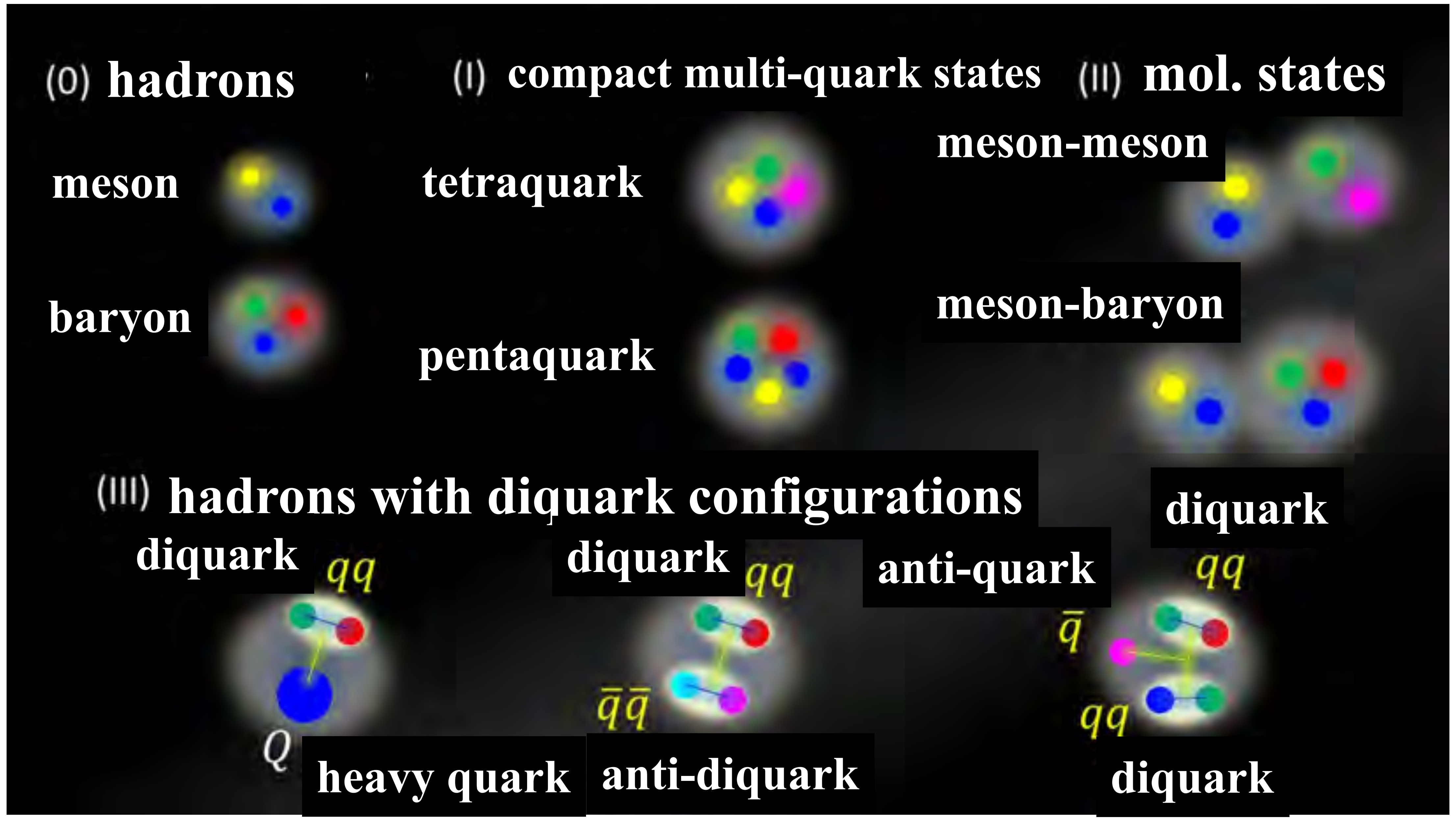
Part 3
Applications to cluster physics

Order in physical systems through <u>formation of subsystems</u>

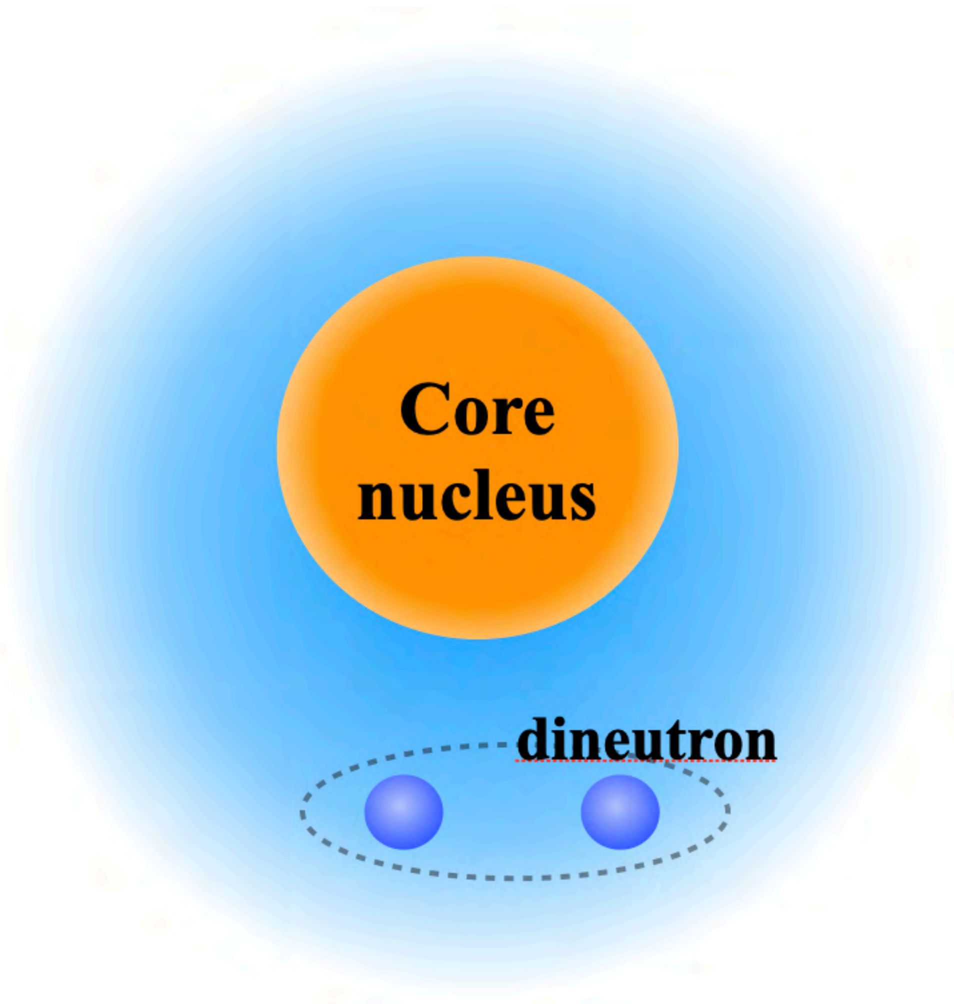
di- / multi-quark correlation in hadrons

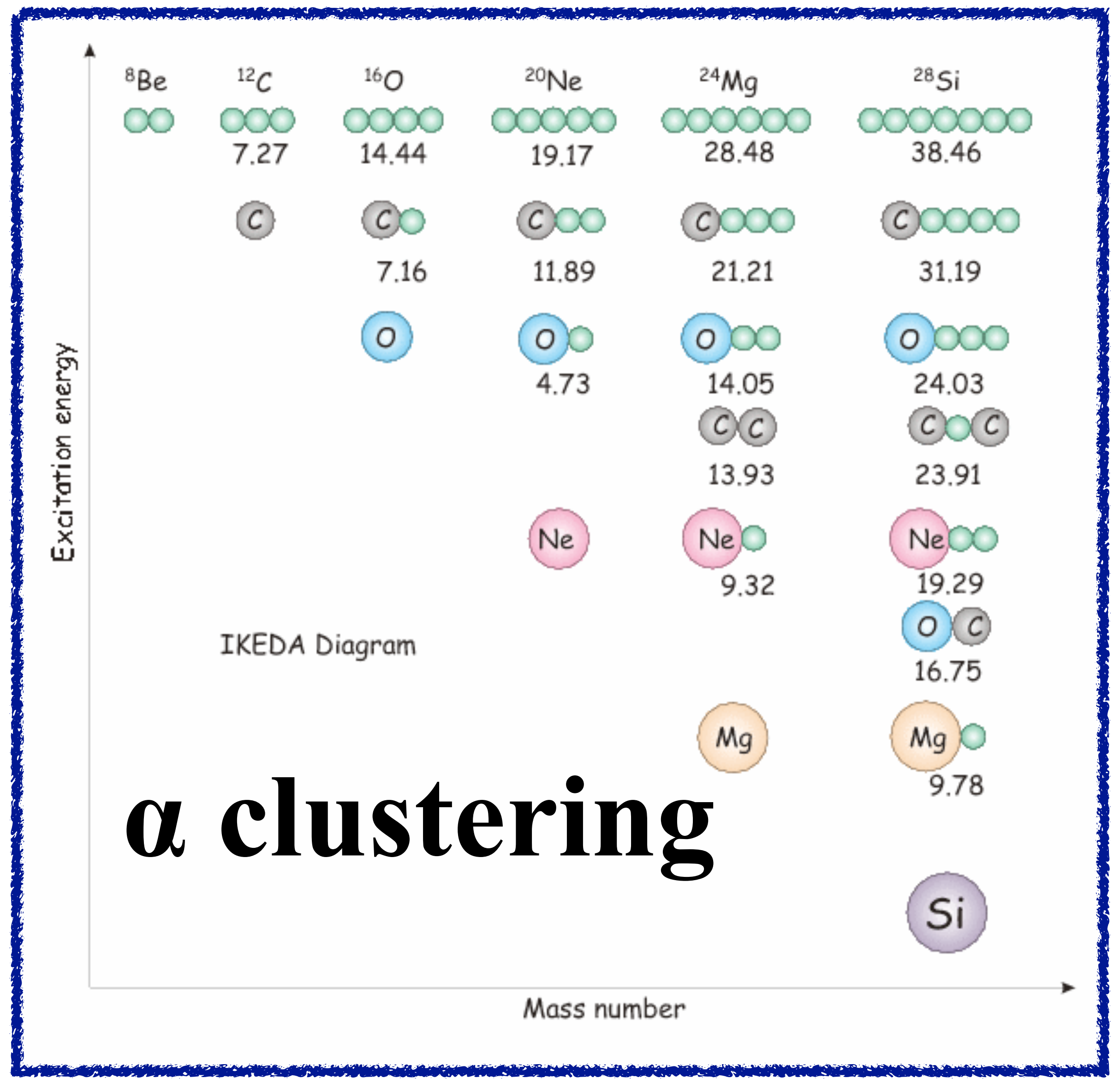


http://kakudan.rcnp.osaka-u.ac.jp/jp/overview/world/Flavor.html (in Japanese)

hadron production

multi-nucleon correlation in neutron drip-line nuclei

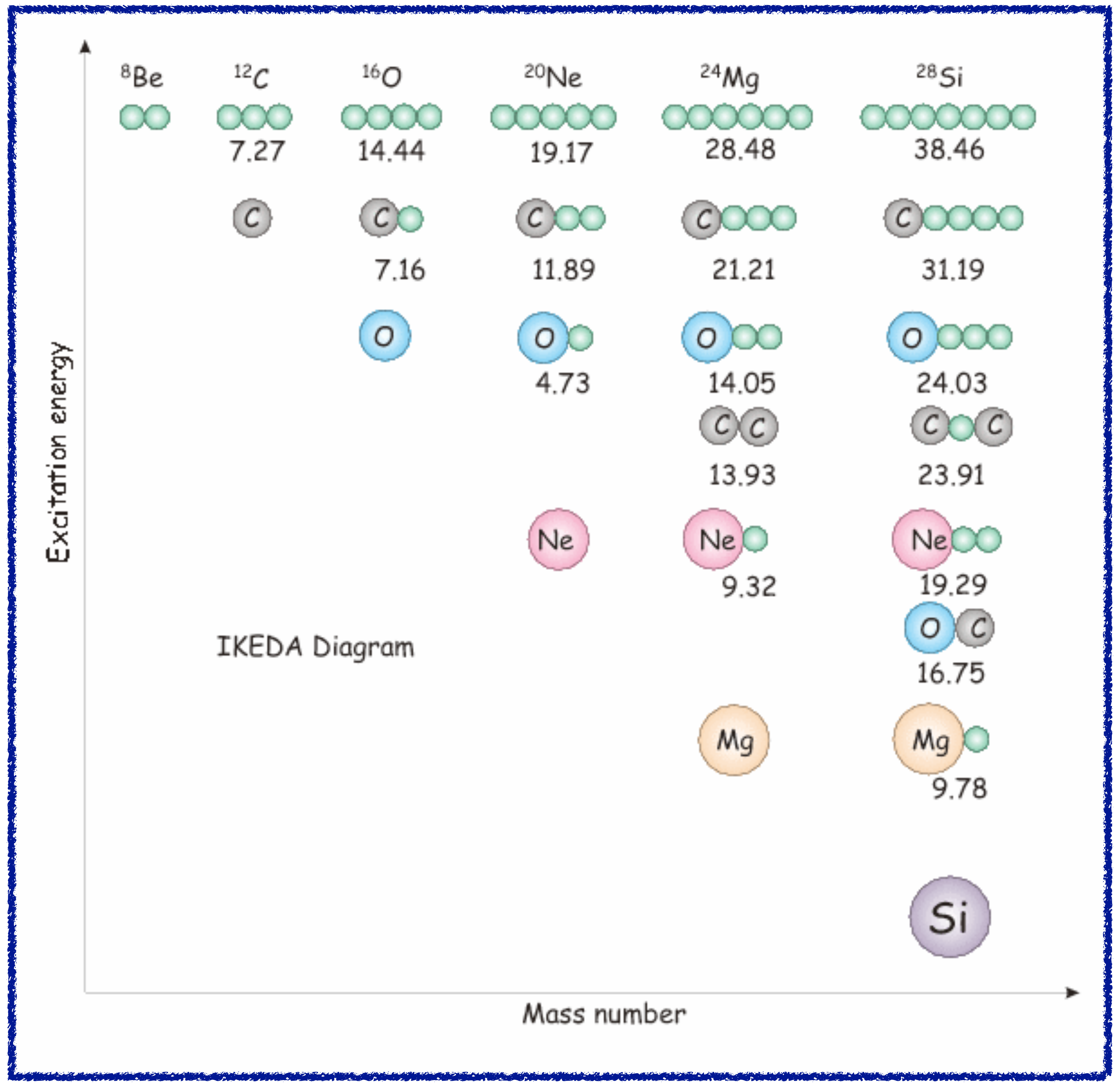




α-particle emission in heavy-ion reactions

Cluster physics

Since the observation of α-decay in 1898
Close connections to nucleosynthesis
"Molecular" picture of nuclei
Insights from the Ikeda diagram
universality of the threshold effects

