ONOKORO Experiments at RCNP for precise measurements of (p, pX) reactions

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1 ONOKORO Project at RCNP

Cluster formation in nuclear matter is a fundamental phenomenon that transcends the mean-field approximation, playing a critical role not only in nuclear structure but also in astrophysical processes including those in neutron stars and supernovae. While early studies primarily focused on clustering in light nuclei, recent theoretical developments have extended the concept to infinite nuclear matter, predicting substantial cluster fractions, particularly at densities around one-tenth of nuclear saturation [1].

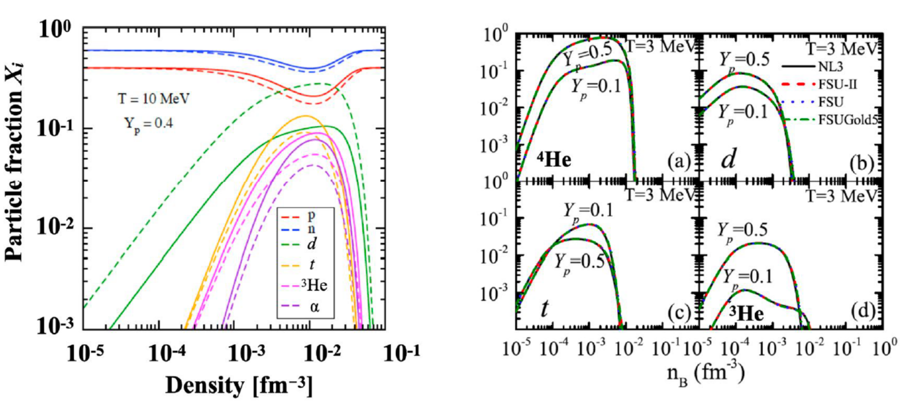

Figure 1: (Left) Cluster fractions in neutron matter predicted by the generalized relativistic density functional theory. (Right) Number fractions of clusters predicted by the generalized nonlinear relativistic mean-field theory.

Calculations [2, 3] demonstrate that cluster composition depends on density, temperature, and proton fraction (Y_p), with triton production being particularly enhanced under neutron-rich conditions (Fig. 1). A connection between cluster formation in infinite nuclear matter and that on the low-density surfaces of heavy nuclei was also proposed [4], and this prediction was experimentally validated at RCNP through the observation of neutron-number-dependent α clustering in $^{112-124}$Sn [5].

Building upon these findings, the "ONOKORO Project" [6, 7] was launched in 2021 to systematically investigate cluster formation in medium- to heavy-mass nuclei via cluster knockout reactions. The project leverages the capabilities of three major intermediate-energy accelerator facilities in Japan: the RCNP Ring Cyclotron, the RI Beam Factory (RIBF) at RIKEN, and the Heavy Ion Medical Accelerator in Chiba (HIMAC) at QST. In the same year, it received approval from the RCNP Physics Program Advisory Committee [8].

The ONOKORO Project pursues the following key objectives[6]:

- To establish the formation of α clusters in heavy nuclei, extending previous $^{112\text{–}124}$Sn(p, pα) studies.
- To elucidate the mechanism of α decay by confirmation of surface α formation in α-decay nuclei.
- To discover deuteron clusters in heavy nuclei and clarify the influence of tensor forces.
- To perform the first measurement of the $t/^3$He cluster ratio and evaluate its dependence on neutron excess.
- To establish a theoretical framework for cluster knockout reactions.
- To develop a comprehensive understanding of cluster formation mechanisms in nuclear matter.

At RCNP, as part of these objectives, stable nuclei from calcium ($Z = 20$) to lead ($Z = 82$) are investigated under normal kinematics using proton-induced (p, pX) reactions. Significant progress was made in 2024, with systematic $(p, p\alpha)$ measurements performed on calcium isotopes, accompanied by background studies using $(p, p\alpha)$ reactions on ^{12}C and ^{16}O. In addition, knockout reaction measurements were conducted to explore new cluster species, including the deuteron (d), triton (t), and helium-3 (^{3}He). The experimental program was further extended to lead nuclei, broadening the mass region under investigation. This article reviews these achievements and discusses future perspectives.

