Knockout reaction studies of clustering in nuclei
– Findings from the ONOKORO project in 2020–2025 –

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1 Clustering in nuclei

The emergence of subsystems within matter is a phenomenon relevant to a wide range of fields in physics. Subsystems in atomic nuclei are referred to as "clusters", and the α-cluster (a ^{4}He nucleus) has received particular attention since the very beginning of nuclear physics and still is the forefront research subject[1, 2]. The existence of the α-cluster is known to exert a significant influence on important processes such as α-decay and the triple-α reaction involved in stellar evolution. The formation of light clusters, including α clusters, is a key factor determining the properties of finite nuclei and nuclear matter formed during supernova explosions; the formation rates and mechanisms of the latter are considered essential for understanding the compact astrophysical objects, and the nucleosynthesis associated with them.

In 2020, we launched a new research project named the ONOKORO project, aiming to comprehensively investigate clustering in nuclei over a wide range of the nuclear chart, using (p, pX) knockout reactions (X : d, t, ^{3}He, and α). Unique features of the project are: 1) all of the light clusters, deuteron, triton, ^{3}He, and α, are investigated. 2) A longer isotopic chain is covered by experiments for stable and unstable nuclei. 3) A wide mass region, from light nuclei such as lithium and carbon isotopes up to α-decay nuclei beyond lead, is covered[3, 4]. The project encompasses experimental studies of stable nuclei at the RCNP cyclotron facility[5] and of unstable nuclei at the RIKEN RI Beam Factory, as well as theoretical investigations of cluster knockout reactions.

The proton-induced cluster knockout reaction employed in the ONOKORO project is regarded as a natural extension of the (p, pN) reactions, which have been successfully used in studies of both stable and unstable nuclei[6, 7, 8, 9, 10, 11]. It is expected that the mechanisms of the cluster knockout reactions are reasonably simple, too, and the distorted-wave impulse approximation (DWIA), the standard reaction analysis framework of the (p, pN) reaction, applies also to the cluster knockout reactions after assessment of the possible effect of the compositeness of clusters. There are several good reasons, in addition to the simple reaction mechanism, to adopt the knockout reactions for the cluster studies: the elementary process is the p-X elastic scattering, for which a rich amount of data at a wide range of incident energies is available. This will help a detailed reaction analysis. The most practical benefit is in the flexibility of kinematics, originating from the three-body final states[12]. The flexibility makes it possible to decouple the low-momentum nuclear structure effects of interest from the high-momentum reaction dynamics, when the reaction kinematics is suitably chosen. The decoupling condition is often referred to as the "*quasi-free*" condition.

Despite being such an excellent experimental method, the existing cluster knockout data are very limited for $A \geq 10$ and $E \geq 100$ MeV: $(p, p\alpha)$ data at $\sim$100 MeV[13], 157 MeV[14], 160 MeV[15], and 1600 MeV[16], (p, pd) and (p, pt) data at $\sim$100 MeV[17], and (p, pd) data at 670 MeV[18]. In most of the previous works, the energy resolution was insufficient to achieve the state-by-state separation, except for those from Maryland [13, 17]. The energy resolution was limited by the adopted detector setup and by the use of a target thick enough to achieve the required statistics.

The state-of-the-art double-arm magnetic spectrometer setup, consisting of the Grand RAIDEN (GR) and the Large Acceptance Spectrometer (LAS) is the world-unique setup that can simultaneously achieve high resolution and high statistics in the (p, pX) knockout reaction experiments, when combined with the high-intensity proton beam at the RCNP Cyclotron facility. . It has been successfly applied to the $(p, 2p)$ reaction studies[19] and recently to the $^{112-124}$Sn$(p, p\alpha)$ reaction[20]. The present project plans to fully exploit the experimental capabilities of the GR-LAS setup and generate the first set of systematics (p, pX) data with a state-by-state separation capability and a reasonably high statistics.

The progress of the ONOKORO project in 2020–2025 is presented in this report.

