PROPOSAL FOR EXPERIMENT AT RCNP

21th December 2020

TITLE:
Deuteron, triton, and ^{3}He clusters in stable calcium isotopes

SPOKESPERSON:

Full Name	Tomohiro Uesaka
Institution	RIKEN Cluster for Pionnering Research & Nishina Center for Accelerator Based-Science
Title or Position	Chief Scientist
Address	2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Phone number	+81-48-467-9383
FAX number	NA
E-mail	uesaka@riken.jp

Full Name	Juzo Zenihiro
Institution	Department of Physics, Kyoto University
Title or Position	Associate Professor
Address	Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan
Phone number	+81- 75-753-3832
FAX number	NA
E-mail	juzo@scphys.kyoto-u.ac.jp

EXPERIMENTAL GROUP:

Name	Institution	Title or Position
T. Uesaka	RIKEN CPR & RNC	Chief Scientist
J. Zenihiro	Kyoto University	Associate Professor
J. Tanaka	RIKEN Nishina Center	Postdoc Reseracher
S. Huang	RIKEN Nishina Center	IPA student
T. Harada	RIKEN Nishina Center	Ph.D Student
S. En'yo	Kyoto University	MSc Student
Y. Hijikata	Kyoto University	MSc Student
R. Tsuji	Kyoto University	MSc Student
T. Aumann	IKP, TU Darmstadt / GSI	Professor
S. Typel	IKP, TU Darmstadt / GSI	Research Scientist
H. Scheit	IKP, TU Darmstadt	Senior Scientist
D. Rossi	IKP, TU Darmstadt / GSI	Senior Scientist
M. Duer	IKP, TU Darmstadt / GSI	Postdoc
A. Jedele	IKP, TU Darmstadt / GSI	Postdoc
K. Ogata	RCNP / Osaka City University	Associate Professor
K. Yoshida	JAEA	Postdoc

Z. H. Yang	RCNP	Postdoc
N. Kobayashi	RCNP	Assistant professor
A. Tamii	RCNP	Associate Professor
M. Murata	RCNP, Osaka University	Technical Assistant
A. Inoue	RCNP, Osaka University	Ph.D Student
K. Inaba	Kyoto University	Ph.D Student
T. Sudo	RCNP, Osaka University	Ph.D Student
H. Mori	RCNP, Osaka University	MSc Student
Y. Maeda	Miyazaki University	Associate Professor
T. Kawabata	Osaka University	Professor
T. Furuno	Osaka University	Assistant professor
S. Adachi	Osaka University	Postdoc
K. Sakanashi	Osaka University	Ph.D Student
K. Inaba	Kyoto University	Ph.D Student
Y. Fujikawa	Kyoto University	Ph.D Student
Y. Matsuda	CYRIC, Tohoku University	Assistant professor
K. Miki	Tohoku University	Assistant professor
K. Sekiguchi	Tohoku University	Associate professor
J. Lou	Pekin University	Assistant professor
D. Beaumel	IJCLab Orsay	Senior Scientist
M. Assie	IJCLab Orsay	Researcher
S. Franchoo	IJCLab Orsay	Researcher

RUNNING TIME:

Installation time without beam	5 days(for each beam time).
Development of device	0 days
Test running time for experiment	0 days
Data runs	11 days

BEAM LINE:		Ring : WS course
BEAM REQUIREMENTS:	Type of particle	proton
	Beam energy	250 MeV
	Beam intensity	> 100 nA
	Other requirements	energy resolution ≤ 200 keV
		halo-free, small emittance

BUDGET:	Travel expenses of participants	500k yen

SAFETY CONTROLLED ITEMS: None

TITLE:
Deuteron, triton, and ^{3}He clusters in stable calcium isotopes

SPOKESPERSON: Tomohiro Uesaka

SUMMARY OF THE PROPOSAL

The proposed study aims at the investigation of the cluster formation in stable calcium isotopes using cluster knockout reactions. Cluster formation characterizes beyond-the-mean-field properties of nuclear matter and is an essential subject in nuclear physics. It also has significant impacts on the neutrino response of nuclear matter in the supernova explosions and on the structure of the inner shell of neutron stars.

The proposed experiment is a natural extension of our previous study on α clustering in tin isotopes. We extend the studies of clustering in medium-to-heavy mass nuclei to more general clustering phenomena, namely deuteron, triton, and ^{3}He clustering. We will start it with stable calcium isotopes of ^{40,44,48}Ca. The fractions of deuteron, triton, ^{3}He clusters will be investigated via proton-induced *(p,pd), (p,pt)*, and *(p,p*^{3}He*)* knockout reactions at 250 MeV. Objectives of the proposed experiment are three-folds: 1) to discover an evidence of deuteron clustering in medium-mass nuclei, 2) to figure out isospin-dependence of t/^{3}He mirror clusters, and 3) to take baseline data needed for establishment of cluster-knockout reaction models

The *(p,pX)* experiment will be carried out using the double-arm spectrometer in the West hall of the RCNP cyclotron facility, the Grand-Raiden and the Large Angle Spectrometer (LAS). An incident proton beam at 250 MeV bombards ^{40,44,48}Ca targets with thicknesses of 10 mg/cm^2 and the scattered proton is analyzed by the Grand Raiden and the knocked-out clusters are analyzed by LAS. Measurements will be carried out for several combinations of the momentum transfer ($q=k_{p;in} - k_{p;out}$) and the Fermi momentum of the cluster (k_i). The (q,k_i) combination can be chosen by changing the settings of spectrometers ($\theta_p, E_p, \theta_X, E_X$).

