



Deposited via The University of York.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/243774/>

Version: Published Version

Article:

Tsuji, R., Zenihiro, J., Ogawa, S. et al. (2026) First Observation of Mirror t and ^3He Clusters in Stable Ca Isotopes via Quasi-free (p , pt) and (p , $p^3\text{He}$) Reactions. Progress of Theoretical and Experimental Physics. 073D02. ISSN: 2050-3911

<https://doi.org/10.1093/ptep/ptag095>

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

First Observation of Mirror t and ^3He Clusters in Stable Ca Isotopes via Quasi-free (p, pt) and $(p, p^3\text{He})$ Reactions

R Tsuji, J Zenihiro, S Ogawa, S Typel, D S Ahn, D Beaumel, J Bian, J Cai, Y Chazono, F Chen, M Dozono, F Endo, S Franchoo, F Furukawa, T Furuno, R Gernhäuser, W Guo, K I Hahn, K Higuchi, Y Hijikata, Y Honda, B Hong, J Hwang, E Ideguchi, G Ikemizu, A Inoue, R Iwasaki, K Itsuno, R Kato, S Kawase, K Kawata, M Khandelwal, M Kim, S Kim, N Kobayashi, Y Kubota, C S Lee, Y Li, Q Li, Y Lin, Y Maeda, Y Matsuda, R Matsumura, K Miki, M Mitsui, T Miyagawa, N Mozumdar, M Murata, T Nakada, H Nakama, K Ogata, S Ogio, G Oh, S Ota, S Paschalis, M Petri, T Pohl, F Saito, S Sakajo, Y Sasagawa, T Sato, H Shibakita, H Sonoda, T Sugiyama, Y Suzuki, J Tanaka, A Tamii, S Umemoto, C Wang, X Wang, M Whitehead, A Yamasaki, R Yamamoto, S Yamazaki, Z Yang, T Yano, K Yasumura, K Yoshida, R Yoshida, J Zhang, K Zhou, T Uesaka

First Observation of Mirror t and ^3He Clusters in Stable Ca Isotopes via Quasi-free (p, pt) and $(p, p^3\text{He})$ Reactions

R. Tsuji ^{1,2,3,*}, J. Zenihiro ¹, S. Ogawa ⁴, S. Typel ^{5,6}, D. S. Ahn ^{7,8}, D. Beaumel ⁹, J. Bian ¹⁰, J. Cai ¹¹, Y. Chazono ⁴, F. Chen ¹¹, M. Dozono ¹, F. Endo ¹¹, S. Franchoo ⁹, F. Furukawa ¹¹, T. Furuno ^{12,13}, R. Gernhäuser ¹⁴, W. Guo ¹², K. I. Hahn ⁷, K. Higuchi ^{2,15}, Y. Hijikata ^{1,2}, Y. Honda ¹², B. Hong ¹⁶, J. Hwang ⁷, E. Ideguchi ¹¹, G. Ikemizu ^{1,3}, A. Inoue ^{11,17}, R. Iwasaki ¹¹, K. Itsuno ¹, R. Kato ¹⁸, S. Kawase ¹⁹, K. Kawata ¹¹, M. Khandelwal ¹¹, M. Kim ¹⁶, S. Kim ⁷, N. Kobayashi ¹¹, Y. Kubota ¹², C. S. Lee ²⁰, Y. Li ^{2,10}, Q. Li ¹⁰, Y. Lin ¹², Y. Maeda ¹⁸, Y. Matsuda ^{11,21}, R. Matsumura ^{12,15}, K. Miki ²², M. Mitsui ^{18,23}, T. Miyagawa ¹¹, N. Mozumdar ⁵, M. Murata ¹¹, T. Nakada ¹, H. Nakama ¹⁸, K. Ogata ^{11,4}, S. Ogio ¹, G. Oh ²⁰, S. Ota ¹¹, S. Paschalis ²⁴, M. Petri ²⁴, T. Pohl ², F. Saito ²¹, S. Sakajo ¹², Y. Sasagawa ¹², T. Sato ¹⁸, H. Shibakita ¹¹, H. Sonoda ¹⁸, T. Sugiyama ^{2,3,15}, Y. Suzuki ¹¹, J. Tanaka ¹¹, A. Tamii ¹¹, S. Umemoto ²¹, C. Wang ¹⁰, X. Wang ¹¹, M. Whitehead ²⁴, A. Yamasaki ²¹, R. Yamamoto ¹⁸, S. Yamazaki ²⁵, Z. Yang ¹⁰, T. Yano ¹, K. Yasumura ²¹, K. Yoshida ¹¹, R. Yoshida ^{1,2}, J. Zhang ¹¹, K. Zhou ¹⁰, and T. Uesaka ^{2,3,15}

¹Department of Physics, Kyoto University, Kitashirakawa, Oiwakecho, Sakyo, Kyoto 606-8502, Japan

²RIKEN Nishina Center for Accelerator-Based Science, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

³RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

⁴Department of Physics, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

⁵Fachbereich Physik, Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 9, 64289 Darmstadt, Germany

⁶GSF Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany

⁷Center for Exotic Nuclear Studies, Institute for Basic Science, 55 Expo-ro, Yuseong-gu, Daejeon 34126, Korea

⁸Facility for Rare Isotope Beams, Michigan State University, 640 South Shaw Lane, East Lansing, MI 48824, USA

⁹Irène Joliot-Curie Laboratoire de Physique des 2 infinis and University Paris-Saclay, Bât. 100, 15 rue Georges Clémenceau, Orsay 91405, France

¹⁰School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

¹¹Research Center for Nuclear Physics, The University of Osaka, 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

¹²Department of Physics, The University of Osaka, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan

¹³Department of Applied Physics, University of Fukui, 3-9-1 Bunkyo, Fukui, Fukui 910-8507, Japan

¹⁴Physik Department, Technische Universität München, James-Frank-Straße 1, Garching 85748, Germany

¹⁵Department of Physics, Saitama University, 255 Shimo - Okubo, Sakura-ku, Saitama, Saitama 338-8570, Japan

¹⁶Department of Physics, Korea University, Seoul 02841, Korea

¹⁷Department of Physics, University of Oslo, Boks 1072 Blindern, Oslo 0316, Norway

¹⁸Faculty of Engineering, University of Miyazaki, 1-1 Gakuenkibanadai-nishi, Miyazaki 889-2192, Japan

¹⁹Department of Advanced Energy Science and Engineering, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan

²⁰*Institute for Rare Isotope Science, Institute for Basic Science, 1 Gukjegdahak-ro, Yuseong-gu, Daejeon 34000, Korea*

²¹*Department of Physics, Konan University, 8 Chome-9-1, Okamoto, Higashinada, Kobe, Hyogo, 658-8501, Japan*

²²*Department of Physics, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, Sendai 980-8578, Japan*

²³*Institute of Physics, University of Tsukuba, 1-1-1 Tennodai, Tsukuba 305-8571, Japan*

²⁴*School of Physics, Engineering and Technology, University of York, Heslington, York YO10 5DD, United Kingdom*

²⁵*Research Center for Accelerator and Radioisotope Science, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan*

Received November 27, 2025; Revised May 8, 2026; Accepted May 15, 2026; Published June 1, 2026

.....
 We report systematic data on the quasi-free (p, pt) and ($p, p^3\text{He}$) reactions of $^{40-48}\text{Ca}$ isotopes at an incident proton energy of 226 MeV under recoil-less conditions, with the aim of investigating t and ^3He cluster correlations in medium-mass nuclei. In addition, data on ^{12}C and ^{16}O were taken to estimate the contribution of ^{16}O impurities originating from surface oxidation of the Ca targets and to provide benchmark data for light $N = Z$ systems. From the experimental data, state-resolved triple differential cross-sections were extracted, together with separation-energy-integrated triple differential cross-sections as a complementary observable. The state-resolved triple differential cross-sections were analyzed within a distorted wave impulse approximation (DWIA) framework, and experimental spectroscopic factors were deduced using Woods–Saxon wave functions. In addition, theoretical triple differential cross-sections were obtained from DWIA calculations employing cluster wave functions derived from generalized relativistic density functional theory (grDFT) and were compared with the experimental results. For the Ca isotopes, pronounced low-lying S -wave peaks are observed in the separation-energy spectra for both the (p, pt) and ($p, p^3\text{He}$) channels. The corresponding low-lying S -wave triple differential cross-sections and experimental spectroscopic factors decrease systematically with increasing neutron number for both the t and ^3He clusters. Comparisons with grDFT-based DWIA calculations show that the calculated triple differential cross-sections are of the same order of magnitude as the experimental low-lying S -wave triple differential cross-sections and capture their global decreasing trend toward neutron-rich Ca isotopes. The separation-energy-integrated triple differential cross-sections exhibit a clear channel-dependent behavior: the integrated strength decreases for the ($p, p^3\text{He}$) channel, whereas it remains nearly constant for the (p, pt) channel. Overall, the present results demonstrate that quasi-free (p, pX) reactions provide a sensitive and versatile probe of cluster correlations in finite nuclei, and strongly motivate further experimental and theoretical studies of t and ^3He cluster formation across a wide range of nuclei.

Subject Index C30, D04, D11, D13, D22

1. Introduction

Cluster formation is a prominent manifestation of nucleon–nucleon correlations beyond the independent-particle picture, and plays an essential role in our understanding of atomic nuclei and nuclear matter [1–4]. Among various cluster configurations, the α cluster has attracted particular attention. A representative example is the Hoyle state in ^{12}C , characterized by a dilute 3α configuration that plays a decisive role in stellar nucleosynthesis [5]. Subsequent investigations have shown that pronounced α -cluster structures are not limited to ^{12}C , but also emerge

*tsuji.ryotaro.r36@kyoto-u.jp

in other light $N = Z$ nuclei such as ^{16}O and ^{20}Ne [6], for which rotational bands, parity-doublet structures, and gas-like condensate features have been discussed [3,7–10].

Beyond finite nuclei, theoretical investigations of infinite nuclear matter provide further insight into the universality of cluster correlations. In particular, generalized relativistic density functional theory (grDFT) predicts that, in addition to α particles, light clusters such as d , t , and ^3He can form in nuclear matter [11,12]. In this framework, clusters are treated as explicit degrees of freedom, and their gradual dissolution into the mean field with increasing density is described through a density-dependent reduction of the cluster binding energy, commonly referred to as a mass shift. This mechanism, known as Mott dissolution, originates from Pauli blocking in the surrounding nuclear medium. As a result, cluster formation becomes significant in low-density regions, of around one-tenth of the nuclear saturation density, and strongly depends on the cluster species, the baryon density, and the degree of isospin asymmetry.

The formation of light clusters at low density is also deeply connected to astrophysical environments. In core-collapse supernovae, light nuclear clusters influence neutrino–matter interactions and neutrino transport properties [13]. Cluster degrees of freedom play an important role in determining the equation of state (EOS) of nuclear matter. For example, α particles are incorporated in widely used supernova EOS models such as the Lattimer–Swesty EOS [14] and the Shen EOS [15]. More recently, EOS tables including d , t , ^3He , and α clusters have been developed, such as the Furusawa–Togashi EOS [16] and those compiled in the CompOSE database [17–19], which provide modern cluster-inclusive EOS models applicable to a wide range of astrophysical conditions.

An important implication of grDFT is that cluster formation may also occur in the surface regions of finite nuclei, including medium- and heavy-mass systems [20]. In this context, a “cluster” refers to a correlated multi-nucleon configuration generated by correlations beyond the mean-field description, rather than to a free-space composite particle. In light nuclei, microscopic many-body approaches have shown that such correlations arise naturally from the nucleon–nucleon interaction, especially for α clusters, which are strongly bound and spatially compact. Representative examples include antisymmetrized molecular dynamics (AMD) calculations [21,22] and ab initio no-core Monte Carlo shell model (MCSM) studies of ^{12}C [23], which reproduce cluster-like configurations without assuming preformed clusters. However, the direct application of these fully microscopic approaches to heavier systems remains challenging because the required model space grows rapidly with mass number. In this respect, although phenomenological in its treatment of clustering, grDFT provides a complementary theoretical framework capable of bridging finite nuclei—including heavy systems—and infinite nuclear matter within a unified description.

A direct experimental approach to such cluster correlations in nuclei is the proton-induced quasi-free cluster knockout reaction, (p, pX) ($X = d, t, ^3\text{He}, \alpha$). This reaction can be regarded as a natural extension of the $(e, e'p)$ [24] and (p, pN) [25] reactions that are widely used to probe single-particle features in nuclei. Such knockout reactions are commonly described within the distorted wave impulse approximation (DWIA) framework under the assumption of a single-step scattering process [24–29]. One of the kinematical requirements for this assumption is the quasi-free condition, in which the momentum transferred to the knocked-out particle is significantly larger than its in-nucleus momentum. In (p, pN) analyses within the DWIA framework,

an experimental spectroscopic factor is defined as the ratio of the measured cross-section to a reference DWIA cross-section calculated using a bound-state wave function with unit spectroscopic factor [29]. This established framework has recently been extended to cluster knockout reactions.

