BRIEF INTRODUCTION TO THE ONOKORO PROJECT:

Knockout Reaction Studies Of Clusters In Heavy Nuclei

CENuM

CENuM Workshop
2025.01.16 - 01.19

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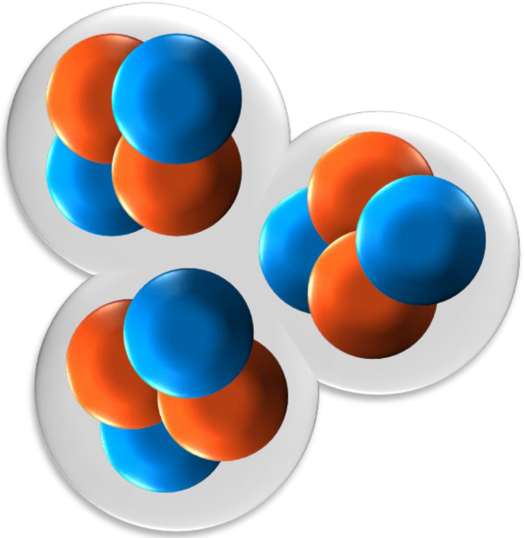
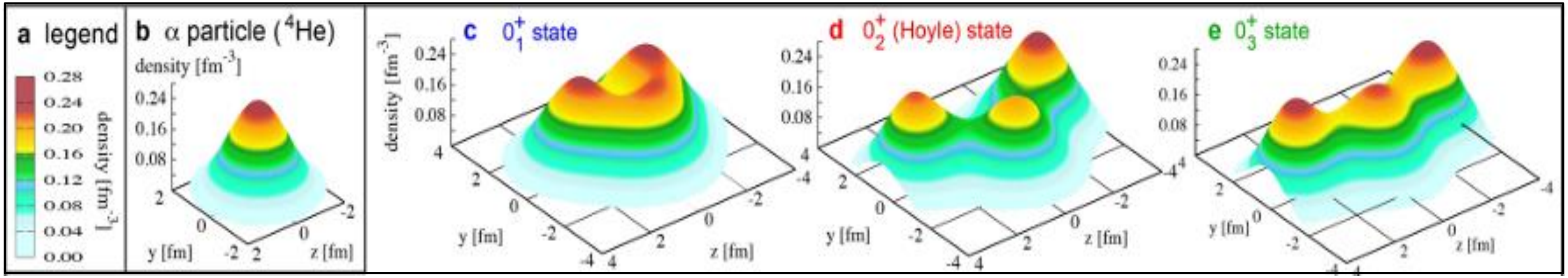
ONOKORO PROJECT RCNP RIKEN

MOTIVATION



- Hoyle State : ^{12}C with three α cluster
- The recent Monte Carlo shell model calculation has confirmed that the ground state (0_1^+) is a mixture of shell-model-like and cluster-model-like configurations.



[Fig] Otsuka, T., Abe, T., Yoshida, T. et al. α-Clustering in atomic nuclei from first principles with statistical learning and the Hoyle state character. Nat Commun 13, 2234 (2022).

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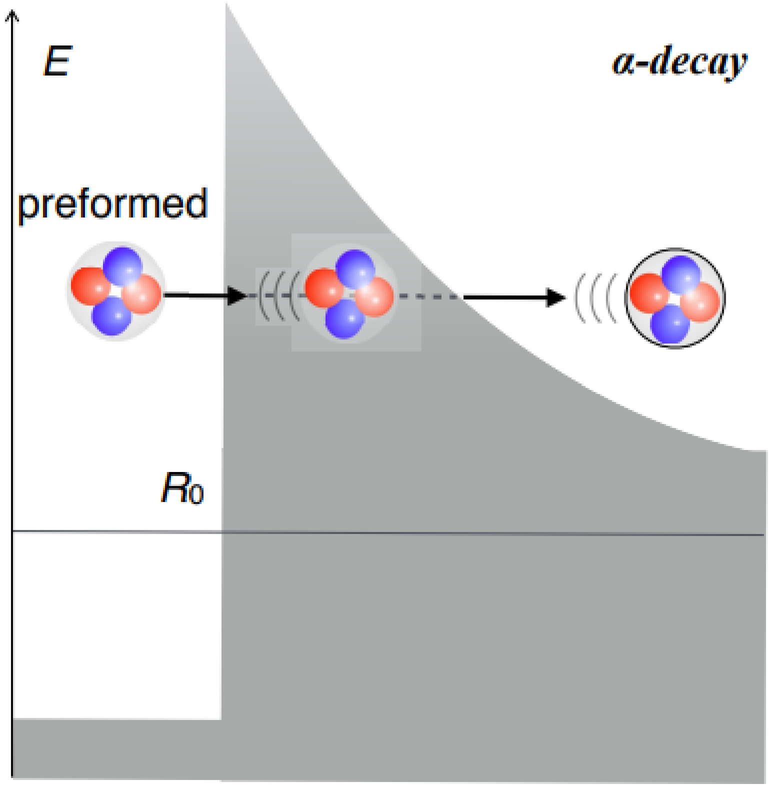
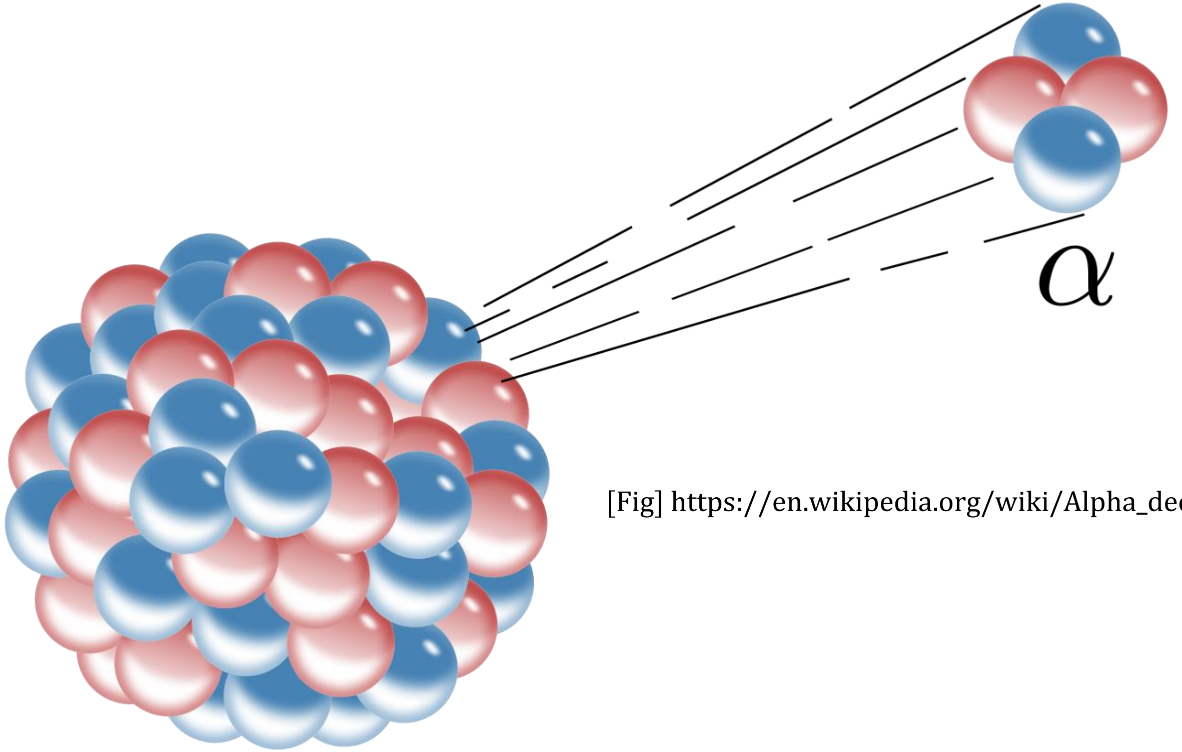


