The ONOKORO project—Toward comprehensive understanding on clustering in heavy nuclei

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A new research project, "ONOKORO project," has started to investigate clustering in heavy nuclei using cluster knockout reactions. Do nuclear systems, in general, have an inherent orientation that breaks uniformity? In this research, we try to answer this question by studying formation mechanisms of deuteron, triton, ^{3}He, and α clusters in stable and unstable nuclei in a wide mass range.

Since early days of nuclear physics, α cluster in nuclei have been discussed, first to explain α decays of heavy nuclei, while clustering is now mainly discussed for light nuclei with masses lighter than 30. On the other hand, there are significant progress in theories of cluster formation in infinite nuclear matter.[1,2] Important predictions of the theories are that clusters develop significantly in the low-density region below 1/10 of the saturation density, and the cluster abundances change significantly with the neutron-proton asymmetry. Typel predicted also such a phenomenon would also occur in the low-density surface of heavy nuclei.[3] Our previous experiment for the $^{112-124}$Sn$(p, p\alpha)$ reaction has confirmed Typel's prediction and has demonstrated the existence of α clusters in those nuclei.[4]

The ONOKORO project will extend the scope to all the light clusters of d, t, ^{3}He, α in stable and unstable nuclei from calcium ($Z = 20$) to heavy nuclei beyond lead ($Z = 82$). The (p, pX) cluster knockout reactions, where X denotes d, t, ^{3}He or α, are used to extract information of clusters in nuclei. Characteristic points of the ONOKORO project are:

- d, t, ^{3}He, α clusters are studied on the same footing
- Both stable and unstable nuclei are covered
- Normal and inverse kinematics experiments are combined

Simultaneous studies of d, t, ^{3}He, α are essentially important because the different clusters would manifest different aspects of clustering depending on its spin and isospin. As is discussed in Refs. 2) and 3), dependence on neutron excess is essential in studies of clustering in heavy finite nuclei and in nuclear matter, and thus the access to unstable nuclei is the core of the project.

In order to cover both stable and unstable nuclei, we will perform experiments at intermediate-energy accelerator facilities in Japan, the RIKEN RIBF, the QST HIMAC, and the Osaka University RCNP cyclotron facility. At RCNP, knockout reaction experiments under normal kinematics for stable nuclear targets are conducted using proton beams and double-arm magnetic spectrometers, Grand Raiden and LAS, to obtain high energy-resolution data. State-by-state separation of the final states enabled by the high resolution is a unique capability in experiments at RCNP. At RIBF and HIMAC, inverse-kinematics experiments will be carried out using unstable and stable heavy-ion beams, respectively. The inverse kinematics experiment has the advantage of covering a broad kinematic region and simultaneous measurements for all clusters of d, t, ^{3}He, α.

In this project, we will construct a detector array, TOGAXSI,[5] designed specifically for inverse kinematics knockout reaction experiments. The array consists of 100-μm pitch silicon strip detectors and GAGG:Ce scintillators. GAGG:Ce scintillators have a good time response of 1 ns rise time and <100 ns decay time. Another good feature of GAGG:Ce is no hygroscopic nature.

The cluster knockout reaction theory based on the impulse approximation will be refined to derive the cluster abundance from the experimental cross sections accurately. In particular, a theory that treats the breakup effect, which is essential in the knockout reaction of weakly-bound deuterons, will be developed using the continuum-discretized coupled-channel method.[6]

By comparing the cluster abundance obtained from the experimental data and the reaction theory with the nuclear structure and nuclear matter theories, we will verify the hypothesis of cluster formation in nuclear matter and clarify the mechanism of cluster formation.

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