The measured cross section data will be compared with DWIA predictions. Spectroscopic factors of each cluster in ^{40,44,48}Ca are determined from the ratio of experimental to theoretical cross sections. The momentum distributions will be interpreted to spatial distributions of clusters with help of the DWIA theory. The spectroscopic factors and the spatial distributions will be compared with predictions by mean-field calculations of Typel and other structure theories.

In the requested 11-days beam time, we will be able to take data of deuteron, triton, ^{3}He clusters in ^{40,44,48}Ca with which we can reach the three-fold goals mentioned above.

DETAILED DESCRIPTION OF PROPOSED RESEARCH

1. Scientific Background

The development of sub-systems in the matter is a phenomenon related to a wide field of physics. Sub-systems in nuclei are called "clusters". In the past, alpha clusters (^{4}He nuclei) have attracted particular attention. They are known to have a big influence on important processes in nature, such as alpha decays and triple-alpha reactions involved in stellar evolution. So far, huge efforts have been devoted to the studies of clustering in light nuclei, where the focus was set primarily on the p- and sd-shell nuclei with masses lighter than A=30.

When we turn our eyes to clusters in nuclear matter, it takes on an even more universal meaning. Nuclear matter, which is the infinite system of hadrons, is a hypothetical entity on the earth, but in the universe, it is an entity that exists in neutron stars and supernovae. Thus, nature of the cluster formation is essential for understanding the structure of these compact astronomical objects and elemental synthesis occurring there. So far, the study of nuclear matter with clustered degrees of freedom has been quite limited.

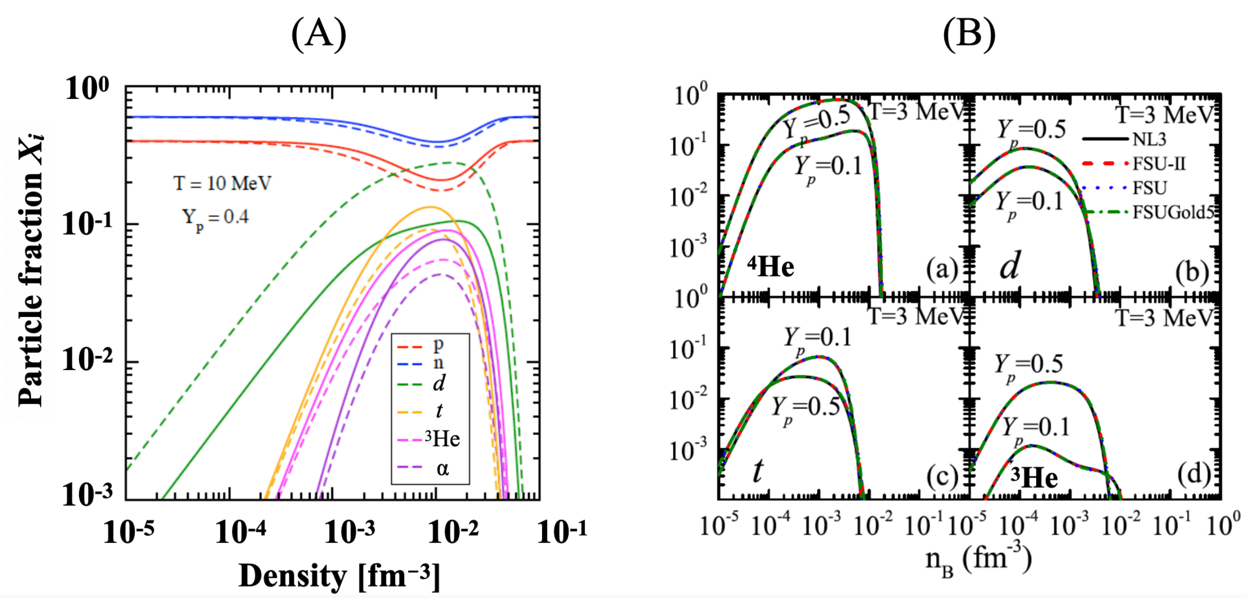

Figure 1. (A) Cluster fractions in neutron-matter predicted with the generalized relativistic density functional theory [Typel13] (B) number fractions of clusters predicted with the generalized nonlinear relativistic mean field theory [Zhang17]