2 Establishment of the reaction theory for the cluster knockout processes

The establishment of the theory for cluster knockout reactions is mandatory for reliable extraction of the cluster structure information from the experimental data, and thus, it is the basis of the project. The starting point is the DWIA employed in analyses of the (p, pN) reactions. The DWIA has already been applied to analyses of the previous $(p, p\alpha)$ knockout reaction data[13, 21].

Of particular significance is the implementation of cluster knockout reaction analysis into a general-purpose DWIA software package, PIKOE, and its subsequent release to the public [22]. Although PIKOE was originally developed for (p, pN) knockout reaction analysis[6], it has been extended to the cluster knockout (p, pX) reactions. PIKOE is used for nearly all analyses and experimental studies in this research project. Moreover, it will also serve as a standard reaction-theory platform for future knockout-reaction analyses of the data from various facilities around the world.

The other significant achievement is the development of a method to describe the knockout reactions of weakly bound clusters, e.g. deuteron clusters, by explicitly incorporating the breakup and recombination processes during the reaction. This was achieved by integrating the Continuum-Discretized Coupled Channel (CDCC) method into DWIA[23]. The CDCC is well-established as the most precise and flexible model for treating the breakup of weakly bound nuclei.

Figure 1 shows the calculated results for the ^{40}Ca(p, pd) deuteron knockout reaction cross section at an incident proton energy of 250 MeV. The black line represents the calculation without the deuteron breakup effects, while the red line shows the full CDCCIA calculation; The deuteron breakup effect is found to be insignificant in this energy range. On the other hand, the breakup effect becomes larger at an incident proton energy of $\sim$100 MeV[24]. This new reaction model, CDCCIA, will be used in analyses of knockout of the weakly-bound clusters such as deuteron and ^{6}He. On top of the breakup effect, the refraction effect due to the optical potential is found to be substantial in the low-energy (p, pd) knockout reaction, e.g. at $\sim$100 MeV[25], while it is not at higher incident energies employed in the ONOKORO project.

Several theoretical aspects of the cluster knockout reaction which lead to new experimental possibilities or contribute to better understanding of the experimental data are studied in the project: effective polarization in the residual nucleus induced by the cluster knockout reaction[26], breakup properties of triton and ^{3}He particles[27], and the nuclear absorption effects in nucleon and α knockout reactions[28].

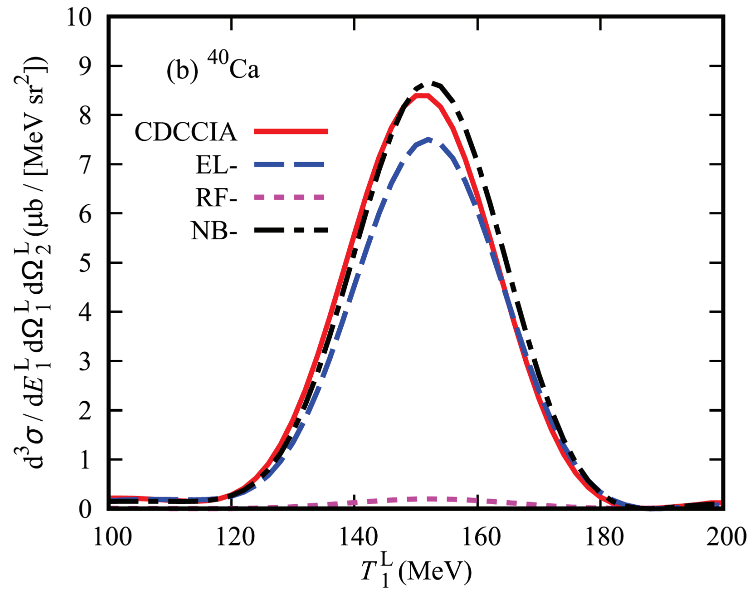

Figure 1: The triple differential cross section for the ^{40}Ca(p, pd) reaction at 250 MeV, predicted by the CDCCIA theory. Reprinted from Ref. [23] with permission from the American Physical Society.

