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Single Particle Levels and $\beta\beta$-Decay Matrix Elements in The Interacting Boson Model

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Abstract. Recently a new method to calculate the occupancies of single particle levels in atomic nuclei was developed in the context of the microscopic interacting boson model, in which neutron and proton degrees of freedom are treated explicitly (IBM-2). The energies of the single particle levels constitute a very important input for the calculation of the occupancies in this method, and further they play important role in the calculation of double beta decay nuclear matrix elements. Here we discuss how the $0\nu\beta\beta$, $0\nu_h\beta\beta$, and $2\nu\beta\beta$-decay nuclear matrix elements (NMEs) are affected when the energies of single particle levels are changed.

1. INTRODUCTION

The question of whether neutrinos are Majorana or Dirac particles, and of what are their masses and phases in the mixing matrix, remains one of the most important in physics today. A direct measurement of the average mass can be obtained from the observation of the neutrinoless double beta decay, $0\nu\beta\beta$. Several experiments are underway to detect this decay, and others are in the planning stage (for review see e.g. [1]). The half-life for this decay can be written as

$$[\tau_{1/2}^{0\nu}]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2 , \tag{1}$$

where $G_{0\nu}$ is a phase space factor, $M_{0\nu}$ the nuclear matrix element and $f(m_i, U_{ei})$ contains physics beyond the standard model through the masses m_i and mixing matrix elements U_{ei} of neutrino species. Concomitant with the neutrinoless modes, there is also the process allowed by the standard model, $2\nu\beta\beta$, which has been observed in several nuclei. For this process, the half-life can be, to a good approximation, factorized in the form

$$\left[\tau_{1/2}^{2\nu}\right]^{-1} = G_{2\nu} \left|M_{2\nu}\right|^2 . \tag{2}$$

In order to extract physics beyond the standard model, contained in the function f in Eq. (1), an accurate calculation of both $G_{0\nu}$ and $M_{0\nu}$ is needed. These calculations serve the purpose of extracting the neutrino mass $\langle m_\nu \rangle$ if $0\nu\beta\beta$ is observed, and of guiding searches if $0\nu\beta\beta$ is not observed.

The fact that $0\nu\beta\beta$-decay is a unique process, and there is no direct probe which connects the initial and final states other than the process itself makes the prediction challenging for theoretical models. Recently we have calculated the occupancies of the single particle levels in order to satisfy a twofold goal: to asses the goodness of the single particle energies and check the reliability of the used wave functions. Both tests are particularly important in the case of nuclei involved in double beta decay, as they affect the evaluation of the NMEs and then their reliability [2]. As part of the calculation single particle energies were updated as shown in Fig. 1 and further discussed in Ref. [3]. The previous and updated sets of single particle levels are obtained from the experimental excitation energies of one-particle states, but in the second case they correspond to nuclei with mass number closer to the values of the nuclei studied in this work, since we are assuming that the energies of the single particle levels change with the value of A. Due to the lack of experimental data in some cases we used interpolated values or we extract the values from systematics in several nuclei. More technical details can be found in [3].

In what follows we report the $0\nu\beta\beta$, $0_h\nu\beta\beta$, and $2\nu\beta\beta$-decay nuclear matrix elements calculated using these updated single particle energies.