For α clusters in the light-mass region, the $(p, p\alpha)$ reaction on ^{20}Ne has been successfully reproduced by DWIA calculations employing AMD wave functions, demonstrating that the reaction framework can quantitatively describe cluster knockout observables when combined with appropriate microscopic structure inputs [30]. Furthermore, systematic $(p, p\alpha)$ measurements on stable Sn isotopes have revealed a monotonic decrease in the cross-section toward the neutron-rich side, in qualitative agreement with grDFT predictions [31]. This result indicates the emergence of α correlations near the nuclear surface even in heavy nuclei and highlights the applicability of the grDFT+DWIA framework over a wide mass range.

For weakly bound clusters such as the deuteron, strong final-state interactions (FSIs) can induce breakup and reformation processes, suggesting the need for their treatment within the DWIA framework [32]. However, at sufficiently high incident energies, the effects of FSIs are expected to become less pronounced. Indeed, recent studies using incident proton energies of around 250 MeV have shown that DWIA calculations with and without explicit treatment of FSI effects yield similar results for (p, pd) reactions, even for such fragile clusters [33]. These developments indicate that the experimental and theoretical groundwork is now being established for exploring not only α clusters but also lighter clusters such as d , t , and ^3He through the (p, pX) reaction [34,35].

Studies of t and ^3He clusters remain extremely limited. Unlike α and deuteron clusters, t and ^3He are fermionic clusters with spin-parity $J^\pi = 1/2^+$ and isospin $T = 1/2$, and their microscopic description is far less developed. Nevertheless, the mirror relationship between t and ^3He motivates the expectation that their formation may respond differently to the isospin asymmetry of the surrounding nuclear medium. Indeed, recent grDFT calculations for infinite nuclear matter suggest a strong isospin dependence in their formation probabilities: t correlations are expected to persist even in neutron-rich environments, whereas ^3He correlations are predicted to be strongly suppressed [12]. This intriguing prediction has not yet been verified experimentally.

Although several studies have reported indications of t and ^3He clustering in specific nuclei, most detailed discussions of their cluster structure have focused on excited states in light nuclei. For excited states of light nuclei, charge-exchange data have suggested the existence of di-trinucleon resonances ($t + t$, $t + ^3\text{He}$, and $^3\text{He} + ^3\text{He}$) in $A = 6$ systems (^6He , ^6Li , and ^6Be) [36,37]. t -cluster structures have also been identified in ^{11}B , which corresponds to an s -hole configuration of ^{12}C , based on the observed $t + ^8\text{Be}$ decay of its excited states [38]. As for the ground state, knockout reaction measurements have suggested a $t + \alpha$ configuration in the ground state of ^7Li [39]. Measurements targeting the ground states of heavier nuclei are more limited. Notable examples include (p, pt) and $(p, p^3\text{He})$ reaction measurements on ^{12}C and ^{16}O , in which comparisons with previous transfer-reaction data have been made [40]. In addition, a (p, pt) measurement on ^{16}O at an incident energy of 101.3 MeV has been reported [41]. Because these measurements were performed at relatively low incident energies ($\lesssim 100\text{MeV}$), the large uncertainties in reaction analyses have prevented definitive conclusions. For heavier Ca isotopes, (p, α) and $(n, \alpha)/(\alpha, ^7\text{Be})$ reactions, corresponding to the removal of t and ^3He clusters, respectively, have been performed [42–45]. Nevertheless, t - and ^3He -clustering in medium-

and heavy-mass nuclei has received comparatively little attention, and systematic ground-state studies are still lacking.

In this study, we investigate t and ${}^3\text{He}$ cluster correlations in medium-mass nuclei through quasi-free (p, pt) and ($p, p^3\text{He}$) reactions on the ${}^{40,42,44,48}\text{Ca}$ isotopic chain. The primary objectives of the present work are to identify the trinucleon cluster correlations experimentally and to examine their systematic evolution along the isotopic chain. The stable Ca isotopic chain offers an optimal testing ground, spanning nuclei from the $N = Z$ system to neutron-rich isotopes, and allowing normal-kinematics measurements with a high energy resolution. Moreover, it includes two doubly magic nuclei, ${}^{40}\text{Ca}$ and ${}^{48}\text{Ca}$, which are particularly suitable for future microscopic theoretical verification.

The measurements were performed under kinematical conditions for which analyses based on the DWIA are expected to be reliable. An incident proton energy of $T_{\text{inc}} = 226$ MeV was employed, and the momentum transfer was chosen to satisfy the quasi-free condition. Furthermore, recoil-less conditions were adopted to selectively probe low intrinsic cluster momenta, thereby enhancing sensitivity to low-angular-momentum components of the relative cluster-core motion, following previous ($p, p\alpha$) studies. For reference and background evaluation, additional measurements were performed using ${}^{12}\text{C}$ and ${}^{16}\text{O}$ targets. These data were used to assess contributions from ${}^{16}\text{O}$ arising from surface oxidation of the Ca targets and to provide reference information from light nuclei, for which reaction mechanisms and nuclear structure are relatively easier to interpret than in medium-mass systems.

The experimental observables were analyzed in two complementary ways within the DWIA framework. First, DWIA calculations using conventional Woods–Saxon cluster wave functions were employed as reference calculations to extract experimental spectroscopic factors and quantify the relative strengths of cluster components. Second, DWIA calculations incorporating cluster wave functions derived from grDFT theory were performed, and the resulting theoretical cross-sections were directly compared with the experimental data.

2. Experiment and kinematical designs

In this section, we summarize the experimental conditions and kinematical settings adopted for the (p, pX) measurements.

2.1. Experiment

The cross-sections for quasi-free (p, pt) and ($p, p^3\text{He}$) reactions on ${}^{40,42,44,48}\text{Ca}$, as well as on ${}^{12}\text{C}$ and ${}^{16}\text{O}$, were measured at the Research Center for Nuclear Physics (RCNP), The University of Osaka. A proton beam extracted from the ECR ion source was accelerated to 226 MeV by the AVF and ring cyclotrons. The beam was transported through the WS beam line in the West experimental hall [46] and delivered onto thin targets with a typical intensity of 100 nA. The beam intensity and its stability were monitored using a beam-line polarimeter 2 (BLP2) located in the WS beam line upstream of the scattering chamber, and a Wall Faraday cup (WallFC) installed about 25 m downstream of the scattering chamber. The BLP2 was positioned before the final bending section leading to the target. The absolute beam-charge normalization was determined using a retractable Faraday cup installed inside the scattering chamber (SCFC), whose position is indicated in Fig. 1.

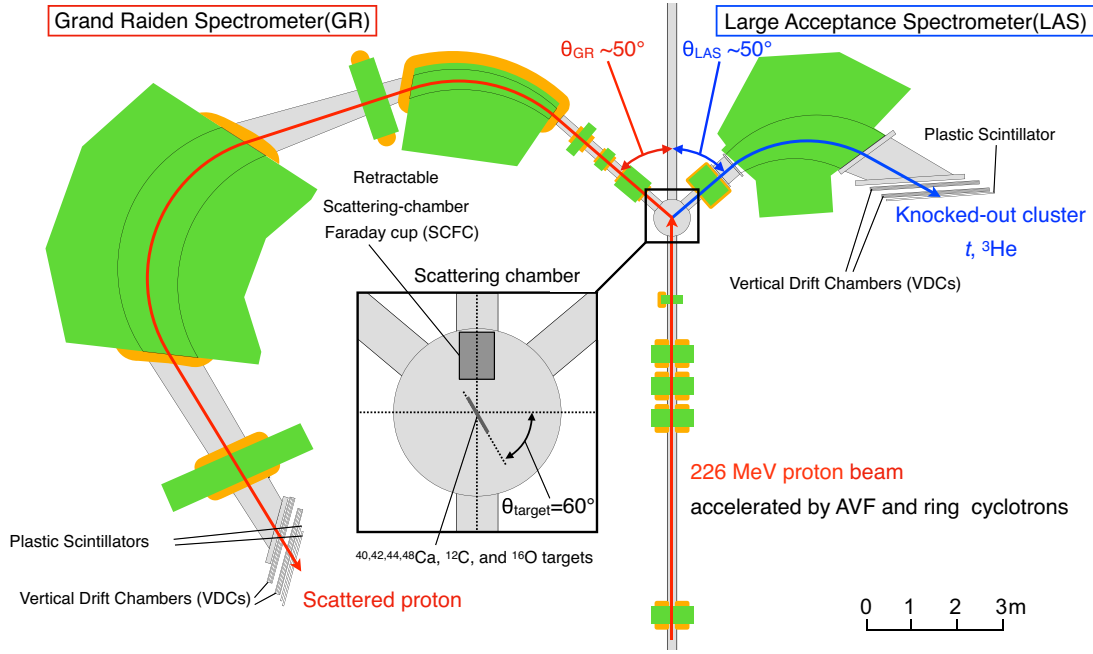


Fig. 1. Schematic view of the experimental setup for the (p, pX) measurements in the West experimental hall of the RCNP. The scattered protons and knocked-out clusters were analyzed using the double-arm spectrometers GR and LAS, arranged in a coplanar geometry at laboratory angles of approximately 50° with respect to the beam axis. The target inside the scattering chamber was rotated by 60° with respect to the beam direction. A retractable Faraday cup (SCFC) for absolute beam-charge normalization is also shown.

The scattered protons and knocked-out clusters were analyzed using the double-arm magnetic spectrometer system, originally developed for $(p, 2p)$ measurements [25]. A schematic view of the experimental setup for this measurement system is shown in Fig. 1. The scattered protons were analyzed with the GR spectrometer [47], while the knocked-out clusters were analyzed with the Large Acceptance Spectrometer (LAS) [48]. In each spectrometer, particle trajectories were reconstructed using vertical drift chambers (VDCs) at the focal plane, while plastic scintillators provided trigger, timing, and energy-loss (ΔE) information for particle identification. Because the outgoing clusters detected in LAS have relatively low energies, the material thickness of the focal-plane detectors was minimized. The VDCs operated with a He (50%)–CH₄ (50%) gas mixture, and a thin 1-mm plastic scintillator was used.

Coincidence events between GR and LAS were recorded. For the trigger condition, GR required a coincidence between its two scintillator layers, whereas LAS used only the single thin scintillator to ensure efficient detection of low-energy cluster particles. To optimize the resolution of the azimuthal (ϕ) angle, GR was operated in under-focus mode [49] and LAS in over-focus mode.

Metallic foils of $^{40,42,44,48}\text{Ca}$ were used as targets. Reference measurements were performed using a ^{12}C target in the form of a self-supporting natural carbon film and a ^{16}O target provided by a Mylar (polyethylene terephthalate, C₁₀H₈O₄) film. The ^{12}C and ^{16}O data were used to evaluate the ^{16}O contamination in the Ca targets arising from surface oxidation [50], and also served as reference data for light $N = Z$ nuclei to benchmark the analysis procedure. The total target thicknesses were determined from independent measurements of mass and area. It should be

Table 1. Total target thicknesses and isotopic compositions (natural abundances for natural targets and enrichments for enriched Ca targets).

Target	Total thickness (mg/cm ²)	Isotopic compositions (%)
¹² C	10.7(2)	98.89 (natural)
¹⁶ O (Mylar)	10.5(2)	99.76 (natural)
⁴⁰ Ca	11.8(2)	96.94 (natural)
⁴² Ca	10.0(6)	93.71
⁴⁴ Ca	9.7(6)	98.78
⁴⁸ Ca	10.0(6)	95.23

noted that the total target thickness includes not only the element of interest (e.g., Ca isotopes) but also contributions from other elements such as hydrogen, carbon, and oxygen. Hydrogen does not contribute to the analyzed (p , pt) or (p , $p^3\text{He}$) channels. In addition, its contribution is negligible for the Ca and carbon targets, whereas it is a structural constituent of the Mylar target, and its amount can be directly determined from the known chemical composition. Accordingly, hydrogen is not explicitly considered in the discussion of the target composition, except for the Mylar target. The enrichment of the ^{42,44,48}Ca targets exceeds 90%. The total target thicknesses and isotopic compositions—natural abundances for natural targets and enrichments for the ^{42,44,48}Ca targets—are summarized in Table 1. The targets were tilted by 60° to minimize variations in the path length of the outgoing low-energy clusters, thereby reducing the degradation of the separation-energy resolution caused by their large and path-length-dependent energy loss in the target.

2.2. Kinematical design and spectrometers setting

The (p , pX) measurements were performed under kinematical conditions corresponding to the quasi-free scattering picture, in which the incident proton undergoes a single-step scattering from the cluster and the residual nucleus acts as a spectator. The experimental conditions were designed in terms of: the separation energy S_X , defined as the energy required to remove the cluster X from the target nucleus; the momentum transfer q to the knocked-out cluster; and the in-nucleus momentum of the cluster k_F . The detailed definitions and formal description of the kinematical framework are provided in Section S1 of the [Supplementary Material](#).