3 First results from the RCNP experiments

In the first series of experiments conducted in 2023–2024 at RCNP, clustering in stable calcium isotopes (^{40,42,44,48}Ca), as well as in ^{12}C and ^{16}O was investigated using proton beams at 226 MeV and 392 MeV accelerated at the Cyclotron Facility. The 226-MeV proton beam was used for the (p, pd), (p, pt), and $(p, p^3\text{He})$ knockout measurements, while the 392-MeV proton was for the $(p, p\alpha)$. The beams bombarded the $\sim$10-mg/cm^2 targets placed in the scattering chamber of the West experimental hall. A Mylar target was adopted as the oxygen target. The scattered protons were momentum-analyzed by the Grand RAIDEN spectrometer, while the knocked-out clusters by the LAS in all the measurements.

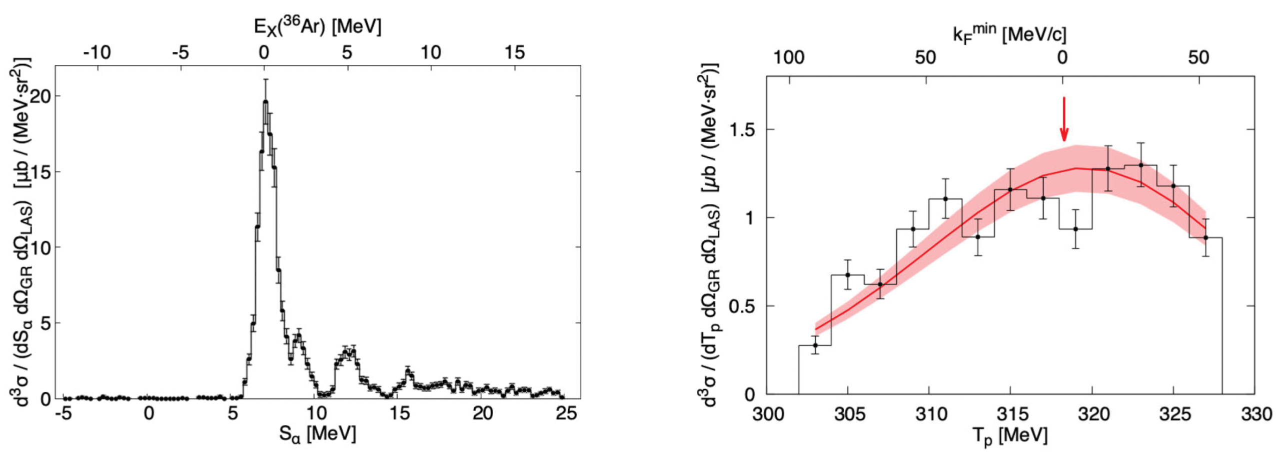

Figure 2: The separation energy spectrum (left) and the proton-energy distribution (right) for the ^{40}Ca$(p, p\alpha)$ reaction at 392 MeV. Reprinted from Ref. [29].

Figure 2 shows the ^{40}Ca$(p, p\alpha)$ results[29]. In the separation energy (S_α) spectrum (left panel), peaks corresponding to the ground and the first excited (2^+, $E_x = 1.97$ MeV) states in ^{36}Ar are identified. The achieved separation-energy resolution is 0.46 MeV in σ, which is dominated by the beam energy spread (0.25 MeV) and the energy loss of the knocked-out α particle in the target (0.36 MeV). The energy resolution is high enough to extract the cross-section to the ground state reliably.

The right figure exhibits the proton-energy dependences of the cross section, which can be interpreted as the momentum (k_F) distribution of the α cluster in the target, for the transition to the ^{36}Ar ground state. The shape of the momentum distribution is found to be well reproduced by the distorted-wave impulse approximation[21] shown with a red line. The magnitude of the cross section is used to determine the "experimental" spectroscopic factor defined as

$$S_{\rm exp} = \frac{\sigma_{\rm exp}}{\sigma_{\rm theory}}, \tag{1}$$

where $\sigma_{\rm exp}$ is the experimental cross section integrated over the acceptance, and $\sigma_{\rm theory}$ is the corresponding theoretical cross section with a unit spectroscopic factor. In the present study, we employ a solution for a Woods-Saxon potential for the α-cluster wave function, and extracted the experimental spectroscopic factor as $S_{\rm exp}$ as 0.51±0.05 (stat) ±0.06 (sys). This value is fairly consistent with that from the reanalysis of the Maryland data at 101.5 MeV [13].