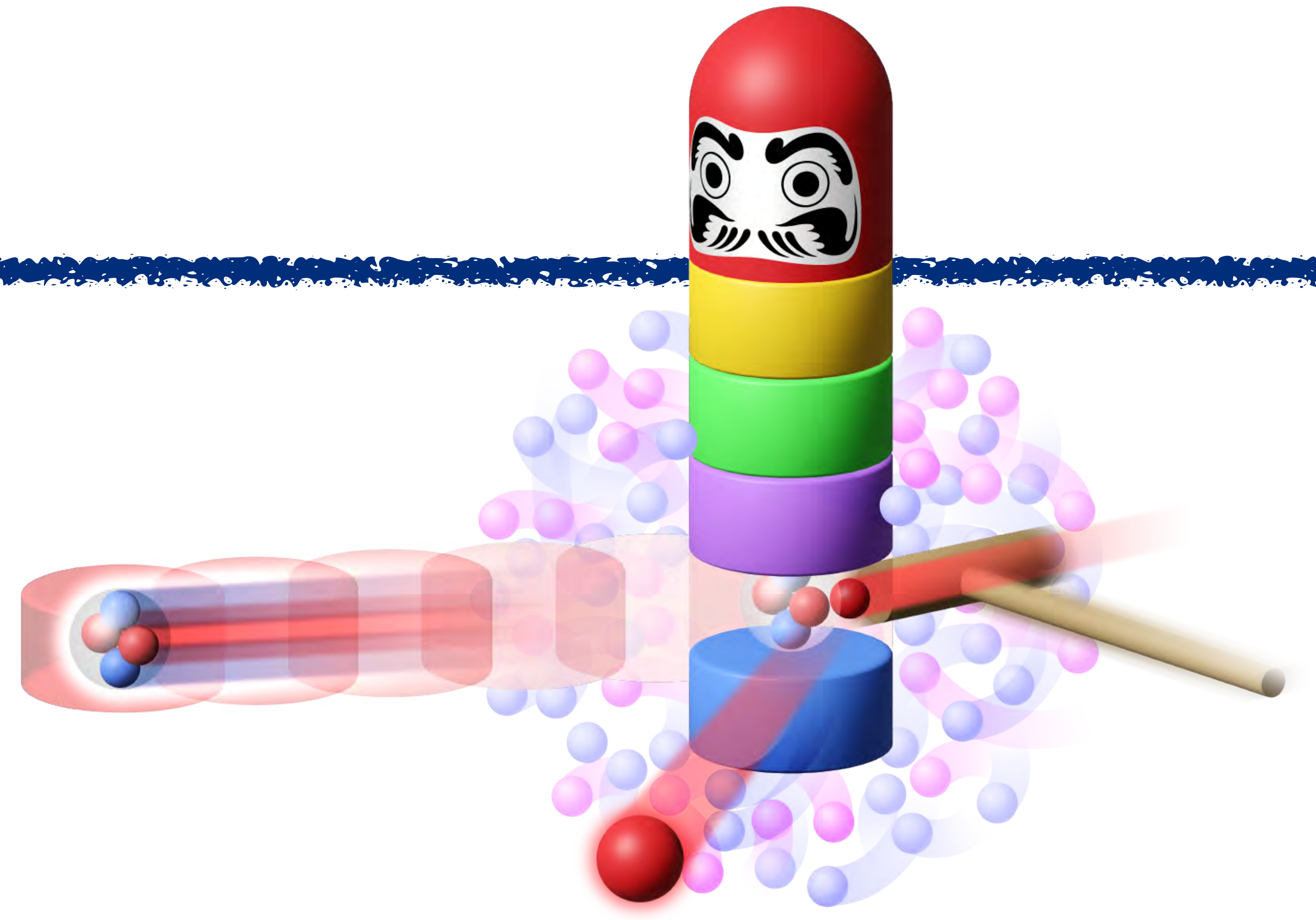


Experimental approaches

Decays
Transfer reactions
Resonant scattering
Inelastic scattering
Knockout reactions
⋮

Reviews
C. Beck (editor), Clusters in Nuclei, Lecture Note in Physics vol. 818.
W. von Oertzen, M. Freer, Y. Kanada-En'yo, Physics Reports 432, 43 (2006).
M. Freer et al., Rev. Mod. Phys. 90, 035004 (2018)
T. Uesaka and N. Itagaki, Phil. Trans. R. Soc. A 382: 20230123 (2023).
K. Wei, Y.-L. Ye, Z.-H. Yang, Nucl. Sci. Tech. 35:216 (2024)

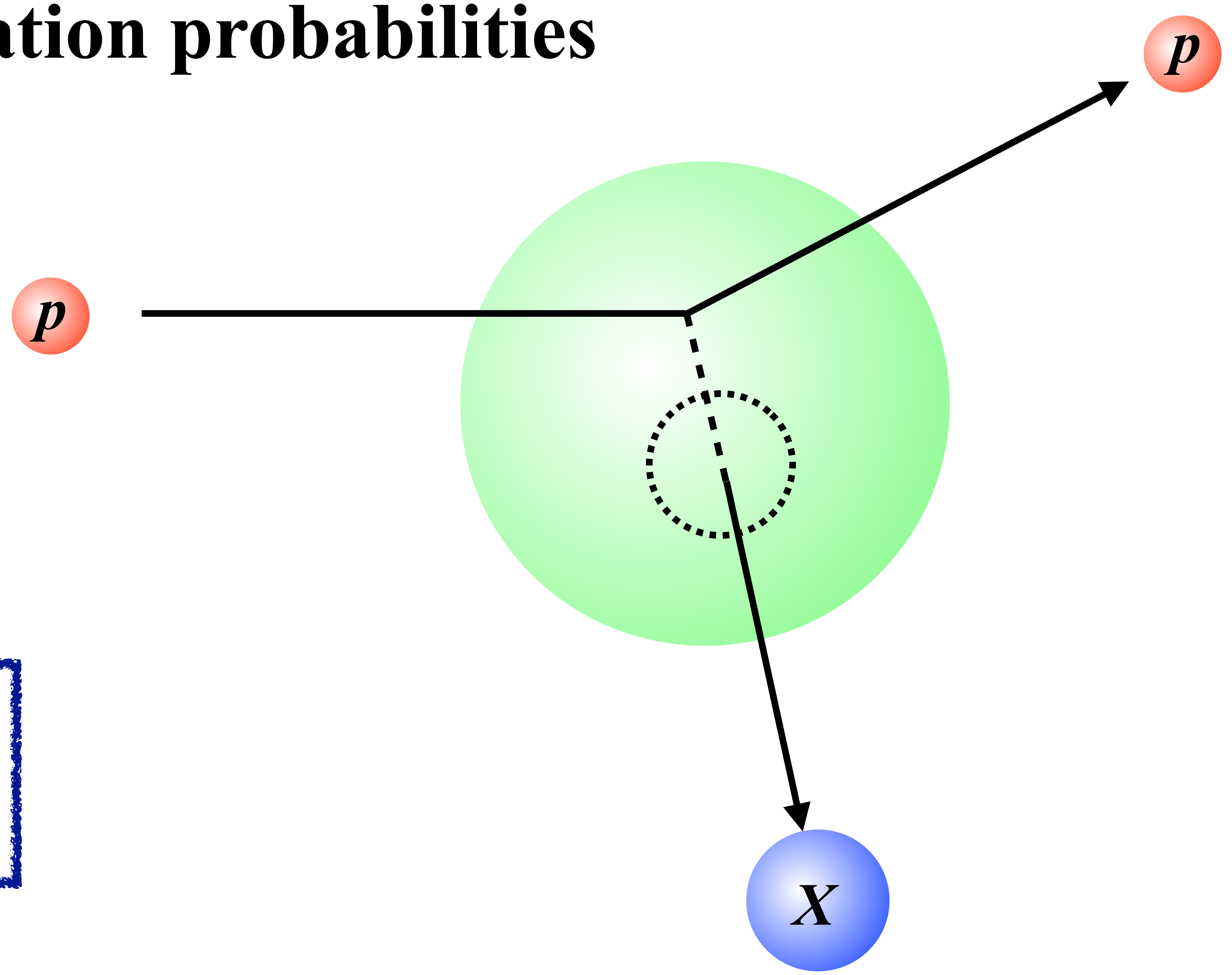
(p,pX) Cluster knockout reaction



As a possible probe to clustering in the groud states

Natural extension of the (p,pN) reaction

- **(*relatively*) Simple reaction mechanism**
- **Flexibilities in choices of the kinematics**
  - **→ reliable extraction of cluster formation probabilities**



***p*-*X* elastic scattering in nuclear medium**

Most of the discussions for (p,2p) reactions can be applied to (p,pX) reactions.

	Normal kinematics w/ a proton beam	Inverse kinematics w/ heavy-ion beams
Nucleon knockout (*p*,*pN*) reactions	**A lot of studies since 1950's** **Basis of our understanding**	**Started in the 21st century** **Proven to be an excellent spectroscopic tool for RI** HIMAC, GSI, RIBF
Cluster knockout (*p*,*pX*) reactions	**Data exist (since 1970's), but quite limited**	**Initiated at RIBF (2018−)**

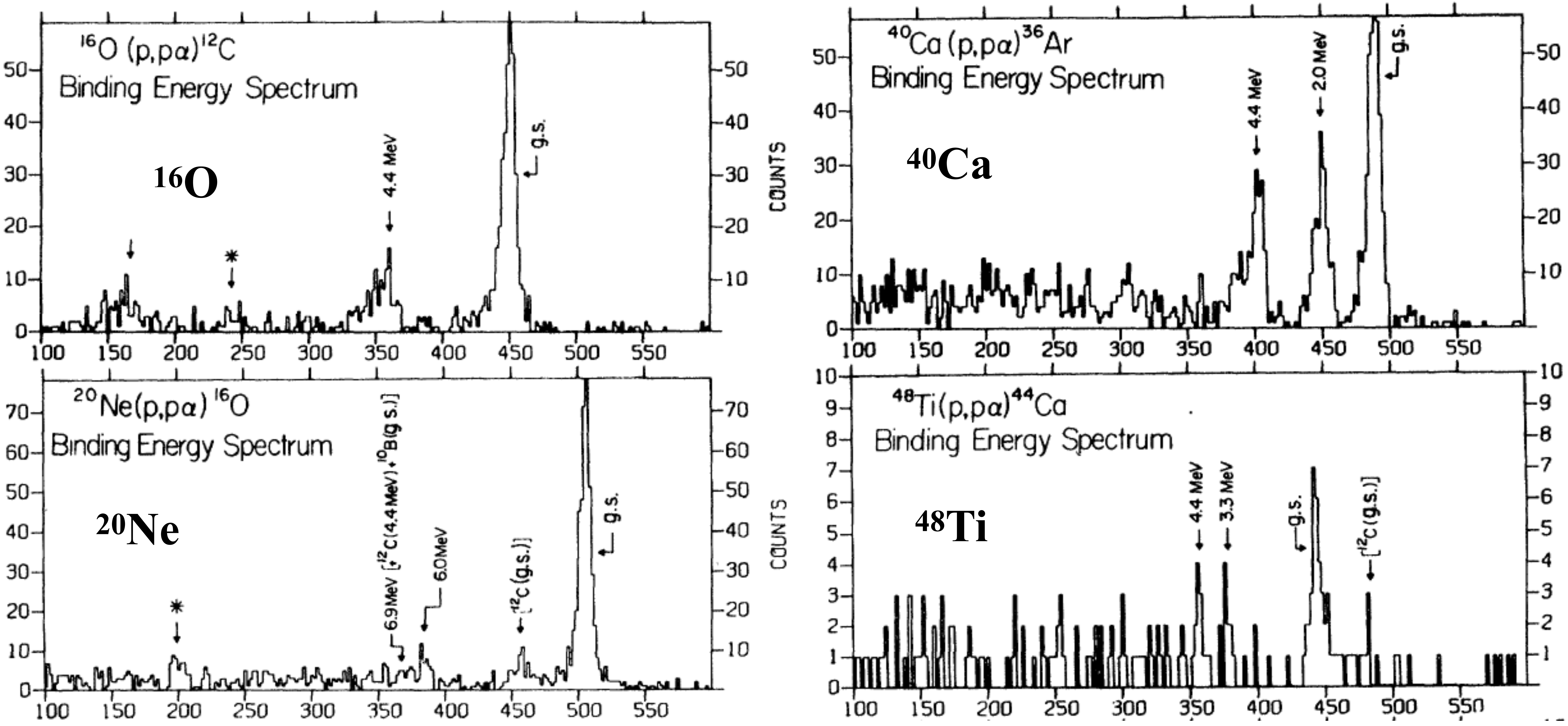
Available cluster knockout (*p,pX*) data

(*p,pα*)	Beam energy	Target	Kinematics	Energy resolution
Harvard	$E_p = 160$ MeV	^{9}Be. ^{12}C, ^{16}O	θ_p=40-102deg, θ_α=30-60deg	ΔE~2MeV
Orsay	$E_p = 157$ MeV	^{24}Mg, ^{28}Si, ^{40}Ca, ^{58}Ni, ^{140}Ce, ^{232}Th	θ_p=60-67deg, θ_α=43-65deg	ΔE~2.6MeV
Saturne	$E_p = 1600$ MeV	^{6,7}Li, ^{12}C, ^{24}Mg, ^{27}Al, ^{40}Ca	θ_p=36deg, θ_α=65deg	ΔE≧10MeV
Maryland	$E_p = 101.5$ MeV	^{16}O, ^{20}Ne, ^{24}Mg. ^{28}Si, ^{32}S, ^{40}Ca, ^{48}Ti, ^{54}Fe, ^{66}Zn	θ_p=70deg, E_p=40--70 MeV	ΔE≦0.5 MeV
iThemba	$E_p = 100$ MeV	^{12}C, ^{40}Ca	θ_p=25--110deg, θ_d=69--26deg	
(*p,pt*)				
Maryland	$E_p = 101.3$MeV	^{16}O	θ_p=40.1deg, θ_d=40deg	ΔE<1MeV
(*p,pd*)				
JINR	$E_p = 670$MeV	^{7}Li, ^{12}C	θ_p=147deg, θ_d=6.5deg	ΔE~16.5MeV
Maryland	$E_p = 101.3$MeV	^{16}O	θ_p=40.1deg, θ_d=40deg	ΔE<1MeV

