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News & Views

Advances in modeling nuclear matrix elements of neutrinoless double beta decay

Jiangming Yao

Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824-1321, USA

The neutrinoless double beta ($0\nu\beta\beta$) decay is a hypothetical weak process which manifests itself in the "low-energy" environment of atomic nuclei as two neutrons in a parent nucleus (A, Z) decays into two protons in a daughter nucleus $(A, Z+2)$ with the emission of two electrons but no (anti) neutrinos [1]. This process violates lepton number – an accidental global symmetry in the Standard Model of particle physics. Its observation would have important implications in the theories those are trying to explain the asymmetry between matter and anti-matter in the Universe. Besides, it would confirm the Majorana nature of neutrinos and provide one of the most promising ways to determine their absolute mass scale. Therefore, the search for $0\nu\beta\beta$ decay has become a priority in nuclear and particle physics.

The experimental search for the $0\nu\beta\beta$ decay is a great challenge as it is an extremely rare process if exists. Currently, the best half-life lower limit (>10^{25} years) is achieved in the experiments on ^{136}Xe [2], ^{76}Ge [3] and ^{130}Te [4]. Next-generation experiments aiming to increase detector mass further to tonne-scale size and to reduce backgrounds as much as possible, are expected to reach a discovery potential of half-life 10^{28} years after a few years of running.

In the standard light-Majorana neutrino-exchange mechanism, the inverse of the decay half-life can be factorized as follows,

$$[T_{1/2}^{0\nu\beta\beta}]^{-1} = g_A^4 G_{0\nu}\left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2 \left|M^{0\nu}\right|^2, \qquad (1)$$

where g_A (unquenched value 1.27) is the nucleon axial charge, and m_e (0.511 MeV) is the electron mass. The nucleus-dependent phase-space factor $G_{0\nu}$ ($\sim 10^{-14}$ yr^{-1}) can be evaluated precisely. The effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle = \left|\sum_{k=1}^{3} U_{ek}^2 m_k\right|$ is a linear combination of neutrino masses m_k weighted by the square of the elements U_{ek} of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix that mixes neutrino flavors.

The null $0\nu\beta\beta$ decay signal from current experiments provides a constraint on the upper limits of effective neutrino mass $\langle m_{\beta\beta}\rangle$ if the decay is mediated by the exchange of light-Majorana neutrinos. In this scenario, the next-generation tonne-scale experiments are expected to provide a definite answer on the mass hierarchy of neutrinos based on our current knowledge on the nuclear matrix element (NME) $M^{0\nu}$ of $0\nu\beta\beta$ decay. The NME $M^{0\nu} = \langle \Psi_F \mid O^{0\nu} \mid \Psi_I\rangle$ cannot be measured, but must be determined from a theoretical calculation, which is a challenge for nuclear theory. The ingredients: transition operator $O^{0\nu}$ and nuclear wave functions $\mid \Psi_{I/F}\rangle$ for the initial and final nuclei, require a consistent treatment of both the strong and weak interactions and a precise modeling of nuclear many-body systems. The popularly used nuclear models based on either an energy density functional (EDF) universal for atomic nuclei throughout the nuclear chart or an effective interaction that is adjusted to atomic nuclei in a particular mass region predict NMEs differing from each other by a factor of about three, causing an uncertainty of an order of magnitude (or more) in the half-life for a given value of the neutrino mass. Resolving this discrepancy among model predictions has been one of the major tasks in nuclear theory community. A great deal of effort has been devoted to understanding how the EDF or effective interaction and the model space affect the predicted NME. However, the systematic uncertainty turns out to be difficult to reduce because each model has its own phenomenology and uncontrolled approximations.