The recent nuclear mean-field theory extends the scope of nuclear clustering to infinite matter. Figure 1 shows two theoretical predictions of cluster formation in nuclear matter at finite temperature at different proton factions (Y_p): Fig. 1(A) is a prediction of the generalized relativistic density functional theory by S. Typel [Typel13] at T=10 MeV and Y_p=0.4. The cluster formation is predicted to be prominent in the density region around 1/10 of the saturation density. Full and dashed lines indicate predictions with and without nucleon-nucleon scattering correlations. The calculation with the nucleon-nucleon scattering correlations predicts that all the clusters of deuterons, tritons, ^{3}He, and ^{4}He have ~10% fractions at around 0.01 fm^{-3}. Figure 1(B) is a prediction by a generalized nonlinear relativistic mean-field theory by Zhang and Chen [Zhang17] at T=3 MeV, Y_p=0.1 and 0.5, where a clear Y_p dependence can be found. Namely, triton, a neutron-rich three-nucleon cluster, increases its fraction in neutron-rich matter with Y_p =0.1, while the ^{3}He fraction decreases.

The formation of clusters in nuclear matter impacts astrophysics. One of the critical elementary processes in supernova explosions is the neutrino-nucleus reactions. Since the weak-interaction responses differ greatly between free nucleons and clusters, the cluster formation will contribute to progress of our understanding of supernova explosions. It also has an impact on the structure of neutron stars. Structures such as nuclear pasta are thought to exist in the inner cores of neutron stars. This structure is currently understood by the excluded volume effect and nuclear-Coulomb competition but is subject to substantial modification if new mechanisms such as those due to pion-exchange effects are found.

S. Typel created a bridge between clustering in infinite nuclear matter and that in heavy nuclei in Ref. [Typel14]. He predicted that the clustering can occur in the low-density surface of heavy nuclei like tin and made quantitative evaluations. The predicted α clustering in $^{112\text{-}124}$Sn was successfully observed in our previous experiment at RCNP where the neutron-number dependence of α fractions was confirmed[Tanaka20].

2. Objectives of the proposed experiment

In the proposed experiment, we extend the studies of clustering in medium-to-heavy mass nuclei to more general clustering phenomena, namely deuteron, triton, and ^{3}He clustering. We will start it with stable calcium isotopes of ^{40,44,48}Ca. The reasons that we choose calcium isotopes instead of tin isotopes will be discussed in the following sections. The fractions of deuteron, triton, ^{3}He clusters will be investigated via proton-induced *(p,pd), (p,pt)*, and *(p,p*^{3}He*)* knockout reactions at around 250 MeV/nucleon. Objectives of the proposed experiment are three-folds:

1. To discover an evidence of deuteron clustering in medium-mass nuclei
2. To figure out isospin-dependence of t/^{3}He mirror clusters
3. To take baseline data for establishment of cluster-knockout reaction models

2-1. Deuteron clustering

A biggest difference between a deuteron (T=0, S=1) and T=1 nucleon pairs is that a deuteron is bound by attraction driven by a nuclear tensor interaction. A goal of the proposed experiment is to determine deuteron-cluster fractions in calcium isotopes and to discuss them in light of tensor-correlation in nuclei.

A deuteron-like correlation in nuclei has been debated theoretically. We pick up one example of theoretical works. It is that by the Argonne group. Figure 2 shows spin-dependent density distributions of T=0 and S=1 pairs in deuteron (^{2}H), ^{4}He and ^{16}O calculated with the variational Monte-Carlo method[Forest96]. A spin-dependent anisotropy, i.e. difference between θ=0 and π/2 in the M_s=±1 state (and in the M_s=0 state), seen in deuteron can be also found in T=0 and S=1 pairs in ^{4}He and ^{16}O. This theoretical prediction indicates that a deuteron-like correlation exists ubiquitously in many nuclei.

Existence of deuteron-like correlation has been also implied by proton inelastic scattering data from RCNP [Matsubara15] and the p-n short-range correlation experiments done at the Jefferson Laboratory[Duer19]. The proposed (*p,pd*) experiment for medium-mass nuclei will open a new opportunity to pin down the deuteron-like correlation driven by the tensor force.

In a study of the deuteron-like correlation, an isotope with *N*=*Z* has a special meaning. In the *N*=*Z* nucleus, overlap between proton and neutron wave functions is maximum, which should affect the deuteron-like correlation. Thus, in the proposed experiment, we set our focus on calcium isotopes of ^{40,44,48}Ca, instead of Sn isotopes where ^{100}Sn is far out of our reach. This is the first reason that we choose calcium isotopes.