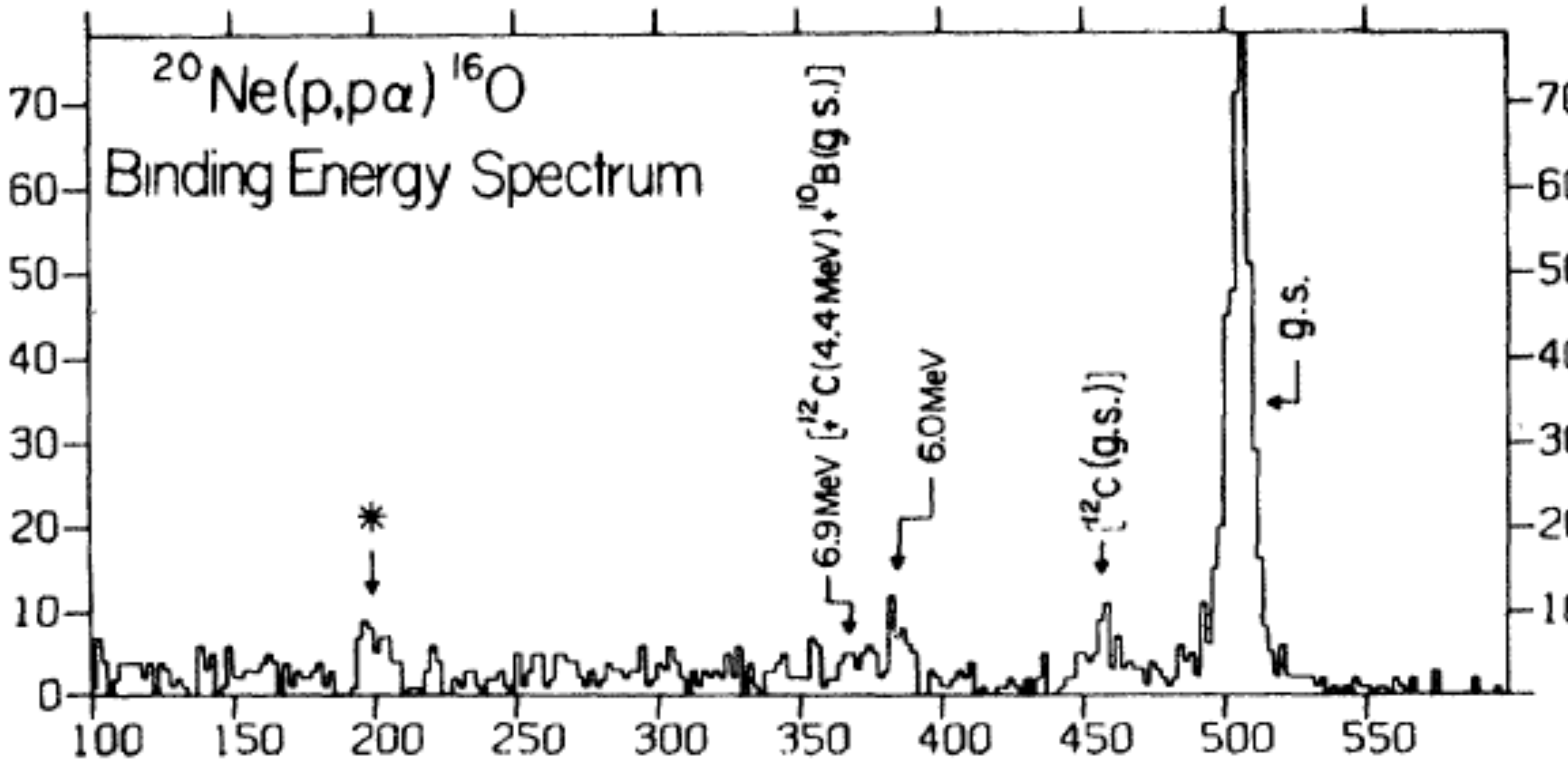
E_p≧100 MeV
A_{target} ≧10

Maryland results on ($p,p\alpha$) at E_p = 100 MeV

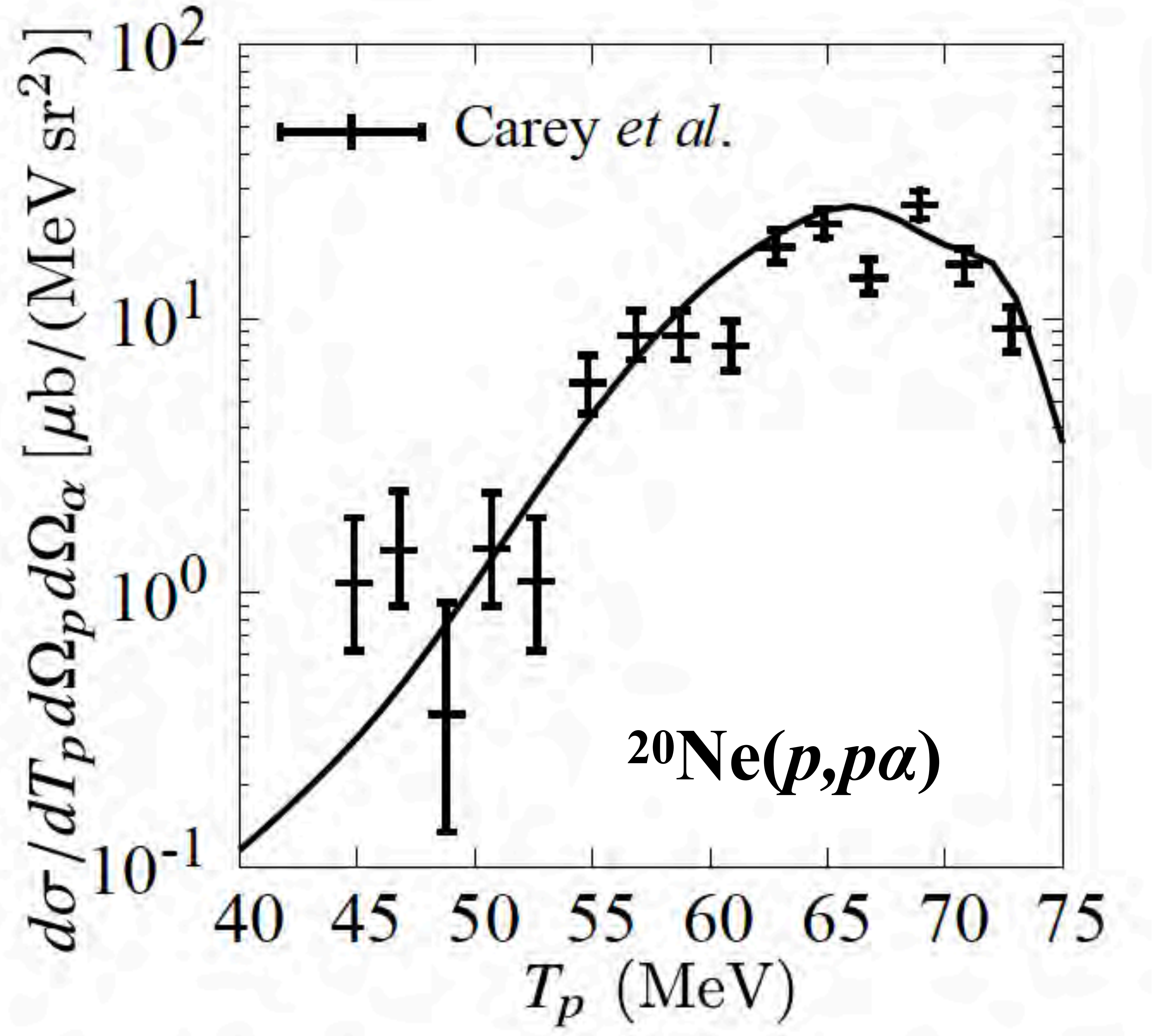
T.A. Carey et al., PRC **29**, 1273 (1984)



Reanalysis by the up-to-date reaction theory



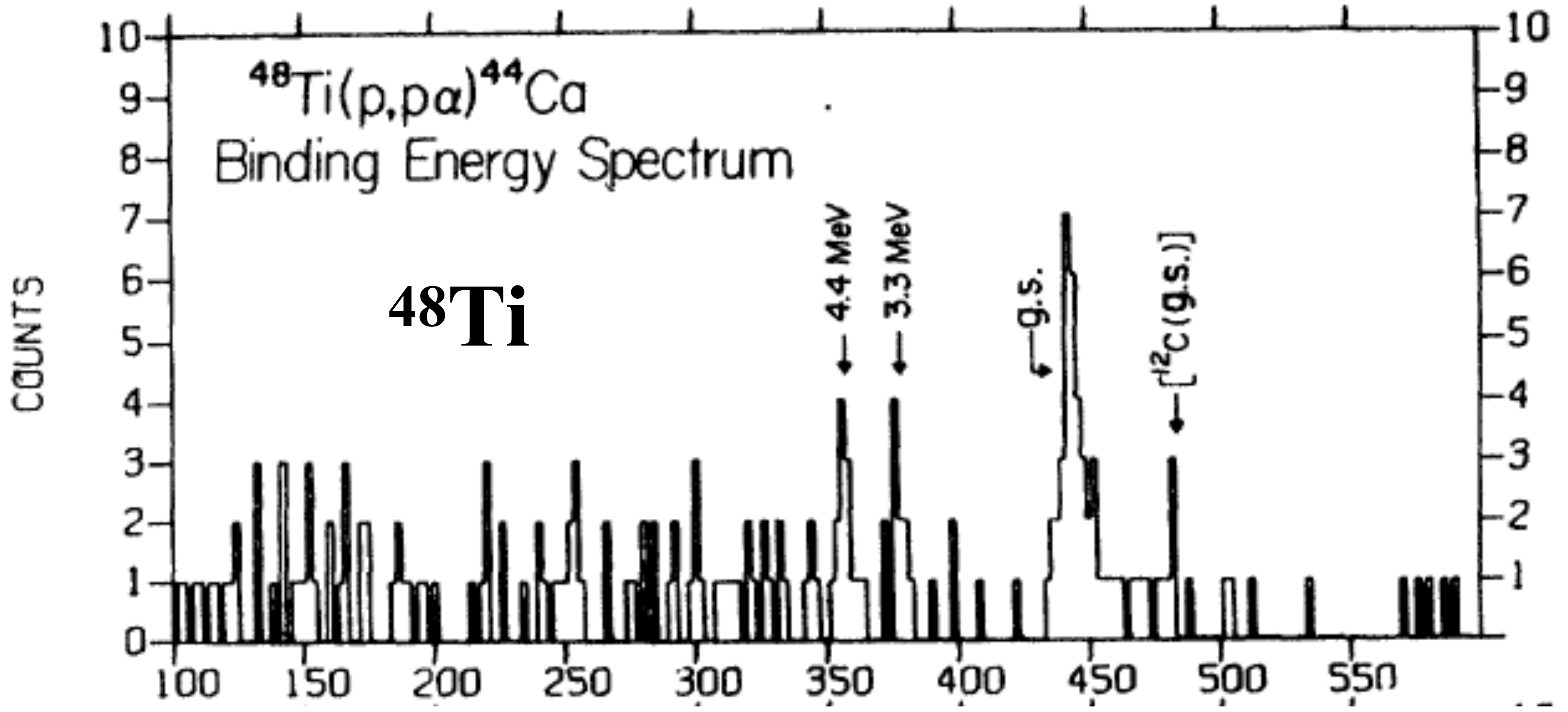
Kazuki Yoshida et al.,
Phys. Rev. C **100**, 044601 (2019).



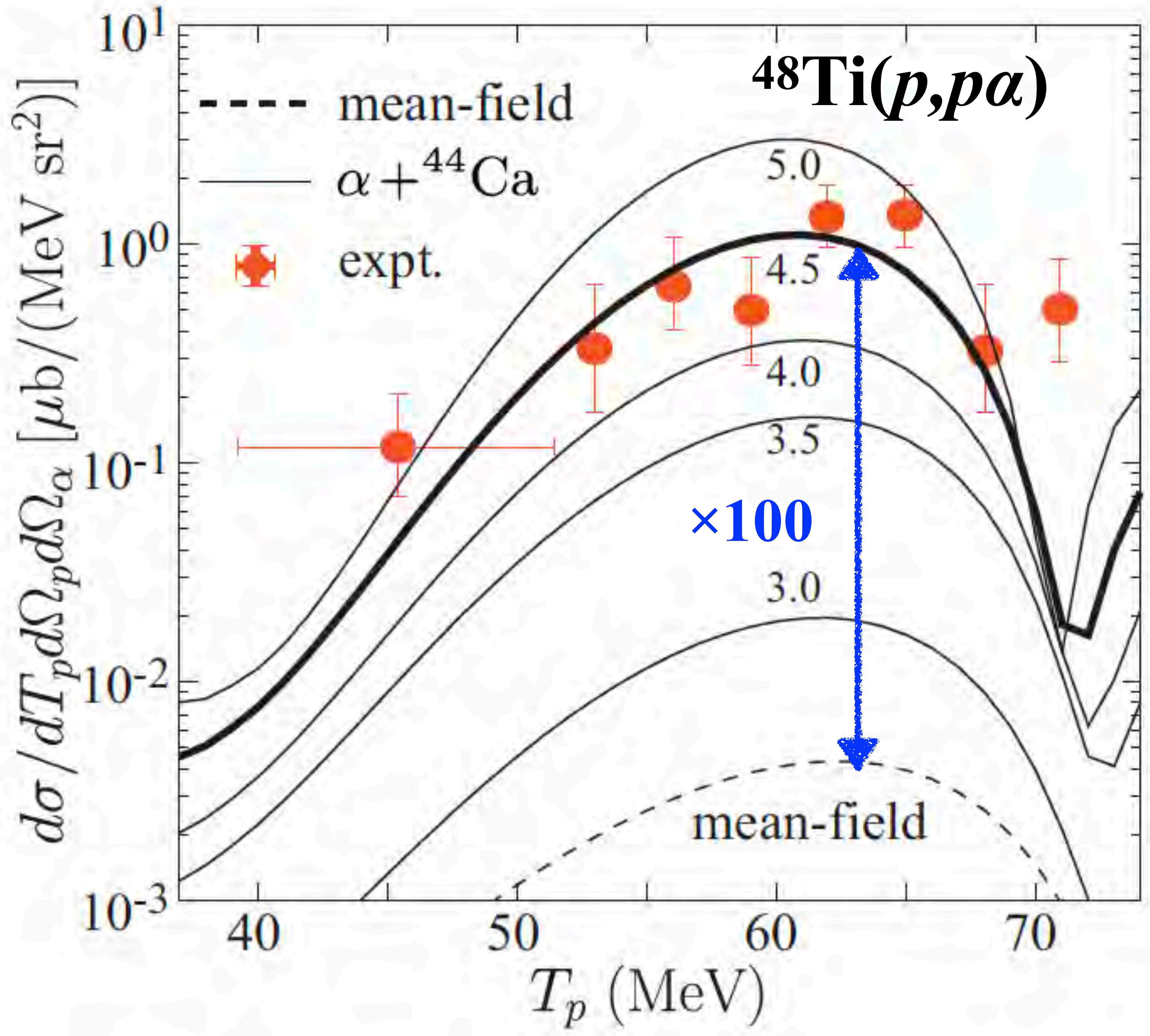
S_α= 0.26

Results for a medium-mass nucleus

T.A. Carey et al., PRC **29**, 1273 (1984)



Y. Taniguchi, Kazuki Yoshida et al.,
Phys. Rev. C 103, L031305 (2021).

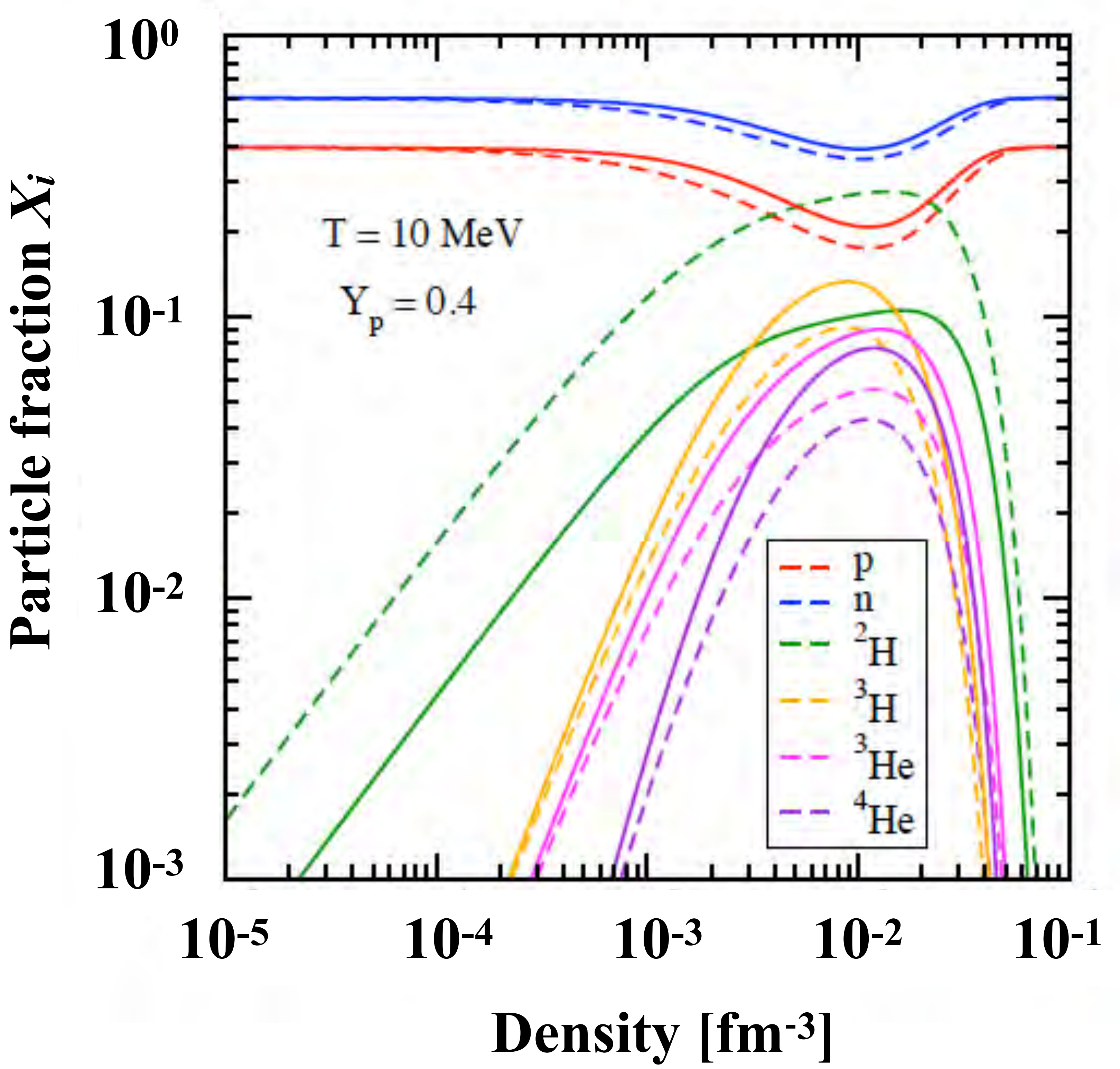


Our understanding of α clustering is far from the reality!