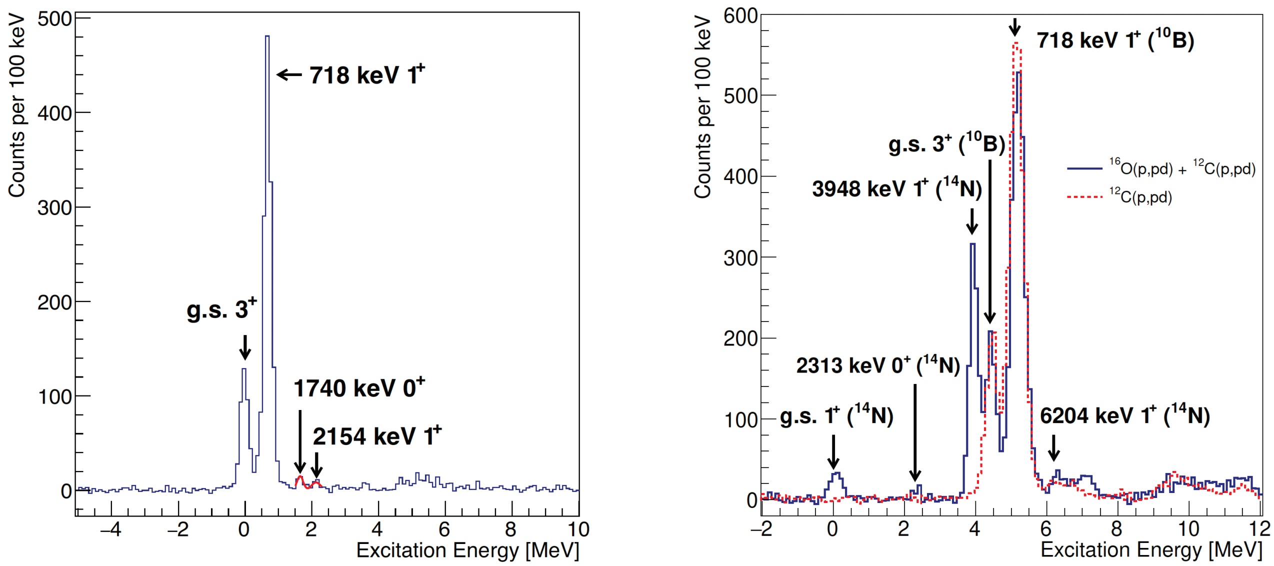

Figure 3: The excitation energy spectra for the ^{12}C(p,pd) (left) and ^{16}O(p,pd) (right) reactions at 226 MeV. The spectrum for ^{16}O is taken with the Mylar target and the contribution from the ^{12}C contaminant shown in red is subtracted using the ^{12}C(p,pd) data. Reprinted from Ref. [30].

The ^{12}C, ^{16}O(p,pd) data taken at 226 MeV clearly indicate that a significant amount of the deuteron-like p-n pairs exist in those nuclei[30]. Figure 3 shows the excitation energy spectra for the ^{12}C(p,pd) (left) and ^{16}O(p,pd) (right) reactions at 226 MeV. The ^{16}O(p,pd) spectrum is taken with the Mylar target, and the contribution from the ^{12}C contaminant shown in red is subtracted using the ^{12}C(p,pd) data. Prominet peaks due to the S-wave deuteron knockout are found in both cases: the 1^+ state in the ^{10}B at 0.718 MeV in the ^{12}C(p,pd) case and the 1^+ state in the ^{14}N at 3.948 MeV in the ^{16}O(p,pd) case. Through the DWIA analyses of the cross-section, we have extracted the experimental spectroscopic factors for the corresponding peaks as 1.59 and 1.90. Those values are 40% and 32% of the maximum p-n pairs numbers in the p-shell of ^{12}C and ^{16}O, and are found to be consistent with the shell model predictions using the Cohen-Kurath interactions.

