Nuclear structure and neutrinoless double beta decay

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Abstract. The status of calculation of the neutrinoless double beta decay ($0\nu\beta\beta$-decay) nuclear matrix elements (NMEs) is reviewed. The spread of published values of NMEs is discussed. The main attention is paid to the recent progress achieved in the evaluation of the $0\nu\beta\beta$-decay NMEs in the framework of the quasiparticle random phase approximation (QRPA). The obtained results are compared with those of other nuclear structure approaches. The problem of reliable determination of the $0\nu\beta\beta$-decay NMEs is addressed. It is manifested that the uncertainty associated with the calculation of the $0\nu\beta\beta$-decay NMEs can be diminished by suitable chosen nuclear probes.

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INTRODUCTION

The fundamental importance of the search for $0\nu\beta\beta$-decay,

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-}, \tag{1}$$

is widely accepted. After 70 years the brilliant hypothesis of Ettore Majorana is still valid and is strongly supported by the discovery of neutrino oscillations and by the construction of the Grand Unified Theories. The $0\nu\beta\beta$-decay is currently the most powerful tool to clarify if the neutrino is a Dirac or a Majorana particle. This issue is intimately related with the origin of neutrino masses having a strong impact also on astrophysics and cosmology.

The main aim of the experiments on the search for $0\nu\beta\beta$-decay is the measurement of the effective Majorana neutrino mass $m_{\beta\beta}$. Under the assumption of the mixing of three massive Majorana neutrinos the effective Majorana neutrino mass $m_{\beta\beta}$ takes the form

$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3. \tag{2}$$

Here, U_{ei} and m_i ($i = 1,2,3$) are elements of Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix and masses of neutrinos, respectively.

Experimental searches for the $0\nu\beta\beta$-decay, of ever increasing sensitivity, are being pursued worldwide. However, interpreting existing results as a measurement of the Majorana neutrino effective mass and planning new experiments, depends crucially on the knowledge of the corresponding nuclear matrix elements that govern the decay rate. Accurate determination of the nuclear matrix elements, and a realistic estimate of their uncertainty, is of great importance.

CURRENT STATUS OF THE $0\nu\beta\beta$-DECAY NMES

The inverse value of the $0\nu\beta\beta$-decay half-life for a given isotope (A,Z) is a product of the effective mass of Majorana neutrinos $m_{\beta\beta}$, the known phase-space factor $G_{0\nu}(Q_{\beta\beta}, Z)$ (depending on nuclear charge Z and the energy release $Q_{\beta\beta}$ of the reaction) and the nuclear matrix element $M^{0\nu}$, which depends on the nuclear structure of the particular isotope under study [1]:

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\ |M^{0\nu}|^2\ |m_{\beta\beta}|^2. \qquad (3)$$

From the measurement of half-life of the $0\nu\beta\beta$-decay only the product $|m_{\beta\beta}|\ |M^{0\nu}(A,Z)|$ of effective neutrino mass and nuclear matrix element can be determined. Clearly, the accuracy of the determination of $|m_{\beta\beta}|$ from the measured $0\nu\beta\beta$-decay half-life is mainly given by our knowledge of nuclear matrix elements. Without accurate calculation of the $0\nu\beta\beta$-decay NMEs, it is not possible to reach qualitative conclusions about neutrino masses, the type of neutrino mass spectrum and CP violation.

The nuclear matrix elements for $0\nu\beta\beta$-decay must be evaluated using tools of nuclear structure theory. Unfortunately, there are no observables that could be directly linked to the magnitude of $0\nu\beta\beta$-decay nuclear matrix elements and that could be used to determine them in an essentially model independent way. The calculation of the $0\nu\beta\beta$-decay matrix elements is a difficult problem because ground and many excited states of open-shell nuclei with complicated nuclear structure have to be considered.