S. Typel's talk in the 2nd QFS-RB

Clustering in dilute nuclear matter

S. Typel,
J. Phys. Conf. Ser. 420, 012078 (2013)

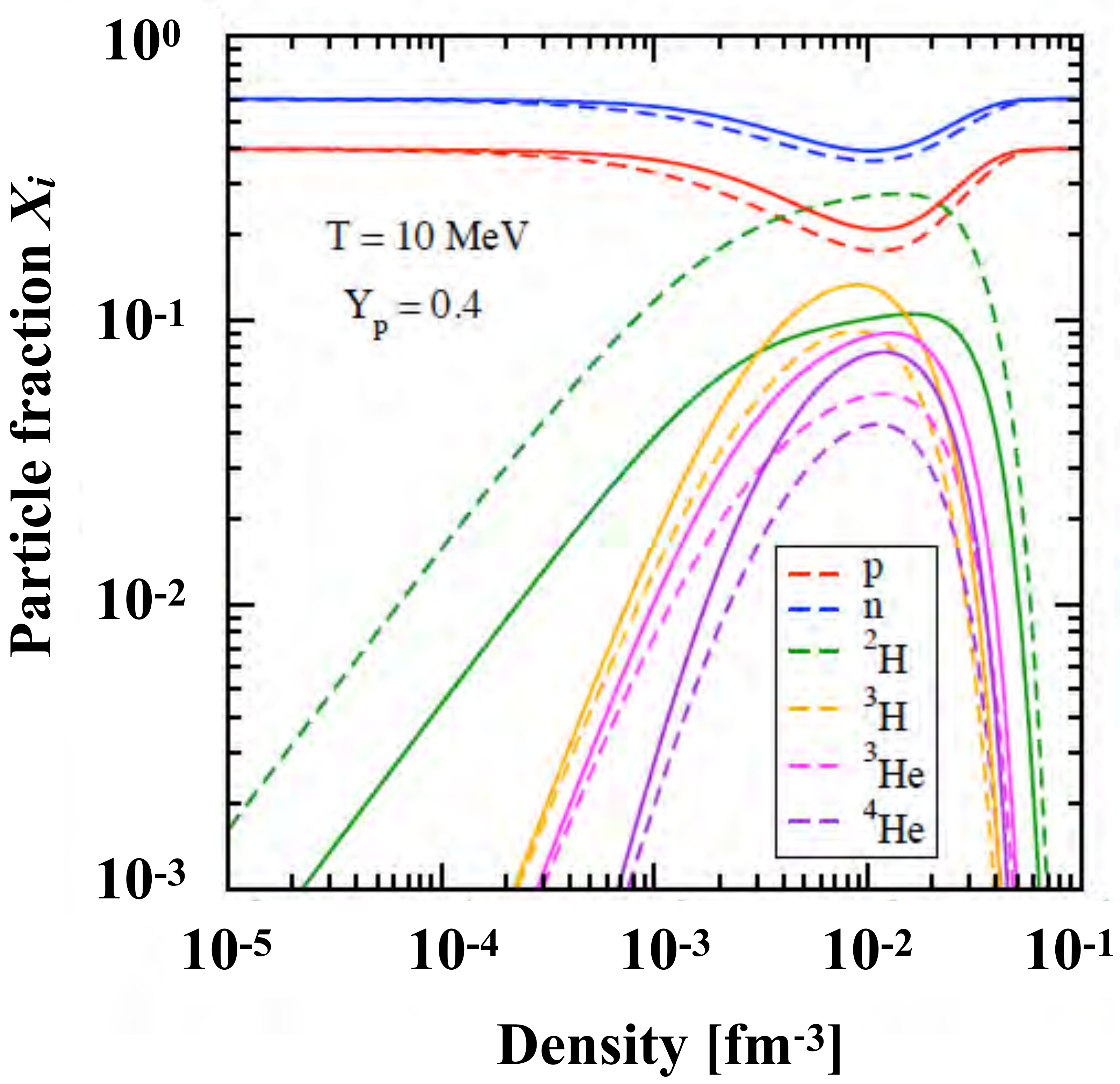


Clusters grow at < 0.1 ρ_{sat}.

S. Typel's talk in the 2nd QFS-RB

Clustering in dilute nuclear matter

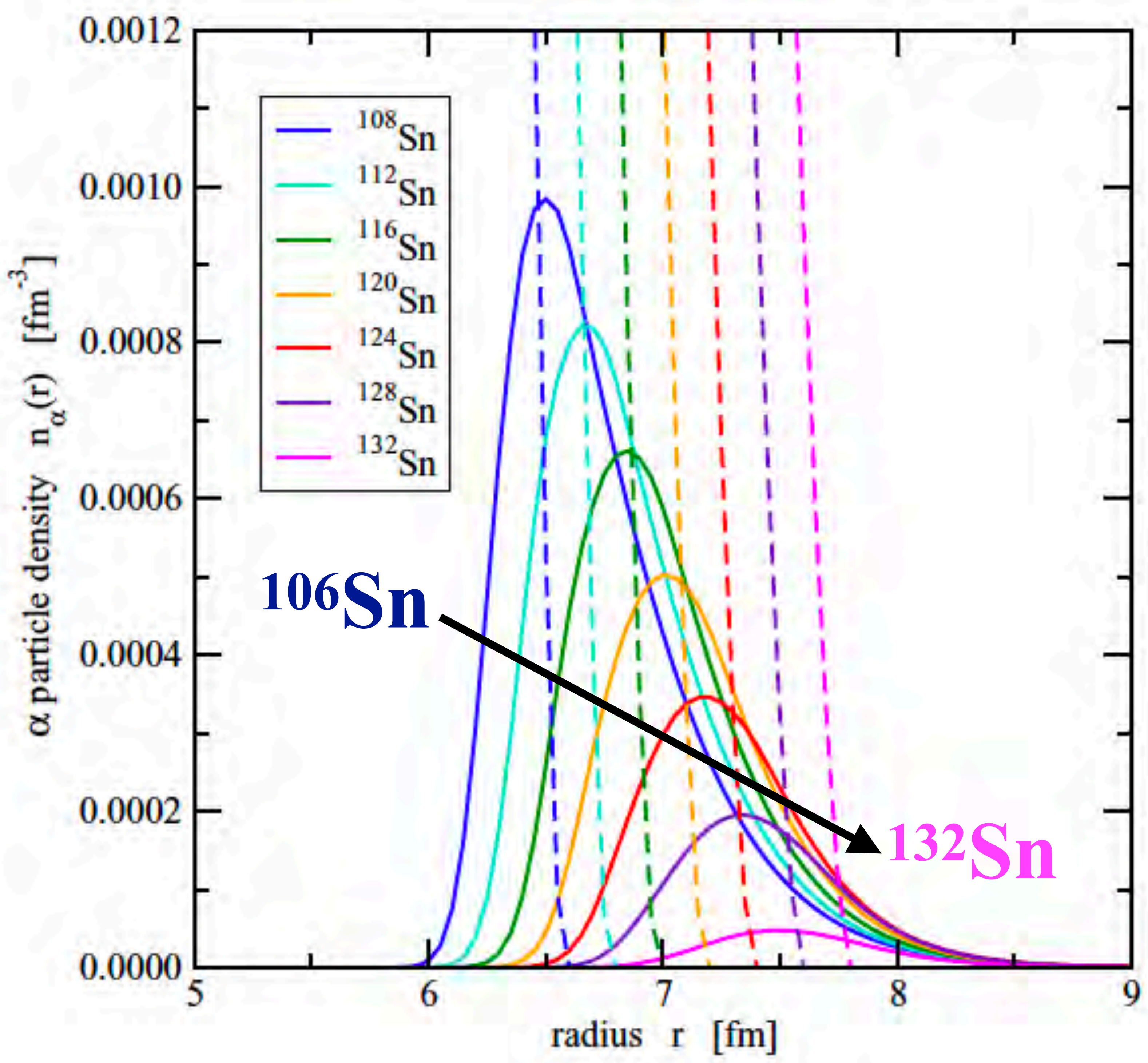
S. Typel,
J. Phys. Conf. Ser. 420, 012078 (2013)

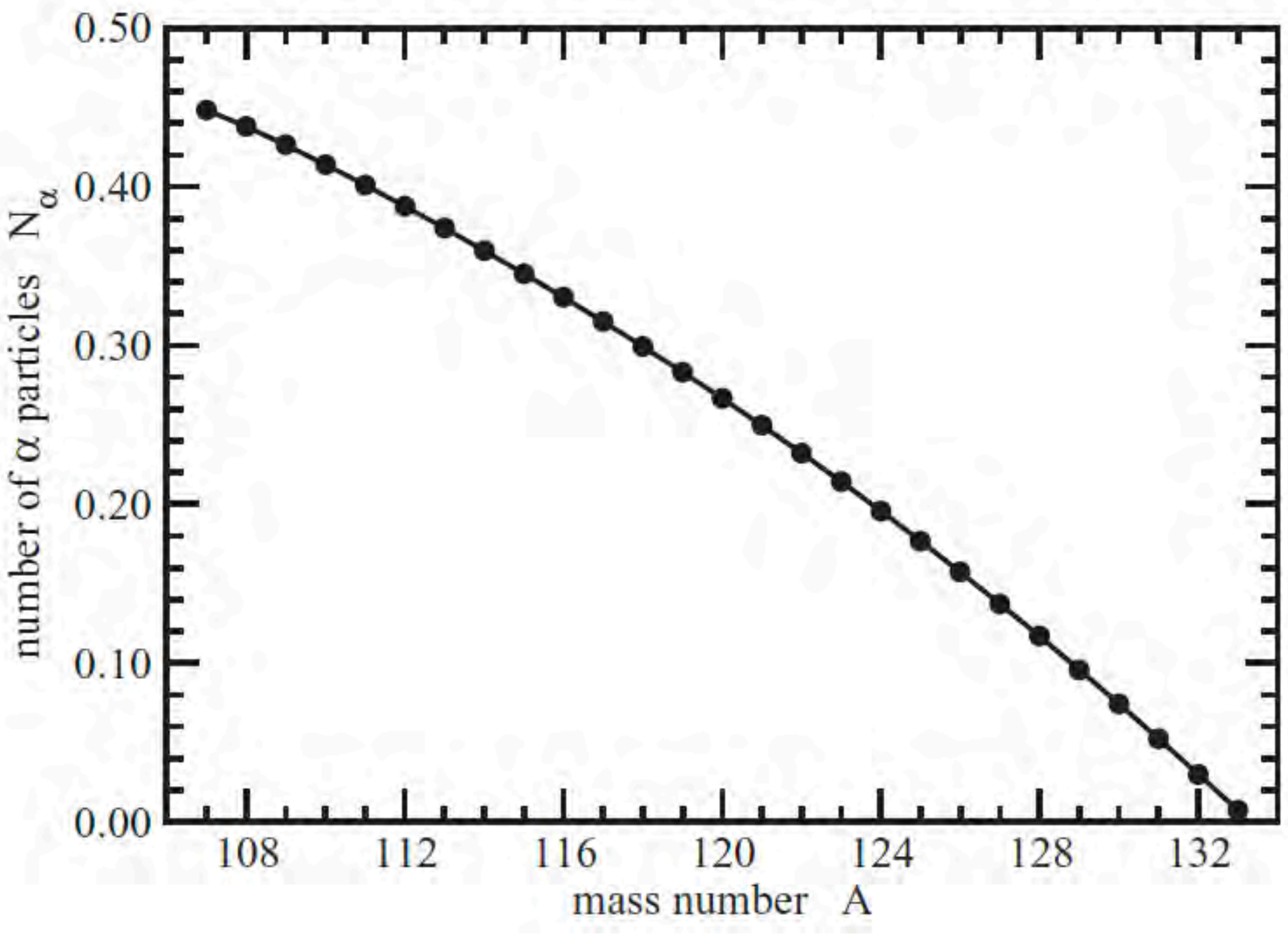


Clusters grow at < 0.1 ρ_{sat}.

On the dilute (=non-saturated) surface of heavy nuclei, clusters develop.