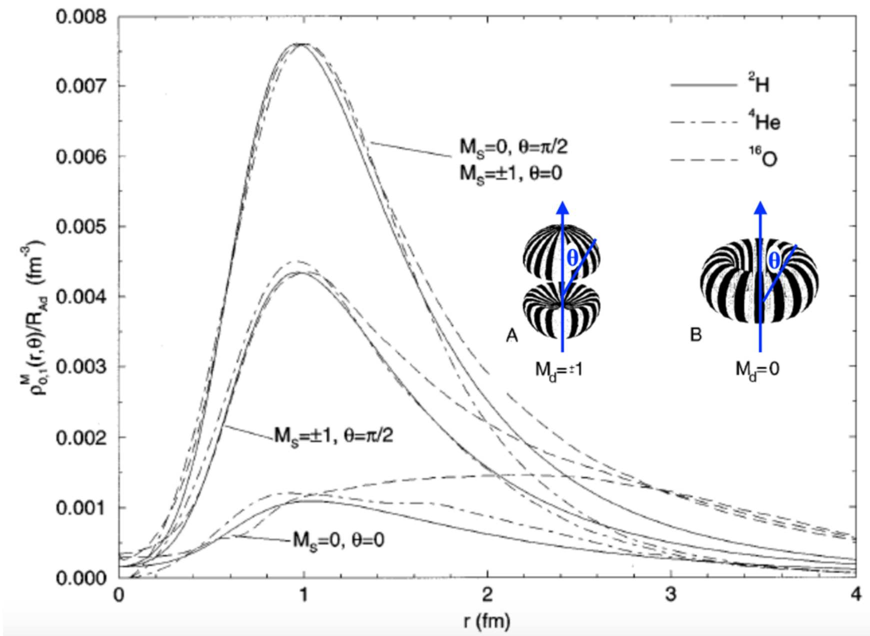

Figure 2. Spin-dependent density distributions of T=0 and S=1 pairs in deuteron (^{2}H), ^{4}He and ^{16}O[Forest96]. A picture of equal density surface taken from the same paper is added by the proponents for ease of explanation.

2-2 Isospin dependence of t/^{3}He mirror clusters

An interesting aspect of triton and ^{3}He clusters is that their fractions are expected to show distinctive isospin dependences. As shown in Fig. 1(B), fractions of triton and ^{3}He clusters are expected to behave in an opposite manner: the fraction of triton clusters increases in a neutron-rich matter (Y_p=0.1 in Fig. 1(B)) than in a symmetric nuclear matter (Y_p=0.5 in Fig. 1(B)) while that of ^{3}He cluster decreases. This phenomenon is simply understood by assuming that a neutron-rich (proton-rich) cluster grows more (less) in a neutron-rich matter.

The (*p,pt*) and (*p,p*^{3}He) measurements in the proposed experiment will enable the first comparison of triton and ^{3}He cluster fractions in ^{40,44,48}Ca isotopes.

2-3 Proton-induced cluster knockout reactions

Our collaboration has a lot of experiences in nucleon knock-out reaction studies of both stable and unstable nuclei(e.g. [Tang20, Kubota20, Kawase18, Panin16, Atar18] for experimental works, and [Wakasa17] for theoretical works). We have also carried out the (*p,pα*) knockout reactions on $^{112-124}$Sn and found evidence of the surface α clustering in the tin isotopes[Tanaka20]. The cluster knockout reaction employed in the proposed experiment is a natural extension of the previous works.

Distorted wave impulse approximation (DWIA) employed in analyses of the (*p,pN*) reactions is a good starting point as well for the cluster knockout reactions. Ogata's group has already been working on the DWIA analyses of the (*p,pα*) reactions [Yoshida18] and the (*p,pd*) reactions [Chazono20]. Of course, the DWIA for (*p,pN*) cannot be applied to the cluster knockout reactions as it is and the effects caused by the compositeness of the clusters should be taken into account. This is especially the case in the (*p,pd*) reactions where effects of deuteron breakup are believed to be significant. The breakup effects are being investigated by means of continuum-discretized channel coupling (CDCC) method of which Ogata's group has an expertise. The group is ready to apply their DWIA codes to the (*p,pt*) and (*p,p*^{3}He) reactions.

Lack of reaction data to be compared with theoretical predictions is rather serious bottleneck in establishment of the cluster knockout reactions as more quantitative tools. This is true, in particular, for the (*p,pd*) and (*p,pt*)/(*p,p*^{3}He) cases. If we limit ourselves to $A \geqq 10$ and $E_p \geqq 100$ MeV (i.e. excluding light nuclei where apparent cluster structures are relevant and low incident-energies where reaction mechanisms other than simple knockout process are relevant), only two data sets for the (*p,pd*) and (*p,pt*) reactions can be found in easily accessible journals. They are ^{16}O(*p,pd*) and ^{16}O(*p,pt*) data at 101.3 MeV [Samanta82] and ^{12}C(*p,pd*) data at 670 MeV [Ero81]. In the former case, data were taken at a single angular setting of θ_p=40.1 deg and θ_d/θ_t=40 deg in the laboratory system and telescopes consisting of silicon + germanium detectors were used to measure energies of proton and the clusters. Binding energy spectra for the ^{16}O(*p,pd*) and ^{16}O(*p,pt*) reactions are shown in Fig. 3(A) and the recoil-proton energy distribution is shown in Fig. 3(B). They are very valuable data, but it is far from satisfactory in the sense that the incident energy is not sufficiently high and the covered angular range is quite limited. Figure 3(C) shows the missing energy spectrum in the ^{12}C(*p,pd*) reaction at 670 MeV[Ero81] where protons were detected by plastic scintillators while deuterons emitted at θ_d=6.5 deg were analyzed by a magnetic spectrometer. The obtained energy resolution is not high enough to discriminate final states in ^{10}B.