The main two basic approaches used for evaluation of double beta decay NMEs are the Quasiparticle Random Phase Approximation (QRPA) [2, 3] and the Large Scale Shell Model (LSSM) [5]. Both methods have the same starting point, namely a Slater determinant of independent particles. However, there are substantial differences between both approaches, namely the kind of correlations they include are complementary. The QRPA treats a large single particle model space, but truncates heavily the included configurations [2]. The LSSM, by a contrast, treats a small fraction of this model space, but allows the nucleons to correlate in arbitrary ways [4].

Due to its simplicity the QRPA is a popular technique to calculate the $0\nu\beta\beta$-decay NMEss. One of the most important factors of the QRPA calculation of the $0\nu\beta\beta$-decay NMEs is the way how the particle-particle strength of the nuclear Hamiltonian g_{pp} is fixed. It has been shown that by adjusting g_{pp} to the $2\nu\beta\beta$-decay rates the uncertainty associated with variations in QRPA calculations of the $0\nu\beta\beta$-decay NMEs can be significantly eliminated [2]. In particular, the results obtained in this way are essentially independent of the size of the basis, the form of different realistic nucleon-nucleon potentials, or on whether QRPA or renormalized QRPA (take into account Pauli exclusion principle) is used.

Matrix elements for the double beta decay are calculated also by angular momentum projected (with real quasi-particle transformation) Hartree-Fock-Bogoliubov (P-HFB) wave functions [6] and by the Interacting Boson Model (IBM) [7]. The P-HFB allows only, that neutron pairs with angular momenta 0^+, 2^+, 4^+, $\cdots$ are transformed into two protons in the $0\nu\beta\beta$-decay. In addition the pairs different from 0^+ are strongly suppressed compared to the results of the LSSM and the QRPA. The approaches LSSM and

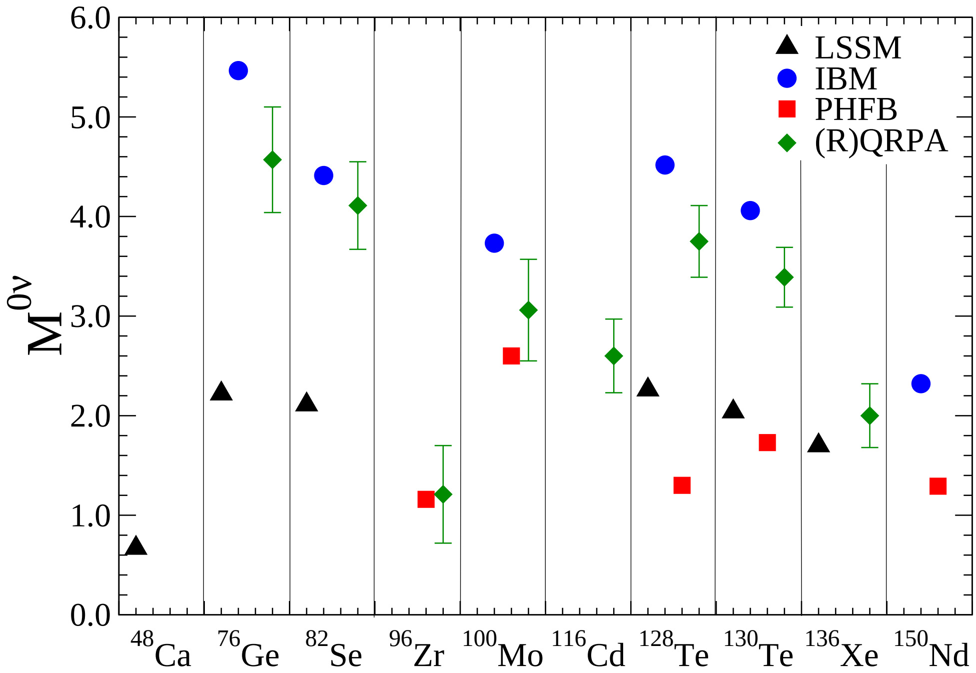

FIGURE 1. The $0\nu\beta\beta$-decay NMEs calculated within different nuclear structure approaches: Large Scale Shell Model (LSSM) [5], (Renormalized) Quasiparticle Random Phase Approximation (R)QRPA [3], Projected Hartree-Fock Bogoliubov approach (P-HFB) [6] and Interacting Boson Model (IBM) [7]. The Miller-Spencer Jastrow two-nucleon short-range correlations are taken into account.