Thanks to the development in high-performance computing and the introduction of similarity renormalization group (SRG) into low-energy nuclear physics in the past decade, significant progress has been made in the *ab initio* modeling of atomic nuclei, in which quantum mechanical many-body problem is solved either exactly for very light nuclei or *quasi-exactly* by employing certain well-controlled approximations for heavier nuclei using nucleons as fundamental degrees of freedom and a nuclear force between them with coupling constants fit to reproduce data in few-nucleon systems. The nuclear force is believed to emerge from the strong interaction described by quantum chromodynamics (QCD), which is, however, non-perturbative in the low-energy regime relevant to nuclear physics. This makes the direct use of QCD for nuclear forces very difficult. The most popularly used nuclear forces in *ab initio* calculations are derived from chiral effective field theory (EFT). In the chiral EFT, one can construct effective Lagrangians that consist of interactions that are consistent with the symmetries of QCD and organized by an expansion in the power of Q/Λ_χ. Here, Q ($\sim$0.14 GeV) is a typical momentum of the interacting system, and Λ_χ ($\sim$ 1.0 GeV) is the breakdown scale of the chiral EFT, which

E-mail address: yaoj@frib.msu.edu

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is associated with physics that is not explicitly resolved. The power counting in the chiral EFT provides a convenient scheme to quantify the uncertainty from nuclear interactions and electroweak operators. Starting from chiral interactions, *ab initio* methods are able to predict nuclear structure properties and single-beta decay rates of atomic nuclei up to mass number $A = 100$ or even beyond [5]. Nevertheless, *ab initio* calculation of the NME of candidate $0\nu\beta\beta$ decay from first principles is not straightforward as the decay evolves deformed nuclei with strong collective correlations for which usual truncation schemes of nuclear many-body methods are ill suited.

Recently, we reported the first *ab initio* calculation for the NME of lightest candidate $0\nu\beta\beta$ decay from spherical ^{48}Ca to deformed ^{48}Ti starting from a SRG-softened chiral two-plus-three-nucleon interaction EM1.8/2.0 with a novel many-body method labeled as GCM-IMSRG [6]. The NME of $0\nu\beta\beta$ decay turns out to be $0.61^{+0.04}_{-0.05}$, which is in good agreement with the values from the most recent two *ab initio* calculations labeled as VS-IMSRG and CCSDT1 respectively. In the VS-IMSRG calculation [7], the Hamiltonian, together with the $0\nu\beta\beta$ decay operator, is decoupled non-perturbatively into a given valence space, which provides inputs for subsequent interacting shell model (ISM) calculation. Their predicted NME for ^{48}Ca is 0.58(1). In the CCSDT1 calculation [8], equation-of-motion techniques are used to compute the NME, in which the ground state of one nucleus is represented as an isospin excitation of another nucleus in the decay. They predicted the NME in between 0.25 and 0.75, where the upper and lower boundary values are obtained from the choice of initial and final state as reference state, respectively.

Fig. 1 summarizes the NMEs of $0\nu\beta\beta$ candidate decays predicted by various nuclear models based on the standard light-Majorana neutirno-exchange mechanism. Compared to the values presented in a recent review paper [9], the updated NMEs from isospin-restored deformed quasi-particle random-phase-approximation (QRPA) calculation [10], the most recent ISM calculation using the Hamiltonian and decay operator constructed from many-body perturbation theory (MBPT) starting from CD-Bonn potential [11] and the three *ab initio* calculations starting from the same chiral interaction [6–8] are included. We note that the VS-IMSRG calculation also predicted NMEs for ^{76}Ge and ^{82}Se [7], which are to be confirmed with other *ab initio* calculations. It is shown that the NMEs by the *ab initio* calculations are generally smaller than the predictions of phenomenological models probably because more short-range correlations are taken into account. It indicates that larger detectors may be required for a given sensitivity of the effective neutrino mass $\langle m_{\beta\beta}\rangle$.

ab initio methods are essential for the calculation of $0\nu\beta\beta$ decay NMEs. However, there are many caveats while interpreting the NMEs from the reported *ab initio* calculations. These values are subject to change when the truncation error for nuclear interactions and transition operators in chiral EFT, and that in many-body methods are taken into account. For the transition operators, the contribution of a recently discovered leading-order (LO) short-range operator [12], together with the next-to-next-to-leading order (N^{2}LO) operators [13] that cannot be absorbed into momentum dependent form factors but could contribute up to $\mathcal{O}(10\%)$ of the NME [14], is missing in the results presented in Fig. 1. The LO short-range operator could either enhance or quench the NME by an amount that is comparable to its size [12,8] depending on the unknown low-energy constant of this operator, which must be determined from future lattice QCD calculations [15]. Besides, the contribution of the two-body weak currents which induce three-nucleon interactions and appear at next-to-next-to-next-to-leading order (N^{3}LO) is not considered yet. It turns out that the two-body weak currents, together with many-body correlations, are important for the accurate calculation of nuclear single-beta decay rates [5]. These two-body weak currents may also have a significant impact on the $0\nu\beta\beta$ decay NMEs. Contribution from other mechanisms, such as heavy-particle exchange, also needs to be examined. For the many-body truncation, recent benchmark studies against "exact solution" from no-core shell-model calculations for very light nuclei [8] provide a hint that the impact of many-body truncation employed in the reported *ab initio* calculations on the NMEs is under control. This truncation