[Fig] Junki Tanaka et al 2020 J. Phys.: Conf. Ser. 1643 012108



[Fig] https://en.wikipedia.org/wiki/Alpha_decay

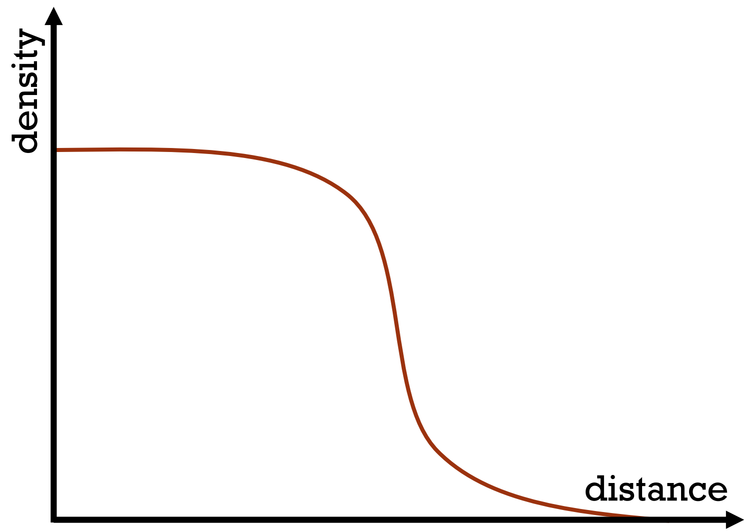
- Alpha dacay

: Quantum tunneling of preformed α particle through a Coulomb barrier

There are many HINT for α clusterization!

MOTIVATION

- Recent theoretical calculations; cluster formed in low-density "dilute" nuclear matter.
- At the surface of nuclei, the density drops fast and it is suggested that light clusters like α will form in this region
- Light clusters on the surface of nuclei might exist universally in ground state of medium to heavy nuclei.



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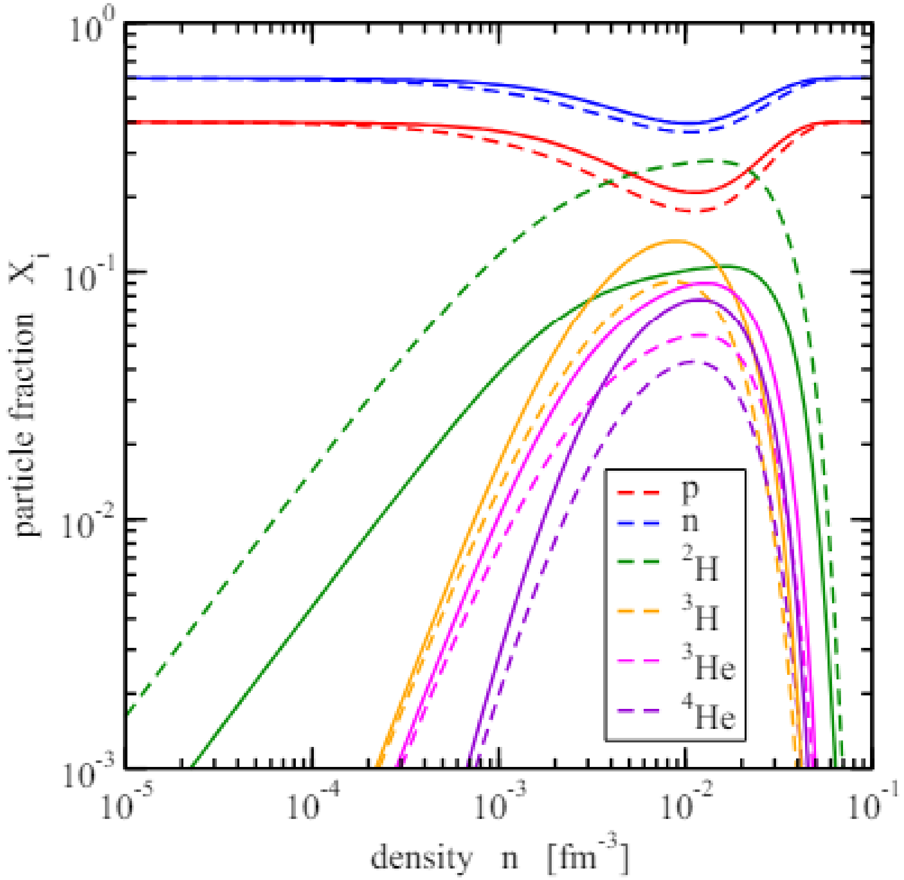
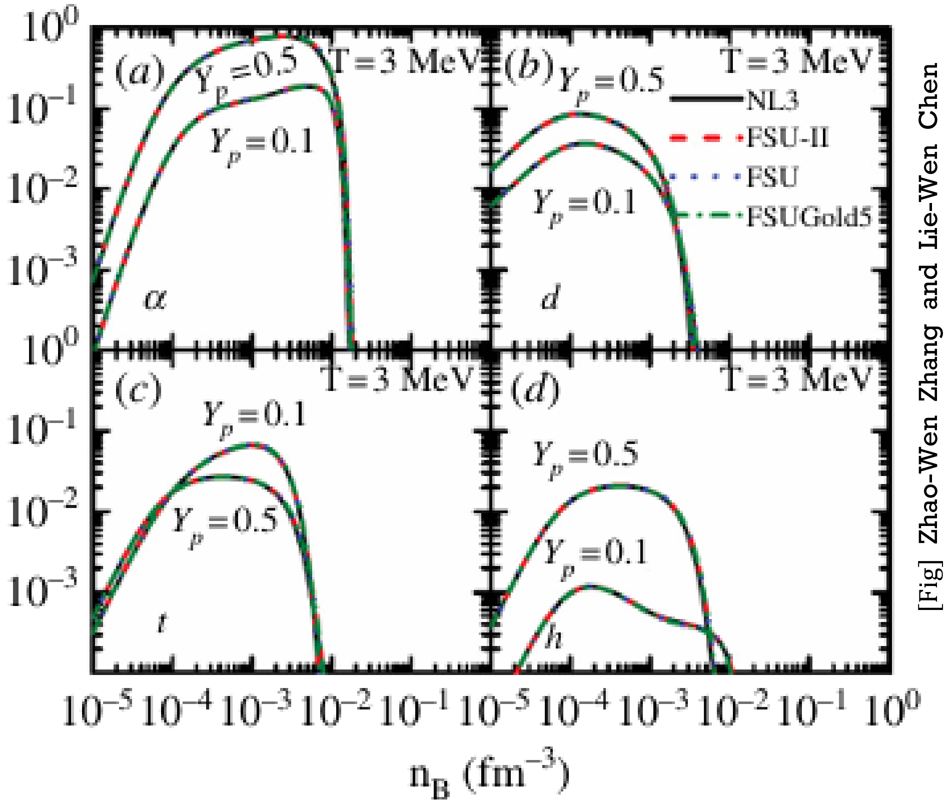
- In dilute nuclear matter ($\rho<0.1\rho_0$);

  various light clusers will appear

  depend on density and isospin asymmetry.