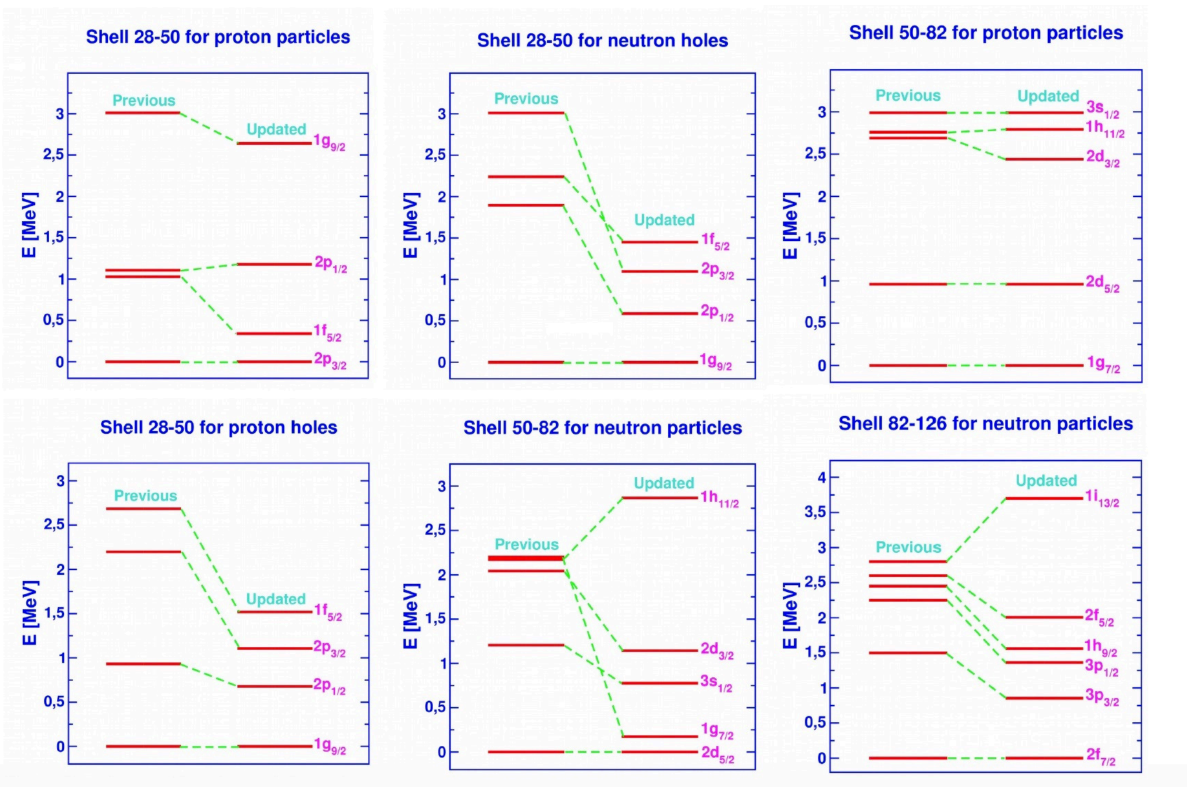

Figure 1. Comparison of previous and updated single particle energies in different shells 28-50 and 50-82 for protons and 28-50 50-82, and 82-126 for neutrons.

2. RESULTS

The method of calculating $\beta\beta$-decay NMEs in IBM-2 is described in detail in Refs. [4, 5] and the method for isospin restoration in Ref. [6]. The used parameters apart from single particle energies are listed in Refs. [5, 7].

2.1. Double beta decay with light neutrino exchange, $0\nu\beta\beta$

Comparison of previous and updated $0\nu\beta\beta$-decay NMEs calculated using IBM-2 is presented in Fig. 2. In general, the use of the updated single particle energies increase the NMEs. The increment is especially notable in the $A = 76 - 100$ region. These nuclei correspond to the proton shell 28-50 and neutron shells 28-50, 50-82 and Fig. 1 reveals that, indeed, the change in single particle energies is prominent in these shells.

