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Neutrinoless double beta nuclear matrix elements around mass 80 in the nuclear shell-model

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Abstract. The observation of the neutrinoless double-beta decay can determine whether the neutrino is a Majorana particle or not. For theoretical nuclear physics it is particularly important to estimate three types of matrix elements, namely Fermi (F), Gamow-Teller (GT), and tensor (T) matrix elements. In this paper, we carry out shell-model calculations and also pair-truncated shell-model calculations to check the model dependence in the case of mass A=82 nuclei.

1 Introduction

The double beta decay is a second order process of the weak interaction which increases the atomic number of a nucleus by two. There are two modes of double-beta decays. The 2ν mode ($2\nu\beta\beta$) is expected within the Standard Model and is characterized by the additional emission of two anti-neutrinos. Up to now $2\nu\beta\beta$ decay half-lives have been measured in ten cases in experiment. In contrast, the 0ν mode can only take place if the neutrino is a Majorana particle. This demands an extension of the Standard Model of electroweak interactions because it violates the lepton number conservation. The 0ν mode ($0\nu\beta\beta$) is one of the best probes for physics beyond the Standard Model. Many theoretical methods have been applied so far to evaluate the nuclear matrix elements, namely, in the shell-model [1, 2], and the quasi-particle random-phase approximation (QRPA) [3] and in the microscopic interacting boson approximation (IBM) [4]. However, there still remain large ambiguities in estimating those nuclear matrix elements in various methods [1–4]. In this paper, we carry out shell-model calculations and pair-truncated shell-model calculations to check the model dependence on nuclear matrix elements in comparison with other models. In this work, we calculate the nuclear matrix elements of the $0\nu\beta\beta$ decay for the transition from ^{82}Se to ^{82}Kr in two different formulations.

2 Shell-model calculations for Nuclear structure

Systematic studies were carried out for even-even and odd-mass nuclei in the mass $A \sim 80$ region in terms of the shell-model (SM) [5]. For single-particle levels, all the four $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$, and $0g_{9/2}$ orbitals in the major shell between the magic numbers 28 and 50 are taken into account for both neutrons and protons. As an effective interaction, we employ the monopole and quadrupole pairing plus quadrupole-quadrupole interaction. The energy spectra obtained are compared with the experimental data for ^{82}Se and ^{82}Kr in Fig. 1. Good agreements between theoretical spectra of the shell model and the experimental ones are achieved. We do not discuss other results here, but electromagnetic properties are also well reproduced. Their results and the detailed theoretical prescriptions are presented in Ref. [5]. In order to investigate the model dependence on the nuclear matrix elements, we also perform pair-truncated shell-model (PTSM) calculations. In the PTSM, the full shell-model space is restricted within the subspace where angular momenta zero (S), two (D) and four (G) collective pairs are used as the building blocks. We construct three types of subspaces, namely, the

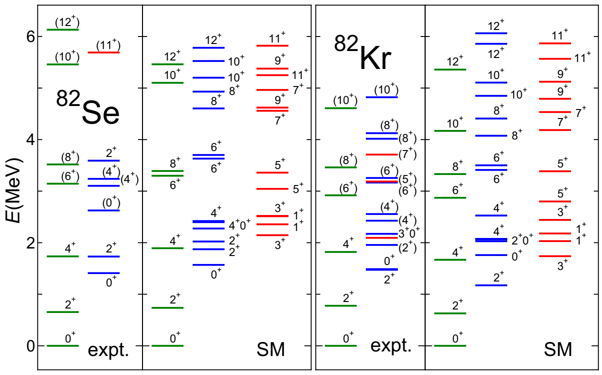

Figure 1. Comparison between the experimental energy spectra (expt.) and those of the shell-model (SM) for ^{82}Se and ^{82}Kr.

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S-subspace only with S pairs, the SD-subspace without G pairs and the SDG-subspace including G pairs. In the following calculations of nuclear matrix elements we perform PTSM calculations in S-, SD- and SDG-subspaces using the same Hamiltonian employed in the full shell model.

