maximum of fifty states, and NTMEs are mostly attaining a stable value.

Summary

In summary, we have calculated the reliable Fermi and Gamow-Teller NTMEs of $0\nu\beta\beta$ decay of ^{124}Sn using a large-scale nuclear shell model. The nonclosure approximation was used to include the true effects on excitation energy of the virtual intermediate nucleus ^{124}Sb. The dependence of NTME on different spin-parity of the intermediate state and number of excitation energy are discussed.

Acknowledgments

We thankfully acknowledge the support of the project from the Board of Research In Nuclear Sciences (BRNS), Government of India (Project No. 58/14/08/2020-BRNS/37085). S.Sarkar is grateful to Dr. Y. Iwata, Kansai University, Japan for allowing to use the high performance computing facility to perform the large scale shell model calculations.

References

[1] Mihai Horoi and Andrei Neacsu, Phys. Rev. C 93, 024308 (2016)

[2] R. A. Sen'kov and M. Horoi, Phys. Rev. C 88, 064312 (2013)

[3] Shahariar Sarkar, Y. Iwata, and P. K. Raina, Phys. Rev. C 102, 034317 (2020)

[4] N. Shimizu *et al.*,Comp. Phys. Comm. 244, 372 (2019)

[5] J. Menéndez *et al.*,Nuclear Physics A 818 (2009) 139–151 (2008)