The spectrometer settings were chosen to cover the separation energy range that corresponds to excitation energies up to approximately 10 MeV. The central separation energies were set to $S_X = 25\text{ MeV}$ for the ^{40–48}Ca(p , pt) and ^{40–44}Ca(p , $p^3\text{He}$) reactions. For the ⁴⁸Ca(p , $p^3\text{He}$), a larger value of $S_X = 35\text{ MeV}$ was adopted to account for its higher ground-state separation energy, as listed in Table 2.

The in-nucleus momentum of the cluster was centered at $k_F = 0$ with an acceptance of about $\pm 50\text{ MeV}/c$, corresponding to the recoil-less conditions. The momentum transfer to the cluster was approximately $q \sim 550\text{ MeV}/c$. Because the quasi-free condition requires q to be much larger than k_F for a valid single-step knockout description, the present kinematics satisfy this requirement.

The kinematical design parameters and corresponding spectrometer settings for GR and LAS are summarized in Table 3. Almost identical central energies and spectrometer angles were used for the (p , pt) and (p , $p^3\text{He}$) reactions in the two spectrometers. In contrast, different magnetic-

Table 2. Ground-state separation energies.

Target	$S_t^{\text{g.s.}}$ (MeV)	$S_{\text{He}}^{\text{g.s.}}$ (MeV)
^{40}Ca	24.996	18.830
^{42}Ca	20.690	20.236
^{44}Ca	20.859	23.332
^{48}Ca	22.559	29.385
^{12}C	27.366	26.280
^{16}O	25.032	22.793

Table 3. Design values of kinematical parameters and spectrometer settings.

Parameter	$^{40-48}\text{Ca}(p, pt)$	$^{40-44}\text{Ca}(p, p^3\text{He})$	$^{48}\text{Ca}(p, p^3\text{He})$
S_X (MeV)	25	25	35
k_F (MeV/c)	0	0	0
q (MeV/c)	552.10	552.06	543.98
θ_{GR}	51.23°	51.23°	50.70°
θ_{LAS}	50.89°	50.89°	49.25°
B_{GR} (mT)	610.6	610.9	591.8
B_{LAS} (mT)	1051.7	549.47	518.1
T_{GR} (MeV)	149.06	149.05	140.60
T_{LAS} (MeV)	53.74	53.75	52.20

field settings of LAS were applied to account for the different charges of the outgoing clusters. For a consistent evaluation of target contamination, natural carbon and Mylar targets were measured under all spectrometer settings listed in Table 3.

3. Data reduction

In this section, we describe the data-reduction procedures used to convert the measured (p, pX) coincidence events into separation-energy (S_X) spectra, to identify the populated states in the residual nuclei, and to extract the corresponding triple differential cross-sections (TDX).

3.1. Event reconstruction and separation-energy determination

Particle identification (PID) to select events originating from the (p, pt) and $(p, p^3\text{He})$ reactions is performed using energy-loss (ΔE) and time-of-flight (TOF) information. The TOF of the detected particles is determined from the time difference between the focal-plane plastic scintillator signal and the radio-frequency (RF) reference signal from the ring cyclotron, which provides a timing reference correlated with the arrival of the beam at the target. In GR, ΔE obtained from the plastic scintillators exhibits a pronounced high-energy-loss tail, making it unsuitable for particle identification. Instead, clear separation of protons is achieved using the TOF information alone, and thus PID in GR is performed solely based on the TOF spectrum by applying a $\pm 10\sigma$ gate around the proton peak. In LAS, the low energies of the outgoing clusters ($\sim 50\text{MeV}$) result in insufficient ΔE resolution from the plastic scintillator. Instead, an alternative ΔE observable is defined from the mean time-over-threshold (TOT) of the hit VDC wires and combined with the TOF information for PID. The TOF gate width is set to $\pm 4\sigma$, while the ΔE gate is applied only on the low-energy-loss side (up to -4σ) to suppress background contributions without introducing a significant event loss.

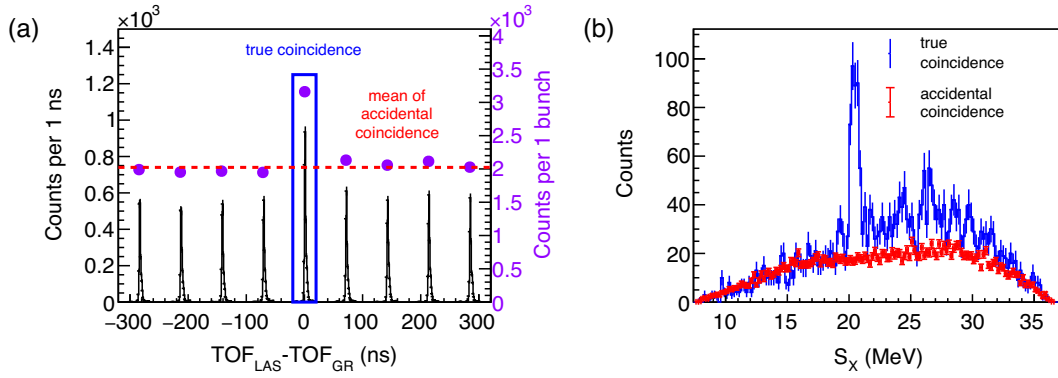


Fig. 2. (a) TOF-difference spectrum between GR and LAS with the PID gate applied. The circular markers represent the counts per bunch, and the red dashed line indicates the mean accidental-coincidence counts per bunch. (b) S_X spectrum showing the true coincidences (blue) and the averaged accidental-coincidence background over eight side bunches (red). The example is from the $^{40}\text{Ca}(p, p^3\text{He})$ reaction.

Even after applying the PID gates, accidental coincidence events not originating from the (p, pX) reactions remain. To extract the true (p, pX) events, the TOF difference between GR and LAS is analyzed under the PID conditions, as shown in Fig. 2(a), where multiple peaks reflect the beam bunch structure. The central peak corresponds to true coincidence events from the same beam bunch but still includes the accidental-coincidence background, which is evaluated by averaging the S_X spectra of the eight surrounding side peaks.

Figure 2(b) compares the S_X spectrum obtained from the true-coincidence region (blue symbols) with the averaged accidental-coincidence-background S_X spectrum (red symbols). Under the present recoil-less kinematical conditions, the recoil energy of the heavy residual nucleus is negligible owing to its large mass. Accordingly, the separation energy S_X is given by

$$S_X = T_{\text{inc}} - T_p - T_X, \quad (1)$$

where T_p and T_X are the kinetic energies of the outgoing proton and the knocked-out cluster measured by GR and LAS, and $T_{\text{inc}} = 226\text{MeV}$ is the incident-beam energy.

3.2. Conversion to acceptance-averaged TDX and treatment of target contamination

The background-subtracted S_X spectra are converted into acceptance-averaged, bin-normalized TDX values, $\Delta\text{TDX}_{\text{exp}}/\Delta S_X$, which are shown as a function of S_X within the experimental acceptance, as defined by the offline analysis cuts:

$$\frac{\Delta\text{TDX}_{\text{exp}}}{\Delta S_X}(S_X) \equiv \frac{1}{\Delta S_X \Delta T_p \Delta \Omega_p \Delta \Omega_X} \frac{N_{(p,pX)}(S_X)}{\epsilon N_{\text{beam}} a_{\text{target}}^{\text{eff}} / \cos \theta_{\text{target}}}. \quad (2)$$

Here, $N_{(p,pX)}(S_X)$ denotes the number of (p, pX) events in each S_X bin after accidental-coincidence-background subtraction and after applying the experimental acceptance cuts as defined below. The S_X spectra are histogrammed with a bin width of $\Delta S_X = 0.2\text{MeV}$. The total detection efficiency ϵ includes the tracking efficiencies of the GR and LAS VDCs and the data-acquisition (DAQ) live time. The evaluated values, together with their typical uncertainties at the 0.1% level, dominated by the DAQ live time, are summarized in Section S2 of the [Supplementary Material](#).

The number of incident protons is determined as $N_{\text{beam}} = Q_{\text{beam}}/e$, where Q_{beam} denotes the accumulated beam charge. The accumulated beam charge is evaluated on a run-by-run basis using the mean counts of the BLP2 beam monitor, which showed stable perfor-

Table 4. Effective target thicknesses and relative atomic amounts with respect to the Mylar target. For the relative atomic amounts, the uncertainties reflect only the statistical uncertainties of the elastic-scattering yields.

Target	Effective thickness (mg/cm ²)	$r_{16\text{O}}$	$r_{12\text{C}}$
Natural carbon (¹² C)	10.7 (13)	0.0219 (3)	1.839 (6)
Mylar (¹⁶ O)	3.5(4)	1	1
⁴⁰ Ca	11.5(11)	0.0944 (4)	0.0057 (1)
⁴² Ca	8.4(8)	0.453 (2)	0.0134 (1)
⁴⁴ Ca	8.7(9)	0.284(1)	0.0046 (1)
⁴⁸ Ca	8.8(9)	0.333 (1)	0.0133 (1)

mance throughout the measurement. The absolute normalization of the BLP2 counts is calibrated with a retractable SCFC installed in the scattering chamber. The stability of the normalization is further verified by occasionally comparing the BLP2 counts with those of the WallFC, and the two monitors are generally consistent within uncertainties, except for occasional unstable runs of the WallFC. The resulting total uncertainty in the beam-charge determination is estimated to be 2% (see Section S3 of the [Supplementary Material](#) for details).

The target tilt angle θ_{target} was fixed at 60°. Accordingly, a correction to the target thickness was applied to account for the geometrical increase owing to the tilt.

The quantity $a_{\text{target}}^{\text{eff}}$ represents the effective areal density of the target nuclei used for the normalization of the TDX. It is derived from the effective target thickness after accounting for the isotopic composition and background contributions from chemical elements other than the element of interest, such as oxygen originating from surface oxidation in the Ca targets and carbon components in the Mylar target. These background contributions are evaluated using the relative atomic amounts introduced below.

The relative atomic amounts of ¹²C and ¹⁶O in each target are determined from the proton elastic-scattering yields measured for the ¹²C(*p*, *p*) and ¹⁶O(*p*, *p*) reactions, which were obtained under identical spectrometer settings and angular acceptance [50]. The resulting relative atomic amounts, $r_{16\text{O}}$ and $r_{12\text{C}}$, are defined with respect to the Mylar target and are summarized in Table 4. Because the relative atomic amounts are determined from ratios of elastic-scattering yields measured under identical experimental conditions, they can be evaluated without requiring detailed knowledge of the absolute target thickness or composition, provided that the beam irradiates the same region of each target. During the beam time, the beam position was periodically monitored using a beam-profile monitor (demagnifier) and was confirmed to pass through the target center within visual accuracy. The uncertainties for the relative atomic amounts listed in Table 4 reflect only the statistical uncertainties of the elastic-scattering yields used for their determination. For the Mylar target, the relative atomic amounts are defined as unity by construction, while its statistical uncertainty is propagated to those of the other targets.

