Effective interaction for f5pg9-shell nuclei and two-neutrino double beta decay matrix elements

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The effective interaction is a key ingredient for successful shell-model calculations. Owing to recent developments in computers as well as novel numerical techniques such as the Monte Carlo shell model[1)], the applicability of the shell model is rapidly expanding. On the other hand, our knowledge of the effective interaction is still insufficient especially for cases where more than one major shell should be taken as the active valence space. Such a treatment is essentially important for describing neutron-rich nuclei.

We have developed a new effective interaction for shell-model calculations in the model space consisting of valence orbits $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ assuming an inert ^{56}Ni core (f5pg9-shell). It can be regarded as a first step for future extensions to the pf+sdg model space. We have carried out the similar iterative fitting calculations as in the case of the the pf-shell[2)]. Starting from a microscopic interaction (renormalized G-matrix)[3)] based on a realistic NN-potential, we have varied 45 linear combinations of Hamiltonian parameters (133 two-body matrix elements and four single-particle energies) by a least-squares fit to the 400 experimental binding and excitation energy data out of 87 nuclei with masses A=63-96. In the latest iteration, we have attained the rms error of 185 keV.

As an applications of this interaction, we have evaluated the nuclear matrix element of the double β-decay for ^{76}Ge and ^{82}Se, focusing on the two-neutrino mode. Shell-model calculations have been carried out in a conventional way by using the code MSHELL.[4)] For these nuclei the double β-decay lifetime has been measured experimentally, which is related to the nuclear matrix elements $M_{GT}^{(2\nu)}$. We can compare the experimental values with our shell-model results, which are calculated according to the following expression

$$M_{GT}^{(2\nu)} = \sum_m \frac{\langle 0_f^+ \parallel T_{\mathrm{GT}-} \parallel 1_m^+ \rangle \langle 1_m^+ \parallel T_{\mathrm{GT}-} \parallel 0_i^+ \rangle}{\frac{1}{2}Q_{\beta\beta} + E_x(1_m^+) - E_0},$$

where E_0 stands for the mass difference between the parent and intermediate nuclei. Since this matrix element depends on both the initial and the final state wave functions as well as the Gamow-Teller strength distribution in the intermediate 1^+ states, it provides us with a stringent test of the theoretical model.

In usual shell-model calculations, the Gamow-Teller operator $T_{\mathrm{GT}-} = \sum_k \sigma_k \tau_k^-$ is multiplied by a "quenching" factor q in order to obtain reasonable comparison with the experimental data. This factor depends on the adopted model space, and one can find a standard value in the literature: q=0.82 for the p-shell[5)], 0.77 for the sd-shell[6)] and 0.74 for the pf-shell.[7)] Thus we first estimated a suitable quenching factor in the present f5pg9-shell by carrying out a fitting calculation to available experimental data for the Gamow-Teller β-decay among low-lying states. As a result, we have obtained the value $q = 0.6$, which is much smaller than that for other model spaces mentioned above.

For the evaluation of $M_{GT}^{(2\nu)}$, we need the excitation energies of the intermediate 1^+ states. Experimentally, the excitation energy of the lowest 1^+ state is 0.044 MeV (0.075 MeV) in ^{76}As (^{82}Br), while our shell model gives 0.286 MeV (0.470 MeV) for this energy. We consider two cases: (1) to use the shell-model excitation energies as they are, and (2) to shift the shell-model energies of all intermediate states commonly so as to reproduce the experimental value of $E_x(1_1^+)$. The results are summarized in table 1. It can be seen that the shell model with the quenching factor $q = 0.6$ reasonably reproduce the experimental values for both ^{76}Ge and ^{82}Se.

Table 1. Comparison of the nuclear matrix element $M_{GT}^{(2\nu)}$ (MeV^{-1}) between the experimental data and the shell-model calculations.

	^{68}Ge	^{82}Se
Exp.[8)]	$0.127^{+0.006}_{-0.004}$	$0.090^{+0.002}_{-0.010}$
Cal. q=0.6, $E_x(1_1^+)_{\mathrm{cal.}}$	0.111	0.106
Cal. q=0.6, $E_x(1_1^+)_{\mathrm{exp.}}$	0.120	0.124
Cal. q=1, $E_x(1_1^+)_{\mathrm{cal.}}$	0.308	0.295
Cal. q=1, $E_x(1_1^+)_{\mathrm{exp.}}$	0.333	0.345

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