[Fig] Stefan Typel 2013 J. Phys.: Conf. Ser. 420 012078



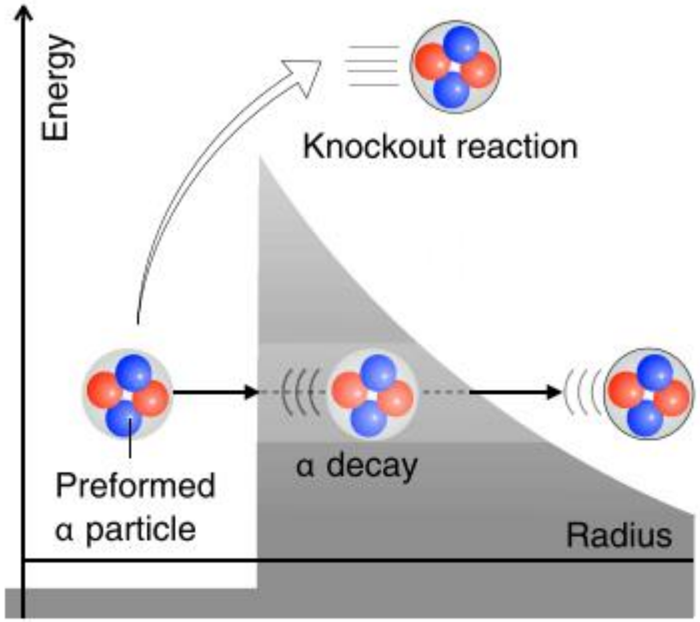
[Fig] Zhao-Wen Zhang and Lie-Wen Chen Phys. Rev. C 95, 064330 (2017)

"Uniform" system made of independent nucleons.

"Non-uniform" system where clusters exist symbiotically with independent nucleons. Many clusters (d, t, 3He, α.) develop in all the nuclei.

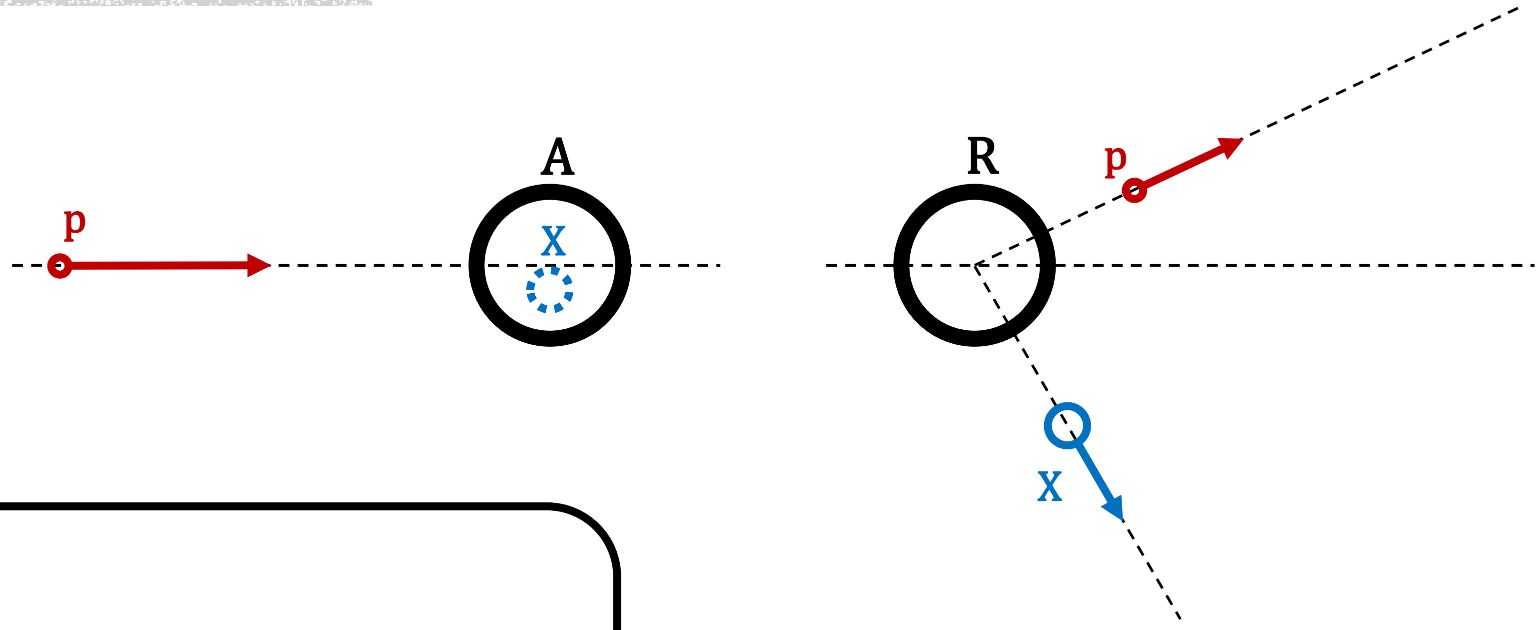
A(p,pX) Kinematics

X= ^{2}H(d), ^{3}H(t), ^{3}He, ^{4}He



- This experiment use "Knockout Reaction"
- High energy-proton knocks out the cluster above the Coulomb barrier.
- This reaction has surface sensitivity, so the reaction is less affected by the inner nuclear structure