S. Typel, PRC **89**, 064321 (2014).





"The surface α" decreases as a function of excess neutron

α clusters in tin isotopes

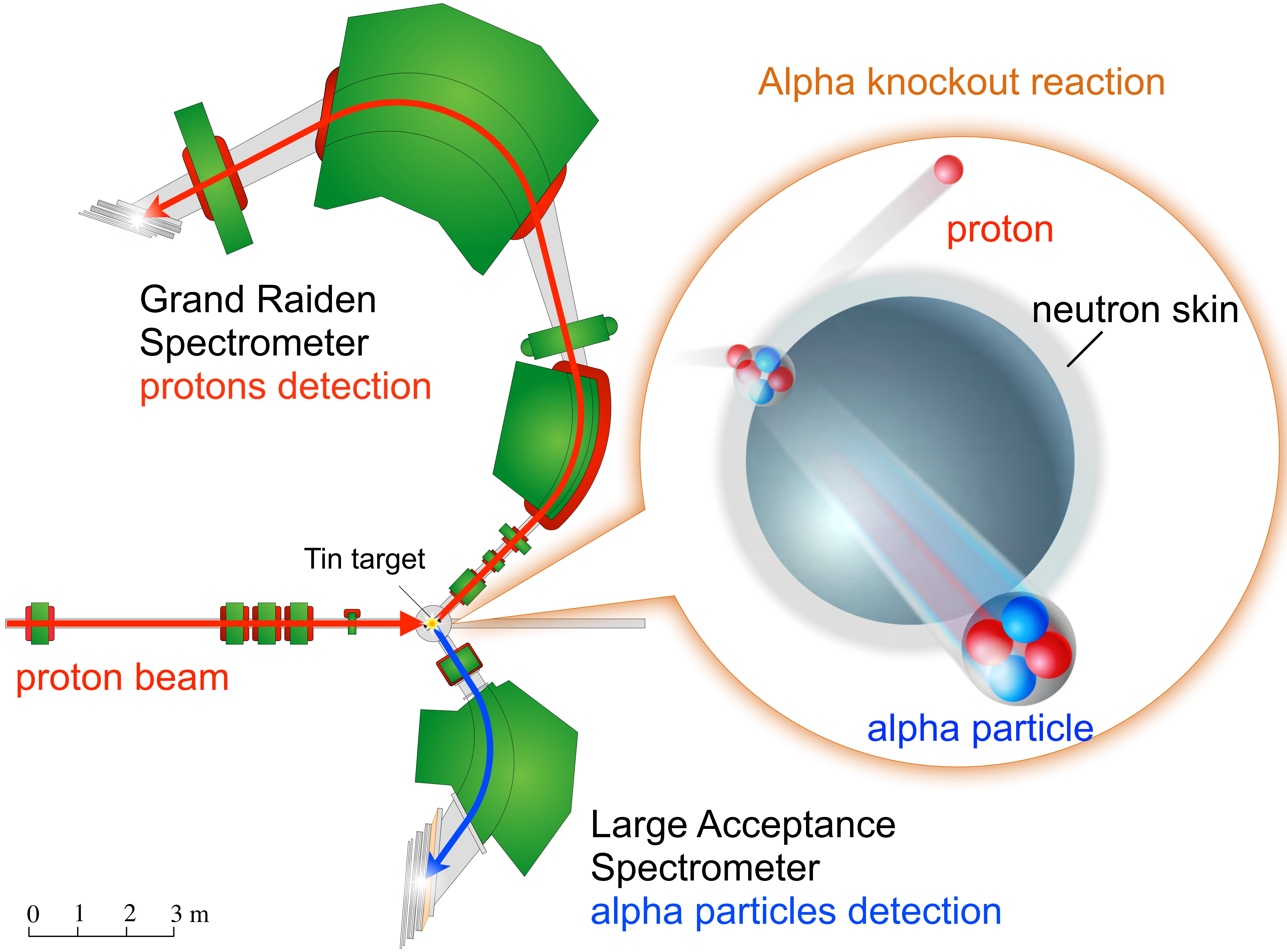
REPORT

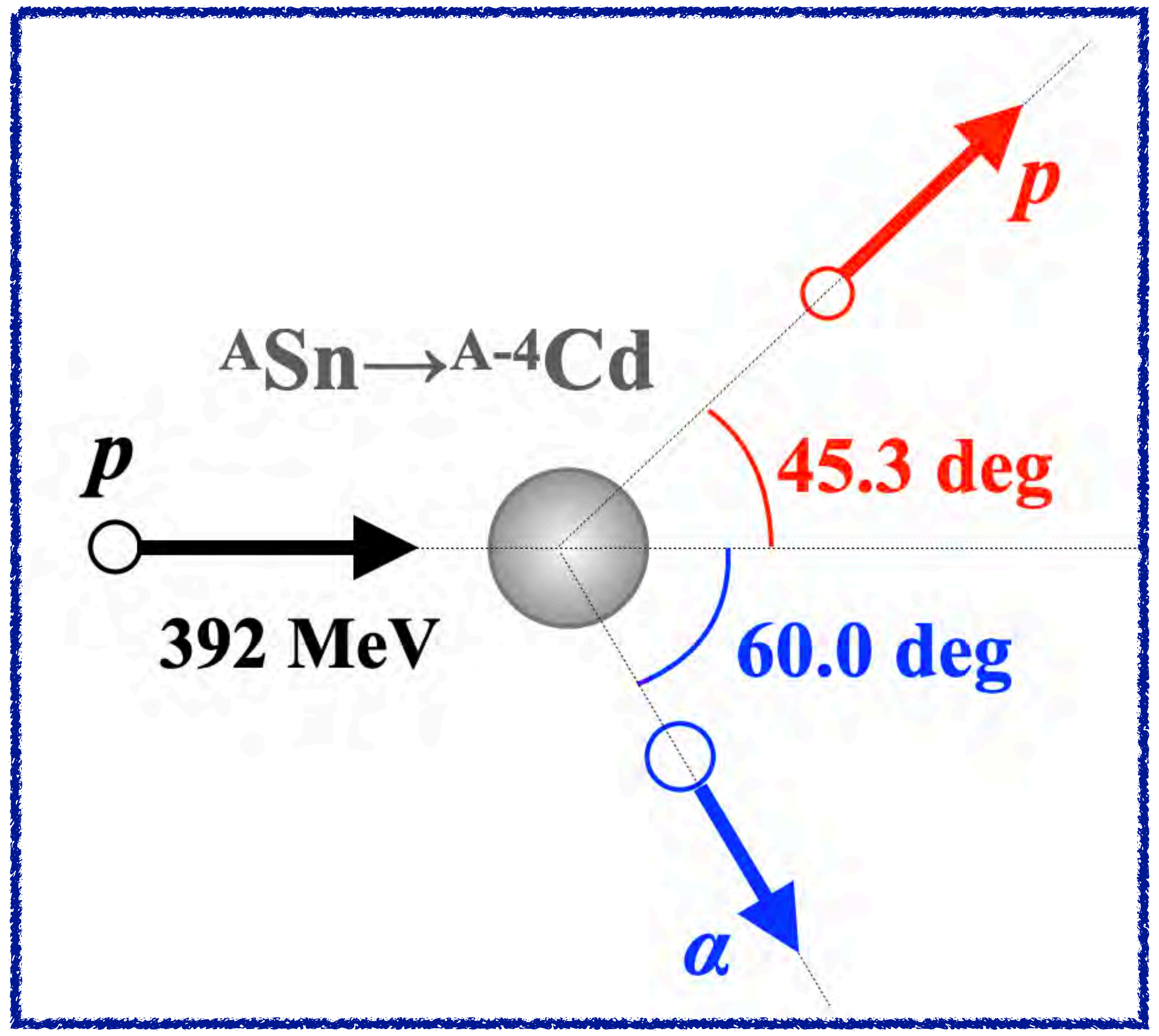
NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

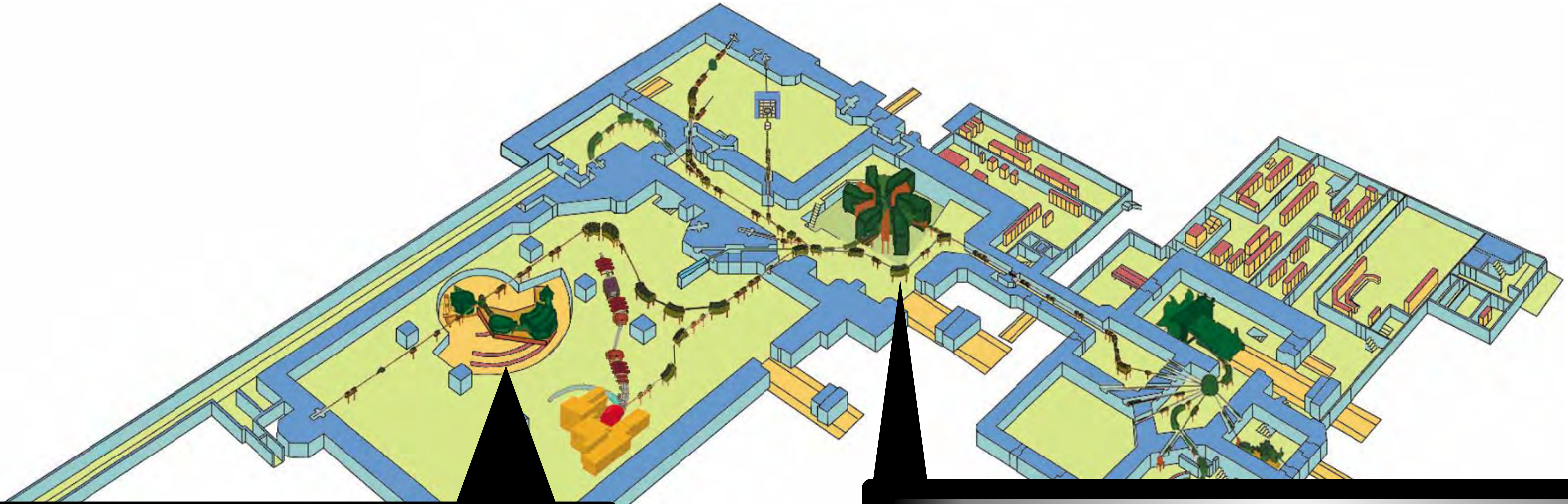
J. Tanaka, Z.H. Yang,
S. Typel, TU, T. Aumann et al.,
Science 371, 260–264 (2021)

^{112,116,120,124}Sn(p,pα)
@ E_p=392 MeV



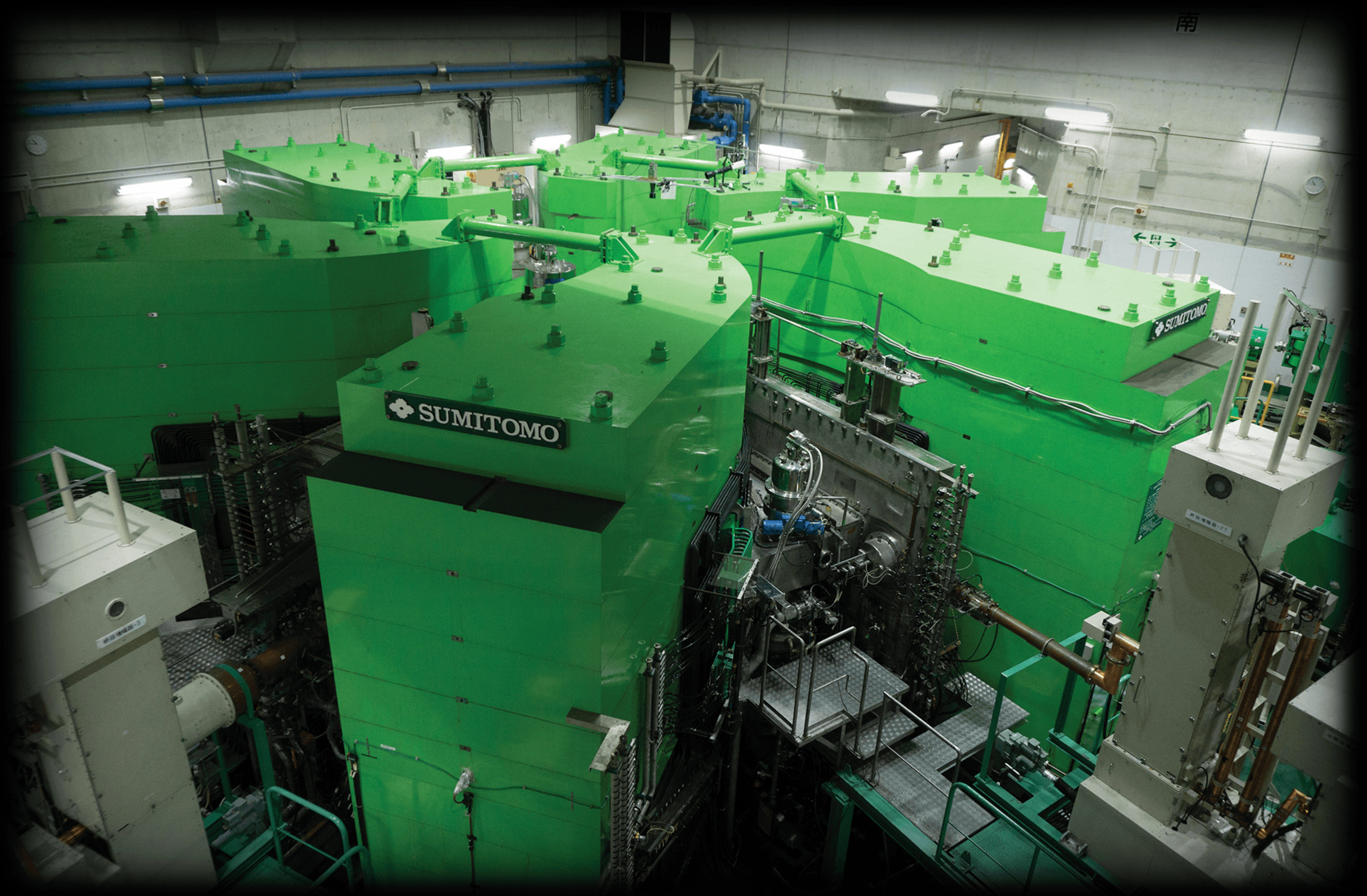


Experiment at RCNP Osaka University

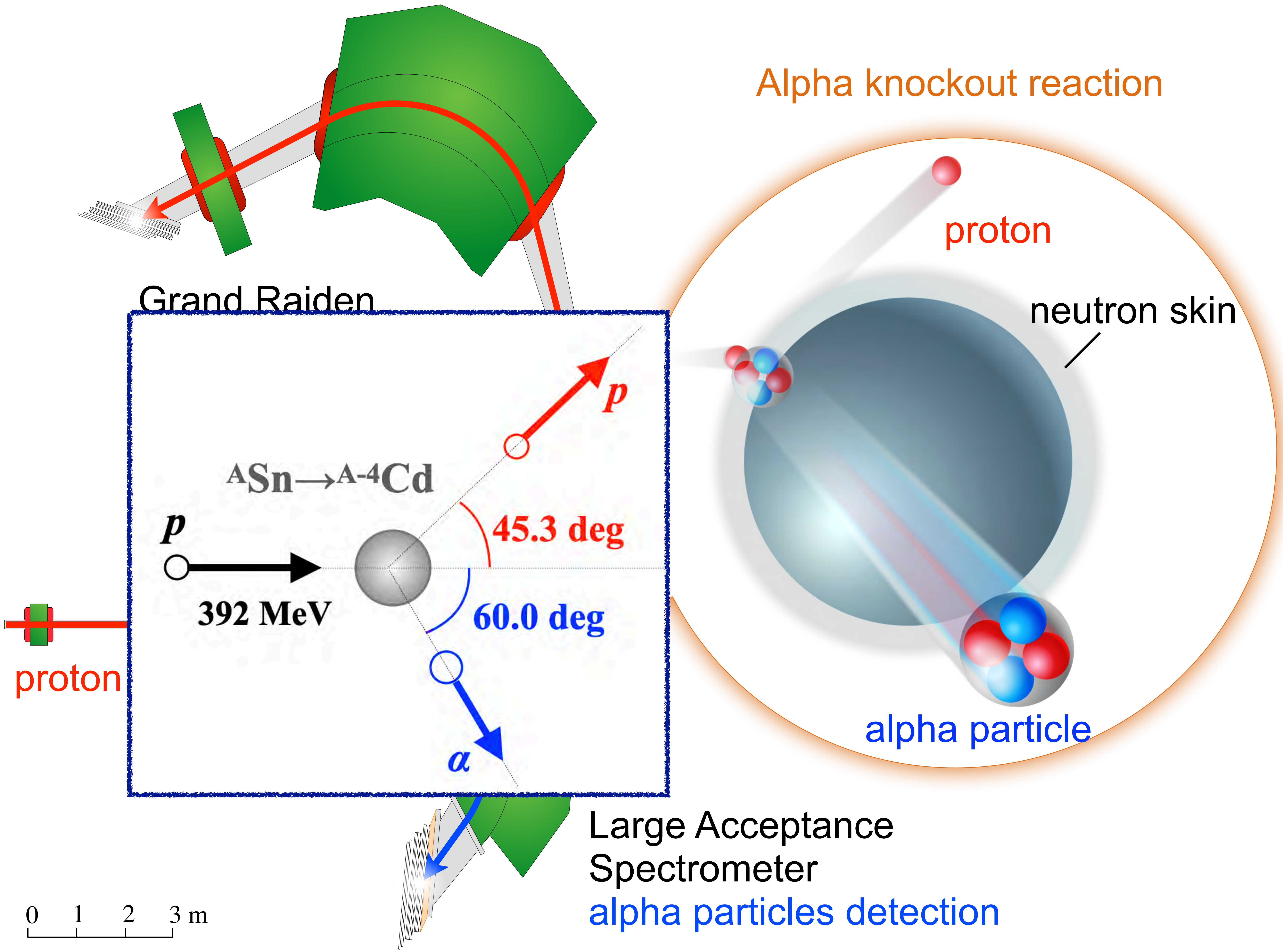


Grand Raiden and LAS spectrometers

Ring Cyclotron



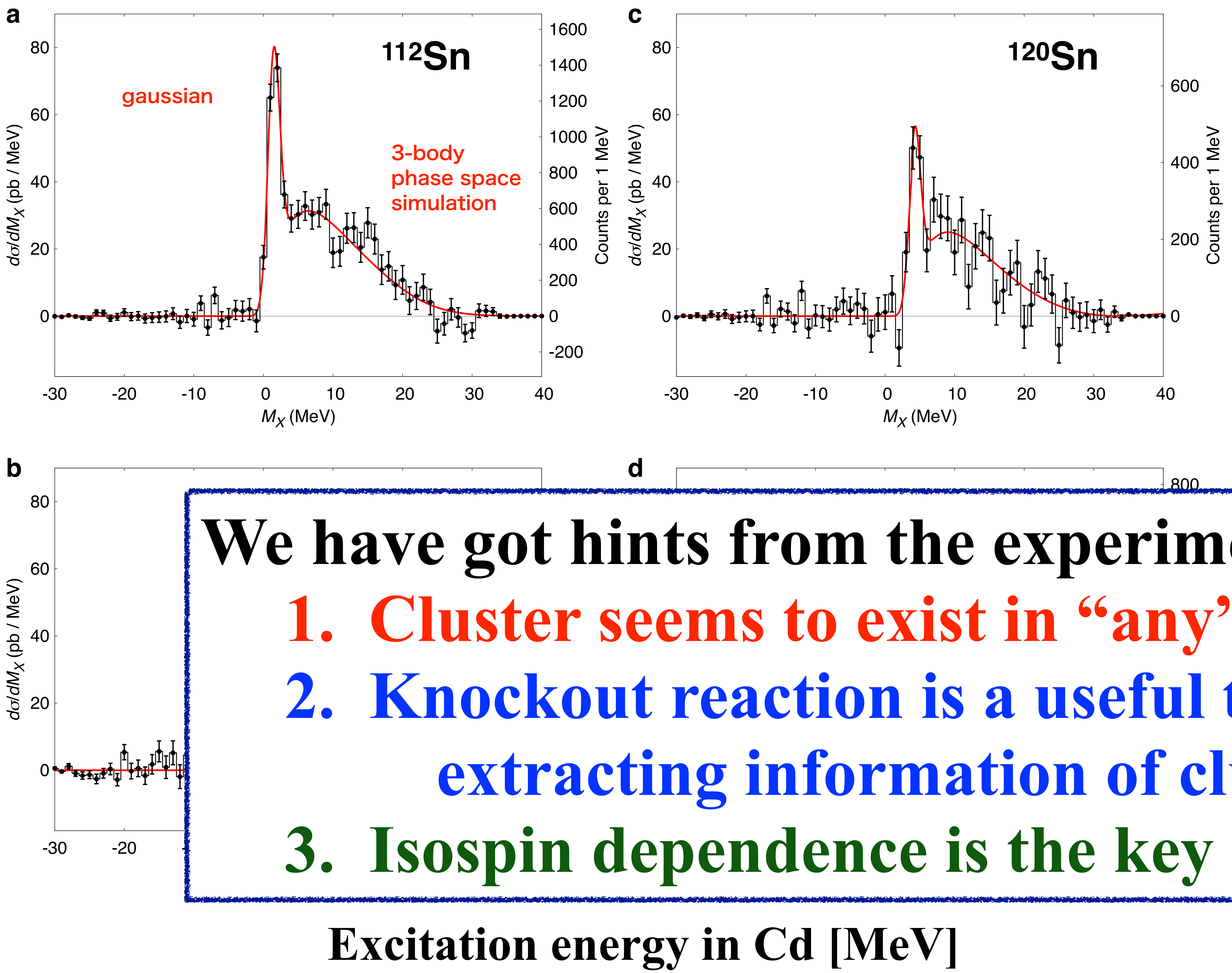
$^{112,116,120,124}Sn(p,p\alpha)$ @ E_p=392 MeV