1.1 Cluster-Knockout Reactions Experiments at RCNP and Data Analysis

Experiments were conducted using proton beams accelerated by the Ring Cyclotron to energies of 230 MeV (E559) and 392 MeV (E545/E596). Measurements were performed at the WS beamline, utilizing the Grand Raiden spectrometer (GR) and the Large Acceptance Spectrometer (LAS). Please see Fig. 2.

The proton beams were incident on targets placed inside the target chamber, with beam intensities ranging from approximately 100 nA to 200 nA. Taking the α knockout reaction in E545 as an example, an incident proton knocks out an α particle from the nucleus. The scattered proton and the knocked-out α particle are analyzed using the GR and LAS spectrometers, set at 46.26 degrees and 58.56 degrees, respectively. These angles correspond to a scattering angle of 60 degrees in the center-of-mass frame of the proton and α particle, selected to satisfy the condition where the residual nucleus is nearly recoil-less. Furthermore, by employing high-energy proton beams, the experimental setup fulfills quasi-free scattering conditions, minimizing the influence of the residual nucleus. Each particle's position and angle, as well as timing and energy loss, are measured by the drift chambers and plastic scintillators located at the focal planes of the spectrometers. Protons are identified through their energy loss spectra measured with standard plastic scintillators.

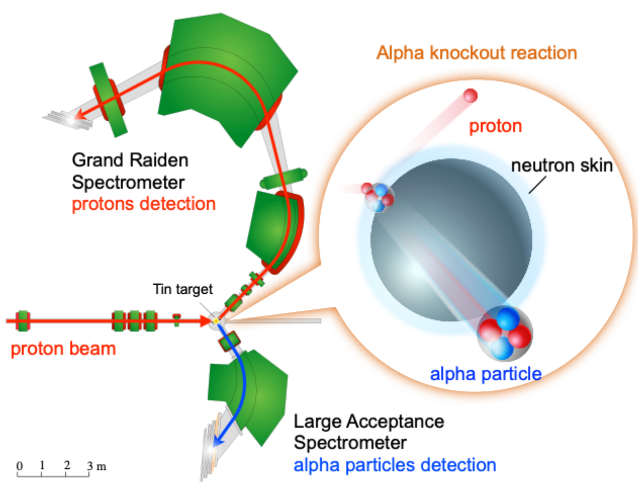

Figure 2: Experimental setup for (p, pX) reactions and schematic illustration of alpha-knockout from the nuclear surface.

For α-particle detection, particular care was taken to prevent α particles from being stopped by the exit window of the drift chamber or by the light-shielding layer of the plastic scintillator. To address this, the drift chamber was positioned close to the vacuum window of the LAS, and a helium–methane (He–CH_4) gas mixture was used in the drift chamber to minimizes energy loss. Nevertheless, the plastic scintillator was sufficiently thick to stop the α particles in a single layer. Consequently, particle identification for α particles was performed using Time Over Threshold (TOT) signals corresponding to the energy loss measured by the drift chambers. The left panel of the figure 3 shows the correlation between the TOT signal from the drift chamber and the LAS-X position. The three loci correspond, from top to bottom, to α particles, deuterons, and protons, respectively. On the low-momentum side of LAS-X (negative X-axis), the energy loss increases, resulting in larger TOT values. By applying a correction to align the loci parallel to each other and projecting onto the corrected TOT axis, the right panel is obtained, enabling quantitative identification of α particles.

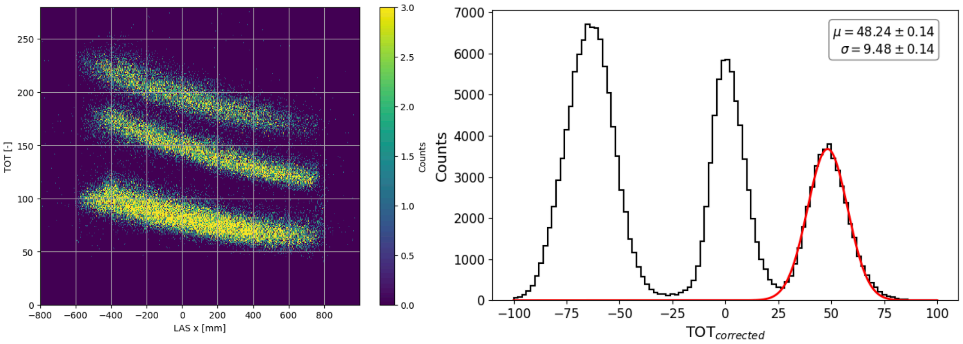

Figure 3: (Left) TOT value versus LAS-X position. (Right) Particle identification using corrected TOT values.