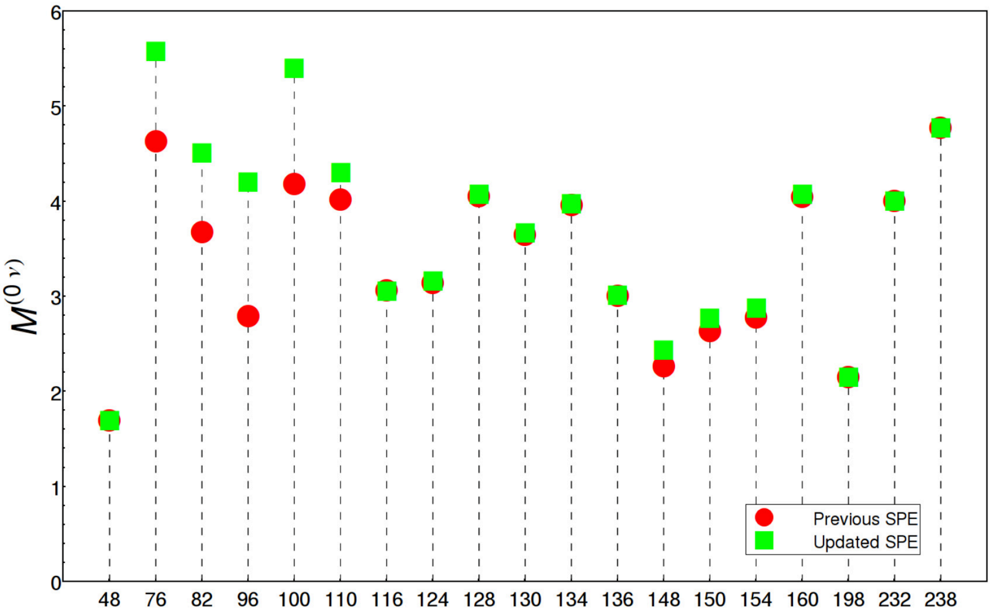

Figure 2. Comparison of previous and updated nuclear matrix elements for $0\nu\beta\beta$-decay with light neutrino exchange calculated using IBM-2.

2.2. Double beta decay with heavy neutrino exchange, $0\nu_h\beta\beta$

Fig. 3 shows the comparison of previous and updated $0\nu_h\beta\beta$-decay NMEs calculated using IBM-2. In case of heavy neutrino exchange the increase is also notable in $A = 76 - 100$ region as in the case of light neutrino exchange, but there is a decrease in $A = 150 - 160$ region. For $A < 76$, $100 < A < 150$, and $A > 160$ nuclei the NMEs stay intact, even though single particle energies are updated.

Note that in Ref. [8] a method of predicting possible contributions of sterile neutrinos to neutrinoless double beta decay using $0\nu\beta\beta$ and $0\nu_h\beta\beta$ NMEs was discussed. Using the NMEs obtained using updated single particle energies, also these predictions can be updated.

2.3. $2\nu\beta\beta$-decay

For comparison we also show $2\nu\beta\beta$-decay NMEs in Fig. 4. Like in the case of light neutrino exchange, the NMEs calculated with the updated single particle energies are generally larger than the previous ones, with the notable exception of $A = 116$. In $A = 76-100$ and $A = 148-160$ regions the increment is notable and when combined with phase space factors, [9], will affect the predicted half-lives. Thus the extracted effective values of g_A will also be affected, if procedure of [5] is followed.

3. DISCUSSION AND SUMMARY

The observed increase in the matrix elemens shown in Figures 2, 3 and 4 can be explained in our calculation scheme by considering what is affected when the single particle energies are changed. In the cases where the increase is observed the single particle energies decrease in general. This

