Large-scale nuclear-structure calculation for constraining neutrino masses

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Neutrinos are quite "abundant" elementary particles in the universe because they are emitted from a nucleus (with mass number *A* and proton number *Z*) during its β decay:

$$^{A}Z \rightarrow {}^{A}(Z-1) + e^{-} + \bar{\nu}_{e},$$

where e^{-} and $\bar{\nu}_{e}$ are an electron and a (electron-) antineutrino, respectively. Nevertheless, many of the neutrino properties are still unknown. This is because these particles are quite hard to detect due to very weakly interacting nature. While neutrinos are proven to be massive particles by the Super-Kamiokande experiment on the basis of neutrino oscillation, it is impossible to measure their absolute masses using the same principle.

Among several possible methods to measure neutrino masses, ββ decay is regarded to be a promising probe. ββ decay occurs for nuclides which are stable or very long-lived against single β decay but are unstable against two simultaneous β decays:

$$^{A}Z \rightarrow {}^{A}(Z-2) + 2e^{-} + 2\bar{\nu}_{e}.$$

The ββ decay is so far observed for about ten nuclides. In addition to this normal ββ decay mode which emits two neutrinos, another ββ decay mode without emitting neutrinos expressed as

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

is possible if neutrinos are Majorana particles, i.e., the particles which are identical with their own antiparticles. Although this decay mode, called zero-neutrino ββ decay, has not been observed yet, Majorana neutrinos are an attractive scenario to account for the extremely small neutrino masses and the dominance of matter over antimatter in the universe, and therefore many experimental projects are running to detect zero-neutrino ββ decay. Once the half-life of zero-neutrino ββ decay is measured, neutrino masses can be derived through

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^{2}\left(\frac{\langle m_{\beta\beta}\rangle}{m_{e}}\right)^{2},$$

where $T_{1/2}^{0\nu}$ and $\langle m_{\beta\beta}\rangle/m_{e}$ are the half-life and the effective neutrino mass in the unit of the electron mass, respectively. While $G^{0\nu}$ is the phase-space factor which is unambiguously given when the masses of the parent and daughter nuclei are provided, $M^{0\nu}$, called nuclear matrix element, cannot be determined without precise information on nuclear many-body properties. Namely, nuclear input is needed to extract the effective neutrino mass from the half-life of zero-neutrino ββ decay. Since the quantity of the nuclear matrix element cannot be directly measured from nuclear experiment, its determination must rely on nuclear-structure theory. In the present study [1], we provide a reliable nuclear matrix element for the zero-neutrino ββ decay in ^{48}Ca, performing a very large-scale nuclear-structure calculation using the K supercomputer.

The nucleus is a quantum many-body system composed of protons and neutrons which interact with one another via the nuclear forces. Since the *A*=48 system (i.e., ^{48}Ca and ^{48}Ti) are still beyond the applicability of the *ab-initio* (first-principles) calculations, one should adopt effective models for the present purpose. Among them, the nuclear shell model (or configuration interaction in terms of quantum chemistry) is usually conceived to provide the most precise nuclear wave function because this model is able to fully include nucleon-nucleon correlation near the Fermi surface, which is essential for describing nuclear structure. In the previous shell-model calculations for the zero-neutrino ββ decay in ^{48}Ca, only the last eight nucleons near the Fermi surface can be explicitly treated as the active model space due to computational limitation at that time. In the present calculation, the degrees of freedom below this active model space are partially treated, and the resulting dimension of the Hamiltonian matrix becomes approximately two billion. We are successful in diagonalizing this large matrix by using the K supercomputer.

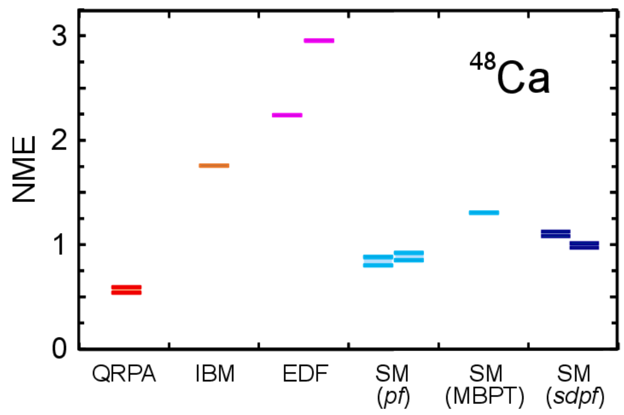

Fig. 1 Nuclear matrix element $\boldsymbol{M^{0\nu}}$ for the zero-neutrino ββ decay of ^{48}Ca compared among various theoretical models in the literature (see [1] and references therein). SM (*sdpf*) and SM (*pf*) stand for the present shell-model calculations and the previous ones, respectively. Two different Hamiltonians are used and compared for EDF, SM (*pf*), and SM (*sdpf*).

In Fig. 1, the nuclear matrix element obtained in this study is compared with other theoretical calculations. The calculated values range from ~0.5 to ~3, indicating large theoretical uncertainty. The previous and present shell-model calculations correspond to SM (*pf*) and SM (*sdpf*), respectively. The comparison between these shell-model calculations shows that the nuclear matrix element enhances by about 30% by taking more nucleon degrees of freedom. Since the present calculation includes the leading correction to the previous calculation, the result should be rather reliable. In fact, nuclear structures in the *A*~40 region are well described with the same setup as the present study [2]. Unlike the shell model, other models (QRPA, IBM and EDF) do not have a systematic way to improve the result.

References

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