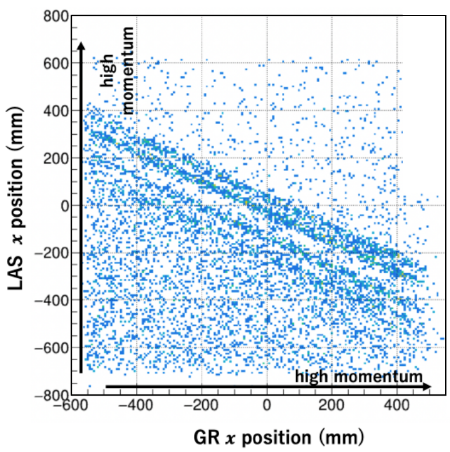

Figure 4: Correlation between GR-X and LAS-X positions for the ^{12}C(p,pd) reaction **??**. Each locus corresponds to either the ground state or one of the excited states of ^{10}B.

One of the characteristic physical quantities in the (p,pX) reaction is the cluster separation energy, S_X, which is defined as the energy required to remove the cluster X from the target nucleus. It is given by the mass difference between the initial and final states as $S_X = M_r + M_X - M_{t\text{-g.s.}}$, where $M_{t\text{-g.s.}}$ is the mass of the target nucleus in its ground state, and M_r denotes the mass of the residual nucleus. Since the residual nucleus is not necessarily in its ground state, M_r generally includes the excitation energy E_x, with the relation $M_r = M_{r\text{-g.s.}} + E_x$, where $M_{r\text{-g.s.}}$ is the mass of the residual nucleus in its ground state. Defining $S_{X\text{-g.s.}}$ as the cluster separation energy for the transition from the ground state of the target nucleus to the ground state of the residual nucleus, the separation energy can be expressed as $S_X = S_{X\text{-g.s.}} + E_x$. Thus, by measuring the distribution of S_X, one can obtain the excitation energy spectrum of the residual nucleus.

Alternatively, S_X can be determined from the measured kinetic energies based on the energy conservation law of the (p,pX) reaction, expressed as $S_X = T_{\text{in}} - (T_p + T_X + T_R) \approx T_{\text{in}} - (T_{\text{pout}} + T_X)$, where T_{in} is the kinetic energy of the incident proton, and T_p, T_X, and T_R are the kinetic energies of the scattered proton, the knocked-out cluster, and the residual nucleus, respectively. Since T_R is much smaller than the other terms, for a given transition, $T_{\text{pout}} + T_X$ can be considered approximately constant. The figure shows the correlation between the x positions at the focal planes of the Grand Raiden (GR) and LAS spectrometers, which correspond to the kinetic energies of the scattered proton and the knocked-out cluster, respectively. In the figure 4, multiple loci corresponding to different constant values of $T_{\text{pout}} + T_X$ are observed in the ^{12}C(p,pd) reaction.

The ion-optics focusing conditions of LAS were revised in the present (2023-) study. In the previous condition, the LAS spectrometer was configured to focus the Y position of the central trajectory at the focal plane along the X axis. However, because LAS has a simpler magnet configuration than GR, under such focusing conditions, good Y focusing was achieved only in the central X region, while at lower and higher momenta, the image broadened, resulting in a ribbon-like distribution on the X–Y plane. It was also found that under this Y-focused condition, sufficient angular resolution for the emitted α particles could not be achieved. Therefore, in this year' s experiment, the magnetic field settings were adjusted to shift the Y focusing plane upstream, enabling good angular resolution across almost the entire acceptance of LAS. The figure 5 shows data obtained with a slit installed at the LAS entrance, measured using the focal-plane detectors. By analyzing the scattering angles based on these data, it becomes possible to reconstruct the three-dimensional momentum vectors of the α particles.