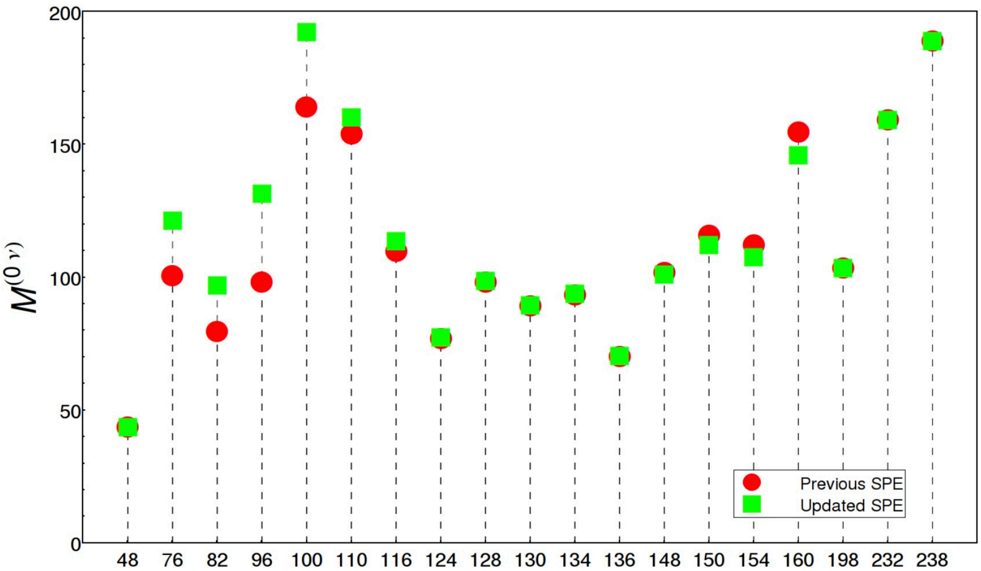

Figure 3. Comparison of previous and updated nuclear matrix elements for $0\nu\beta\beta$-decay with heavy neutrino exchange calculated using IBM-2.

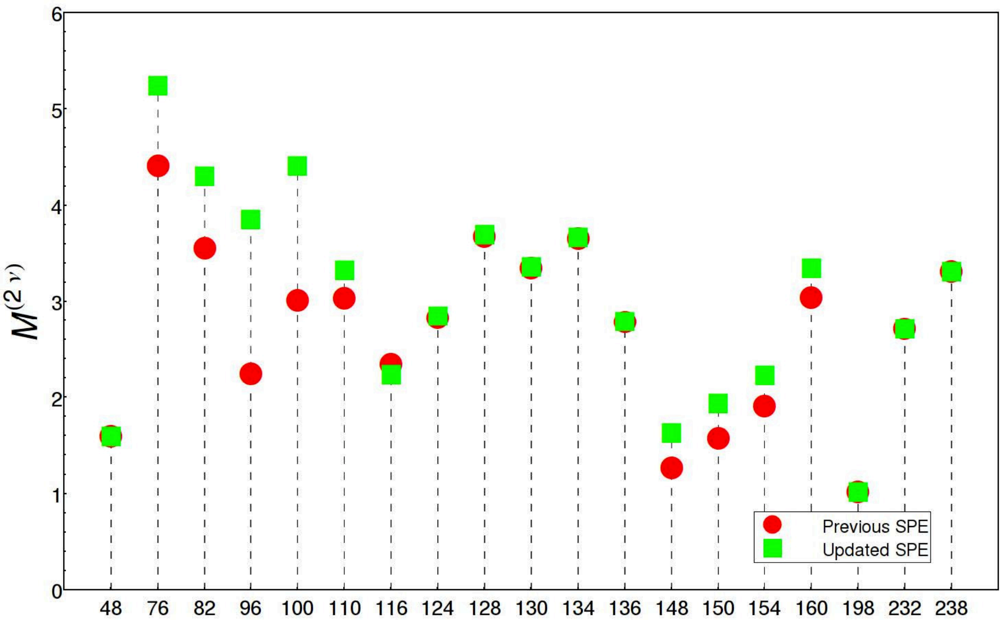

Figure 4. Comparison of previous and updated nuclear matrix elements for $2\nu\beta\beta$-decay calculated using IBM-2.

decrease or compressing of the levels produces higher values of the structure coefficients of the S and D pairs, which appear in products and raised to exponents which depends on the number of pairs or equivalently the number of bosons (see reference [4] for details). This effect is combined in protons and neutrons for $A = 76 - 100$ and only in neutrons for $A = 148 - 160$, which explains why the increasing values are at lesser extend in the last cases. Also the case $A = 110$ is less affected because of the low number of protons outside closed shell.

In summary, we have calculated nuclear matrix elements relevant for double beta decay (with two and zero neutrinos for light and heavy neutrino exchange) using an updated set of single particle energies which describe their measured occupancies fairly well. In some cases the new values of the matrix elements are higher than those of previous calculations, showing that the single particle level energies have an impact in our calculations, especially when both protons and neutrons are affected and the number of valence particles outside closed shells is higher.

4. ACKNOWLEDGMENTS

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