The effective target thicknesses, including the corrections for impurity contributions, are also summarized in Table 4. The uncertainty in the effective target thickness is estimated to be of the order of 10%. For the Ca targets, uncertainties associated with the nominal target thickness and the evaluation of surface oxidation contribute at a comparable level, while

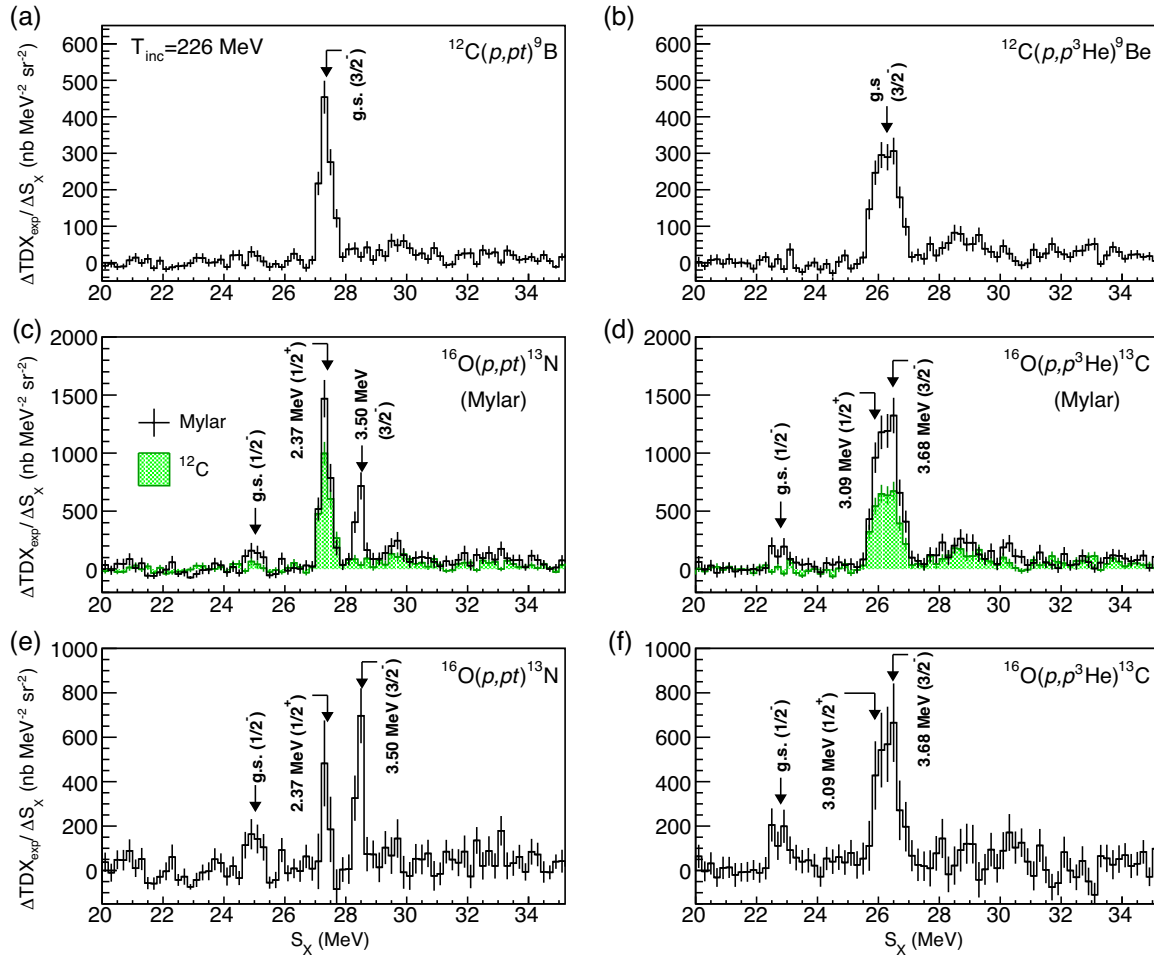


Fig. 3. S_X spectra for the (p, pt) and $(p, p^3\text{He})$ reactions on light nuclei. Panels (a)–(d) show the spectra for the natural-carbon and Mylar targets. The estimated $^{12}\text{C}(p, pt)$ and $(p, p^3\text{He})$ backgrounds in the Mylar data are shown with green hatching. Panels (e) and (f) present the ^{16}O spectra obtained by subtracting the carbon contributions from the Mylar spectra.

for the ^{16}O (Mylar) and ^{12}C targets, the dominant contribution originates from thickness non-uniformity.

Details of the evaluation of the effective target thickness and the determination of the relative atomic amounts, and their associated uncertainties, are described in Section S4 of the [Supplementary Material](#).

The quantities ΔT_p , $\Delta\Omega_p$, and $\Delta\Omega_X$ denote the experimental acceptances in the outgoing-proton kinetic energy and in the laboratory solid angles of the outgoing proton and cluster, respectively. These acceptances are defined as software gates in the offline analysis. The uncertainties in the angular acceptances $\Delta\Omega_p$ and $\Delta\Omega_X$ are each estimated to be about 2%. Details of the acceptance definition and the numerical values for each experimental setting are summarized in Section S5 of the [Supplementary Material](#).

4. Results

The resulting acceptance-averaged S_X spectra are shown in Figs. 3 and 4. The S_X resolution was typically 0.2MeV for the (p, pt) reactions and 0.4MeV for the $(p, p^3\text{He})$ reactions, which

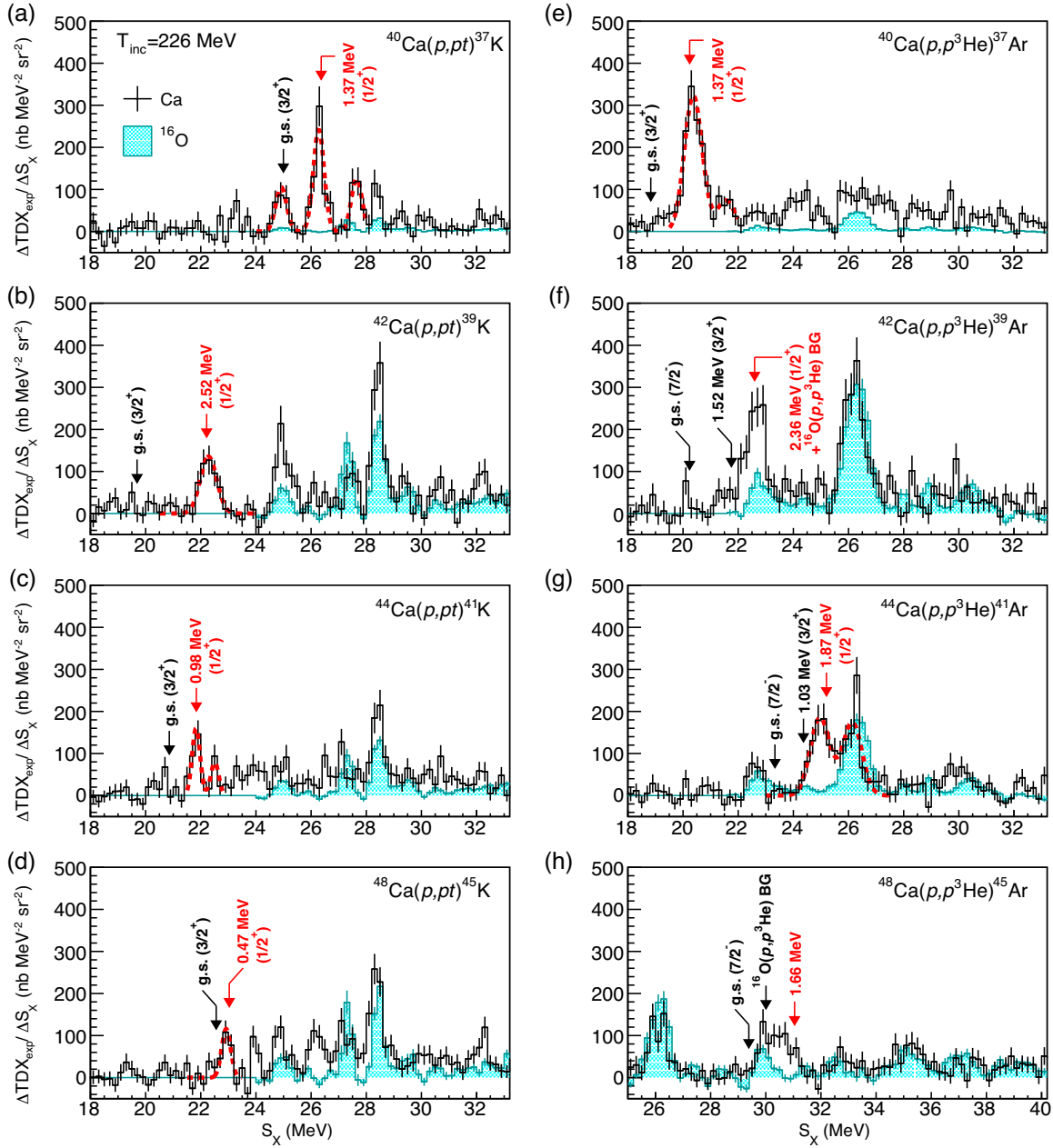


Fig. 4. S_X spectra for the (p, pt) and $(p, p^3\text{He})$ reactions on the $^{40,42,44,48}\text{Ca}$ targets. Panels (a)–(d) correspond to the (p, pt) reactions and panels (e)–(h) to the $(p, p^3\text{He})$ reactions. The estimated $^{16}\text{O}(p, pt)$ and $(p, p^3\text{He})$ backgrounds are shown in cyan hatching. The red arrows and labels mark the $1/2^+$ states of the residual nuclei. The red dashed curve denotes the fitting function used to extract the cross-section of these $1/2^+$ states.

was mainly determined by the difference in the energy loss of the outgoing clusters inside the target.

4.1. Peak identification and TDX extraction

To extract state-resolved TDX values, the excited states of the residual nucleus are identified by mapping the excitation energies listed in the NNDC database. The corresponding peaks are fitted with single or multiple Gaussian functions. The S_X resolution (Gaussian σ) is treated as

a single common parameter for all peaks within each spectrum. If significant overlap with impurity components is present, impurity background subtraction using the fixed relative atomic amounts is applied. When the peak of interest is free from impurity contributions, the fit is performed on the spectrum without impurity background subtraction. The extracted experimental TDX values are summarized in Tables 5 and 6 for the light nuclei and the Ca isotopes, respectively.

Figures 3(a) and (b) show the S_X spectra for the $^{12}\text{C}(p, pt)$ and $^{12}\text{C}(p, p^3\text{He})$ reactions, respectively. In both cases, a single prominent peak corresponding to the $3/2^-$ ground state of the residual ^9B and ^9Be nuclei is observed and fitted accordingly. Figures 3(c) and (d) show the S_X spectra obtained from the Mylar target for the (p, pt) and $(p, p^3\text{He})$ reactions, respectively. The hatched green histograms represent the $^{12}\text{C}(p, pt)$ and $(p, p^3\text{He})$ spectra, scaled by the relative atomic amounts of ^{12}C between the Mylar and ^{12}C targets, and thus correspond to the ^{12}C contribution in the Mylar spectra. The corresponding $^{16}\text{O}(p, pt)$ and $^{16}\text{O}(p, p^3\text{He})$ spectra, estimated after subtraction of the ^{12}C contribution, are shown in Figs. 3(e) and (f). In these spectra, clear peaks corresponding to the $1/2^-$ ground states, as well as to the $1/2^+$ and $3/2^-$ excited states of the residual ^{13}N and ^{13}C nuclei, are observed. The ground states and the $3/2^-$ state of ^{13}N are free from carbon background and are analyzed directly. The other states are extracted after carbon subtraction: the $1/2^+$ state of ^{13}N is obtained from a fit, whereas the unresolved $1/2^+$ and $3/2^-$ states of ^{13}C are treated by integrating the spectrum over $[S_X(1/2^+) - 3\sigma, S_X(3/2^-) + 3\sigma]$, with $\sigma = 0.4$ MeV, corresponding to the typical S_X resolution of the $(p, p^3\text{He})$ measurement.

The S_X spectra for the $^{40,42,44,48}\text{Ca}(p, pt)$ and $(p, p^3\text{He})$ reactions are shown in Fig. 4. The hatched cyan histograms represent the $^{16}\text{O}(p, pt)$ and $(p, p^3\text{He})$ spectra, scaled by the relative atomic amounts of ^{16}O between the Mylar and Ca targets, and thus correspond to the ^{16}O contribution in the Ca spectra. The displayed ^{16}O background spectra are mildly Gaussian-smoothed to suppress statistical fluctuations. For each bin in the S_X spectra, the bin content and its two neighboring bins are weighted using a Gaussian function with widths corresponding to the experimental S_X resolution [0.2 MeV for (p, pt) and 0.4 MeV for $(p, p^3\text{He})$]. This effect is particularly pronounced for the ^{16}O background spectrum in the $^{48}\text{Ca}(p, p^3\text{He})$ channel; for consistency, the same smoothing procedure is applied to the displayed ^{16}O background spectra in the other cases as well.

For the Ca targets, a pronounced peak corresponding to the $1/2^+$ state of the residual K and Ar nuclei is consistently observed in the S_X spectra and serves as the primary focus of the present analysis. For $^{48}\text{Ca}(p, p^3\text{He})$, the 1.66-MeV excited state of ^{45}Ar , previously observed in the $^{48}\text{Ca}(\alpha, ^7\text{Be})^{45}\text{Ar}$ reaction, is treated as the $1/2^+$ candidate [45]. For the (p, pt) reactions on $^{40-48}\text{Ca}$, as well as for the $(p, p^3\text{He})$ reactions on ^{40}Ca and ^{44}Ca , the peak corresponding to the $1/2^+$ state of the residual nucleus is well separated from the ^{16}O background and fitted directly, as shown by the red curves in Fig. 4. The peak width for the $1/2^+$ state in ^{39}K is somewhat larger than those for the other nuclei, which may reflect statistical fluctuations or unresolved background contributions in this region. However, the nearby known states involve larger angular momenta and are expected to be weak under the present recoil-less conditions, and this region is essentially free from the ^{16}O background. Therefore, the strength in this low- S_X region is considered to be dominated by the $1/2^+$ component. In contrast, for the $(p, p^3\text{He})$ reactions on ^{42}Ca and ^{48}Ca , the oxygen contribution is non-negligible and is subtracted prior to the fit, as shown in Fig. 5.