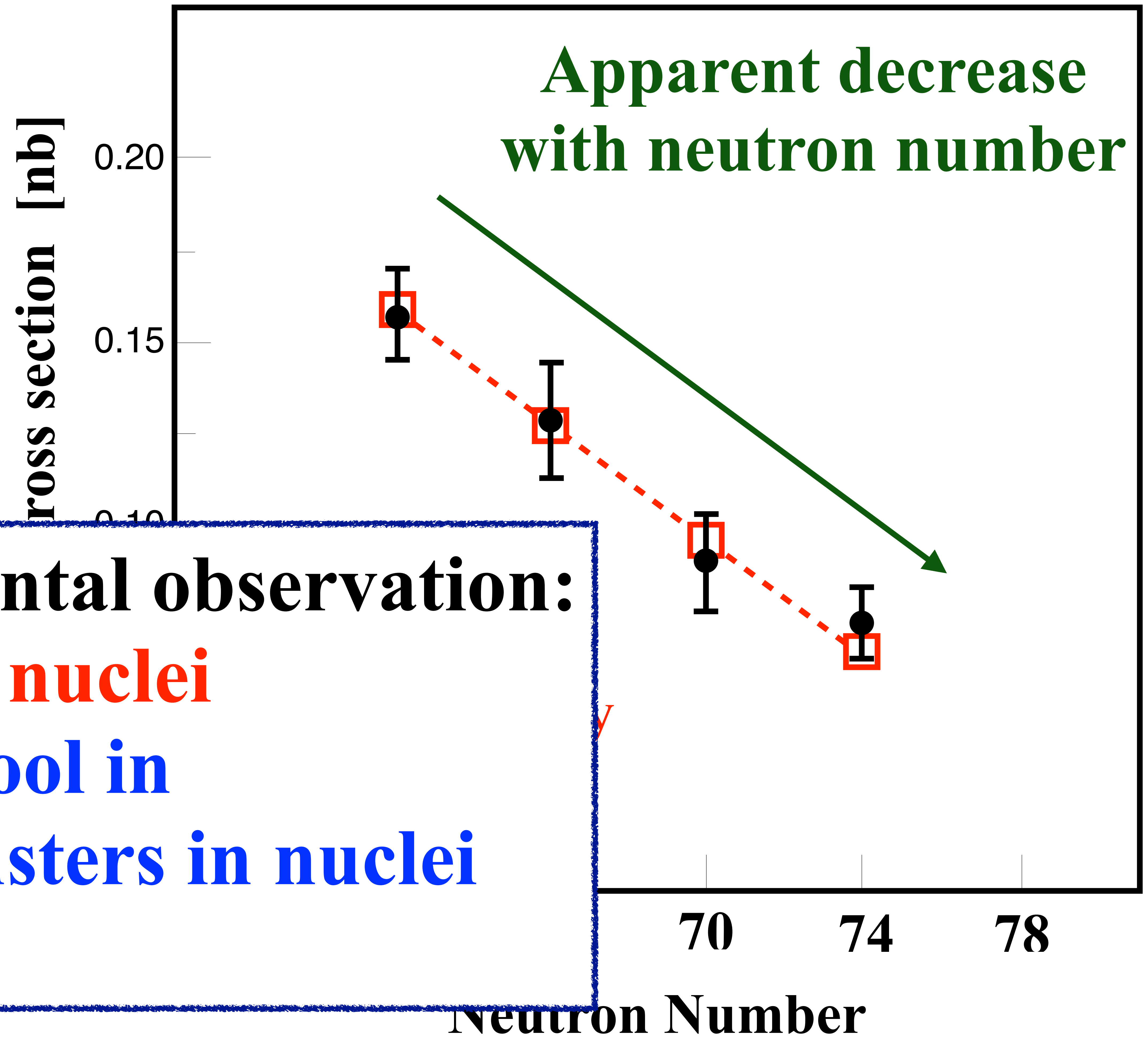


What we observed

The tendency is consistent with theoretical prediction based on a surface-α hypothesis!

$^{A}Sn(p,p\alpha)^{A-4}Cd$ missing mass spectrum





We have got hints from the experimental observation:

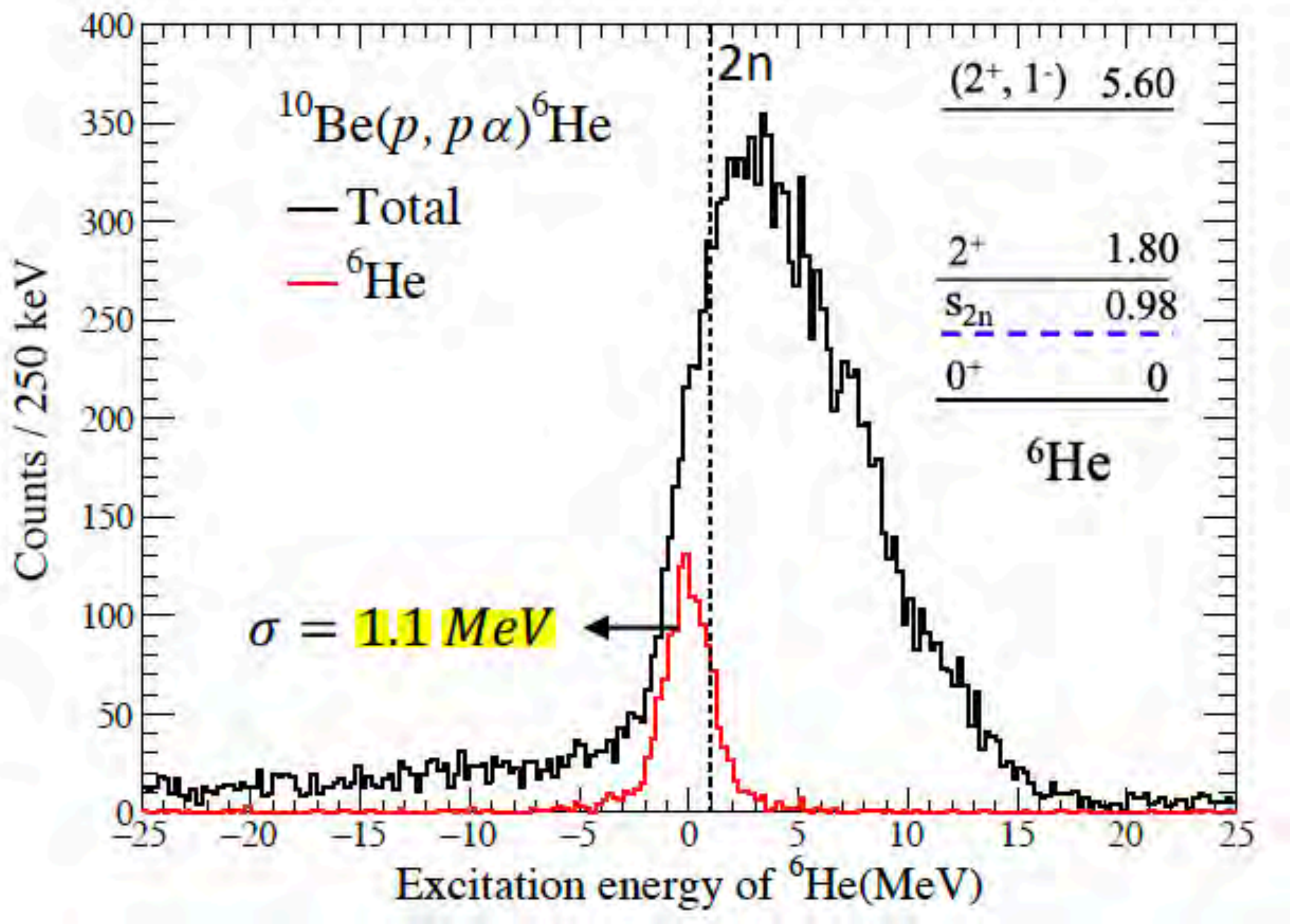
1. **Cluster seems to exist in "any" nuclei**
2. **Knockout reaction is a useful tool in extracting information of clusters in nuclei**
3. **Isospin dependence is the key**

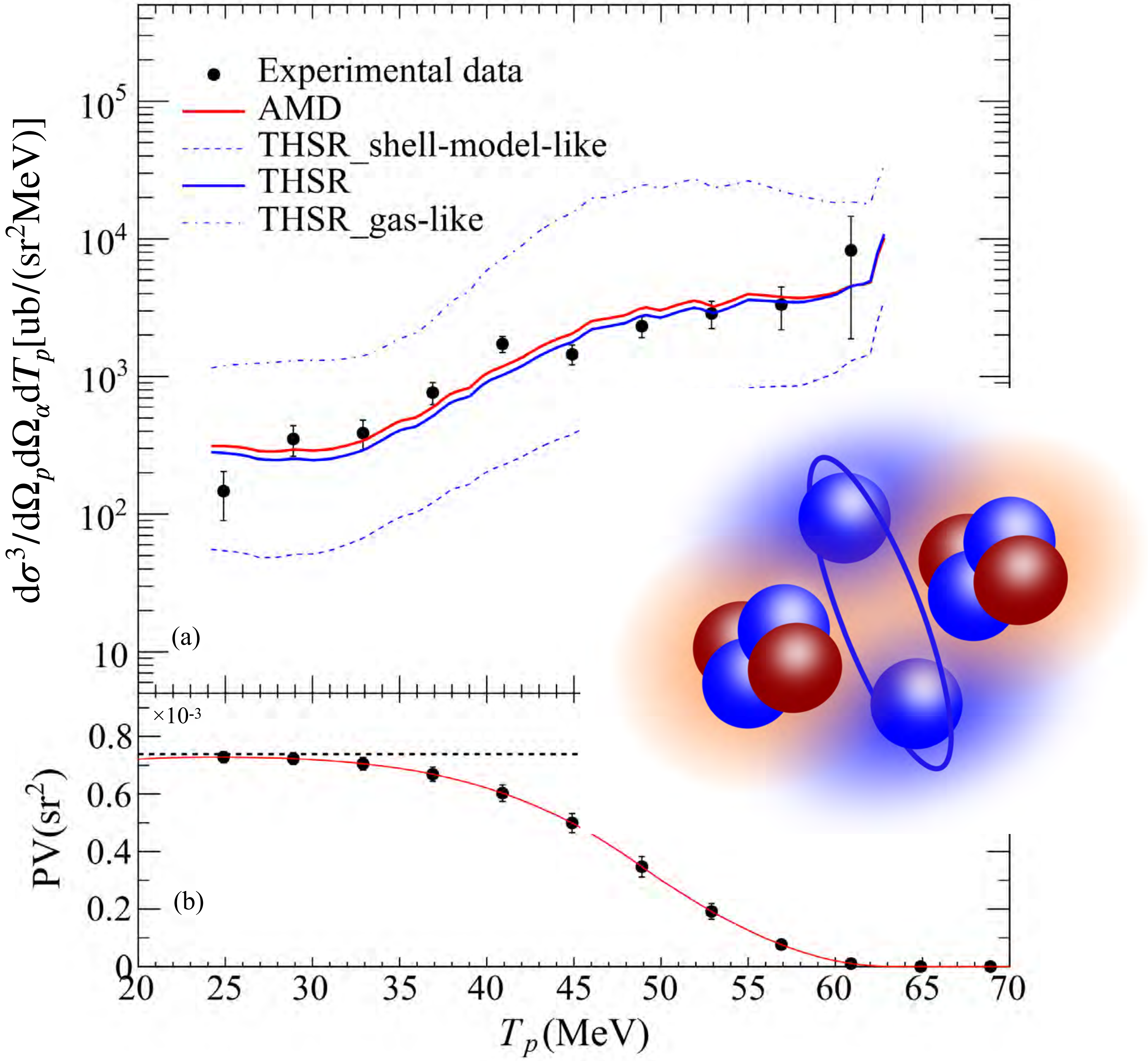
Molecular structure in Be isotopes

Pengjie Li, D. Beuamel et al., PRL 131, 212501 (2023).

