A3-Foresight theory collaboration for nuclear data library: A3LIB

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A quantitative understanding of the r-process nucleosynthesis requires nuclear data across the nuclear chart, including the vicinities of the neutron drip line, which are experimentally inaccessible. Thus the nuclear theory plays a decisive role to bridge between nuclear experiments at RI beam facilities and microscopic inputs of the r-process simulation.

The condition of the r-process is given by an astrophysical environment of explosive phenomena with some possible scenarios. Although nuclear physics that enters the reaction network may depend on the scenario, the most important nuclear data are the nuclear masses, β-decay properties, and neutron capture rates;[1,2] Given the neutron-number density, temperature, and entropy, the seed nuclei are formed through the nuclear statistical equilibrium. Here, the nuclear masses are a key nuclear physics quantity. When the temperature decreases in the order of 100 keV, various nuclear reactions take place, and the neutron-capture process generates neutron-rich nuclei. If the neutron-number density is high, it proceeds to the production of the heaviest nuclei, and fission occurs. In every process, competition with the β-decay should be considered. The β-decay and the β-delayed neutron emission play a role in shaping the final abundance distributions observed in nature.

The nuclear energy-density functional (EDF) approach is a possible theoretical model to describe the above-mentioned nuclear properties in a vast mass region of the nuclear chart in a single framework. Researchers in the A3 (Chine, Japan, and Korea) countries have developed the nuclear EDF method and computational techniques. It is natural to start collaboration on the construction of the nuclear data table necessary for the r-process modeling and the development of the associated nuclear many-body theory.

I briefly explain a rough plan of the theory collaboration. As shown in Fig. 1, the development of the theory and model for each nuclear property is strongly related. The key to success is the construction of the EDF. Given the EDF, the binding energy of a nucleus and the single-particle level density are obtained in a Kohn–Sham scheme. Parallel to an attempt at the microscopic construction of EDF from an interparticle interaction, a phenomenological construction is planned in collaboration with the researchers in Korea. The KIDS functional was introduced to better describe the neutron-star equation of state. We apply the KIDS functional to open-shell nuclei, where the nucleonic superfluidity and shape deformation show up. Subsequently, the KIDS functional is improved for finite nuclei. We developed a novel method for describing odd mass nuclei for a systematic calculation of the nuclear mass. The implementation is performed in the KIDS code.

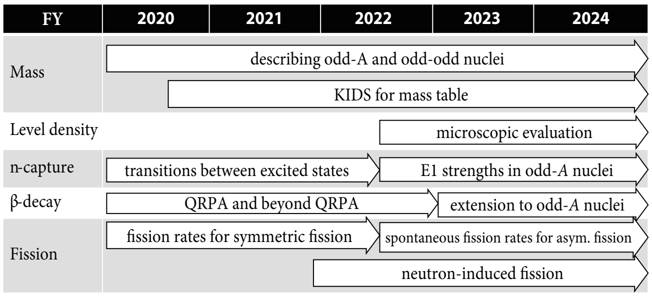

Fig. 1. Plan for the development of A3LIB.

To describe the neutron capture and β decay rates, we employ the EDF-based quasiparticle RPA (QRPA). In neutron-rich nuclei where the neutron separation energy is approximately a few MeV, the direct capture process dominates over the compound process. In such a case, the low-lying excited states and transitions are evaluated microscopically. The description of the transitions among excited states is in progress. For β decay, we take two approaches: a beyond QRPA method for magic nuclei to describe the spreading effect and the QRPA for deformed nuclei.

The microscopic calculation of the fission rate is a big challenge in nuclear theory. The mass parameters and potential energy in the collective (effective) Hamiltonian for fission are microscopically calculated in an EDF approach. The fission rate is then evaluated, *e.g.*, by WKB approximation. Hybrid modeling for the fission yield is planned, where the parameters of the phenomenological model, such as the Langevin approach, are evaluated by a microscopic EDF method.

Finally, the uncertainty quantification is essential in developing a new generation of the nuclear data table. The A3LIB is based on the EDF method; thus, all the calculated quantities are correlated through the coupling constants of EDF. We plan to perform the correlation analysis at each step of the calculation. The results will be provided in the existing data library online.

References

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2) T. Kajino *et al.*, Prog. Part. Nucl. Phys. **107**, 109 (2019).

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