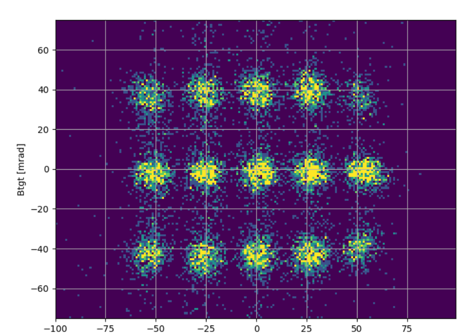

Figure 5: Horizontal (X) and vertical (Y) angles of the angle-calibrated sieve slit for LAS.

2 Systematic $(p, p\alpha)$ Reaction Measurements on Calcium Isotopes (E545) [10]

Among the calcium isotopes, ^{40}Ca and ^{48}Ca are known as doubly magic nuclei. In this study, we investigated how magic numbers and neutron excess influence the formation of α clusters, as well as the effects that arise when neutrons are added to ^{40}Ca and begin to occupy higher nuclear shells. Since calcium readily oxidizes, accurate determination of the oxygen content in the targets is essential for knockout reaction experiments using calcium. This is particularly important because the peak of the α-separation energy spectrum from oxygen lies close to that from calcium, and the knockout cross section for oxygen is significantly larger. Consequently, even a small degree of oxidation can introduce substantial background contributions to the calcium spectrum. To address this issue, dedicated calibration measurements were conducted using a 65 MeV proton beam to quantitatively evaluate the oxygen contamination in each calcium target. The targets used had typical areal thicknesses of approximately 10 mg/cm^2, and the oxidation levels determined through this procedure were applied to both the E545 and E559 experiments to correct for background contributions. This approach enabled a reliable assessment of target purity and ensured accurate interpretation of the knockout data. Based on the oxygen (and carbon) content determined in this manner, and the $(p, p\alpha)$ data measured for ^{16}O and ^{12}C, the background α-separation energy spectrum from oxygen and carbon impurities in the ^{44}Ca target was quantitatively predicted. As shown in the figure 6, the predicted background reproduces the measured spectrum from the ^{44}Ca target in absolute magnitude, and the observed peak is assigned to the ^{44}Ca$(p, p\alpha)^{40}$Ar ground-state transition.

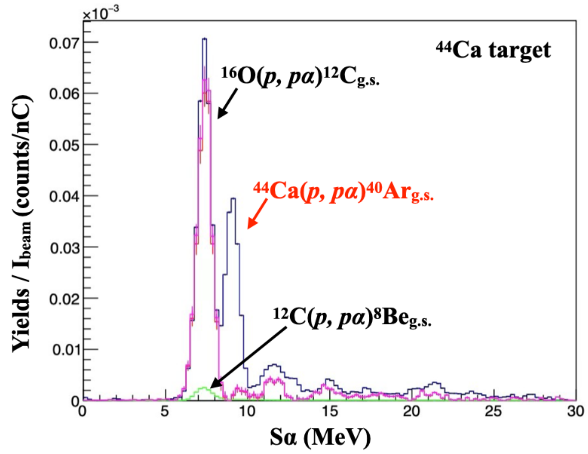

Figure 6: Alpha-separation energy spectrum obtained with the ^{44}Ca target. Contributions from ^{16}O and ^{12}C knockout reactions are also identified.

3 (p, pd), (p, pt), and $(p, p^3\mathrm{He})$ Reactions in Calcium Isotopes (E559)[11]

A central objective of the ONOKORO Project is to investigate how the types of clusters formed in nuclei vary with neutron excess. Tritons (t) and helium-3 (^{3}He) are isobars with mass number $A = 3$, differing only in their proton and neutron numbers. The cross-section ratio $\sigma(p, pt)/\sigma(p, p^3\mathrm{He})$ provides a sensitive observable for probing the dependence of cluster formation on neutron excess. In addition, the (p, pd) reaction plays an important role in exploring the probability of proton−neutron pairing in a deuteron-like configuration within nuclei. In this study, systematic measurements of (p, pX) reactions were carried out using calcium isotopes ^{40,42,44,48}Ca as targets, aiming to knock out d, t, and ^{3}He clusters. All reactions exhibited clear peak structures in the cluster separation energy spectra, indicating the presence of preformed clusters within the nucleus. The figure 7 shows a group photo taken during the experiment. The measurement was conducted through an international collaboration involving researchers from both Japan and abroad.