It should also be noted that the cross section to the $T = 1$, 0^+ states (the 1.740 MeV state in ^{10}B and the 2.313 MeV state in ^{14}N) are populated only very weakly. Since these states cannot be populated in a *direct* deuteron knockout process, the negligible cross section can be regarded as evidence of the dominance of the direct deuteron knockout in the (p,pd) reaction at the incident energy. This shows a good contrast to the (e,ed) reaction at 466 MeV[31] where the $T = 1$, 0^+ state in ^{10}B is populated with an amplitude comparable to the $T = 0$, 1^+ state.

In the first experiments, we also took data for triton and ^{3}He knockout from stable Ca isotopes[32]. The isotope dependences of the cross section for the S-wave triton/^{3}He knockouts exhibit a tendency decreasing with the neutron number, qualitatively similar to what was found in $^{112-124}$Sn$(p,p\alpha)$. The ^{12}C, ^{16}O$(p,p\alpha)$ and the $^{40-48}$Ca(p,pd) data also show interesting aspects of nuclear clustering. The results will be published in the near future.

In addition to the cluster knockout reactions, we also investigated the p-d breakup reaction, whose data are mandatory for a more detailed assessment of the CDCCIA theory. In the last decades, precise and systematic data of the p-d elastic scattering have been taken, mainly for the three-nucleon force studies, while the p-d breakup data are still scarce, in particular in the kinematical domain needed for the CDCCIA analyses. In the project, the p-d breakup data in the p-n final-state interaction kinematics, specifically in the p-n relative energy region of 0–7.8 MeV have been taken. In Ref. [33], possible effects of the three-nucleon force in the cross-section ratio of the breakup reaction to the elastic scattering are discussed.

4 Toward the RI-beam experiments:

As has been demonstrated in the $^{112-124}$Sn$(p, p\alpha)$ study, the isotope dependence of the cluster knockout cross section can provide us with significant information on the cluster formation mechanisms in nuclei. This motivates us to extend the cluster knockout reaction studies to unstable isotopes with more or fewer neutrons than stable isotopes.

The ONOKORO collaboration has constructed the detector telescope dedicated to the inverse-kinematics cluster knockout reactions, named TOGAXSI. The telescope consists of 100-μm-thick, 100-μm-pitch silicon strip detectors for tracking and GAGG:Ce scintillation detectors for calorimetric measurements. TOGAXSI is designed to measure scattering angles and energies of recoil protons and knocked-out clusters with an acceptance as large as possible and with required angular ($\sim$3 mrad) and energy resolutions ($\Delta E/E \sim 1\%$). The results of early developments are reported in Refs. [34, 35].

In 2025, the collaboration completed the “demonstrator” setup[4], with a smaller acceptance than the original full-array design, and successfully applied it to the $^{50-52}$Ca experiment at the RI Beam Factory. The same setup is planned to be used in the experiment to investigate 4- and 6-neutron systems using the $(p, p\alpha)$ and $(p, 3p)$ reactions[36].

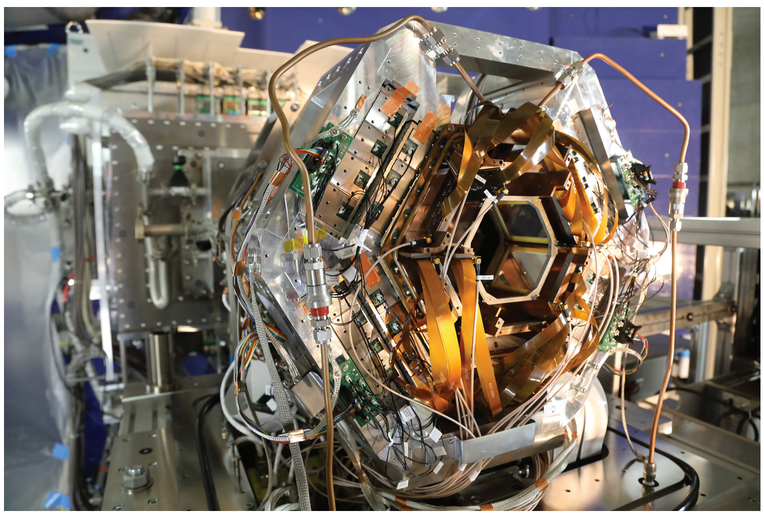

Figure 4: TOGAXSI installed at the secondary-target position of the SAMURAI spectrometer.