A(p,pX) Kinematics

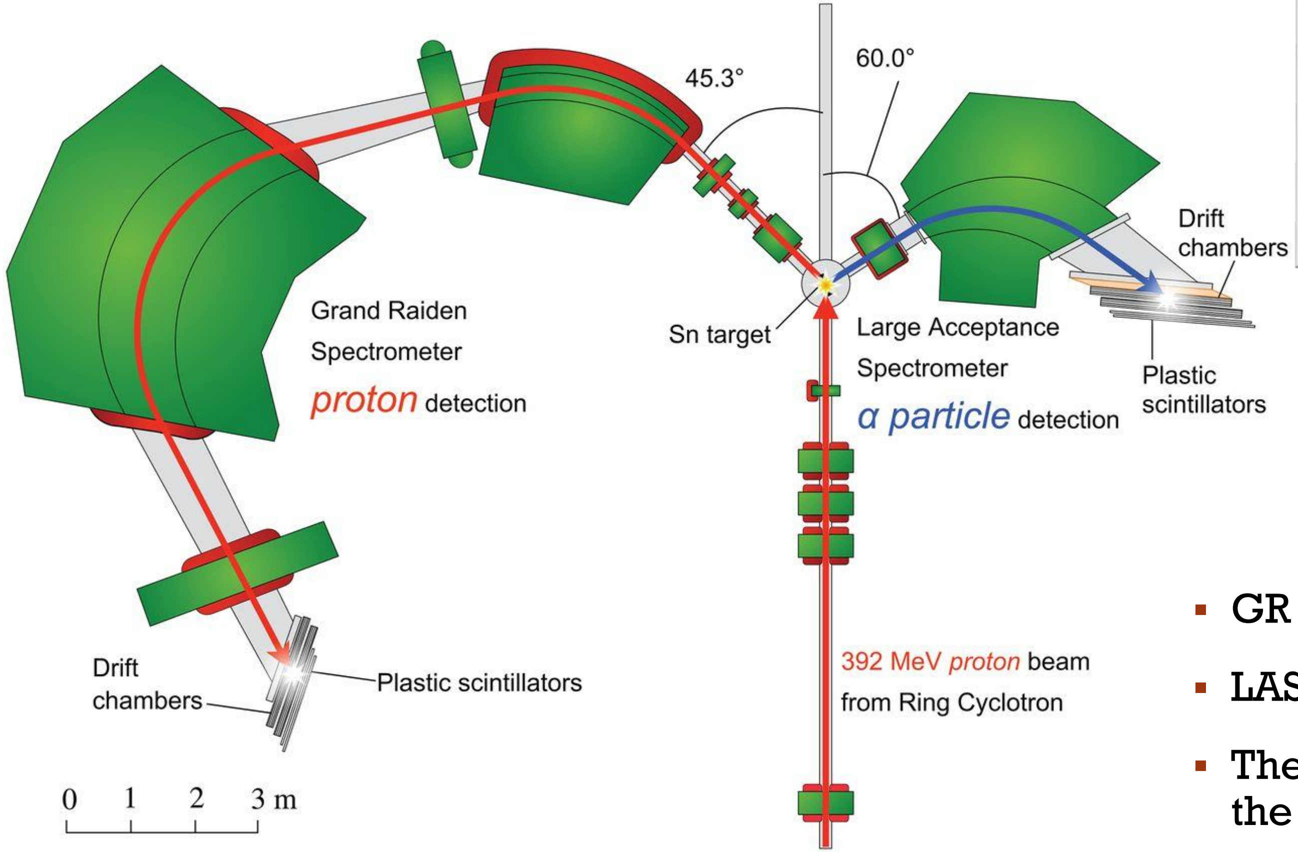


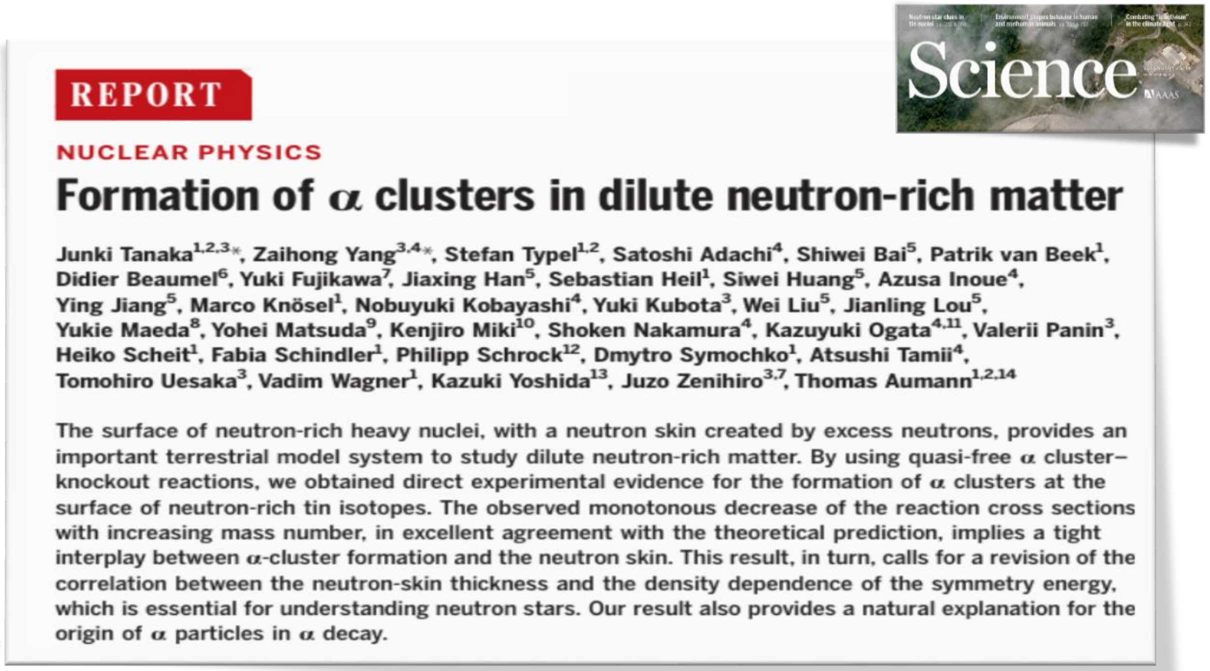
Energy conservation

$$E_{p,in} + E_A = E_{p,out} + E_X + E_R$$
$$m_p + T_{p,in} + m_A = m_p + T_{p,out} + m_X + T_X + m_R + T_R$$
$$S_X \equiv m_X + m_R - m_A = T_{p,in} - T_{p,out} - T_X - T_R \,, \qquad T_R \sim 0$$

$$S_X = T_{Beam} - T_p - T_X$$

$^{112\text{-}124}$Sn(p,pα) reaction
Experimental Setting




Science

REPORT

NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

Junki Tanaka[1,2,3*], Zaihong Yang[3,4*], Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]

The surface of neutron-rich heavy nuclei, with a neutron skin created by excess neutrons, provides an important terrestrial model system to study dilute neutron-rich matter. By using quasi-free α cluster–knockout reactions, we obtained direct experimental evidence for the formation of α clusters at the surface of neutron-rich tin isotopes. The observed monotonous decrease of the reaction cross sections with increasing mass number, in excellent agreement with the theoretical prediction, implies a tight interplay between α-cluster formation and the neutron skin. This result, in turn, calls for a revision of the correlation between the neutron-skin thickness and the density dependence of the symmetry energy, which is essential for understanding neutron stars. Our result also provides a natural explanation for the origin of α particles in α decay.

Tanaka et al., Science 371, 260–264 (2021)

- Target : ^{112,116,120,124}Sn
- Normal kinematics with proton beam

- GR : high resolution
- LAS : large acceptance
- There are two vertical drift chambers for general use as the focal plane position counters of the spectrometer

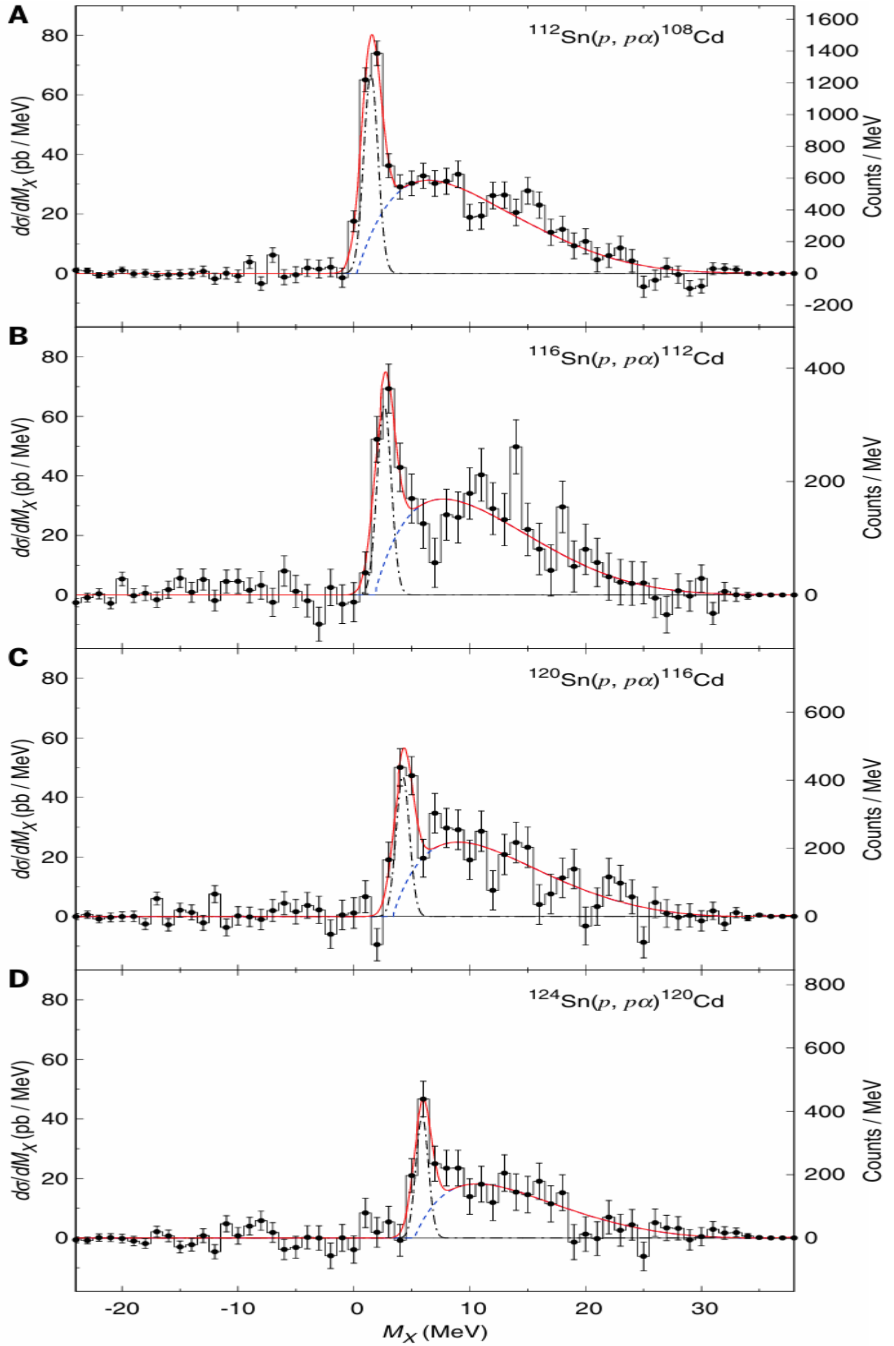
Result

- Right figure : The missing-mass spectra,

$$M_X = 392\text{MeV} - T_p - T_\alpha ,$$

for the α -knockout reactions for Sn targets, which is from the previous experiment in RCNP