Table 5. Experimental and WS-based DWIA triple-differential cross-sections, TDX_{exp} and TDX_{WS} , together with the experimental spectroscopic factors s_{exp} , for the $1/2^+$ state of the residual nuclei in the ^{12}C and $^{16}\text{O}(p, pt)$ and $(p, p^3\text{He})$ reactions. The uncertainties of TDX_{exp} and s_{exp} represent the total uncertainties obtained by combining the statistical and systematic components. For the TDX_{WS} values, the (p, pt) results are scaled by a factor of 1.45 to account for the elementary-process asymmetry. The extracted s_{exp} values are affected accordingly. For reference, the $\text{TDX}_{\text{WS}}^{(\text{raw})}$ and $s_{\text{exp}}^{(\text{raw})}$ obtained without applying the elementary-process scaling are also listed.

Target	State of the residual nucleus	Cluster	(n, L, J)	TDX_{exp} (nb MeV $^{-1}$ sr $^{-2}$)	$\text{TDX}_{\text{WS}}^{(\text{raw})}$ (nb MeV $^{-1}$ sr $^{-2}$)	$s_{\text{exp}}^{(\text{raw})}$	TDX_{WS} (nb MeV $^{-1}$ sr $^{-2}$)	s_{exp}
^{12}C	g.s. ($3/2^-$)	t	(1, 1, $1/2$)	$2.1(3) \times 10^2$	5.44×10^2	0.39(6)	3.74×10^2	0.56(8)
		^3He		$3.2(4) \times 10^2$	5.61×10^2	0.56(8)	5.61×10^2	0.56(8)
^{16}O	g.s. ($1/2^-$)	t	(1, 1, $1/2$)	$0.9(3) \times 10^2$	5.70×10^2	0.15(5)	3.92×10^2	0.22(7)
		^3He		$1.3(4) \times 10^2$	5.58×10^2	0.24(7)	5.58×10^2	0.24(7)
^{16}O	$1/2^+$	t	(2, 0, $1/2$)	$1.4(6) \times 10^2$	2.39×10^3	0.06(2)	1.65×10^2	0.08(3)
^{16}O	$3/2^-$	t	(1, 1, $3/2$)	$2.8(5) \times 10^2$	3.98×10^2	0.69(12)	2.74×10^2	1.0(2)
^{16}O	$1/2^+$ and $3/2^-$	^3He	–	$6.3(12) \times 10^2$	–	–	–	–

Table 6. Experimental and WS-based DWIA triple-differential cross-sections, TDX_{exp} and TDX_{WS} , together with the experimental spectroscopic factors s_{exp} , for the $1/2^+$ state of the residual nuclei in the $^{40-48}\text{Ca}(p, pt)$ and $(p, p^3\text{He})$ reactions. The uncertainties of TDX_{exp} and s_{exp} represent the total uncertainties obtained by combining the statistical and systematic components. For the TDX_{WS} values, the (p, pt) results are scaled by a factor of 1.45 to account for the elementary-process asymmetry. The extracted s_{exp} values are affected accordingly.

Target	Cluster	TDX_{exp} (nb MeV ⁻¹ sr ⁻²)	TDX_{WS} (nb MeV ⁻¹ sr ⁻²) ($s = 1$)	s_{exp}
⁴⁰ Ca	<i>t</i>	$1.2(2) \times 10^2$	1.07×10^3	0.11(2)
	³ He	$2.6(3) \times 10^2$	1.60×10^3	0.16(2)
⁴² Ca	<i>t</i>	$1.0(2) \times 10^2$	1.14×10^3	0.09(2)
	³ He	$2.0(4) \times 10^2$	1.40×10^3	0.14(3)
⁴⁴ Ca	<i>t</i>	$0.6(1) \times 10^2$	1.12×10^3	0.05(1)
	³ He	$1.6(3) \times 10^2$	1.21×10^3	0.13(2)
⁴⁸ Ca	<i>t</i>	$0.5(1) \times 10^2$	1.04×10^3	0.05(1)
	³ He	$1.0(3) \times 10^2$	8.5×10^2	0.11(3)

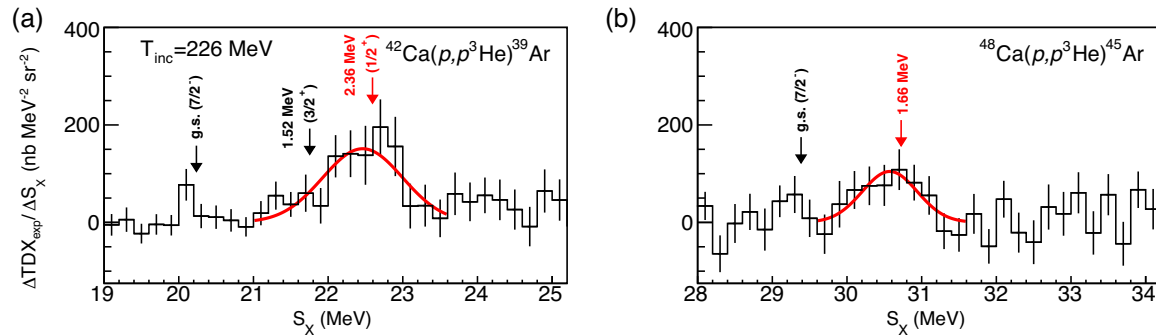


Fig. 5. S_X spectra for the $^{42,48}\text{Ca}(p, p^3\text{He})$ reactions after subtraction of the $^{16}\text{O}(p, p^3\text{He})$ contributions. The red curves show the fits to the $1/2^+$ states of the residual nuclei; for ^{45}Ar , the $1/2^+$ assignment corresponds to the candidate state discussed in the text.

4.2. Integration of TDX

In the Ca isotopes, the S_X spectra shown in Fig. 4 exhibit channel- and isotope-dependent fragmentation patterns. In the (p, pt) reaction on ^{40}Ca , the $3/2^+$ ground state is clearly observed together with the low-lying $1/2^+$ state, and additional strength is present at higher excitation energies. For the S_X spectra of the (p, pt) reactions on the neutron-rich Ca isotopes, significant strength is distributed at excitation energies above the identified $1/2^+$ peak, although individual states cannot always be uniquely assigned. In contrast, in the $(p, p^3\text{He})$ channel, the strength is largely concentrated in the $1/2^+$ state across the Ca isotopes, with this concentration becoming particularly pronounced for ^{42}Ca and heavier isotopes.

To visualize the strength distributed beyond the identified low-lying $1/2^+$ states of the residual nuclei in the (p, pt) and $(p, p^3\text{He})$ reactions on Ca isotopes, a complementary analysis is performed by evaluating the S_X -integrated TDX values, with an S_X -dependent acceptance correction, denoted as TDX_{int} .

The measured S_X spectra are affected by the experimental acceptance, which depends on S_X through the available phase-space volume in the in-nucleus momentum of the cluster

Table 7. S_X -integrated triple differential cross-sections TDX_{int} for the $^{40-48}\text{Ca}(p, pt)$ and $(p, p^3\text{He})$ reactions. The uncertainties of TDX_{int} represent the total uncertainties obtained by combining the statistical and systematic components.

Target	(p, pt) $\text{TDX}_{\text{int}}(\text{nb MeV}^{-1} \text{ sr}^{-2})$	$(p, p^3\text{He})$ $\text{TDX}_{\text{int}}(\text{nb MeV}^{-1} \text{ sr}^{-2})$
^{40}Ca	$3.8(6) \times 10^2$	$6.4(8) \times 10^2$
^{42}Ca	$3.0(7) \times 10^2$	$2.8(9) \times 10^2$
^{44}Ca	$3.9(7) \times 10^2$	$1.9(7) \times 10^2$
^{48}Ca	$3.9(8) \times 10^2$	$1.3(6) \times 10^2$

and the center-of-mass solid angle of the elementary p - X scattering process. To account for this effect, an S_X -dependent acceptance correction is applied based on the phase-space factor $\Delta^3 k_F \Delta \Omega_{p-X}^{\text{cm}}(S_X)$ evaluated using Monte Carlo simulations. The S_X spectra are then corrected using the weight function

$$\frac{\Delta^3 k_F \Delta \Omega_{p-X}^{\text{cm}}(S_X^{1/2+})}{\Delta^3 k_F \Delta \Omega_{p-X}^{\text{cm}}(S_X)}, \quad (3)$$

where the normalization at $S_X^{1/2+}$ corresponds to the excitation energy of the low-lying $1/2^+$ state of the residual nuclei. The validity of the acceptance-correction procedure is examined by comparing the S_X dependence of the phase-space factor $\Delta^3 k_F \Delta \Omega_{p-X}^{\text{cm}}(S_X)$ used in the correction with that of the TDX obtained from DWIA calculations. The close agreement between the two indicates that the observed S_X dependence of the measured spectrum is governed largely by the experimental acceptance, while reaction-mechanism effects incorporated in the DWIA calculation play a relatively minor role. This supports the reliability of the present correction scheme (see Section S6 of the [Supplementary Material](#) for details).

The integration is performed over the excitation-energy range $S_X - S_X^{\text{g.s.}} = 0$ –8 MeV for all isotopes, a range that captures the main low-lying strengths while avoiding the region where the acceptance rapidly decreases and the correction becomes unreliable. Contributions from the ^{16}O impurities are subtracted from the spectra. The resulting S_X -integrated values, TDX_{int} , are summarized in Table 7.

4.3. Uncertainty of extracted TDX

The uncertainties in the extracted TDX values consist of statistical contributions, dominated by the experimental yields, and systematic contributions, dominated by the absolute normalization. The statistical uncertainty includes the counting statistics of the events and the propagated uncertainties from the subtraction of accidental-coincidence and impurity backgrounds. For the state-resolved TDX values obtained by spectral fitting, the statistical uncertainty is given by the fitting uncertainty of the corresponding peak yields, whereas for the S_X -integrated TDX values, it is determined directly from the integrated event counts. The resulting statistical uncertainty typically amounts to 10–25% and constitutes the dominant contribution to the total uncertainty.

Among the systematic uncertainties affecting the absolute scale of the TDX, the dominant contribution arises from the uncertainty in the effective target thickness. This uncertainty, associated with the determination of the effective areal density, is estimated to be about 10% for all targets used in the present experiment.

Other systematic uncertainties, including those associated with the beam-charge determination, the angular acceptances of the spectrometers, and the relative atomic amounts used for scaling the impurity background, are comparatively small and amount to about 3–4% in total.

The uncertainties associated with the relative atomic amounts used for scaling the impurity-background contributions in the S_X spectra are propagated to the extracted TDX values through the background-subtraction procedure, and their impact depends on the relative contribution of the impurity components. For most observables, the impurity contribution is either outside the relevant S_X region or small. In the latter case, the resulting uncertainty remains at the level of a few percent even when a conservative systematic uncertainty of about 10% is assumed for the relative atomic amounts, and is subdominant compared with the other statistical and systematic uncertainties. However, for observables with larger background contributions, the impact becomes more pronounced. A conservative estimate of this uncertainty of about 10% is obtained from consistency checks, including comparisons with the $(p, p\alpha)$ yields in Ref. [50] and with the values expected from the nominal target composition and thickness. Details of the evaluation of the propagated uncertainties of the TDX values arising from the conservatively assumed uncertainty of the relative atomic amounts are given in Section S4 of the [Supplementary Material](#).

5. Reaction analysis

The extracted TDX values are compared with DWIA calculations, a framework known to provide a reliable description of quasi-free (p, pN) reactions [25] and previously applied to $(p, p\alpha)$ reactions [30,51,52]. The present calculations for (p, pt) and $(p, p^3\text{He})$ reactions are performed using the code PIKOE [29], following these earlier knockout analyses [53].

To allow for a direct comparison with the experimental TDX values, the DWIA TDX values are calculated as acceptance-averaged quantities,

$$\text{TDX}_{\text{DWIA}} = \frac{\int dT_p d\Omega_p d\Omega_X \left(\frac{d^3\sigma}{dT_p d\Omega_p d\Omega_X} \right)_{\text{DWIA}}}{\int dT_p d\Omega_p d\Omega_X}, \quad (4)$$

where the integration variables correspond to the experimental acceptance.

5.1. Input for DWIA

The DWIA calculations require the following inputs: (i) the optical potential for the incident proton–target system; (ii) that for the scattered proton–residual system; (iii) that for the knocked-out cluster–residual system; (iv) the elementary proton–triton and proton– ^3He elastic-scattering amplitude; and (v) the bound-state wave function of the cluster inside the nucleus.

For (i) and (ii), microscopic folding optical potentials commonly employed in (p, pN) analyses are used. The folding potentials are constructed using the g -matrix interaction [54] with the Brieva–Rook localization procedure [55–57]. The nucleon density distributions of the target and residual nuclei are taken from Hartree–Fock calculations with the Gogny D1S interaction [58,59].

For (iii), the composite nature of the knocked-out cluster is taken into account by employing a double-folding potential [60], where the nucleon density distributions in t and ^3He are obtained from calculations based on the Gaussian expansion method [61].