5 Summary and prospects

In 2020–2025, the ONOKORO collaboration has developed the theoretical and experimental bases for the cluster-knockout reaction studies. The reaction theory based on DWIA and CDCCIA is ready to be used for the analysis of the data to be taken at RCNP and RIBF: the general-purpose DWIA code PIKOE is released to the public, and the compositeness of clusters is found to be well under control when the breakup effects are taken into account using the CDCCIA model.

Results from the first experiments demonstrate the potential of the cluster-knockout reactions in revealing new aspects of clustering in nuclei. The results of the ^{40}Ca$(p, p\alpha)$ and ^{12}C, ^{16}O(p, pd) have been published, and those of $^{40-48}$Ca$(p, pt)/(p, p^3\text{He})$ and the p-d breakup reaction are submitted. The data of the ^{12}C, ^{16}O$(p, p\alpha)$ reactions and the $^{40-48}$Ca(p, pd) reaction are being analyzed and will be reported in the near future. All the experimental works benefit from the GR+LAS setup, which is the best-ever setup for the knockout reaction studies.

The cluster knockout studies are being extended to unstable nuclei with the newly constructed TOGAXSI telescope. The first physics run with the TOGAXSI has been conducted for neutron-rich $^{50-52}$Ca beams in June 2025.

Based on the progress made in the first period (2020–2025), the ONOKORO project will further pursue the physics of clustering in nuclei using knockout reactions. At RCNP, the measurements of the cluster momentum distributions in calcium isotopes (E545, E559), the demonstration of the cluster Maris effect by the spin asymmetry measurement in the (p, pd) reaction, and the exclusive measurement of the p-d breakup reaction (KK02), the α knockout reaction from the α-decaying neodymium isotope (E544), the feasibility study of two-nucleon knockout (p, pNN) reaction (E594), the measurement of the mass dependences of $d/t/^3$He clustering in nuclei (E595), and the α knockout studies of lead isotopes (E556) are planned. It is expected that the quality of the data will be substantially improved by the implementation of the LAS upgrade plan led by S. Ota and his colleagues.

At RIBF, experimental studies of clustering in the neutron-deficient and neutron-rich tin isotopes, the $N = Z$ isotopes from scandium to zinc, and the α-decaying thorium isotopes are planned under the proposal of a scientific program entitled "Comprehensive research of cluster formation in medium to heavy nuclei – ONOKORO Project –".

The experimental and corresponding theoretical studies will reveal unknown features of clustering in nuclei in the next decade.

Acknowledgement

The authors would like to express their sincere gratitude to the accelerator group at the Research Center for Nuclear Physics (RCNP), Sumitomo Heavy Industries Accelerator Service Ltd. (SAS), and all supporting staff for providing the high-quality proton beam and their invaluable technical assistance during the experiments. This work has been supported by Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (JSPS) KAKENHI, Grant No. JP21H04975. This work was performed under the research project KKProject-002 of the Research Center for Nuclear Physics, the University of Osaka. This work was partially supported by National Research Foundation (NRF) grants (TOPTIER, RS-2024-00436392, RS-2023-00282876, RS-2024-00333673, and IBS-R031-D1) by the Korea government of Ministry of Science and ICT (MSIT). This work was partially supported by the JSPS A3 Foresight Program "Nuclear Physics in the 21st Century", also in part by the National Key RD Program of China (Grants No. 2023YFE0101500, No. 2022YFA1605100), the National Natural Science Foundation of China (Grant No. 12275006).

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