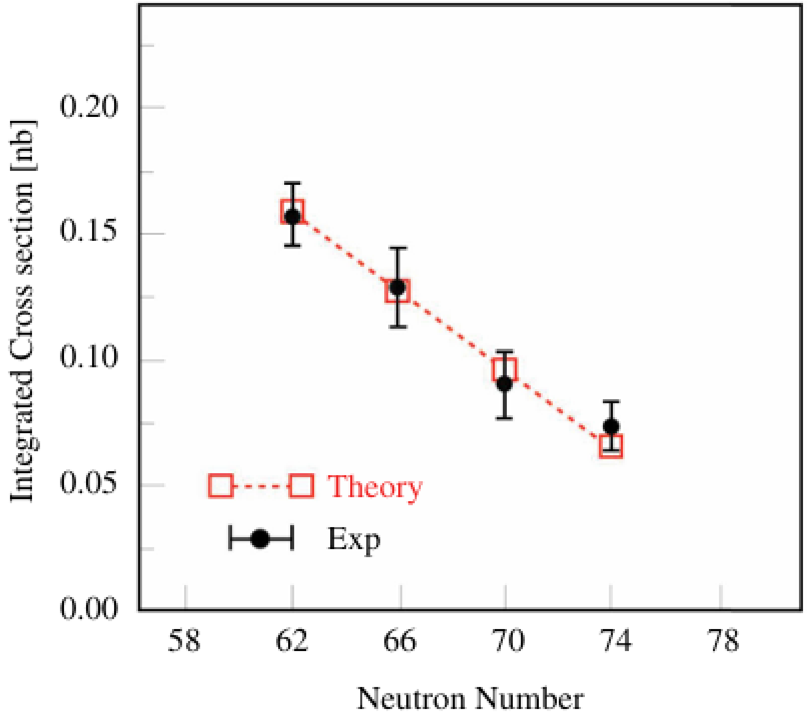
- The peak positions of the ground state for the different targets agree well with the known α separation energies



Result

- Right Figure shows the neutron-number dependence of the cross-section integrated over the low-energy peak

- The formation of alpha clusters gets hindered by the development of a neutron skin.

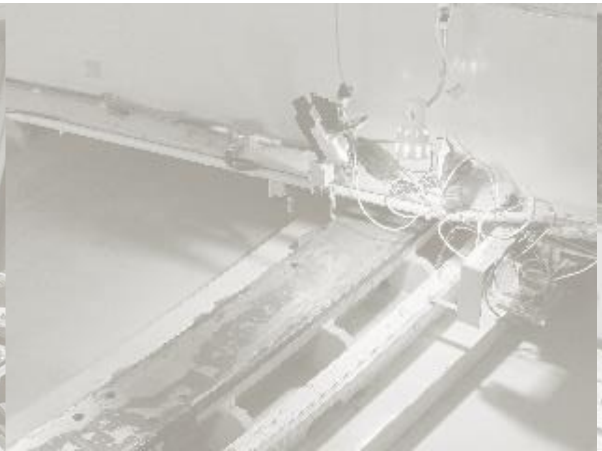


E559 $^{40\text{-}48}$Ca(p,pX) reaction experiment

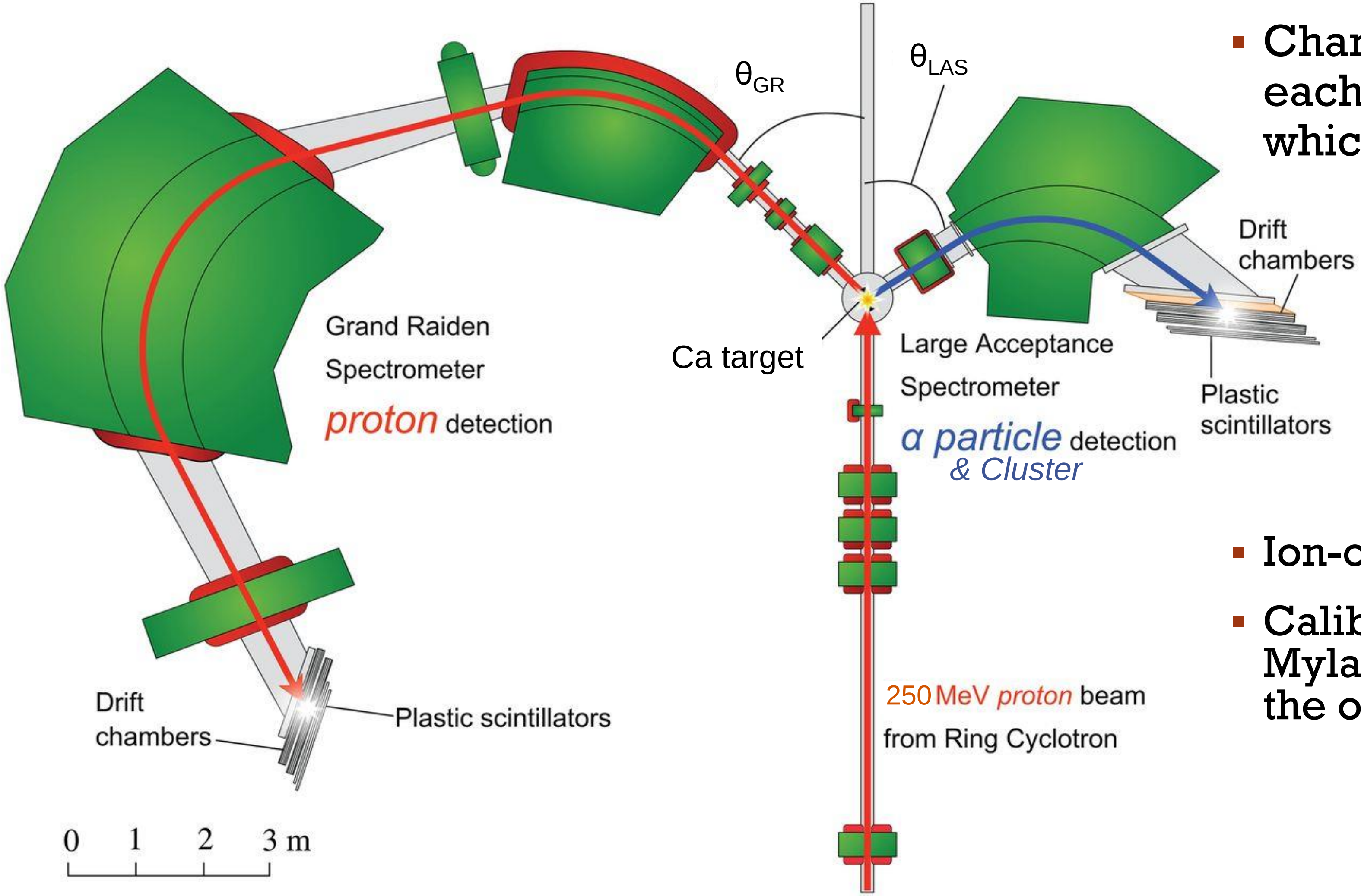
RCNP, Osaka University
2024.04.16 - 2024.04.21