For (iv), the corresponding free-scattering energy T_{eq} is lower than the incident-beam energy $T_{\text{inc}} = 226\text{MeV}$. Under the present acceptance, T_{eq} falls in the range of 180–200MeV. Because experimental p – t and p – ^3He elastic-scattering data are scarce in this energy region, the

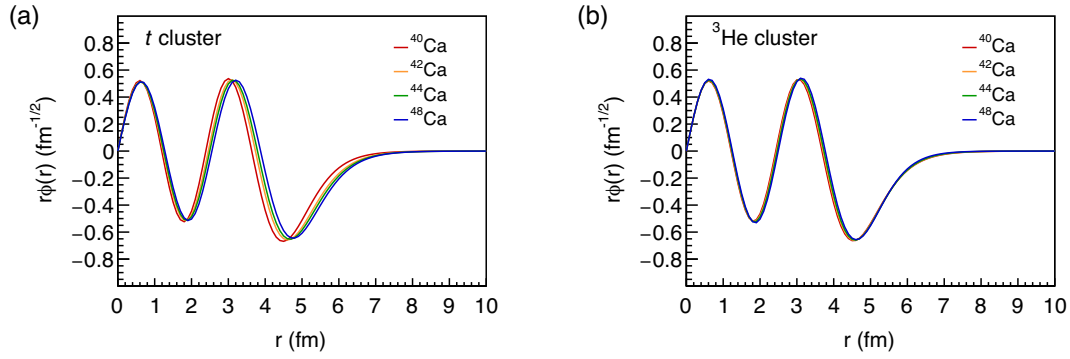


Fig. 6. Radial wave functions $r\phi(r)$ for (a) t clusters and (b) ${}^3\text{He}$ clusters in the Ca isotopes calculated with the WS model. The spatial distributions of the t and ${}^3\text{He}$ wave functions show little isotopic dependence.

elementary scattering amplitudes are calculated using folding potentials within the Kerman–McManus–Thaler (KMT) multiple-scattering formalism [62].

For (v), two distinct cluster wave functions are employed according to the purpose of the analysis. First, conventional Woods–Saxon (WS) wave functions are adopted to provide a reaction-mechanism reference for the state-resolved TDX_{exp} , from which experimental spectroscopic factors are extracted. Second, grDFT-based wave functions are used to obtain theoretical TDX values that can be directly compared with the experimental data.

5.2. WS-based TDX and experimental spectroscopic factor

For each state, a TDX is calculated using a WS wave function normalized to unity. The TDX, denoted as TDX_{WS} , serves as a reference in the following. The experimental spectroscopic factor is then defined as

$$s_{\text{exp}} = \frac{\text{TDX}_{\text{exp}}}{\text{TDX}_{\text{WS}}}. \quad (5)$$

The quantity s_{exp} serves as a phenomenological measure of the cluster component within the WS-based DWIA framework.

The WS wave functions are calculated within the PIKOE code. The WS potential includes central and Coulomb terms together with a non-local correction. The geometrical parameters are set to $r_0 = 1.41\text{fm}$, $a = 0.65\text{fm}$ [41], and $r_c = 1.20\text{fm}$, and the depth of the central term is adjusted to reproduce the cluster separation energy. The spin–orbit term is omitted, as no established prescription exists for the spin–orbit interaction in cluster–residual-nucleus systems. Each WS wave function is characterized by (n, L, J) , where n is the radial node number, L the orbital angular momentum, and $J = L \oplus S$ with $S = 1/2$.

The radial wave functions $r\phi(r)$ obtained with the WS model for the cluster–residual relative motion are shown in Fig. 6. The WS cluster wave functions for the t and ${}^3\text{He}$ clusters in the Ca isotopes, which populate the $1/2^+$ states of the residual nuclei after knockout, are characterized by the quantum numbers $(n, L, J) = (3, 0, 1/2)$. The spatial distributions of $r\phi(r)$ exhibit only weak isotopic dependence.

5.3. grDFT-based TDX

In order to compare experimentally observed TDX values with more realistic theoretical predictions, DWIA calculations are also performed using cluster density distributions in the Ca isotopes obtained within the grDFT framework. It should be noted that the cluster density dis-

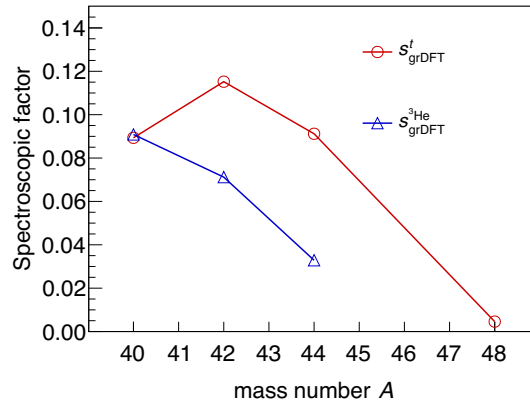


Fig. 7. Isotopic dependence of the grDFT-based spectroscopic factors s_{grDFT} of t and ${}^3\text{He}$ clusters for ${}^{40-48}\text{Ca}$. Red circles correspond to the t channel and blue triangles to the ${}^3\text{He}$ channel. The ${}^3\text{He}$ value for ${}^{48}\text{Ca}$ is omitted because its amplitude is negligibly small.

Table 8. The grDFT-based triple differential cross-section values $\text{TDX}_{\text{grDFT}}$ and spectroscopic factors s_{grDFT} for the Ca isotopes. For the theoretical $\text{TDX}_{\text{grDFT}}$ values, the (p, pt) results are scaled by a factor of 1.45 to account for the elementary-process asymmetry.

Target	t cluster	(p, pt) $\text{TDX}_{\text{grDFT}}$ (nb MeV $^{-1}$ sr $^{-2}$)	${}^3\text{He}$ cluster	$(p, p^3\text{He})$ $\text{TDX}_{\text{grDFT}}$ (nb MeV $^{-1}$ sr $^{-2}$)
	s_{grDFT}		s_{grDFT}	
${}^{40}\text{Ca}$	0.089	4.25×10^2	0.091	5.98×10^2
${}^{42}\text{Ca}$	0.115	4.89×10^2	0.071	4.31×10^2
${}^{44}\text{Ca}$	0.091	4.41×10^2	0.033	2.00×10^2
${}^{48}\text{Ca}$	0.0046	3.6×10^1	–	–

tributions are assumed to be isotropic in the present grDFT theory for the finite nuclei. Consequently, the grDFT cluster densities are considered to correspond to S -wave cluster configurations. Accordingly, the comparison is made to the data for the S -wave clusters.

In the grDFT framework, this isotropic cluster structure is described by the radial density distribution $D(r)$. The integral of this density,

$$s_{\text{grDFT}} = \int d^3r D(r), \quad (6)$$

is interpreted as the theoretical spectroscopic factor, or equivalently as the cluster number. The isotopic dependence of the s_{grDFT} values for the Ca isotopes is shown in Fig. 7, and the numerical values are listed in Table 8. For the ${}^3\text{He}$ channel, the s_{grDFT} values decrease monotonically with increasing neutron number. The ${}^3\text{He}$ component in ${}^{48}\text{Ca}$ is excluded from the discussion because its amplitude is too small to be observed in the experiment. In contrast, for the t channel, the s_{grDFT} values show a slight increase from ${}^{40}\text{Ca}$ to ${}^{42}\text{Ca}$, followed by a monotonic decrease toward ${}^{48}\text{Ca}$.

In these calculations, the cluster wave function $\phi(r) = \sqrt{4\pi D(r)}$ derived from the grDFT calculation is used as input to the DWIA framework. The radial wave functions $r\phi(r)$ derived from the grDFT model are shown in Fig. 8. While the amplitudes exhibit isotopic dependence, the spatial shapes of the distributions remain largely unchanged.

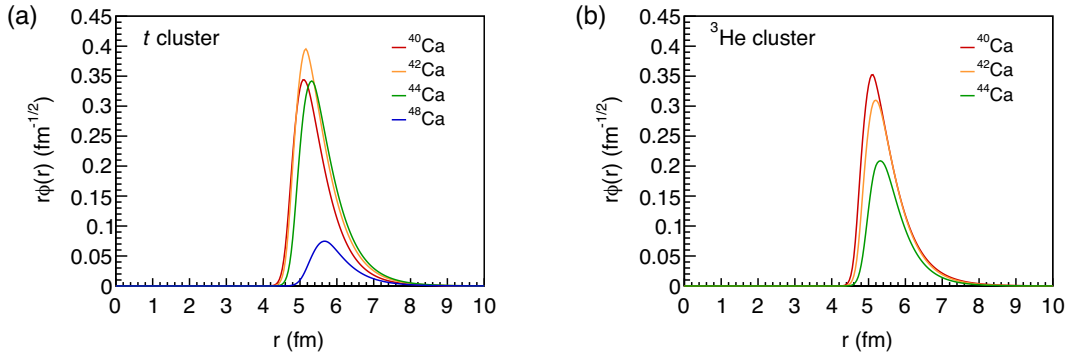


Fig. 8. Radial wave functions $r\phi(r)$ for (a) t clusters and (b) ${}^3\text{He}$ clusters in the Ca isotopes calculated with grDFT. The amplitudes reflect the spectroscopic factors s_{grDFT} , showing a decrease with increasing neutron number. The ${}^3\text{He}$ cluster in ${}^{48}\text{Ca}$ is excluded because no significant spectroscopic factor is calculated. In contrast, the spatial distributions exhibit no major differences.

The grDFT-based TDX values, $\text{TDX}_{\text{grDFT}}$, were calculated using these wave functions, assuming $L = 0$, $J = 1/2^+$, and the S_X corresponding to the low-lying $1/2^+$ state of the residual nucleus, so as to enable a direct comparison with the low-lying S -wave TDX_{exp} values.

5.4. Application to light nuclei

To examine the behavior of the present analysis framework, the WS-based DWIA calculations are applied to the ${}^{12}\text{C}$ and ${}^{16}\text{O}$ (p , pt) and (p , $p^3\text{He}$) reactions. The WS-based TDX values and the experimental spectroscopic factors, denoted as $\text{TDX}_{\text{WS}}^{(\text{raw})}$ and $s_{\text{exp}}^{(\text{raw})}$, together with the cluster configurations (n , L , J) adopted for the WS-based DWIA calculations, are summarized in Table 5.

For the present (p , pt) and (p , $p^3\text{He}$) data on ${}^{12}\text{C}$ and ${}^{16}\text{O}$, the TDX_{exp} values for (p , $p^3\text{He}$) are approximately 50% larger than those for (p , pt). This asymmetry persists in the extracted experimental spectroscopic factors $s_{\text{exp}}^{(\text{raw})}$, with a magnitude of approximately 50%.

In this measurement, although particles with different charges (t and ${}^3\text{He}$) were measured using the same detection system, the detector response was optimized and verified for each particle species, including the trigger-threshold settings and the VDC tracking efficiencies. The ion-optical calibration was also performed separately under the respective magnetic-field settings for (p , pt) and (p , $p^3\text{He}$). Therefore, the observed t - ${}^3\text{He}$ asymmetry cannot be attributed to measurement-related effects.

Possible origins of the observed t - ${}^3\text{He}$ asymmetry can be discussed within the DWIA framework in terms of three components: (i) distortion effects due to the optical potentials; (ii) the elementary p - t and p - ${}^3\text{He}$ scattering cross-sections; and (iii) the structure of the bound clusters.

For (i), the present calculations employ microscopic folding optical potentials and show no noticeable asymmetry between the two channels. This is consistent with a global analysis of elastic scattering data, which reported nearly charge-symmetric behavior for t and ${}^3\text{He}$ scattering from stable nuclei [63]. For (iii), under the assumption of approximate charge symmetry of the nuclear interaction, there is presently no established theoretical framework that predicts a substantial charge-dependent difference between the t and ${}^3\text{He}$ cluster wave functions in light $N = Z$ nuclei.

For (ii), in contrast, existing data for the elementary p - t and p - ^3He elastic scattering at 156 MeV show that the p - ^3He cross-section exceeds that of p - t by about 50% in the momentum-transfer region relevant to the present kinematics [64]. The tendency is consistent with the present (p, pt) and $(p, p^3\text{He})$ results. It should be noted that the excess of the p - ^3He cross-section over the p - t one cannot be reproduced by the present folding model calculation, which predicts approximately equal cross-sections for p - ^3He and p - t .

At lower incident energies (75 MeV), previous measurements for ^{12}C and ^{16}O reported nearly charge-symmetric behavior in both the (p, pt) and $(p, p^3\text{He})$ cross-sections and the extracted spectroscopic factors [40]. This symmetry can be understood from the fact that, in this energy region, the elementary p - t and p - ^3He cross-sections are themselves nearly symmetric, as established by experimental data.

