Joint project for large-scale nuclear structure calculations in 2018

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We have been promoting a joint project for large-scale nuclear structure calculations since the year 2002, based on a collaboration agreement between the RIKEN Accelerator Research Facility (currently RIKEN Nishina Center) and the Center for Nuclear Study, the University of Tokyo. This agreement was completed successfully in March 2018 successfully. Based on this project, 62 original papers and 56 proceedings have been published and some are being prepared under various collaborations with many experimentalists (*e.g.* Refs. 1–3)). In 2018, we performed several theoretical studies for understanding the nuclear structure. Among these studies, we briefly show three theoretical achievements: a statistical method for the uncertainty quantification of shell-model studies,[4)] the development of an *ab initio* nuclear structure calculation,[5)] and the theoretical estimation of nuclear matrix elements that are required for surveying physics beyond the standard model.[3,6–9)]

We proposed a novel method to quantify the theoretical uncertainty stemming from the effective interactions of the nuclear shell model.[4)] In this method, the uncertainty is discussed by estimating the probability distribution of the parameter set of the effective interaction in the multidimensional parameter space. This enables us to quantify an extent of the agreement between the theoretical results and experimental data in a statistical manner, and the resulting confidence intervals show unexpectedly large variations. In addition, we pointed out that a large deviation of the confidence interval of the energy in the shell-model calculations from the corresponding experimental data can be used as an indicator of some exotic property, *e.g.*, α clustering.

In order to investigate the medium-mass nuclei based on the underlying nuclear interactions in an *ab initio* way, the unitary-model-operator approach (UMOA)[5)] was developed. In the UMOA, the many-body Hamiltonian is transformed by a unitary transformation such that one-particle-one-hole and two-particle-two-hole excitations do not occur. We calculated the binding energies and radii of ^{4}He, ^{16}O, and ^{40}Ca using the similarity-renormalization-group (SRG) evolved chiral effective-field-theory interaction consisting of two-nucleon and three-nucleon forces. The resulting binding energies and radii were consistent with the recent ab initio results obtained using the same Hamiltonian, and we significantly underestimated the radii compared to the experimental data. To clarify the origin of this underestimation, we also calculated the radii using the effective operators obtained from consistent SRG evolution in two- and three-body spaces. It turned out that the SRG evolution of the radius operator gives a minor modification and the underestimation still remains. For a unified description of the binding energies and radii, a further understanding of the nuclear force itself is essential.

We also studied two-neutrino double-beta decays and double-electron capture. We developed an effective theory that, based on data on beta decays and electron capture, describes well measured double-beta transitions, making predictions for several unknown decays.[6)] Subsequently, we calculated the double electron-capture half-life of ^{124}Xe into the final nucleus ^{124}Te.[7)] Our large-scale shell model results predicted a half-life of about 10^{22} y, which is shorter than that predicted by other theoretical approaches, suggesting that an observation of the double-electron capture of ^{124}Xe is within the reach of current experimental searches.

In addition, we performed shell-model calculations to study the possible scattering of dark matter off atomic nuclei. These interactions could reveal the nature of dark matter, and we investigated how to discriminate experimentally the signal from different dark matter–nucleus couplings.[8)] In addition, together with the XENON collaboration, we analyzed for the first time, the coupling of dark matter particles to the pions exchanged between two nucleons,[3)] a contribution that has so far not been constrained experimentally. Finally, we calculated the more general dark matter-nucleus interactions that can receive coherent contributions from several nucleons in fluorine, silicon, argon, germanium, and xenon targets.[9)]

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