Use of (*p,pα*) knockout reaction under the inverse-kinematics

^{10}Be(*p,pα*)^{6}He$^{(GS)}$



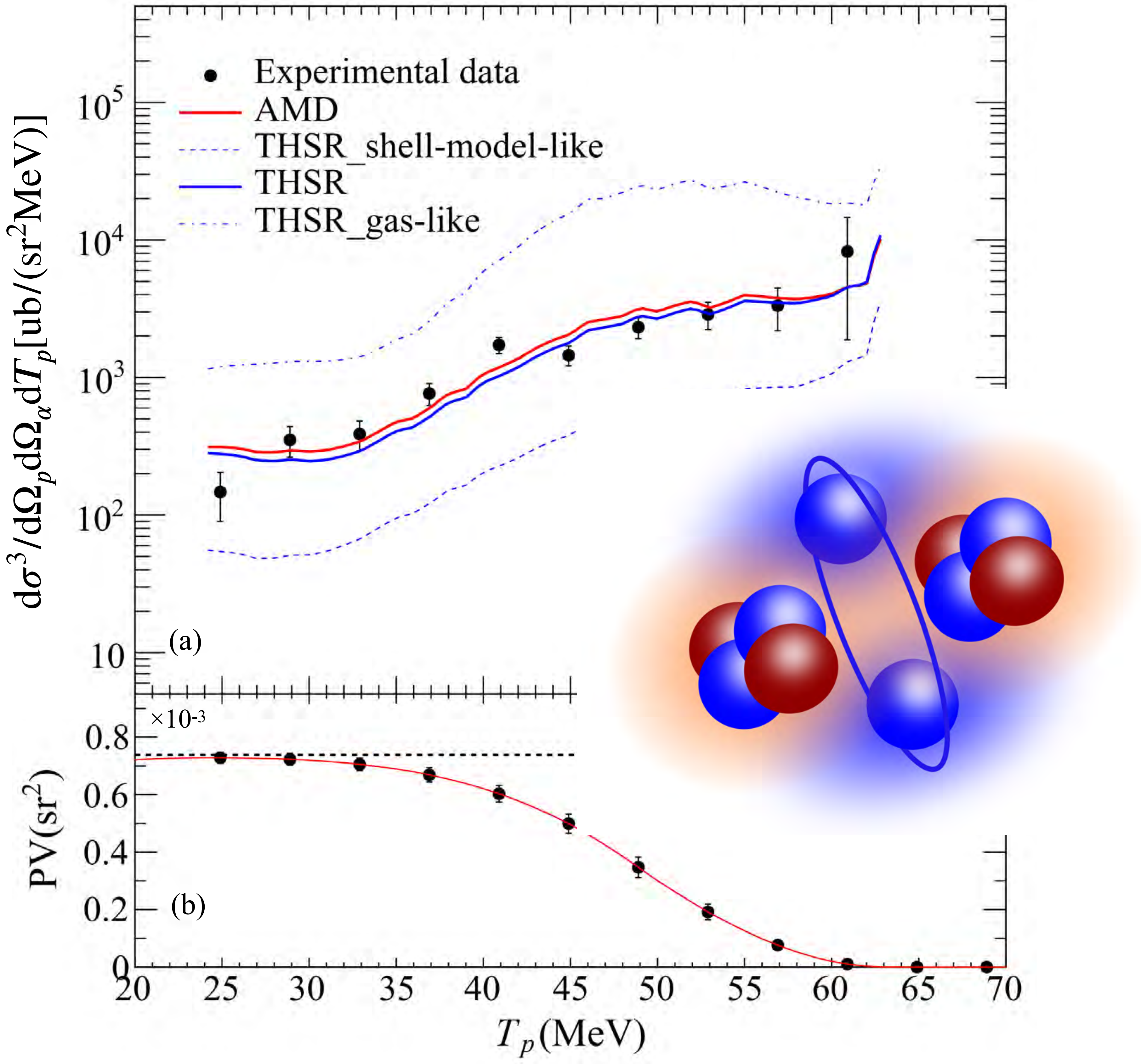


Particle decays following the (*p,pα*) reaction

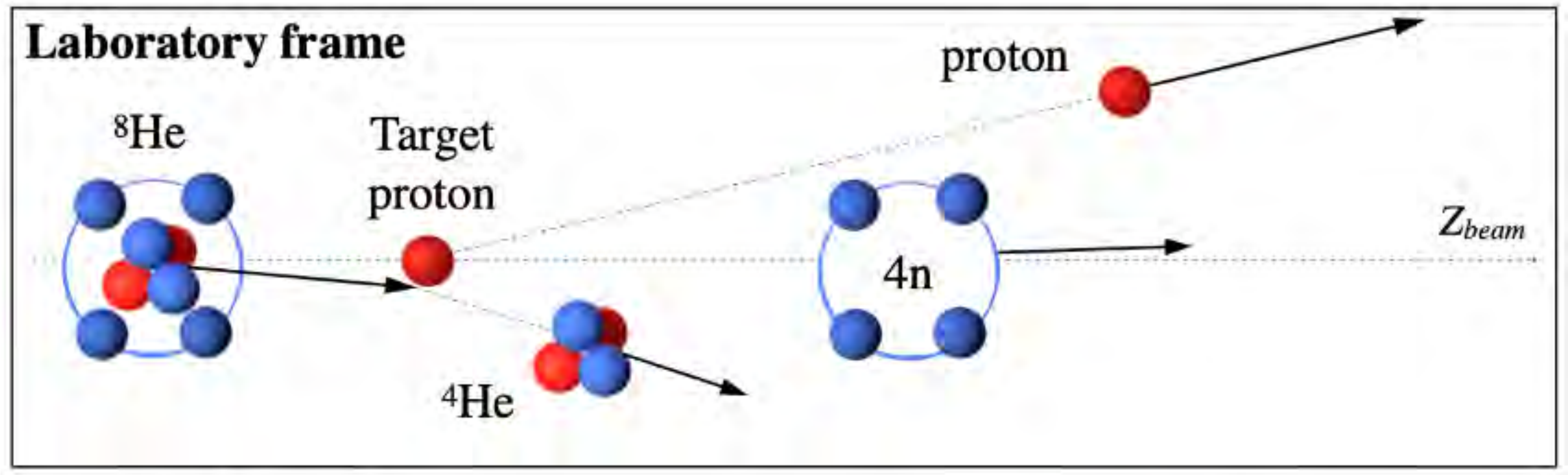
Application of the ($p,p\alpha$) reactions to RI-beam experiments

Pengjie Li, D. Beuamel et al.,
PRL 131, 212501 (2023).

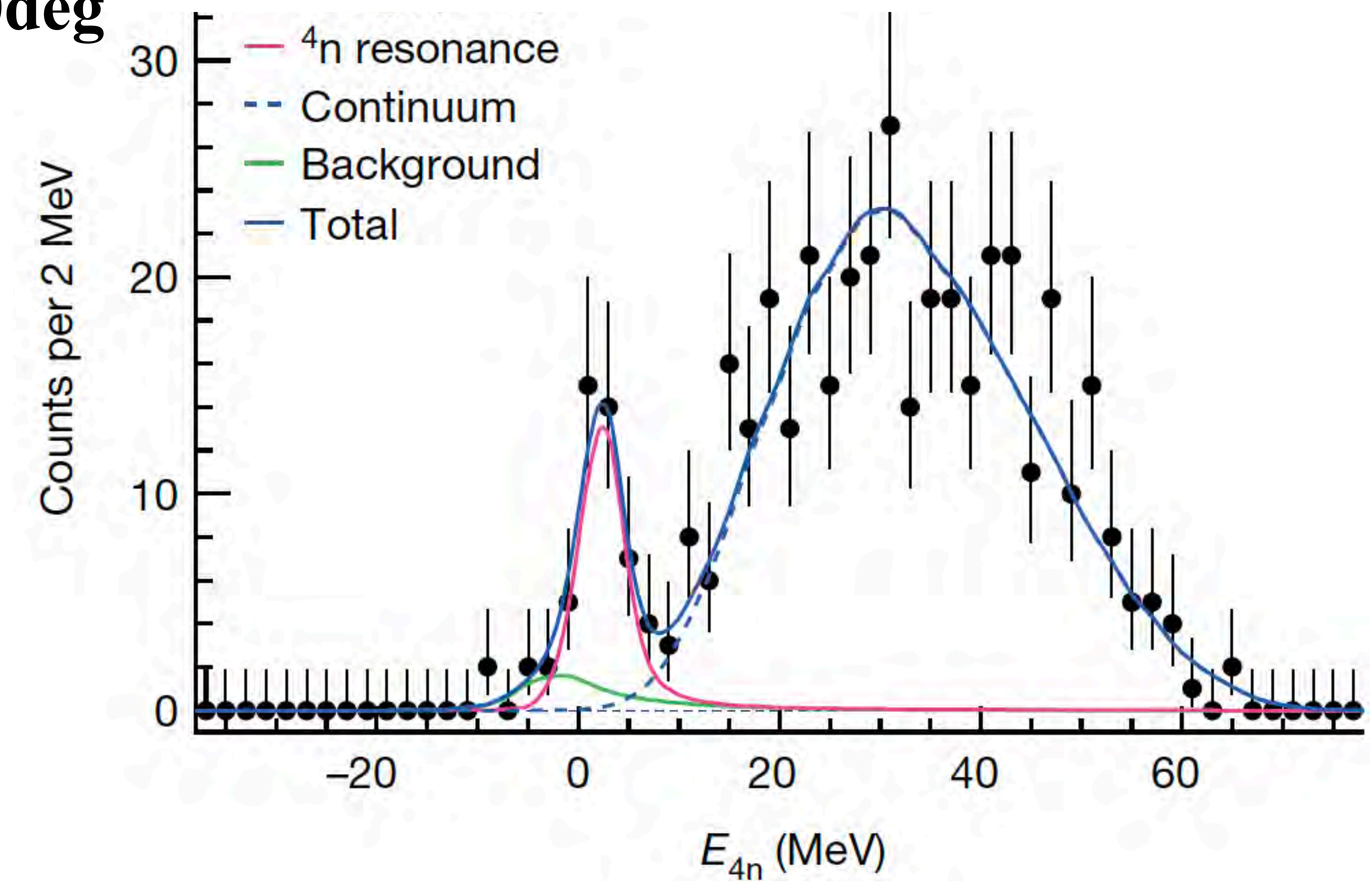
$^{10}Be(p,p\alpha)^{6}He^{(GS)}$



M. Duer et al., Nature 606 (2022).



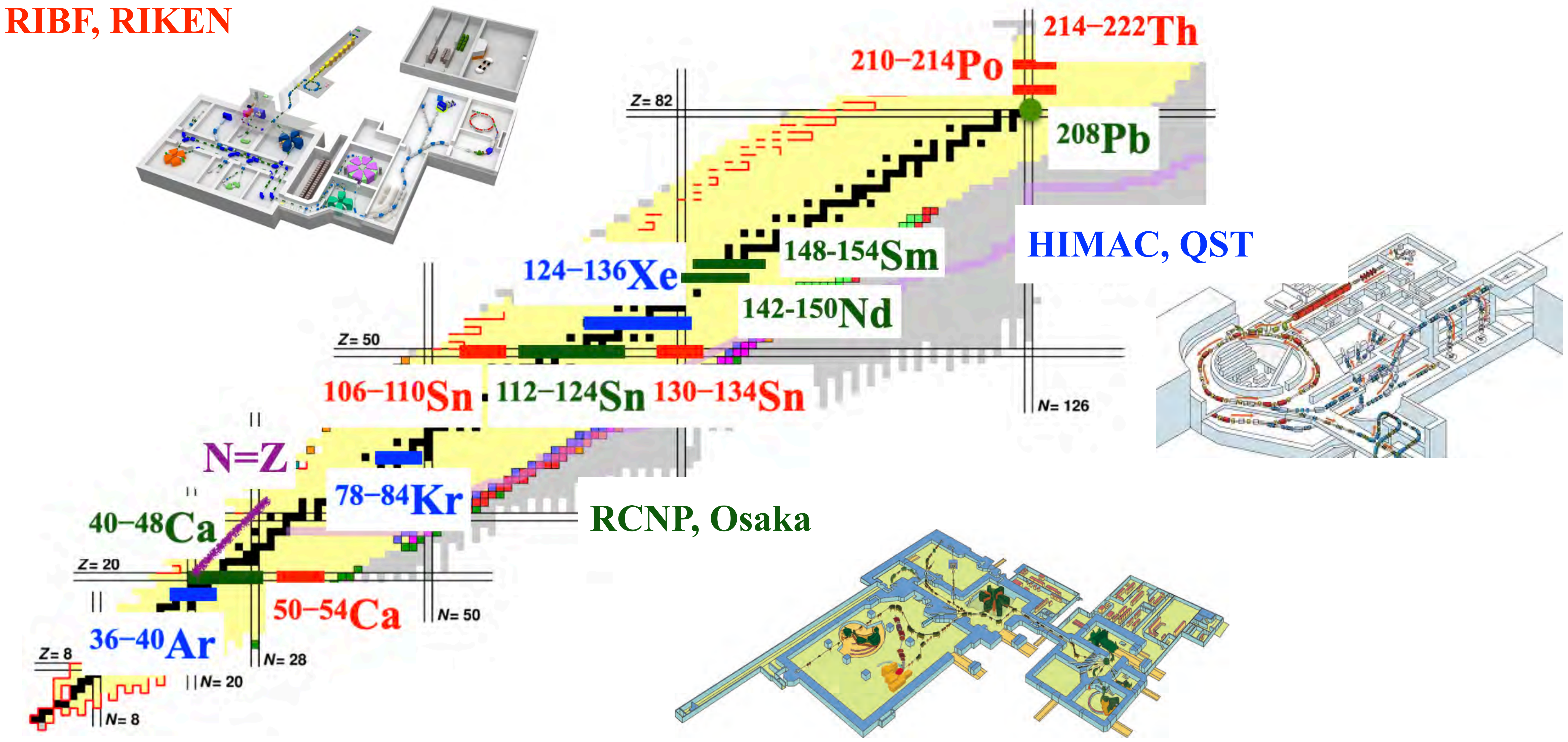
$^{8}He(p,p\alpha)^{4}n$
@ θ_{CM}=180deg



ONOKORO Project

Looking for *d*, *α*, *t*, and ^{3}He in stable & unstable isotopes using (*p*,*pX*) knockout reactions at 200−300 MeV/u

- Relevance of deuteron clusters to short-range correlation
- α cluster formation and and understanding of α-decay
- Their coexistence with *independent* nucleons
- Possible peculiarity around low-density surface?

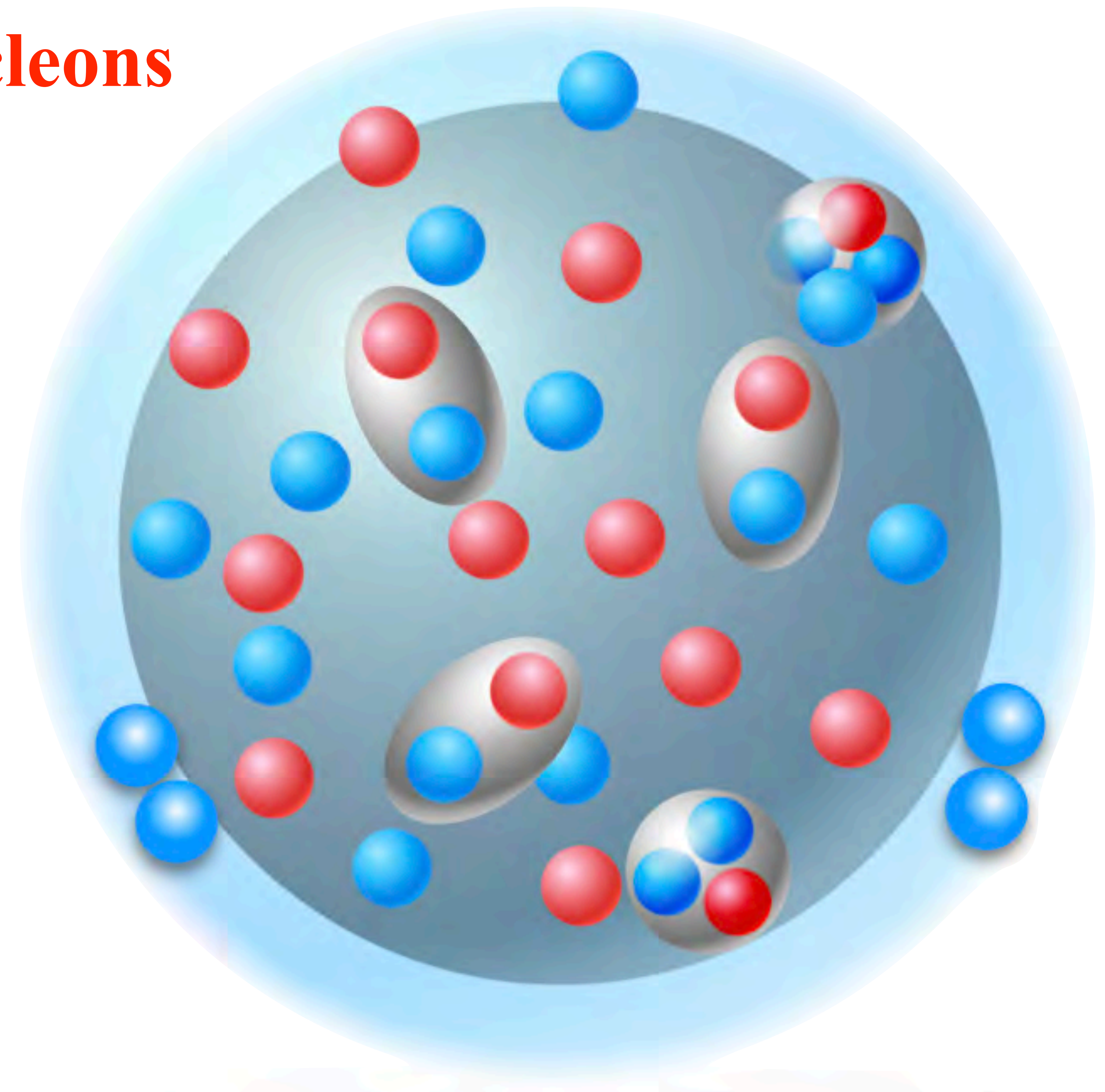


2023−2024 1st experiment for stable nuclear @RCNP
June 2025 : 1st experiment for unstable nuclei @RIBF

Physics of ONOKORO project

- **Cluster formation mechanism in finite nuclei and in nuclear matter**

  Tensor-force and 3-nucleon force effects
  Density and isospin-asymmetry dependences
  Coexistence of different clusters & independent nucleons
  Impacts on nuclear-matter properties



The Astrophysical Journal, 748:70 (27pp), 2012 March 20 doi:10.1088/0004-637X/748/1/70

NEW EQUATIONS OF STATE IN SIMULATIONS OF CORE-COLLAPSE SUPERNOVAE

M. Hempel[1], T. Fischer[2,3], J. Schaffner-Bielich[4], and M. Liebendörfer[1]
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[2] GSI, Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany
[3] Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 9, 64289 Darmstadt, Germany
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Received 2011 August 3; accepted 2012 January 17; published 2012 March 6

An important aspect of the supernova EOS is the formation of light nuclei and their properties in the hot and dense medium.

