Joint project for large-scale nuclear structure calculations in 2015

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A joint project for large-scale nuclear structure calculations has been promoted 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. Currently, we maintain 16 PC servers with Intel CPUs for large-scale nuclear shell-model calculations. In 2015, we reinforced the system by introducing two computer nodes equipped with Intel Xeon CPUs with 32 cores and 20 cores, respectively. Based on this project, we performed shell-model calculations of the various nuclides that have been measured or are proposed to be measured at the RIKEN RI Beam Factory, such as ^{37,38}Si[1], ^{50}Ar[2], ^{27,29}F, ^{29}Ne, ^{54,56,58,60}Ti, and ^{8,9}C, under various collaborations with many experimentalists. Theoretical studies have also been performed in parallel. Among them, hereafter, we briefly show four achievements of this project.

We have investigated shell evolution in neutron-rich nuclei around $N = 28$ by comparing recent experimental data taken in RIBF with shell-model calculations using the SDPF-MU interaction[3]. Low-lying unnatural-parity levels in ^{37}Si[1] are well reproduced. This indicates that the $N = 20$ shell gap is almost unchanged on increasing the neutron number due to the cross-shell $T = 1$ monopole matrix elements whose strengths are nearly zero. The SDPF-MU interaction also successfully accounts for the 2^+_1 level in ^{50}Ar[2]. The calculation suggests that the $N = 32$ shell gap is preserved in Ar isotopes. In addition, we predict that the $N = 34$ shell gap is enlarged on decreasing the proton number from $Z = 20$. This prediction provides a strong motivation for measuring the 2^+_1 level in ^{52}Ar in the SEASTAR project.

Among the *ab initio* subjects directly related to the experiments at the RIBF, the study of the nuclear structure of proton-rich carbon isotopes (^{8}C and ^{9}C) via neutron-transfer reactions using a ^{10}C secondary beam is ongoing in collaboration with the experimentalists. For ^{8}C, the energies of the 0^+ ground and 2^+ excited states have been calculated using KSHELL in smaller basis spaces (from two to four major shells). No-core MCSM calculations in larger basis spaces (from five to seven major shells) on the K computer are awaited, so as to obtain the converged ground-state and excitation energies. The evaluation of the spectroscopic factor is also planned to investigate the cross section of neutron-transfer reactions in the near future. In association with this study, we also focus on the anomalously large magnetic dipole moment of the ^{9}C nucleus. For this purpose, we are now carrying out the no-core MCSM calculations for that in a relatively large basis space (up to seven major shells) on the K computer.

We proposed a new method of estimating the level density stochastically based on nuclear shell-model calculations[4]. In order to count the number of eigenvalues of the shell-model Hamiltonian matrix, we performed contour integration of a complex function, $f(z) = \langle\phi|\frac{1}{z-H}\phi\rangle$, with H being the Hamiltonian matrix. $|\phi\rangle$ is taken as a random vector to estimate the trace stochastically. The shifted Krylov subspace method enables its efficient computation. By using this method, we successfully reproduced the experimentally observed parity equilibration of the level densities of ^{58}Ni.

As an attempt to connect medium-mass neutron-rich nuclei to the nuclear force, we derived the effective interaction for the shell model starting from the nuclear force. Standard many-body perturbation theory can only be applied to a single major shell because of the divergence appearing in perturbative expansion. However, in this area of the nuclear chart, the larger model spaces of at least more than one major shell have to be considered. Then, we developed a novel revision of the many-body perturbation theory, named the Extended Kuo-Krenciglowa (EKK) method.[5] We applied the EKK method to derive the effective interaction for the valence space of the sd+pf-shell, starting from the χEFT N^{3}LO interaction. Three-nucleon force (3NF) is also added as an effective two-body force by integrating out one of the three nucleons as the hole line of the ^{16}O core. Then, we performed the shell-model calculations of even-even isotopes of Ne, Mg, and Si and succeeded in reproducing the basic properties of those nuclei, *i.e.* the binding energies, excitation energies of the first 2^+ states, E2 transition probabilities, and so on. In particular, it is well known, as the "island of inversion", that the shell gap of $N = 20$ is broken for Ne and Mg, but not for Si. We reproduced the physics of "island inversion" well and our work is the first calculation of this subject starting from the nuclear force and microscopic theories.

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