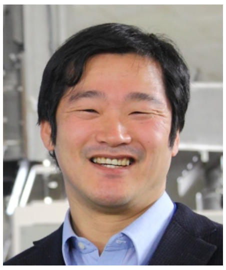
【Grant-in-Aid for Specially Promoted Research】

Science and Engineering



Title of Project : Comprehensive research of cluster formation in nuclear matter

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Research Project Number : 21H04975 Researcher Number : 60322020
Term of Project : FY2021-2025 Budget Allocation : 490,900 Thousand Yen
Keyword : clusters, nuclear matter, knockout reactions, alpha decay, proton-neutron correlations

【Purpose and Background of the Research】

Manifestation of subsystems in matter is relevant to a wide range of fields in physics. Subsystems in nuclei are called "clusters". The alpha cluster (^{4}He nucleus), which has attracted particular attention in the past, has a significant impact on well-known processes in nature, such as alpha decay and the triple alpha reaction involved in stellar evolution. In the decades, advances in nuclear theory and in large-scale calculations together with those in experimental techniques have led to significant progress in the study of cluster structures, but these studies have been limited mainly to light nuclei with masses below 30.

On the other hand, theoretical studies of cluster formation in infinite nuclear matter have recently made significant progress. It has been theoretically predicted that clusters develop significantly in the low-density region below 1/10 of the standard nuclear density (0.17 nucleons/fm^3), and that the cluster abundances depend on the neutron-proton asymmetry. S. Typel predicted that such a phenomenon would also occur in the low-density surface of heavy nuclei, and this prediction was confirmed by the experiments performed by our group.

Does nuclear matter in general have an inherent orientation that breaks uniformity? In this research, we will answer this question by studying the formation mechanism of alpha, deuterons and other clusters using knockout reactions.

【Research Methods】

Using the cluster knockout reaction method, we will determine the abundance of d, t, ^{3}He, and α clusters in heavy nuclei ranging from calcium to lead isotopes and elucidate the mechanism of cluster formation.

The cluster knockout reaction cross sections for stable and unstable nuclei in a wide mass region will be measured using the characteristic beams available at major accelerator facilities in Japan, the RIKEN RIBF, the QST HIMAC, and the Osaka University RCNP cyclotron facility.

At RCNP, we will perform knockout reaction experiments under normal kinematics for stable targets using proton beams and double-arm magnetic spectrometers to obtain data with high energy resolution.

At RIBF and HIMAC, knockout reaction experiments will be carried out in inverse kinematics 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, and α.

In this project, we will fabricate a detector array designed specifically for inverse kinematics knockout reaction experiments at RIBF and HIMAC. The array consists of 100-μm pitch silicon strip detectors and GAGG:Ce scintillators with excellent time response.

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 (CDCC) method.

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

【Expected Research Achievements and Scientific Significance】

The following are expected to be obtained in this research.

- Establishment of surface alpha formation in heavy nuclei and understanding of alpha-decay mechanism
- Discovery of deuteron clusters in heavy nuclei and. clarification of the tensor force effects
- First determination of the ratio of triton and ^{3}He clusters in heavy nuclei and its neutron-excess dependence
- Establishment of theories of cluster knockout reactions
- Comprehensive understanding of the cluster formation in nuclear matter based on the above results.

We believe that this research will clarify that cluster formation is a phenomenon that occurs universally in all nuclei.

The formation of clusters in the nuclear matter will also have an impact on astrophysics, as it has a significant effect on neutrino responses of dilute nuclear matter occurring in supernova explosions and on the structure of nuclear pasta, which is thought to exist in the inner crust of neutron stars.

【Publications Relevant to the Project】

- J. Tanaka, Z.H. Yang, S. Typel, K. Ogata, T. Uesaka, J. Zenihiro et al., “Formation of αclusters in dilute neutron-rich matter”, Science 371, 260 (2021).
- K. Ogata and T. Uesaka, “Knock It Out of the Nucleus—New Structure of Nuclei Revealed by Knockout Reactions—”, to be published in BUTSURI Vol 76.

【Homepage Address and Other Contact Information】

Under preparation.