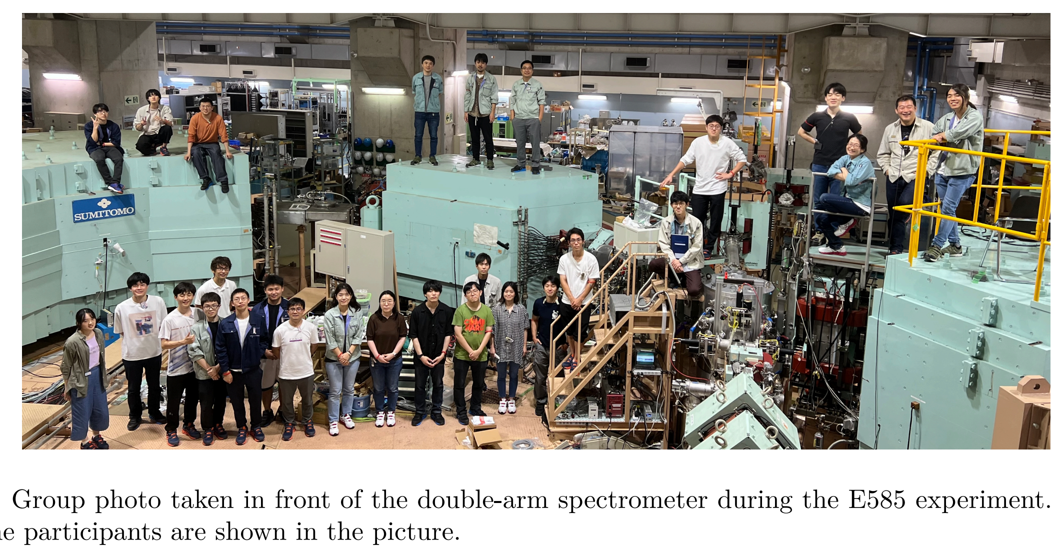

Figure 7: Group photo taken in front of the double-arm spectrometer during the E585 experiment. Note that not all the participants are shown in the picture.

4 Extension to Heavy Nuclei Pb: $^{208}\text{Pb}(p, p\alpha)$ (E596) [12]

The nucleus of ^{208}Pb is the heaviest stable nucleus and exhibits a well-developed neutron skin due to its neutron-rich nature. Consequently, measuring the neutron skin thickness and determining the slope parameter of the nuclear equation of state based on this value are critical research objectives. In a theoretical study applying the concept of α-cluster formation to finite nuclei, it was suggested that if α clusters form on the surface of ^{208}Pb, the protons contained within the α particles could broaden the proton distribution, thereby influencing the neutron skin thickness. This scenario implies a competition between α-cluster formation and neutron skin development. In this year's experiment, the primary objective was to determine whether α-knockout reactions could be observed from a lead target. Using a 392 MeV proton beam with an intensity of 200 nA, we accumulated 16 hours of $^{208}\text{Pb}(p, p\alpha)$ data. During online analysis, a peak corresponding to oxygen impurities in the target became visible after extended data accumulation; however, a distinct peak attributable to lead was not yet identified. Careful calibration and background subtraction through offline analysis will be necessary to clarify the results. Additionally, as data analysis progresses, it will be important to review and optimize the measurement conditions for the remaining five days out of the six days of allocated machine time.

5 Summery and Outlook

A large amount of experimental data was collected during fiscal year 2024. At present, the analysis of these data is actively being carried out by many collaborators, bringing the ONOKORO project a step closer to achieving its goals. At RCNP, several approved experimental programs remain, and these experiments will be carried out in the near future. In fiscal year 2025, the first machine time for ONOKORO experiments at RIKEN has also been assigned, and further progress in wide-ranging research using RI beams is anticipated.

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