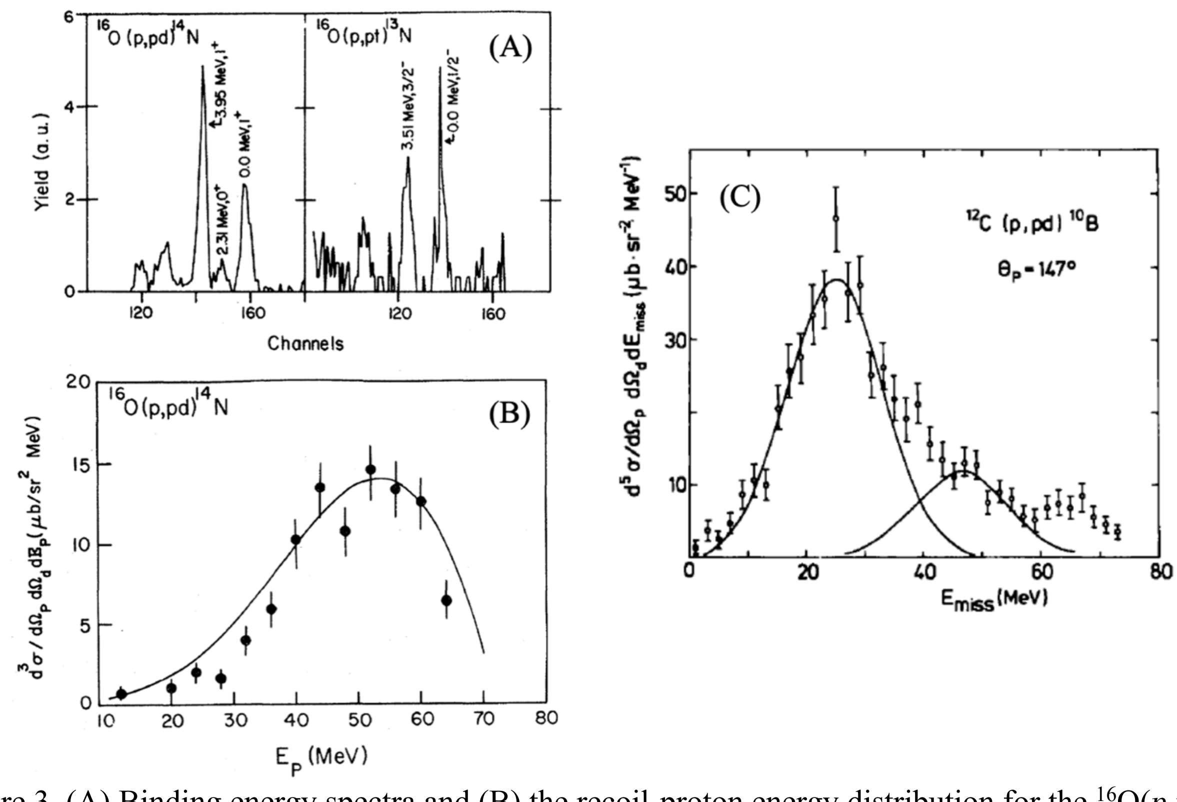

Figure 3. (A) Binding energy spectra and (B) the recoil-proton energy distribution for the ^{16}O(*p,pd*) and ^{16}O(*p,pt*) reactions at 101.3 MeV [Samata82], and (C) the missing energy spectrum in the ^{12}C(*p,pd*) reaction at 670 MeV[Ero81].

In the proposed experiment, we plan to take data at E_p = 250 MeV in a wide range of scattering angles with a sufficiently high energy resolutions. This exploits the unique experimental capabilities of RCNP where a high-intensity proton beam and a double-arm magnetic spectrometer are available. The obtained data will be the baseline in future cluster knockout studies. Measurements at different incident energies and of spin-polarization data are within our scope and kept to be proposed in near future.

2-4 Relationship with other planned experiments

The proposed experiment is a part of more comprehensive research project of clustering in medium-to-heavy nuclei. The collaboration has proposed alpha knockout reaction experiments for $^{142\text{-}146}$Nd and $^{148\text{-}154}$Sm[Yang18], and $^{40\text{-}48}$Ca [Tanaka18] at RCNP, in parallel to $^{214\text{-}222}$Th(p,pα) at RIBF[Tanaka20-2]. They also proposed a d/t/^{3}He/α knockout experiment for $^{50\text{-}52}$Ca at 250 MeV to the RIBF PAC [Uesaka20] and Xe(*p,pt*)/(*p,p*^{3}He)/(*p,pα*) at HIMAC.

In Table 1, comparison of experimental capabilities at different facilities is shown: at RIBF and HIMAC, advantages to use a thick liquid hydrogen target and to detect all the clusters with the same setup are exploited. The uniqueness of RCNP is that the excitation energy resolution is as high as 0.3 MeV and thus we can identify the final states clearly. Since this is necessary for detailed discussions of coupling between the cluster and the residual nucleus and of the mechanism of the cluster knockout reaction, we decided to propose the new experiment to RCNP.