QRPA show also, that other neutron pairs contribute strongly, which can not be included into real P-HFB. One would need to extend the P-HFB approach to complex quasi-particle transformations and probably also to several orthogonal P-HFB configurations. IBM is even more restrictive: It allows only that 0^+ and 2^+ neutron pairs are changed into proton pairs.

The calculated $0\nu\beta\beta$-decay NMEs within these approaches are presented in Fig. 1. It is surpricing that the IBM results agree well with the QRPA ones. Results of these aproaches exhibit some dependence on A unlike the LSSM values, which are practically the same except for ^{48}Ca. The value of the $0\nu\beta\beta$-decay NME for this isotope is suppressed as ^{48}Ca is a magic nucleus.

REDUCING THE UNCERTAINTY IN NMES

The improvement of the calculation of double beta decay nuclear matrix elements is a very important and challenging problem. The uncertainty associated with the calculation of the $0\nu\beta\beta$-decay NMEs can be diminished by suitable chosen nuclear probes. A complementary experimental information from related processes like charge-exchange reactions, muon capture and charged current (anti)neutrino-nucleus reactions is highly required. A direct confrontation of nuclear structure models with data from these processes might improve quality of nuclear structure models. The constrained parameter space of nuclear models is a promising way to reduce uncertainty in the calculated $0\nu\beta\beta$-decay NMEs.

As a practice, knowledge of the $2\nu\beta\beta$-decay rate and of the ordinary decay ft values were used to constrain the nuclear model parameters, in particular when the quasiparticle random phase approximation (QRPA) was employed [3]. Clearly, when other relevant data become available, and the nuclear model is constrained to reproduce them, confidence in the deduced $0\nu\beta\beta$-decay NMEs is increased. Recently, a set of such data, the occupation numbers of neutron valence orbits in the initial ^{76}Ge and final ^{76}Se nuclei, were determined in a series of measurements of cross sections for neutron and proton adding and removing transfer reactions [8].

The occupancies of valence neutron and proton orbits determined experimentally in Refs. [8], represent important constraints for nuclear models used in the evaluation of the $0\nu\beta\beta$-decay NMEs. In Ref. [9] the input mean field has been modified in such a way that the valence orbits in the model obey these constraints. Within QRPA and its generalizations it was found that it is important to also choose the variant of the basic method that makes such comparison meaningful by conserving the average particle number in the correlated ground state. When following this procedure, but otherwise keeping the same steps as in evaluation of $M^{0\nu}$ within QRPA before, the conclusion was that for the $^{76}Ge \rightarrow ^{76}Se$ transition the matrix element is smaller by 25%, reducing the previously bothersome difference with the shell model prediction noticeably. Clearly, having the experimental orbit occupancies available and adjusting the input to fulfill the corresponding constraint makes a difference. It would be very useful to have similar constraints available also in other systems, in particular for ^{130}Te and/or ^{136}Xe.

Charge-exchange reactions of (p,n) and (n,p) type at intermediate energies and at forward angles, i.e., low momentum transfers ($q_{tr} \sim 0$ and $\Delta L = 0$), selectively excite Gamow-Teller (GT) transitions owing to the dominance of the $V_{\sigma\tau}$ component of the effective interaction. However, experiments which employ the elementary (p,n) and (n,p) reactions have rather limited resolution and alternatives to them have now successfully been established through the (n,p)-type $(d,^2He)$ or $(t,^3He)$ reactions and the (p,n)-type $(^3He,t)$ reaction. Resolutions on the order of 100 keV in the case of $(d,^2He)$, 190 keV for $(t,^3He)$ and 30 keV for $(^3He,t)$ have routinely been achieved [10].