GOALS OF EXPERIMENT E559

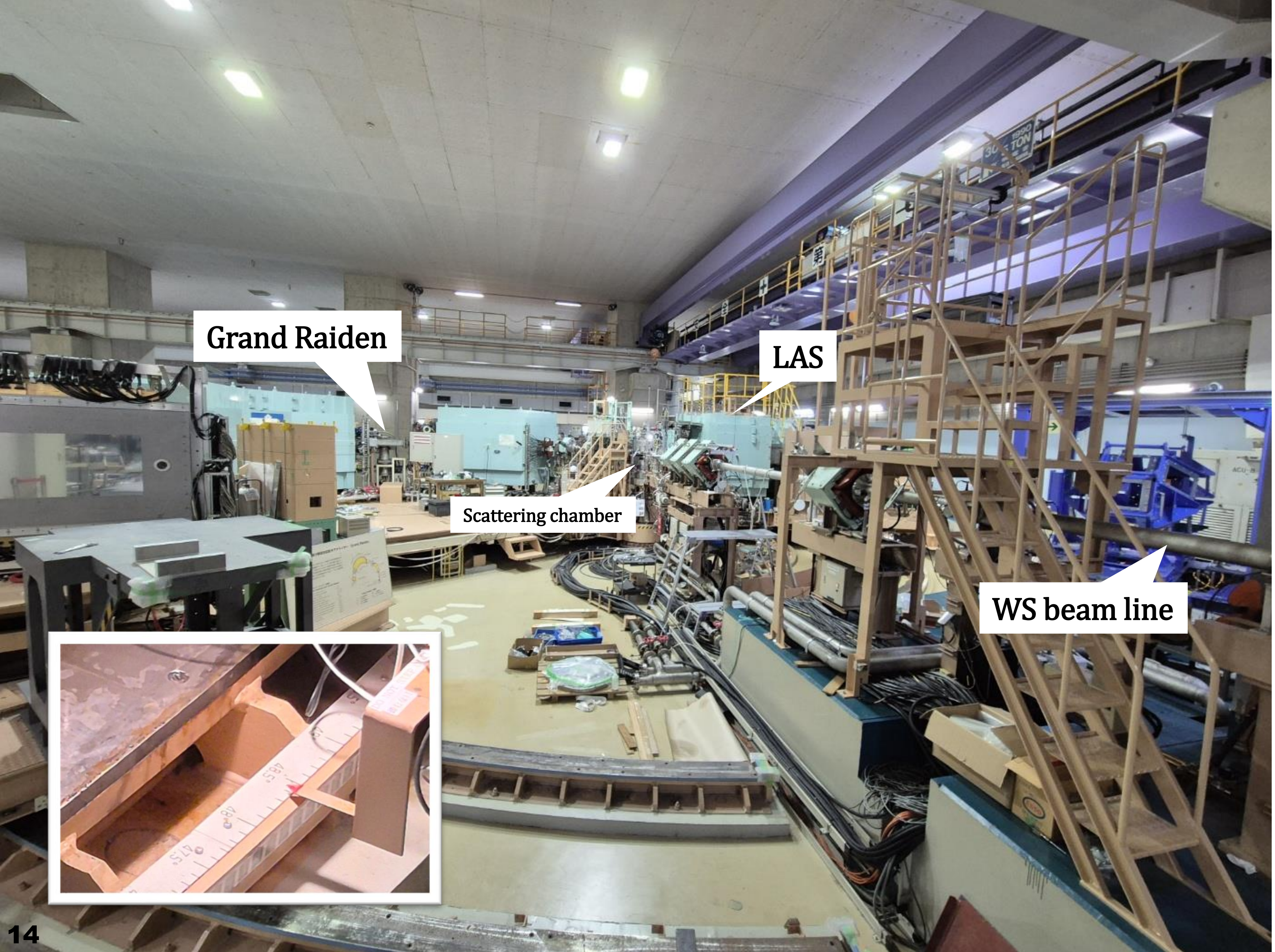
- 1. To discover an evidence of deuteron clustering in medium-mass nuclei
- 2. To figure out isospin-dependence of t/^{3}He mirror clusters
- 3. To take baseline data for establishment of cluster-knockout reaction models