Facility	Kinematics	Luminosity[$cm^{-2}s^{-1}$]	$\Delta\Omega_p\Delta\Omega_X$ [sr^2]	d/t/^{3}He/αmeas.	Δ E [MeV]
RCNP	normal	10^{32}	10^{-4}	separate	0.3
RIBF	inverse	10^{27}	4	simultaneous	2−3
HIMAC	inverse	10^{30}	4	simultaneous	2−3

Table 1. Comparison of experiments at different facilities.

When combined with the $^{40\text{-}48}$Ca(*p,pα*) data and the $^{50\text{-}52}$Ca(*p,pX*) [*X: d, t,* ^{3}He, *α*] data, results of the proposed experiment will provide a useful data set of clustering in calcium isotopes of A=40—52. This is the second reason that we choose calcium isotopes instead of tin isotopes.

Since the proposed experiment aims at probing clustering at low-density surface of nuclei, detailed information of proton and neutron density distributions is quite relevant. We have already taken proton elastic scattering data for $^{40\text{-}48}$Ca and published data of ^{40,48}Ca[Zenihiro18]. A part of the collaboration (Zenihiro and Uesaka) together with theorists proposed new ways to extract information from the density distributions of the ^{40,48}Ca data[Yoshida20,Zenihiro20]. The data of ^{42,44}Ca are under analyses. We have also proposed a new experiment to measure density distributions in ^{50,52}Ca to the RIBF PAC[Zenihiro20-2].

Discussion with the cluster fractions obtained from the knockout reactions and the density distributions obtained from the proton elastic scattering leads to consistent understanding of clustering in the low-density surface of nuclei. This is an essential part of our research project.

3. Details of the proposed experiment

We plan to perform the (*p,pX*) experiment using the double-arm spectrometer in the West hall of the RCNP cyclotron facility, the Grand-Raiden and the Large Angle Spectrometer (LAS). An incident proton beam at 250 MeV bombards ^{40,44,48}Ca targets with thicknesses of 10 mg/cm^2 and the scattered proton is analyzed by the Grand Raiden and the knocked-out clusters are analyzed by LAS.

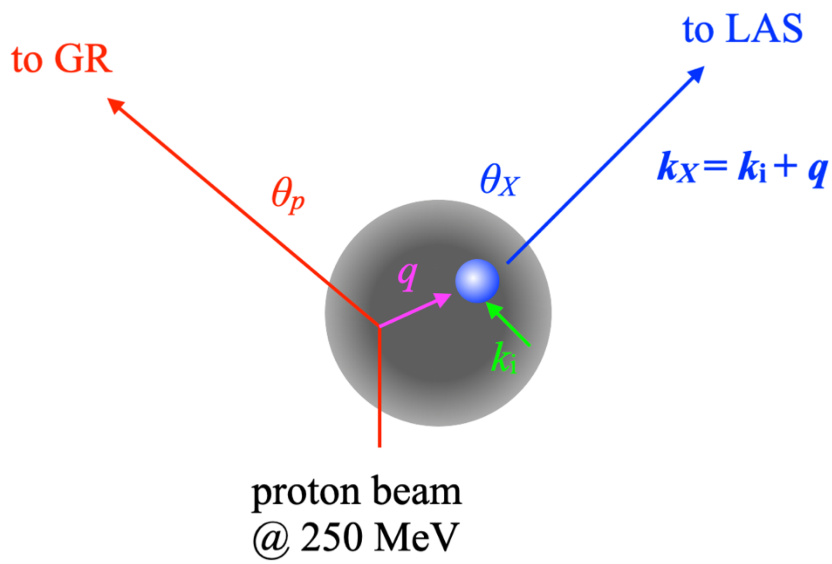

Figure 4. Kinematics of the (*p,pX*) reactions. The momentum transfer q and the Fermi momentum of the knocked-out cluster k_i are key quantities in the proposed experiment.

Measurements will be carried out for different combinations of the momentum transfer (q=$k_{p;in} - k_{p;out}$) and the Fermi momentum of the cluster (k_i). The (q,k_i) combination can be chosen by changing the settings of spectrometers (θ_p,E_p,θ_X, E_X).

<u>Measurement #1 : θ_{CM} scan for k_i=0</u>

First, we will carry out measurements by scanning θ_{CM} of the *p-X* scattering under the recoilless condition (k_i=0). In the following, the goal and method of the measurement are explained by taking the (*p,pd*) case as example. They are basically the same in the (*p,pt*) and (*p,p*^{3}He) cases.

Figure 5 is an angular distribution of the *p-d* elastic scattering cross section at 250 MeV[Hatanaka02]. It shows a characteristic shape where the *t*-channel scattering dominates at forward angles of $\theta_{CM} \leqq 120$ deg while the *u*-channel (neutron transfer) dominates at backward angles. If a picture that the (*p,pd*) scattering is described as a *p-d* elastic scattering in a nuclear medium holds, the (*p,pd*) scattering data should show a similar angular distribution.

