Joint project for large-scale nuclear structure calculations in 2014

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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. One of the servers has 40 CPU cores and 1TB main memory. Based on this project, we performed shell-model calculations of the various nuclides which had been measured at the RIKEN RI Beam Factory, such as ^{31}Ne, ^{33}Mg, and ^{50}Ar under collaborations with many experimentalists.[1)] Since the results of these collaborations are presented in other reports, here we introduce four theoretical achievements of this project in 2014: development of a shell-model code, shell-model analyses of the isomeric states of ^{43,44}S and high-spin states of neutron-rich Cr, Fe isotopes, and an application of the extended Kuo-Krenciglowa (EKK) method in understanding the island of inversion.

We developed a new code, named “KSHELL” for large-scale shell-model calculations on state-of-the-art supercomputers[2)]. In nuclear shell-model calculations, we solve an eigenvalue problem of the Hamiltonian matrix, whose dimension tends to be huge, by including many-body correlations fully inside the model space. The newly developed code enables us to solve this eigenvalue problem by using many CPU cores efficiently.

We have investigated the structure of exotic nuclei in the $N \sim 28$ region, which attracts much attention in experimental studies using RIBF. In our most recent work[3)], we focus on the nature of exotic isomeric states in neutron-rich S isotopes, in particular strongly hindered $E2$ decay from 4^+_1 and 2^+_1 in ^{44}S[4)]. This study is based on shell-model calculations using the SDPF-MU interaction[5)] which was developed in this joint project. In order to extract intrinsic states from the shell model, we carry out the variation after angular-momentum projection (AM-VAP). The AM-VAP calculation shows that the 4^+_1 level is dominated by a $K = 4$ intrinsic state and that this is the origin of the strong $E2$ hindrance. The 4^+_1 level in ^{44}S is the lightest high-K isomer among the ones ever identified in the $A \sim 100$, $A \sim 130$, $A \sim 180$, and $A \sim 250$ regions.

We have performed large-scale shell model calculations for natural- and unnatural-parity states in Cr and Fe isotopes with $N \leq 35$[6)]. Unnatural positive-parity states in odd-mass Cr and Fe nuclei with $N \leq 35$ were observed experimentally from low-lying energy levels to high-spin ones. These states are dominated by one-particle one-hole excitation across the $N = 40$ shell gap. The model space of our calculation is composed of fp-shell + $0g_{9/2}$ + $1d_{5/2}$ orbits with the truncation allowing $1\hbar\omega$ excitation of a neutron. It effectively describes and predicts the energy levels up to the high-spin states. The effective single-particle energies of $\nu 0g_{9/2}$ in Cr and Fe isotopes are rather constant in the region with $N \leq 35$. This indicates that the sharp drop of the $9/2^+_1$ levels in this mass region, which is discussed as an indication of the evolution of $\nu 0g_{9/2}$, is explained by the Fermi surface approaching the $\nu 0g_{9/2}$ orbit with the increase of neutron number.

Investigation of the neutron-rich nuclei starting from the fundamental nuclear force has been accomplished by the newly constructed EKK method[7)]. To construct the effective interaction for the shell model starting from the nuclear force, we usually utilize the many-body perturbation theory, but the standard perturbation theory ends up with a series of divergences when applied to a large shell-model space, for example, the model space spanned by two major shells. The EKK method avoids a divergence with a re-summation of the perturbative series and makes it possible to construct the effective interaction for more than one major shell. We constructed the effective interaction for the $sdpf$-shell, starting from the N3LO interaction with the EKK method. The contribution from the three-body force is also added as effective two-body interactions. We found that this interaction consistently describes the ground state energies and low-lying levels of even-even nuclei (O, Ne, Mg, Si isotopes). In particular, the disappearance of the $N = 20$ gap of Ne, Mg isotopes and the restoration of the $N = 20$ gap of Si and S isotopes are well described.

References

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