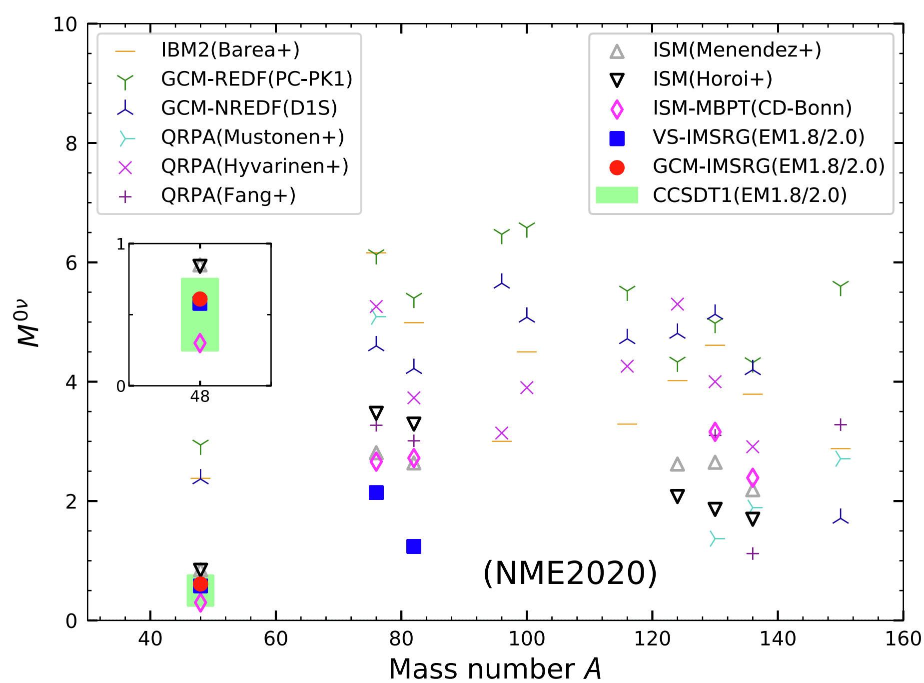

Fig. 1. (Color online) The NMEs of candidate $0\nu\beta\beta$ decay from the calculations of both phenomenological and *ab initio* nuclear models based on the mechanism of exchange light Majorana neutrinos.

error may become significant in the candidate decays of heavier nuclei and must be investigated. Thus, lots of work still remains to be done to produce NMEs with fully quantified theoretical uncertainties.

In summary, accurate NMEs for $0\nu\beta\beta$ decay of candidate nuclei are important for the design and interpretation of future experiments. Significant progress has been made in the modeling of these NMEs from first principles. The NME for ^{48}Ca shows a good agreement among three different *ab initio* calculations starting from the same nuclear interaction constructed within the chiral EFT and the same decay operator. These studies open the door to *ab initio* calculations of the matrix elements for the decays of heavier nuclei such as ^{76}Ge, ^{130}Te, and ^{136}Xe. The ultimate goal is the computation of NMEs in many-body methods with controllable approximations using nuclear interactions and weak transition operators derived consistently from the chiral EFT with the feature of order-by-order convergence. We are expecting more progress towards this goal in the near future.

Conflict of interest

The author declares that he has no conflict of interest.

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Jiangming Yao received his doctorate degree in Nuclear Physics from Peking University in 2009. After holding research positions at Southwest University, Université libre de Bruxelles, Tohoku University, and University of North Carolina at Chapel Hill, he joined in the National Superconducting Cyclotron Laboratory (NSCL/FRIB) at Michigan State University in 2018 as a research associate. His research interest is nuclear theory and its application to interdisciplinary fundamental problems in nuclear physics, particle physics and astrophysics.