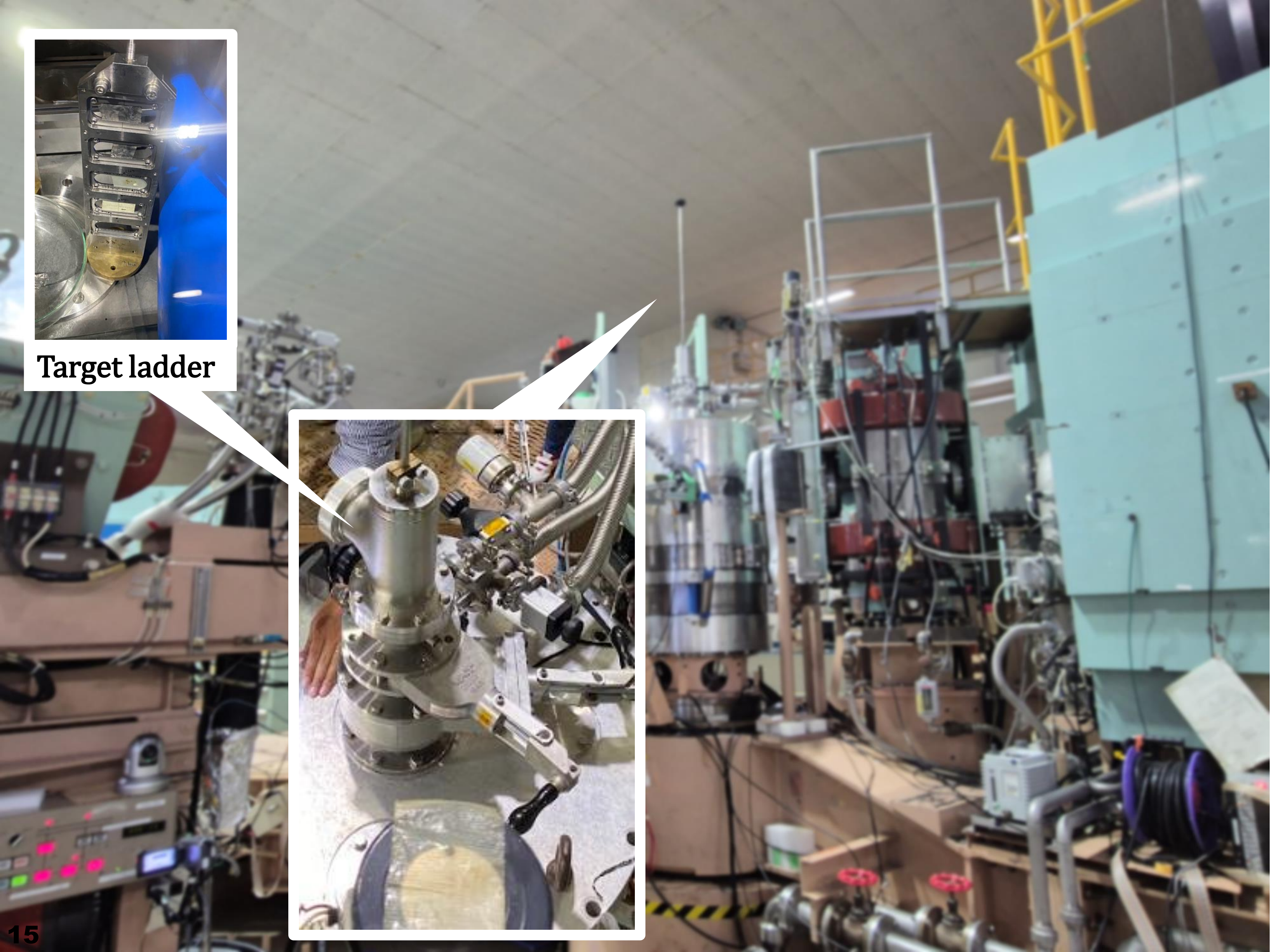


$^{40\text{-}48}Ca(p,pX)$ reaction
Experimental Setting



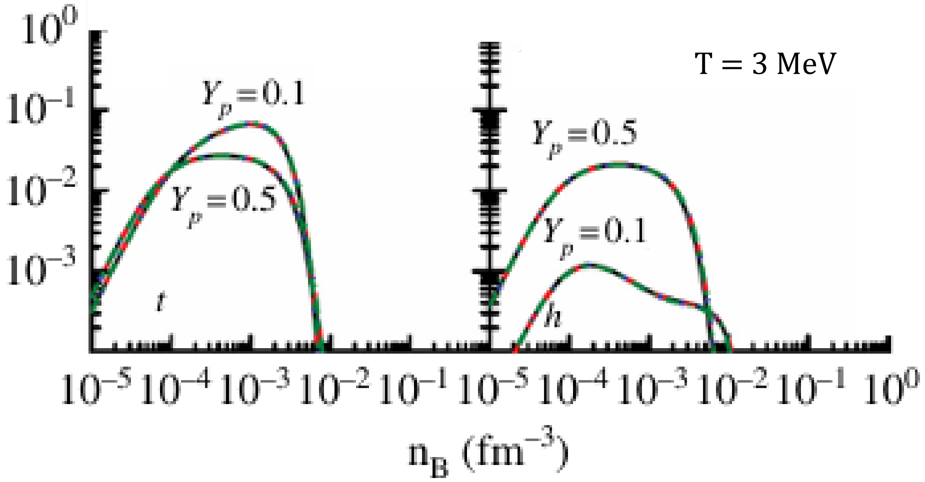
- Target : $^{40,42,44,48}Ca$
- Normal kinematics with proton beam
- Change Magnetic field and Angle for each target and knockouted cluster which we want to detect.
- Ion-optics with sieve slit
- Calibration data with Mylar(which include ^{16}O, due to the oxidation of Ca), and natC


Grand Raiden
LAS
Scattering chamber
WS beam line


Target ladder

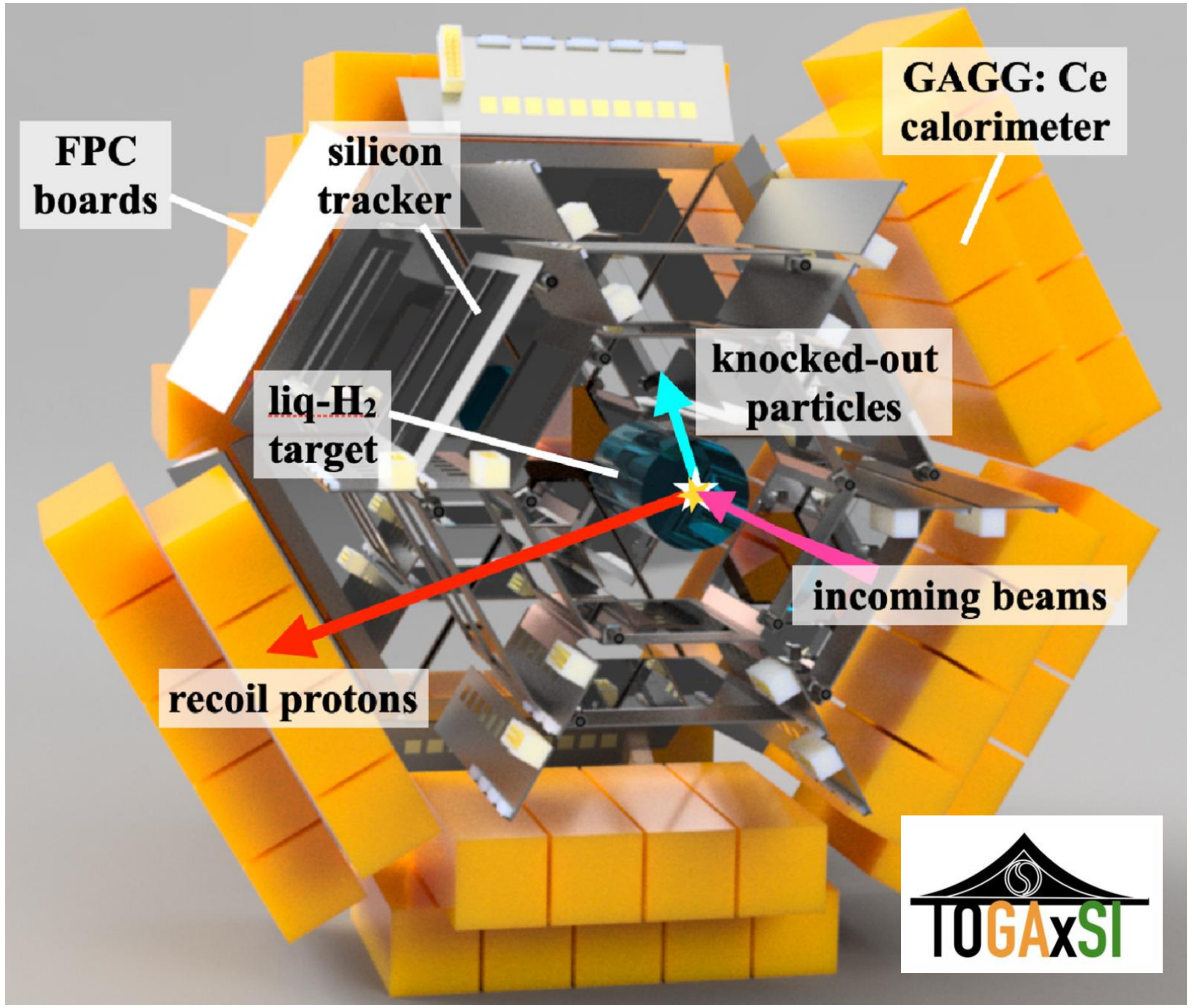
Expected Result

- Fractions of t and ^{3}He clusters are expected to have opposite behavior :
- the fraction of triton clusters increases in a neutron-rich matter than in a symmetric nuclear matter 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