In light of the above considerations, the asymmetry observed between the (p, pt) and $(p, p^3\text{He})$ TDX values and the experimental spectroscopic factors in the present data for light $N = Z$ nuclei may be attributed to the elementary reaction process. To correct for possible differences in the elementary p - t and p - ^3He process, a scaling factor is determined using the ^{12}C data, for which the experimental uncertainties are smallest. The factor was chosen such that the experimental spectroscopic factors for the $^{12}\text{C}(p, pt)^9\text{B(g.s.)}$ and $^{12}\text{C}(p, p^3\text{He})^9\text{Be(g.s.)}$ reactions become equal. The resulting scaling factor, $s_{\text{exp}}^{(\text{raw})}(^3\text{He}) / s_{\text{exp}}^{(\text{raw})}(t)$, is 1.45(15). The theoretical TDX for the (p, pt) reaction is divided by this scaling factor, because the theoretical description is consistent with the available elementary p - ^3He data, whereas it systematically overestimates the available elementary p - t data. The uncertainty of the scaling factor is evaluated by propagating the statistical uncertainty and the systematic uncertainties excluding that associated with the absolute target thickness, because the target-thickness uncertainty cancels in the ratio of the experimental spectroscopic factors $s_{\text{exp}}^{(\text{raw})}$.

5.5. Results of the reaction analysis

Based on the light-nucleus analysis, an elementary-process scaling factor is introduced to down-scale the DWIA-calculated (p, pt) TDX values, and the experimental spectroscopic factors are corrected accordingly. The resulting WS-based TDX values and experimental spectroscopic factors, denoted as TDX_{WS} and s_{exp} , both of which include the elementary-process scaling, are summarized in Table 5 for the light nuclei and in Table 6 for the low-lying $1/2^+$ states of the residual nuclei populated via the knockout of a t or ^3He cluster from the Ca isotopes.

The $\text{TDX}_{\text{grDFT}}$ values obtained from the grDFT-based DWIA calculations for the Ca isotopes, after applying the same elementary-process scaling, are listed in Table 8. The corresponding s_{grDFT} values are purely structural quantities derived from the grDFT calculation and are not subject to the elementary-process scaling.

It should be noted that the present light-nucleus results do not show quantitative agreement with some previous (p, pt) and $(p, p^3\text{He})$ studies performed at lower incident energies [40,41]. At such lower energies, the applicability of the DWIA framework may be limited, and spectroscopic factors significantly exceeding unity were reported, rendering a direct structural interpretation difficult. In contrast, the present higher-incident-energy data yield experimental spectroscopic factors that remain of order 0.1, supporting the reliability of the present reaction analysis within the DWIA framework. Owing to the availability of high-precision microscopic structure calculations for light nuclei, such as AMD and no-core MCSM approaches, the

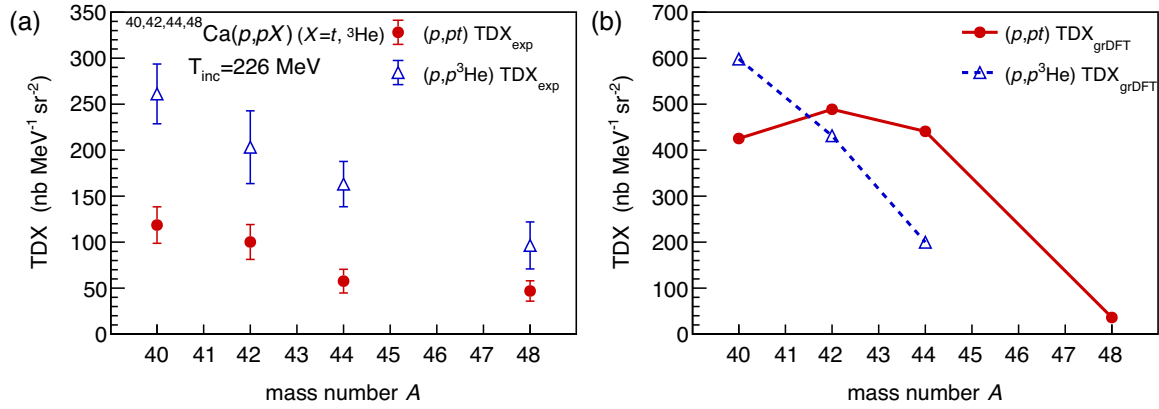


Fig. 9. Isotopic dependence of the experimental and grDFT-based TDX values for the low-lying S -wave states in the (p, pt) and $(p, p^3\text{He})$ reactions on $^{40-48}\text{Ca}$. (a) Experimental TDX values, TDX_{exp} , for the low-lying $1/2^+$ states, shown as red filled circles for the (p, pt) channel and as blue open triangles for the $(p, p^3\text{He})$ channel. (b) grDFT-based TDX values, $\text{TDX}_{\text{grDFT}}$, shown as red filled circles connected by solid lines for the (p, pt) channel and as blue open triangles connected by dashed lines for the $(p, p^3\text{He})$ channel.

present data provide a promising benchmark for future quantitative comparisons with microscopic nuclear-structure theories.

6. Discussion

For the Ca isotopes, the peaks corresponding to the low-lying $1/2^+$ residual nuclei states are observed in the S_X spectra for both the (p, pt) and $(p, p^3\text{He})$ reactions, corresponding to the S -wave ($L = 0$) cluster components that are selectively enhanced under recoil-less conditions by the reaction mechanism. The observation of such peaks therefore indicates the presence of cluster-like three-nucleon correlations even in medium-mass Ca nuclei.

The TDX_{exp} values for the low-lying S -wave states exhibit a systematic decrease with increasing neutron number, as shown in Fig. 9(a). The experimental spectroscopic factors s_{exp} , which are derived within the WS-based DWIA framework to quantify cluster components, show the same decreasing trend in Fig. 10, suggesting a reduction of the intrinsic low-lying S -wave t and ^3He cluster components toward neutron-rich Ca isotopes.

The absolute magnitudes of $\text{TDX}_{\text{grDFT}}$ are found to be of the same order as those of the experimental low-lying S -wave TDX_{exp} values. This result indicates that the grDFT-based cluster densities, when incorporated into the DWIA framework, provide a reasonable description of the overall scale of the observed cluster-knockout strengths.

The $\text{TDX}_{\text{grDFT}}$ values exhibit a global decreasing trend with increasing neutron number, similar to that observed experimentally. This behavior directly reflects the isotopic dependence of the grDFT spectroscopic factors s_{grDFT} , as shown in Fig. 7, which represent the cluster numbers predicted within the grDFT framework. A similar reduction of cluster strength with increasing neutron number has also been reported in $(p, p\alpha)$ reactions on Sn isotopes, where both experimental data and grDFT theory indicate a decreasing α -cluster component toward neutron-rich nuclei [31].

Upon closer inspection, slight differences are found in the detailed isotopic trends. In particular, in the (p, pt) channel, the $\text{TDX}_{\text{grDFT}}$ values exhibit a modest increase from ^{40}Ca to ^{42}Ca , followed by a decrease toward ^{48}Ca . A similar tendency is seen in the corresponding s_{grDFT} val-

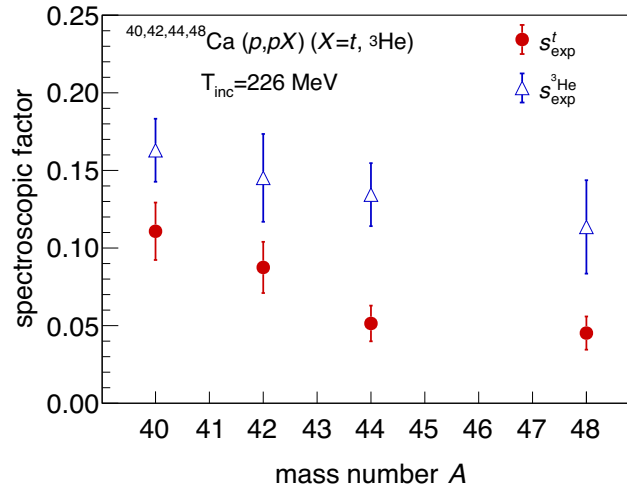


Fig. 10. Isotopic dependence of the experimental spectroscopic factors, s_{exp} , for the low-lying S -wave t and ^3He cluster components probed by the (p, pt) and $(p, p^3\text{He})$ reactions on $^{40-48}\text{Ca}$. The s_{exp} values were extracted using the reference TDX_{WS} values obtained from WS-based DWIA calculations. Red filled circles and blue open triangles denote the s_{exp} values for the t and ^3He clusters, respectively.

ues, indicating that this behavior reflects the underlying structure information in the grDFT framework.

The grDFT framework employs density-dependent cluster formation fractions and constructs cluster density distributions in finite nuclei based on the nucleon density distributions of the corresponding nuclei. As a consequence, the grDFT cluster densities are not restricted to specific low-lying configurations, and may naturally include contributions from cluster components beyond the experimentally identified low-lying S -wave states. Indeed, the $\text{TDX}_{\text{grDFT}}$ values calculated using the grDFT-based cluster densities are found to be of the same order of magnitude as the experimental low-lying S -wave TDX_{exp} values, but systematically larger by a factor of a few.

It is noted that for the $N = Z$ nucleus ^{40}Ca , the experimentally extracted spectroscopic factor s_{exp} for the ^3He channel is approximately 50% larger than that for the t channel, even after applying the correction for the elementary process discussed above. At present, the origin of the observed t - ^3He asymmetry cannot be explained within existing theoretical frameworks. In particular, the present grDFT calculations do not reproduce such a channel-dependent behavior. Furthermore, when charge symmetry is taken into account, a nearly symmetric formation of t and ^3He clusters is generally expected, especially in $N = Z$ nuclei; however, the observed asymmetry goes beyond what can be understood within this framework.

In contrast to the behavior observed in the low-lying S -wave TDX_{exp} values, the S_X -integrated TDX_{int} values, introduced as a complementary observable, exhibit a clear channel-dependent isotopic behavior. As shown in Fig. 11, the TDX_{int} values remain nearly constant for the (p, pt) channel, whereas a pronounced decrease with increasing neutron number is observed for the $(p, p^3\text{He})$ channel.

A closer inspection reveals that, for the $(p, p^3\text{He})$ channel, the TDX_{int} value for ^{40}Ca is significantly larger than the TDX_{exp} value for the low-lying S -wave state, whereas for $^{42-48}\text{Ca}$, the two values become comparable. This suggests that, within the present recoil-less conditions, the

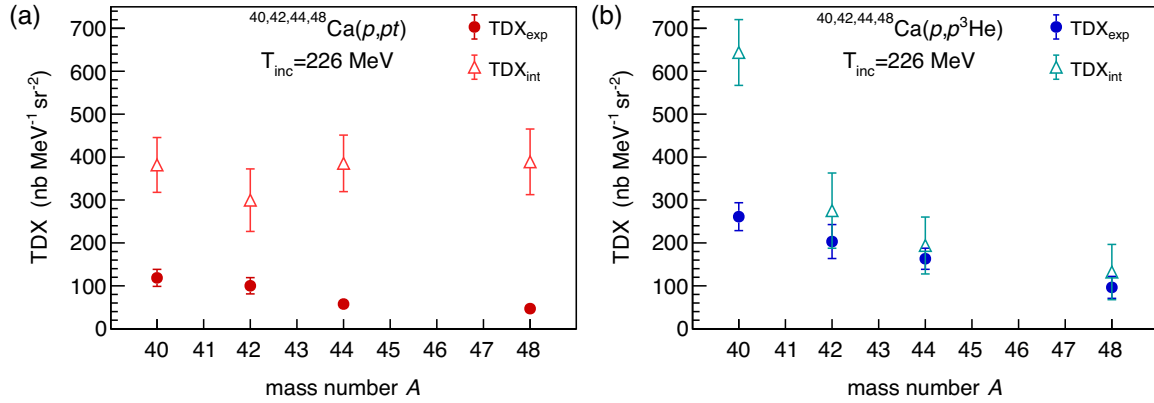


Fig. 11. Isotopic dependence of the low-lying S -wave TDX_{exp} and the S_X -integrated TDX_{int} for (a) the (p, pt) reactions and (b) the $(p, p^3\text{He})$ reactions on $^{40-48}\text{Ca}$. The TDX_{exp} values are shown as filled circles, and the TDX_{int} values as open triangles.

contribution from components other than the low-lying S -wave for the ^3He clusters is strongly reduced toward neutron-rich Ca isotopes.

In contrast, for the (p, pt) channel, the TDX_{int} values show little variation across the Ca isotopic chain, while the low-lying S -wave TDX_{exp} values exhibit a monotonic decrease. This indicates that, although the total t -cluster knockout strength remains nearly unchanged, the relative contribution of the low-lying S -wave component is progressively reduced toward neutron-rich Ca isotopes. In the S_X spectra, as shown in Figs. 4(a)–(d), this behavior manifests itself as a fragmentation of the strength from the low-lying S -wave region toward higher excitation energies with increasing neutron number.

7. Conclusions and future prospects

We performed the measurements of the $^{40-48}\text{Ca}(p, pt)$ and $(p, p^3\text{He})$ reactions, together with light nuclei ^{12}C and ^{16}O , at an incident proton energy of 226 MeV under quasi-free and recoil-less conditions.