The connection between the two-neutrino double beta decay ($2\nu\beta\beta$-decay) half-life and the GT transition strength B(GT) is as follows:

$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu}(Q,Z)\left|M_{DGT}^{2\nu}\right|^2, \tag{4}$$

where $G^{2\nu}(Q,Z)$ is a phase-space factor depending on the Q-value of the reaction and the Z-value of the decaying nucleus. It contains squared the weak interaction coupling constant g_A. The $2\nu\beta\beta$-decay matrix element can be deduced by combining GT^+ and GT^- distributions in the following way:

$$\begin{aligned} M_{DGT}^{2\nu} &= \sum_m \frac{M_m^{GT^+} \cdot M_m^{GT^-}}{Q_{\beta\beta}/2 + m_e + E_x(1_m^+) - E_0}, \\ B(GT^\pm) &= \frac{1}{2J_i+1}\left|M^{GT^\pm}\right|^2. \end{aligned} \tag{5}$$

Here, $(E_x(1^+_m) - E_0)$ is the energy difference between the m^{th} intermediate 1^+ state and the initial ground state. $Q_{\beta\beta}$ is the Q-value of the $\beta\beta$-decay, and the $\sum_m$ runs over all states of the intermediate nucleus. In this approach the effect of a destructive interference among contributions of different states of intermediate nucleus to $M^{2\nu}_{DGT}$ is neglected.

The results of the charge-exchange reaction experiments therefore furnish important information about the nuclear physics relevant for double β-decay [10]. This information directly feed into model calculations, which are aimed at describing reliably the nuclear physics around both decay variants, the $2\nu\beta\beta$-decay and the $0\nu\beta\beta$-decay. A high energy resolution of the order of 30 keV, which can presently only be obtained at the RCNP facility in Osaka, allows a precise determination of the GT strength distribution. The high resolution can give significant insight into the details of the nuclear structure. It may be important to understand if the concentration of the low-energy B(GT) strength within a single strong transition, as was observed in the case of ^{96}Zr and ^{100}Mo, is a somewhat general feature of nuclei with masses $A \sim 100$ or above [10]. An open question is the $2\nu\beta\beta$-decay half-life of ^{136}Xe, which has been not measured yet. The reason of suppression of this process is not known. Clearly, explanation of these effects has significant bearing on the double β-decay rate.

we note that a possibility to study charge-changing and particle transfer reactions at iThemba Labs in South Africa is under discussion.

CONCLUSION AND OUTLOOK

Many new projects for measurements of $0\nu\beta\beta$-decay have been proposed, which hope to probe effective neutrino mass $m_{\beta\beta}$ down to 10-50 meV. Nuclear matrix elements need to be evaluated with uncertainty of less than 30% to establish the neutrino mass spectrum and CP violating phases. The improvement of the calculation of the nuclear matrix elements is a very important and challenging problem.

Recently, there has been significant progress in understanding the source of the spread of calculated NMEs. Nevertheless, there is no consensus among nuclear theorists about their correct values, and corresponding uncertainty. However, a recent development in the field is encouraging. There is a reason to be hopeful that the uncertainty will be reduced.

An important cross-check for nuclear models would be to explore the structure of the intermediate odd-odd nuclei by the charge exchange reactions. There are possibilities for improving the QRPA calculation of NMEs, e.g., by taking into account the deformation of parent and daughter nuclei. Further progress in the NSM calculation will be possible due to increasing computer speed and memory. This will allow to extend the considered model spaces. The exactly solvable models can also help to find the ultimate solution of this important problem. It is also clear that in order to have confidence in calculated NMEs multiple $0\nu\beta\beta$-decay experimental results are required.

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