We will take the cross section data at an angular range corresponding to $\theta_{pd;CM}$=40—130 deg by setting the spectrometers to the conditions shown in Table 2. With this measurement, we can cover the momentum transfer range of q=1.58—4.27 fm^{-1}. Red crosses in Fig. 5 indicate the measurement points. The data will be compared with the DWIA predictions.

The measurements will be done for the the (*p,pt*) and (*p,p*^{3}He) knockout reactions where we cover θ_{CM}=40—100 deg. Since values of the cross section are significantly small at backward angle of θ_{CM} > 100 deg in the (*p,pt*) and (*p,p*^{3}He) reactions, we give up the measurement in the region.

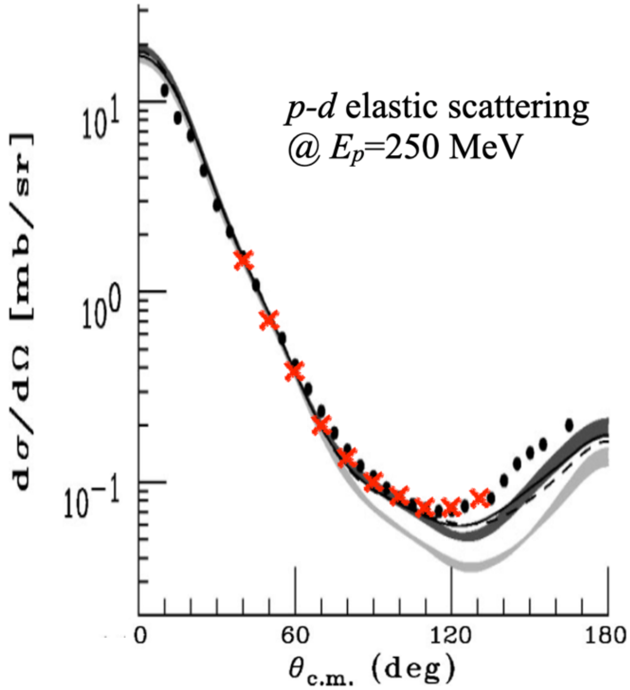

Figure 5. Angular distribution of the *p-d* elastic scattering cross section at 250 MeV [Hatanaka02]. Red crosses indicate the measurement points in the proposed experiment..

θ_{CM} [deg]	θ_p [deg]	E_p [MeV]	θ_d [deg]	E_d [MeV]	q [fm^{-1}]
40	25.53	223.7	69.46	26.3	1.58
50	32.15	209.8	64.35	40.2	1.95
60	38.94	193.7	59.27	56.3	2.31
70	45.95	175.9	54.21	74.1	2.66
80	53.23	157.0	49.18	93.0	2.99
90	60.88	137.4	44.17	112.6	3.3
100	68.99	117.8	39.18	132.2	3.58
110	77.70	98.89	34.22	151.1	3.84
120	87.21	81.10	29.28	168.9	4.07
130	97.79	65.03	24.37	185.0	4.27

Table 2. Kinematics of the θ_{CM}-scan measurement for the (*p,pd*) knockout reaction.

Measurement #2 : Momentum (k_i) distribution at fixed θ_{CM}

Following the θ_{CM}-scan measurement, we will carry out momentum distribution measurements at fixed θ_{CM}. The measurement will provide us with the cluster momentum distributions in calcium isotopes. The θ_{CM} is fixed at

θ_{CM}=80 deg for the (*p,pd*) reaction ,
θ_{CM}=70 deg for the (*p,pt*) and (*p,p*^{3}He) reactions,

by optimizing the momentum transfer (*q*) and the cross section. In the momentum distribution measurement, *q* should be kept sufficiently high so that the quasi-free condition is satisfied. The values of 3 fm^{-1} at θ_{CM}=80 deg for the (*p,pd*) reaction and at θ_{CM}=70 deg for the (*p,pt*) and (*p,p*^{3}He) reactions are reasonably high and we can safely keep the quasi-free condition. The expected yields for unit cluster spectroscopic factors at *q*=0 fm^{-1} are

1.7 counts/second at θ_{CM}=80 deg for the (*p,pd*) reaction ,
1.0 counts/second at θ_{CM}=70 deg for the (*p,pt*) and (*p,p*^{3}He) reactions,

where we assume a beam-intensity of 100 pnA and a target thickness of 10 mg/cm^2.

With these values of yield rates, we can complete momentum distributions for deuteron, triton, and ^{3}He clusters for the ^{40,44,48}Ca isotopes in a reasonable amount of beam-time.

The measured cross section data will be compared with DWIA predictions. Spectroscopic factors of each cluster in ^{40,44,48}Ca are determined from the ratio of experimental to theoretical cross sections. The momentum distributions will be interpreted to spatial distributions of clusters with the help of DWIA theory. The spectroscopic factors and the spatial distributions will be compared with predictions by mean-field calculations of Typel and other structure theories.