The low-lying peaks corresponding to the S -wave cluster components are observed in both the (p, pt) and $(p, p^3\text{He})$ channels for the Ca isotopes. The triple differential cross-sections extracted for these low-lying S -wave states, as well as the corresponding experimental spectroscopic factors obtained from the WS-based DWIA analyses for both the (p, pt) and $(p, p^3\text{He})$ channels, exhibit a systematic reduction with increasing neutron number, indicating a reduction of the intrinsic low-lying t and ^3He cluster components toward neutron-rich Ca isotopes.

DWIA calculations based on grDFT cluster densities were performed and compared with the experimentally extracted low-lying S -wave triple differential cross-sections. The resulting triple differential cross-sections are found to be of the same order of magnitude and to exhibit a similar global decreasing trend toward neutron-rich Ca isotopes for both the (p, pt) and $(p, p^3\text{He})$ channels. It should be noted that the grDFT-based calculations may include contributions from cluster components beyond the experimentally identified low-lying S -wave states and therefore represent a more inclusive measure of the total cluster strength.

The complementary analysis using the separation-energy-integrated triple differential cross-sections provides additional insight into the fragmentation of cluster strength beyond the low-lying S -wave region. In particular, the contrasting behaviors observed for the (p, pt) and

($p, p^3\text{He}$) channels demonstrate distinct evolutions of cluster strength with neutron excess: the ($p, p^3\text{He}$) channel shows an increasing concentration of strength in the low-lying S -wave component accompanied by a decrease in the total strength, whereas the (p, pt) channel exhibits a fragmentation of the strength toward higher excitation energies while the total strength remains nearly unchanged.

To clarify the origin of the behaviors observed for the (p, pt) and ($p, p^3\text{He}$) reactions on the Ca isotopes, further experimental and theoretical efforts are required. In particular, measurements of the in-nucleus momentum distributions of the clusters would enable a decomposition of orbital angular-momentum components and provide direct constraints on the cluster orbital configurations and their strengths. Such measurements are expected to be essential for understanding the concentration of strength in the low-lying S -wave region observed for the ($p, p^3\text{He}$) channel and the fragmentation of strength toward higher excitation energies in the (p, pt) channel, as well as for extracting the integrated S -wave strength in a manner that allows direct comparison with theoretical predictions such as those of the grDFT .

From a theoretical perspective, further developments of microscopic nuclear-structure models for t and ^3He clusters in finite nuclei are needed to achieve a more quantitative interpretation of the present observables. Furthermore, the present DWIA analysis relies on a limited set of approximate cluster wave functions and on experimental data obtained under fixed recoil-less kinematical conditions. Given the strong surface sensitivity of quasi-free (p, pX) reactions, which probe low-density regions such as the nuclear surface where cluster formation is expected, systematic experimental studies under varied kinematical conditions, together with precise nuclear-structure calculations, will be crucial for establishing a consistent and quantitative understanding of cluster formation in finite nuclei.

The present study provides experimental indications for the formation of t and ^3He clusters in medium-mass nuclei and reveals their distinct and characteristic isotopic dependences for the Ca isotopes. These findings motivate further theoretical studies of fermionic and isospin-asymmetric cluster formation, as well as experimental studies extending to heavier nuclei, while demonstrating the effectiveness of quasi-free (p, pX) reactions as a powerful probe of cluster correlations in finite nuclei.

Acknowledgements

The authors are deeply grateful to the accelerator group at the Research Center for Nuclear Physics (RCNP), The University of Osaka, and to the staff of Sumitomo Heavy Industries Accelerator Service Ltd. (SAS) for their excellent operation and maintenance of the cyclotron facilities.

Supplementary material

Supplementary material is available at [Progress of Theoretical and Experimental Physics](#) online.

Funding

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI (Grants No. JP21H04975 and No. JP24K17077) and by the JSPS A3 Foresight Program “Nuclear Physics in the 21st Century”. This work was also partially supported by the National Key R&D Programs of China (Grants No. 2023YFE0101500 and No. 2022YFA1605100) and the National Natural Science Foundation of China (Grant No. 12275006). This work was additionally sup-

ported by the National Research Foundation of Korea (NRF), funded by the Ministry of Science and ICT, under Grant Nos. RS-2024- 00333673 and RS-2024-00436392, and by the Institute for Basic Science (IBS-R031-D1).

Data availability

The data underlying this article are available from the corresponding author upon reasonable request.

References

- [1] T. Uesaka and N. Itagaki, *Philos. Trans. R. Soc. A* **382**, 20230123 (2024).
- [2] K. Wei, Y. Ye, and Z. Yang, *Nucl. Sci. Tech.* **35**, 216 (2024).
- [3] M. Freer, H. Horiuchi, Y. Kanada-En'yo, D. Lee, and U-G. Meißner, *Rev. Mod. Phys.* **90**, 035004 (2018).
- [4] W. von Oertzen, M. Freer, and Y. Kanada-En'yo, *Phys. Rep.* **432**, 43 (2006).
- [5] F. Hoyle, *Astrophys. J. Suppl. Ser.* **1**, 121 (1954).
- [6] K. Ikeda, N. Takigawa, and H. Horiuchi, *Prog. Theor. Phys. Suppl.* **E68**, 464 (1968).
- [7] A. Tohsaki, H. Horiuchi, P. Schuck, and G. Röpke, *Phys. Rev. Lett.* **87**, 192501 (2001).
- [8] Y. Funaki, H. Horiuchi, W. von Oertzen, G. Röpke, P. Schuck, A. Tohsaki, and T. Yamada, *Phys. Rev. C* **80**, 064326 (2009).
- [9] S. Adachi et al. *Phys. Lett. B* **819**, 136411 (2021).
- [10] B. Zhou, Y. Funaki, H. Horiuchi, Y.-G. Ma, G. Röpke, P. Schuck, A. Tohsaki, and T. Yamada, *Nat. Commun.* **14**, 8206 (2023).
- [11] S. Typel, *J. Phys. Conf. Ser.* **420**, 012078 (2013).
- [12] Z. Zhang and L. Chen, *Phys. Rev. C* **95**, 064330 (2017).
- [13] M. Hempel and J. Schaffner-Bielich, *Nucl. Phys. A* **837**, 210 (2010).
- [14] J. M. Lattimer and F. D. Swesty, *Nucl. Phys. A* **535**, 331 (1991).
- [15] H. Shen, H. Toki, K. Oyamatsu, and K. Sumiyoshi, *Astrophys. J. Suppl. Ser.*, **197**, 20 (2011).
- [16] S. Furusawa, K. Sumiyoshi, S. Yamada, and H. Suzuki, *Nucl. Phys. A* **957**, 188 (2017).
- [17] S. Typel, M. Oertel, and T. Klähn, *Phys. Part. Nucl.* **46**, 633 (2015).
- [18] M. Oertel, M. Hempel, T. Klähn, and S. Typel, *Rev. Mod. Phys.* **89**, 015007 (2017).
- [19] S. Typel et al. *Eur. Phys. J. A* **58**, 221 (2022).
- [20] S. Typel, *Phys. Rev. C* **89**, 064321 (2014).
- [21] Y. Kanada-En'yo and H. Horiuchi, *Prog. Theor. Phys. Suppl.* **142**, 205 (2001).
- [22] Y. Kanada-En'yo, M. Kimura, and A. Ono, *Prog. Theor. Exp. Phys.* **2012**, 01A202 (2012).
- [23] T. Otsuka, T. Abe, T. Yoshida, Y. Tsunoda, N. Shimizu, N. Itagaki, Y. Utsuno, J. Vary, P. Maris, and H. Ueno, *Nat. Commun.* **13**, 2234 (2022).
- [24] G. Jacob and T. A. J. Maris, *Rev. Mod. Phys.* **38**, 121 (1966).
- [25] T. Wakasa, K. Ogata, and T. Noro, *Prog. Part. Nucl. Phys.* **96**, 32 (2017).
- [26] G. Jacob and Th. A. J. Maris, *Rev. Mod. Phys.* **45**, 6 (1973).
- [27] N. S. Chant and P. G. Roos, *Phys. Rev. C* **15**, 57 (1977).
- [28] N. S. Chant and P. G. Roos, *Phys. Rev. C* **27**, 1060 (1983).
- [29] K. Ogata, K. Yoshida, and Y. Chazono, *Comput. Phys. Commun.* **297**, 109058 (2024).
- [30] K. Yoshida, Y. Chiba, M. Kimura, Y. Taniguchi, Y. Kanada-En'yo, and K. Ogata, *Phys. Rev. C* **100**, 044601 (2019).
- [31] J. Tanaka et al. *Science* **371**, 260 (2021).
- [32] Y. Chazono, K. Yoshida, and K. Ogata, *Phys. Rev. C* **106**, 064613 (2022).
- [33] K. Yoshida, Y. Chazono, and K. Ogata, *Phys. Rev. C* **110**, 014617 (2024).
- [34] R. Matsumura et al. *Prog. Theor. Exp. Phys.* 2026, 043D01 (2026).
- [35] C. S. Lee et al. *Prog. Theor. Exp. Phys.* 2026, 053D01 (2026).
- [36] H. Akimune et al. *Phys. Rev. C* **67**, 051302 (2003).
- [37] T. Yamagata et al. *Phys. Rev. C* **71**, 064316 (2005).
- [38] M. Yosoi et al. *Phys. Lett. B* **551**, 255 (2003).
- [39] R. Warner, B. Vaughan, D. Friesel, and P. Schwandt, J. Yang, G. Caskey, A. Galonsky, B. Remington, and A. Nadasen, *Nucl. Phys. A* **453**, 605 (1986).

- [40] J. Y. Grossiord, M. Bedjidian, A. Guichard, and M. Gusakow, J. R. Pizzi, T. Delbar, G. GrÉgoire, and J. Lega, Phys. Rev. C **15**, 843 (1977).
- [41] C. Samanta, N. S. Chant, P. G. Roos, A. Nadasen, and A. A. Cowley, Phys. Rev. C **26**, 1379 (1982).
- [42] L. Roesch, O. Abou-Zeid, and W. Falk, Nucl. Phys. A **333**, 157 (1980).
- [43] W. R. Falk, Phys. Rev. C **8**, 1757 (1973).
- [44] J. K. Dickens, Nucl. Sci. Eng. **48**, 78 (1972).
- [45] N. A. Jelley, K. H. Wilcox, R. B. Weisenmiller, G. J. Wozniak, and J. Cerny, Phys. Rev. C **9**, 2067 (1974).
- [46] T. Wakasa et al. Nucl. Instr. Methods Phys. Res. A **482**, 79 (2002).
- [47] M. Fujiwara et al. Nucl. Instr. Methods Phys. Res. A **422**, 484 (1999).
- [48] N. Matsuoka et al. RCNP Ann. Rep. 1991, 186 (1991).
- [49] H. Fujita et al. Nucl. Instr. Methods Phys. Res. A **469**, 55 (2001).
- [50] J. Tanaka, R. Matsumura, and T. Miyagawa, and [for the ONOKORO Collaboration], EPJ Web Conf. (2025) in press, [[arXiv:2512.22438](https://arxiv.org/abs/2512.22438)] [[Search inSPIRE](#)].
- [51] K. Yoshida, K. Minomo, and K. Ogata, Phys. Rev. C **94**, 044604 (2016).
- [52] K. Yoshida, K. Ogata, and Y. Kanada-En'yo, Phys. Rev. C **98**, 024614 (2018).
- [53] S. Ogawa et al. (in progress).
- [54] K. Amos, P. J. Dortmans, H. V. Von Geramb, S. Karataglidis, and J. Raynal, in J. W. Negele and Erich Vogt, eds, Advances in Nuclear Physics, Vol. 25, 276 (Springer, New York, NY, 2000).
- [55] F. A. Brieva and J. R. Rook, Nucl. Phys. A **291**, 299 (1977).
- [56] F. A. Brieva and J. R. Rook, Nucl. Phys. A **291**, 317 (1977).
- [57] F. A. Brieva and J. R. Rook, Nucl. Phys. A **297**, 206 (1978).
- [58] D. Gogny, Nucl. Phys. A **237**, 399 (1975).
- [59] J. Dechargé and D. Gogny, Phys. Rev. C **21**, 1568 (1980).
- [60] M. Toyokawa, T. Matsumoto, K. Minomo, and M. Yahiro, Phys. Rev. C **91**, 064610 (2015).
- [61] S. Ogawa, S. Watanabe, T. Matsumoto, and K. Ogata, Phys. Rev. C **108**, 024604 (2023).
- [62] A. K. Kerman, H. McManus, and R. M. Thaler, Ann. Phys. **8**, 551 (1959).
- [63] D. Y. Pang, P. Roussel-Chomaz, H. Savajols, R. L. Varner, and R. Wolski, Phys. Rev. C **79**, 024615 (2009).
- [64] H. Langevin-Joliot and Ph. Narboni, J. P. Didelez, G. Duhamel, L. Marcus, and M. Roy-Stephan; Nucl. Phys. A **158**, 309 (1970).