3 Theoretical framework and results for neutrinoless double beta decay

The $0\nu\beta\beta$ decay half-life is given by

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} \left|M^{(0\nu)}\right|^2 \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}}\right)^2 , \qquad (1)$$

where $G_{0\nu}$ is a phase-space factor, $\langle m_\nu \rangle$ is the effective mass of the electron neutrino, m_{e} is the electron mass, and $M^{(0\nu)}$ is the nuclear matrix element between wave functions of two particular nuclei. Here we focus our attention on the nuclear matrix element:

$$M^{(0\nu)}_{Type} = \left\langle {}^{82}\mathrm{Se}\left(0^+_{\mathrm{g.s.}}\right)\right| \hat{V}^{(\lambda)}_{s_1 s_2} \left| {}^{82}\mathrm{Kr}\left(0^+_{\mathrm{g.s.}}\right)\right\rangle . \qquad (2)$$

Three types of matrix elements play a particularly important role, Fermi (F), Gamow-Teller (GT), and tensor (T) matrix elements. The F, GT, and T transition operators can be expressed using the neutrino potential $\hat{V}^{(\lambda)}_{s_1 s_2}$ by [4]. Other details are given in Ref. [4]. In Tomoda's formulation [3], the nuclear matrix elements are written as

$$M^{(0\nu)} = -\left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_F + M^{(0\nu)}_{GT} , \qquad (3)$$

where all the details are given in Ref. [3]. The SM results and the PTSM results in S-, SD- and SDG-spaces are shown in Table 1 in comparison with those of the IBM [4] and the QRPA [3]. The total matrix elements obtained by and the SM are roughly twice or three times smaller compared to the previous results in other models.

Table 1. Neutrinoless matrix elements in units of fm^{-1} for the SM, the PTSM, the IBM [4] and the QRPA [3] in Tomoda's formulation for mass $A = 82$. For the PTSM calculations, the results within the SDG subspace (SDG) and those within the SD subspace (SD) and those within the S subspace (S) are presented.

Model	$M^{(0\nu)}_F$	$M^{(0\nu)}_{GT}$	$M^{(0\nu)}$
SM	−0.076	+0.115	+0.163
PTSM (SDG)	−0.118	+0.128	+0.203
PTSM (SD)	−0.126	+0.105	+0.185
PTSM (S)	−0.192	+0.231	+0.353
IBM	−0.211	+0.346	+0.481
QRPA	−0.131	+0.293	+0.377

In Šimkovic's formulation [6], the nuclear matrix elements are given as

$$M^{(0\nu)} = -\left(\frac{g_V}{g_A}\right)^2 M^{(0\nu)}_F + M^{(0\nu)}_{GT} + M^{(0\nu)}_T , \qquad (4)$$

where all other details are given in Ref. [6]. The results are shown in Table 2 in comparison with those of the IBM [4]. The obtained results are similar to those in Tomoda's formulation. In general contributions from Tensor type are not large, but its importance is enhanced in the shell model since other type (F and GT) contributions become relatively small in comparison with the IBM results.

Table 2. Neutrinoless matrix elements in dimensionless units for the SM, the PTSM and the IBM [4] in Šimkovic's formulation for mass $A = 82$. For the PTSM calculations, the results within the SDG subspace (SDG) and those within the SD subspace (SD) and those within the S subspace (S) are presented.

Model	$M^{(0\nu)}_F$	$M^{(0\nu)}_{GT}$	$M^{(0\nu)}_T$	$M^{(0\nu)}$
SM	−0.800	+1.164	−0.384	+1.292
PTSM (SDG)	−1.230	+1.316	−0.608	+1.496
PTSM (SD)	−1.308	+1.105	−0.667	+1.274
PTSM (S)	−1.984	+2.366	−0.809	+2.826
IBM	−2.197	+3.260	−0.254	+4.412

4 Summary

In the present study, we evaluate the nuclear matrix elements of neutrinoless double beta decay in terms of the SM and the PTSM. Compared to other models, such as, the QRPA and the IBM, our model predicts smaller transition matrix elements, indicating the strong sensitivity on nuclear matrix elements calculated by using different wave functions of various nuclear models. Compared to the IBM results, our shell model calculations predict roughly ten times longer half lives for the neutrinoless double beta decay from ^{82}Se to ^{82}Kr.

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