4. Yield estimation

The cross section is estimated based on the DWIA/PWIA ratio evaluated by the impulse approximate calculations done by K. Ogata and the cross sections of elementary processes, the *p-d*, *p-t*, and *p*-^{3}He elastic scatterings at the same incident energies[Hatanaka02,Hasell86]. The DWIA/PWIA ratio represents the absorption effect by the nuclear optical potential and is evaluated to be

0.05 for the (*p,pd*) reaction,
0.03 for the (*p,pt*) and (*p,p*^{3}He) reactions.

We assume a beam-intensity of 100 pnA and a target thickness of 10 mg/cm^2. The beam intensity is mainly limited by an accidental coincidence rate and the target thickness is limited by an emittance growth of the incident beam and by energy losses of knocked-out particles.

Requested beam-time is summarized as:

Measurement #1 : θ_{CM} scan for k_i=0

θ_{CM}=40—130 deg (10-deg step)	for the ^{40}Ca(*p,pd*)	12 h
θ_{CM}=40—100 deg (10-deg step)	for the ^{40}Ca(*p,pt*)	24 h
	for the ^{40}Ca(*p,p*^{3}He)	24 h
	TOTAL	60 h

Measurement #2 : Momentum (k_i) distribution at fixed θ_{CM}

q=−0.5 − +1fm^{-1} (4 settings q= -0.5, 0.0, +0.5, +1.0 fm^{-1})

at θ_{CM}=80 deg	for the ^{40,44,48}Ca(*p,pd*)	36 h
at θ_{CM}=70 deg	for the ^{40,44,48}Ca(*p,pt*)	72 h
at θ_{CM}=70 deg	for the ^{40,44,48}Ca(*p,p*^{3}He)	72 h
	TOTAL.	180 h

Including 1-day needed for the detector setup, we request 11 days:

Detector setup	1.0 day
θ_{CM} scan	2.5 days
Momentum distribution	7.5 days

References

[Typel13] S. Typel, J. Phys. Conf. Ser. **420**, 012078 (2013).

[Zhang17] Z.-W. Zhang and L.-W. Chen, Phys. Rev. C **95**, 064330 (2017).

[Typel14] S. Typel, Phys. Rev. C **89**, 064321 (2014).

[Tanaka20] J. Tanaka, Z.H. Yang et al., accepted for publication in Science.

[Forest96] J.L. Forest, V. R. Pandharipande et al., Phys. Rev. C **54**, 646 (1996).

[Matsubara15] H. Matsubara, A. Tamii et al., Phys. Rev. Lett. **115**, 102501 (2015).

[Duer19] M. Duer, et al. Phys. Rev. Lett. **122**, 172502 (2019) and references therein.

[Tang20] T.L.Tang, T. Uesaka et al., Phys. Rev. Lett. **124**, 212502 (2020).

[Kubota20] Y. Kubota, A. Corsi et al., Phys. Rev. Lett. **125**, 252501 (2020).

[Kawase18] S. Kawase, T. Uesaka et al., Prog. Theo. Exp. Phys. **2018**, 021D01 (2018).

[Panin16] V. Panin, T.Aumann et al., Phys. Lett. B **753**, 204 (2016).

[Atar18] L. Atar, T. Aumann et al., Phys. Rev. Lett. **120**, 052501 (2018).

[Wakasa17] T. Wakasa, T. Noro, and K. Ogata, Prog. Part. Nucl. Phys. 96, 32 (2017).

[Yoshida18] K. Yoshida, K. Ogata, Y. Kanada-En'yo, Phys. Rev. C **98**, 024614 (2018).

[Chazono20] Y. Chazono, K. Yoshida, K. Yoshida, K. Ogata, arXiv:2007.06771.

[Samanta82] C. Samanta, N.S. Chant et al., Phys. Rev. C **26**, 1379 (1982).

[Ero81] J. Erö, Z. Fodor et al., Nucl. Phys. A **372**, 317 (1981).

[Yang18] Z. Yang et al., RCNP proposal E544 "From α clustering to α decay : Quasi-Free (p, pα) reactions with Nd and Sm isotopes"

[Tanaka18] J. Tanaka et al., RCNP proposal E545 "What is the origin of α-cluster formation on the surface of nuclei ?"

[Tanaka20-2] J. Tanaka et al., RIBF proposal SAMURAI60.

[Uesaka20] T. Uesaka, J. Zenihiro et al., RIBF proposal SAMURAI57.

[Zenihiro18] J. Zenihiro et al., submitted to Phys. Rev. Lett. and arXiv:1810.11796 (2018).

[Yoshida20] S. Yoshida, H. Sagawa, J. Zenihiro, and T. Uesaka, Phys. Rev. C **102**, 064307 (2020).

[Zenihiro20] J. Zenihiro, T. Uesaka. H. Sagawa, and S. Yoshida, submitted to PTEP (2020).

[Hatanaka02] K. Hatanaka, Y. Shimizu et al., Phys. Rev. C **66**, 044002 (2002).

[Hasell86] T.K, Hasell, A. Bracco et al., Phys. Rev. C **34**, 236 (1986).