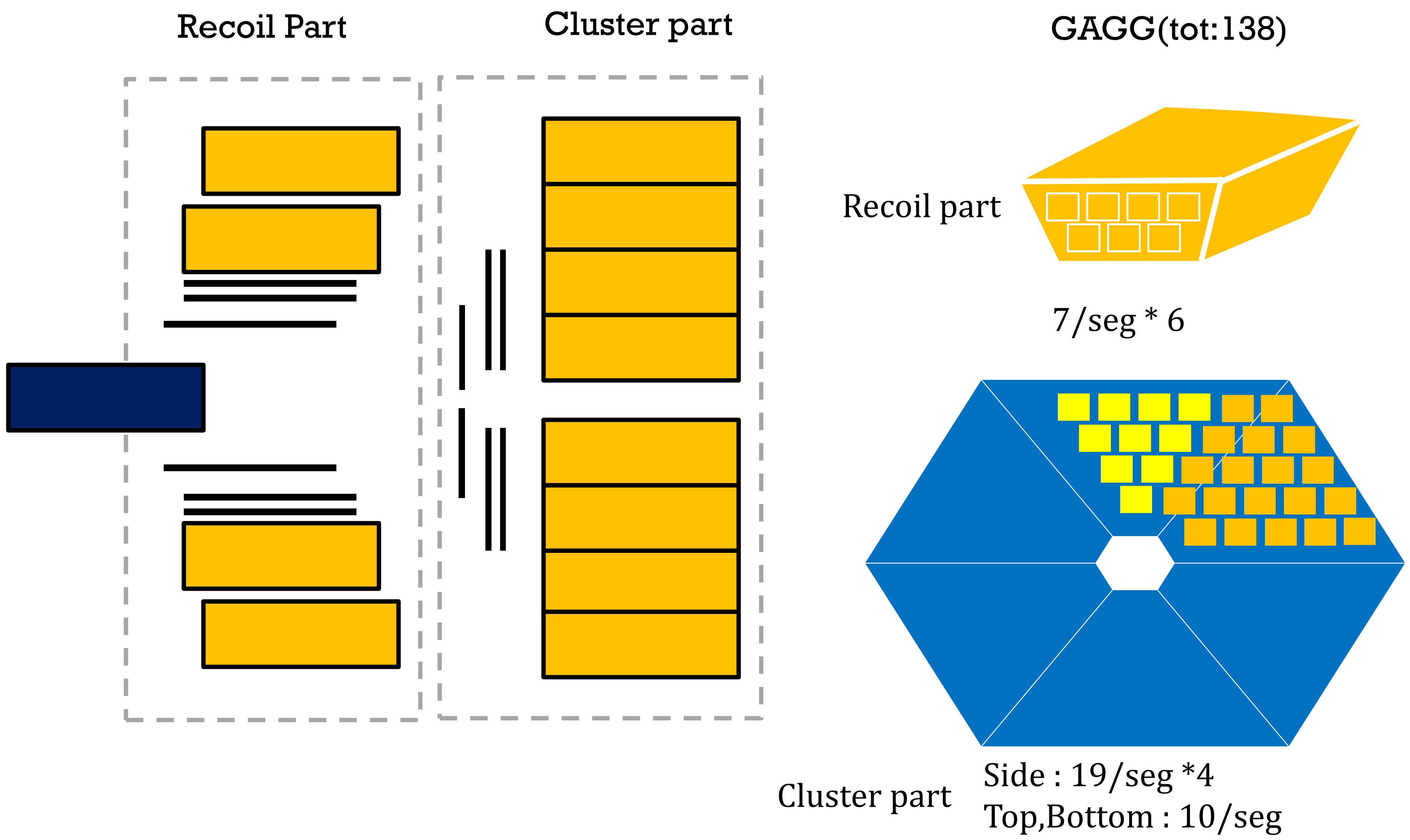


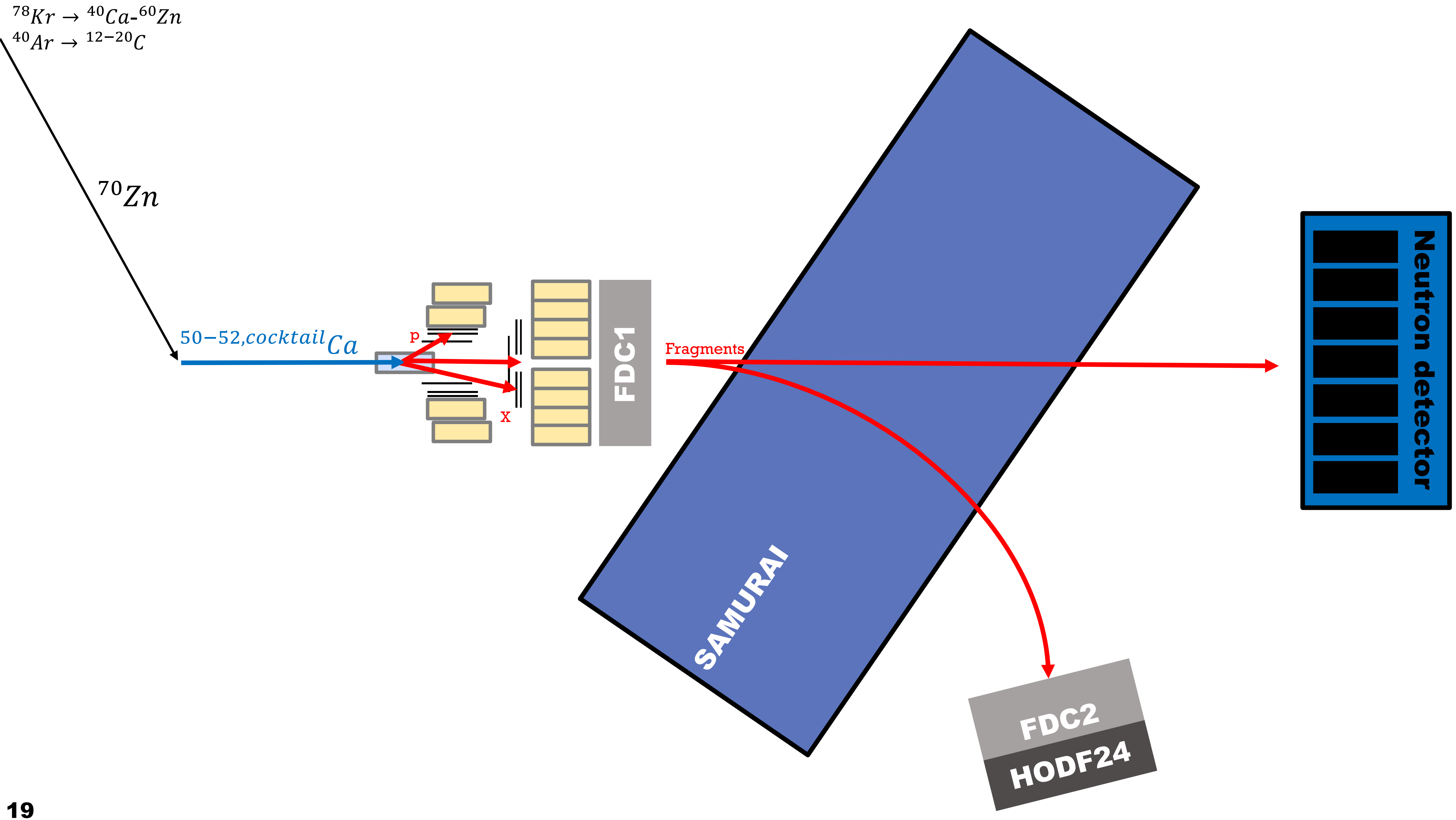
The TOGAXSI array

- **To**tal energy measurement by **GA**GG and verte**x** measurement by **Si** strips
- The new detector array for inverse-kinematics cluster knockout reaction measurements at HIMAC, **RIBF**.
- 3 layers of rectangular Si tracker for recoil protons and another 3 layers of trapezoidal Si for knocked-out clusters.
- The liquid hydrogen target from STRASSE collaboration will be used.



https://doi.org/10.1016/j.nimb.2023.05.054


Recoil Part
Cluster part
GAGG(tot:138)
Recoil part
7/seg * 6
Cluster part
Side : 19/seg *4
Top,Bottom : 10/seg


$^{78}Kr \rightarrow {}^{40}Ca$-$^{60}Zn$
$^{40}Ar \rightarrow {}^{12-20}C$
^{70}Zn
$^{50-52,cocktail}Ca$
p
X
FDC1
Fragments
SAMURAI
Neutron detector
FDC2
HODF24

References

- Junki Tanaka et al 2020 J. Phys.: Conf. Ser. 1643 012108
- Stefan Typel 2013 J. Phys.: Conf. Ser. 420 012078
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- Uesaka T, Itagaki N. 2024 Nuclear clustering—manifestations of non uniformity in nuclei. Phil. Trans. R. Soc. A 382: 20230123
- J. Tanaka et al., Nucl. Instr. Meth. B 542, 4 (2023).
- Spokesperson of experiment E559 : Tomohiro Uesaka, Juzo Zenihiro
- T. Uesaka, J. Zenihiro et al., RCNP proposal E559 "Deuteron, triton, and 3 He clusters in stable calcium isotopes"

Thank You