Thermodynamic variables, like, e.g., the symmetry energy, are modified due to the appearance of light nuclei.

In the supernova environment light nuclei can possibly influence the neutrino transport and consequently the supernova neutrino signal and dynamics.

Physics of ONOKORO project

- **Cluster formation mechanism in finite nuclei and in nuclear matter**

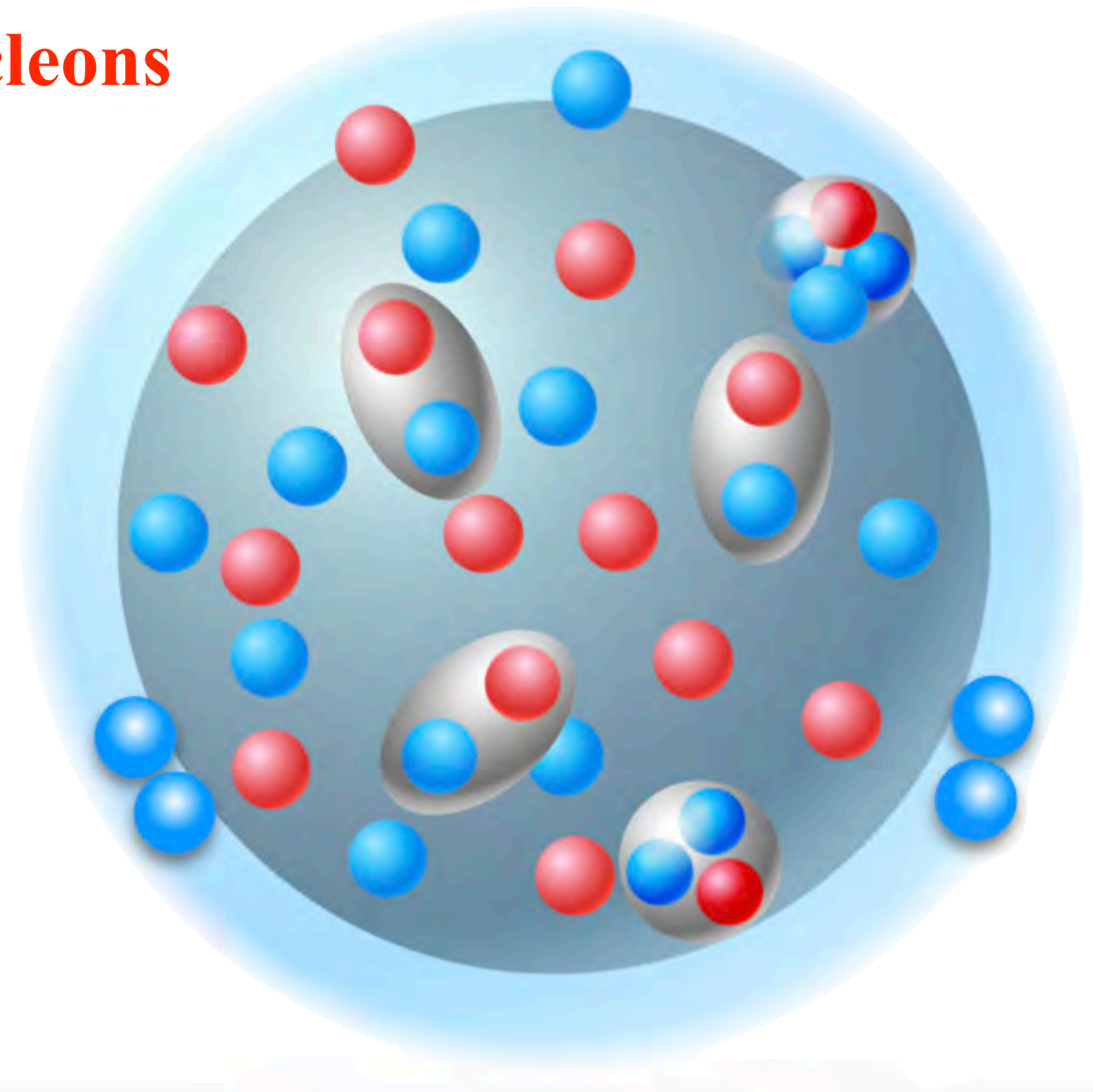
  Tensor-force and 3-nucleon force effects
  Density and isospin-asymmetry dependences
  Coexistence of different clusters & independent nucleons
  Impacts on nuclear-matter properties

- **Interests specific to each cluster**

  Possible access to α preformed in α-decay nuclei

  Search for deuteron clusters which embody tensor-correlations in nuclei

  First determination of t/^{3}He ratio



ONOKORO Project: Progress in 2021−2026

Knockout reaction theory DWIA + CDCC

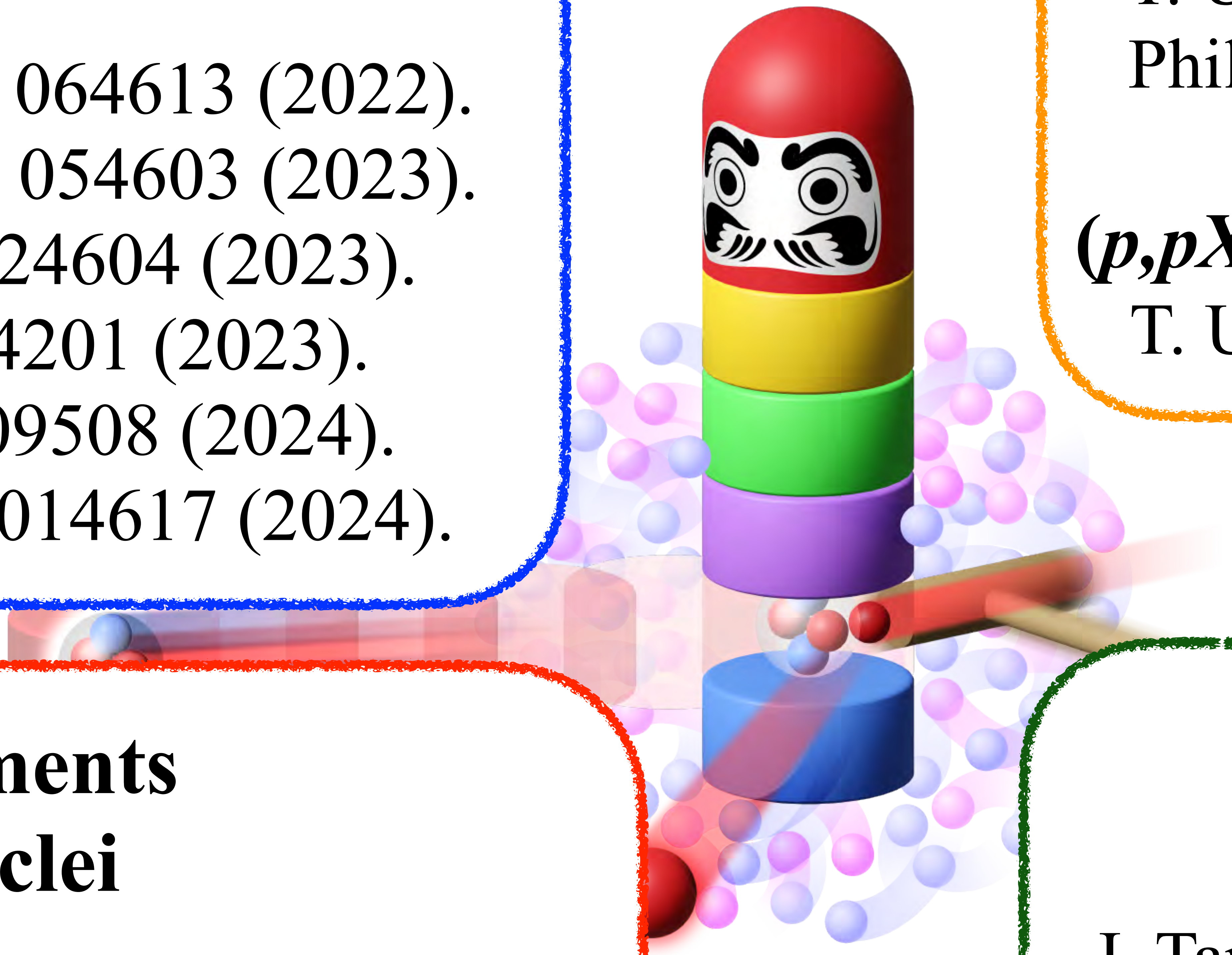
Y. Chazono et al., PRC **106**, 064613 (2022).
T. Edagawa et al., PRC 107, 054603 (2023).
S. Ogawa et al., PRC 108, 024604 (2023).
S.I. Shim et al., JPSJ 92, 094201 (2023).
K. Ogata et al., CPC 297, 109508 (2024).
K. Yoshida et al., PRC 110, 014617 (2024).

Short review of cluster physics

T. Uesaka and N. Itagaki,
Phil. Trans. R. Soc. A **382**: 20230123 (2023).

(*p*,*pX*) reaction kinematics

T. Uesaka. PTEP **2024**, 083D01 (2024).



RCNP experiments for stable nuclei

R. Matsumura et al., PTEP **2026**, 043D01 (2026).
C.S. Lee et al., PTEP **2026**, 053D01 (2026).
R. Tsuji et al., PTEP **2026**, 073D02 (2026).
Y. Maeda et al., submitted to PTEP.

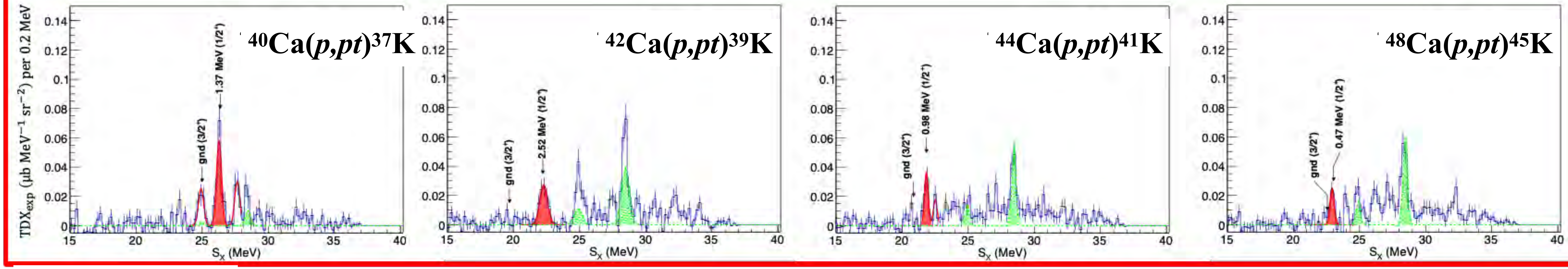
TOGAXSI development and RIBF exp.

J. Tanaka, et al., NIMB **542**, 4 (2023).
K. Higuchi et al., NIMB **542**, 84 (2023).
Y. Kubota et al., NPA **1060**, 123123 (2025).
First exp. for $^{50\text{-}52}Ca$ in June 2025 & application of TOGAXSI to *xn* exp.

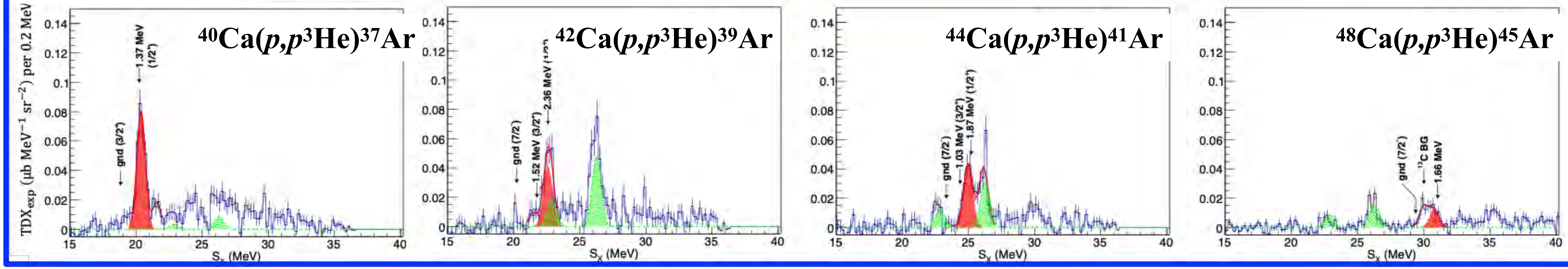
The first $(p,pt)/(p,p^3He)$ data set for medium mass nuclei

R. Tsuji, J. Zenihiro et al., Prog. Theo. Exp. Phys. **2026**, 053D01.

$^{40\text{-}48}Ca(p,pt)$



$^{40\text{-}48}Ca(p,p^3He)$

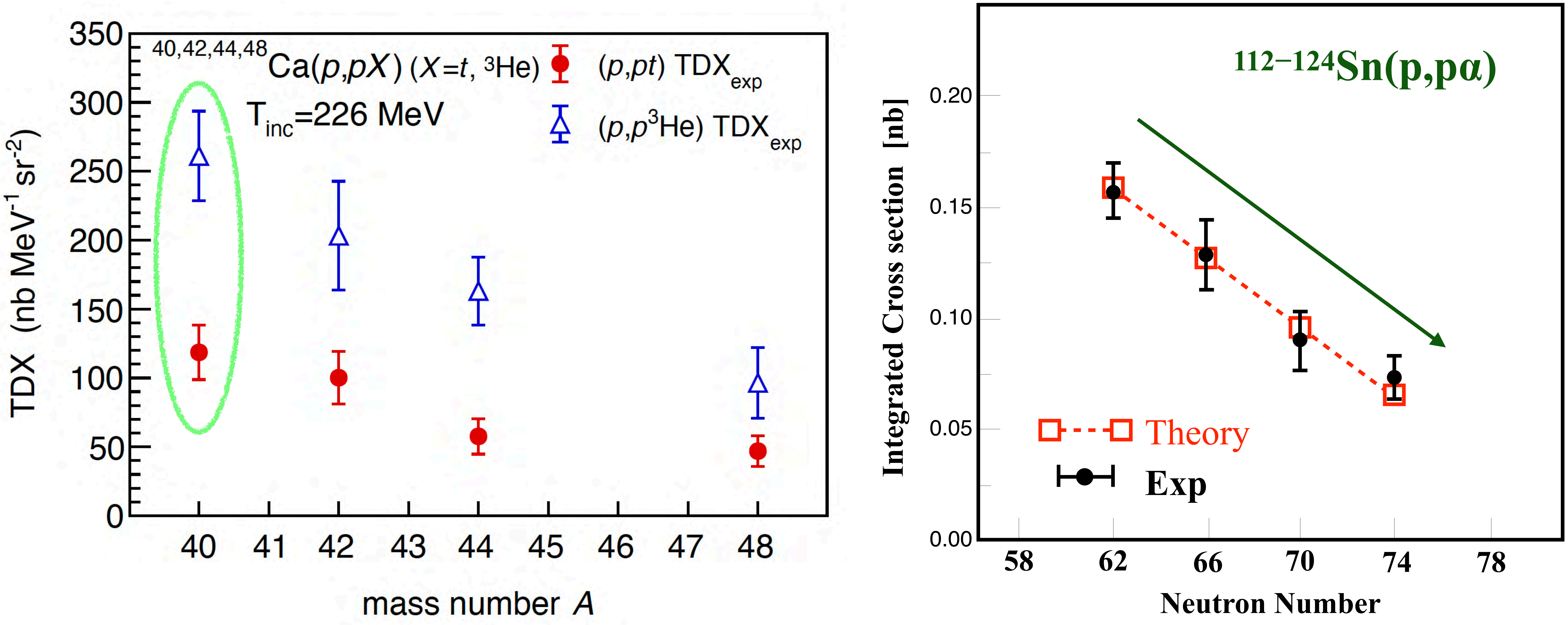


Open the new opportunities of triton & ^{3}He cluster studies in medium to heavy nuclei.

Red: $1/2^+$ state
Green: oxygen background

The first (*p*,*pt*)/(*p*,*p*^{3}He) data set for medium mass nuclei

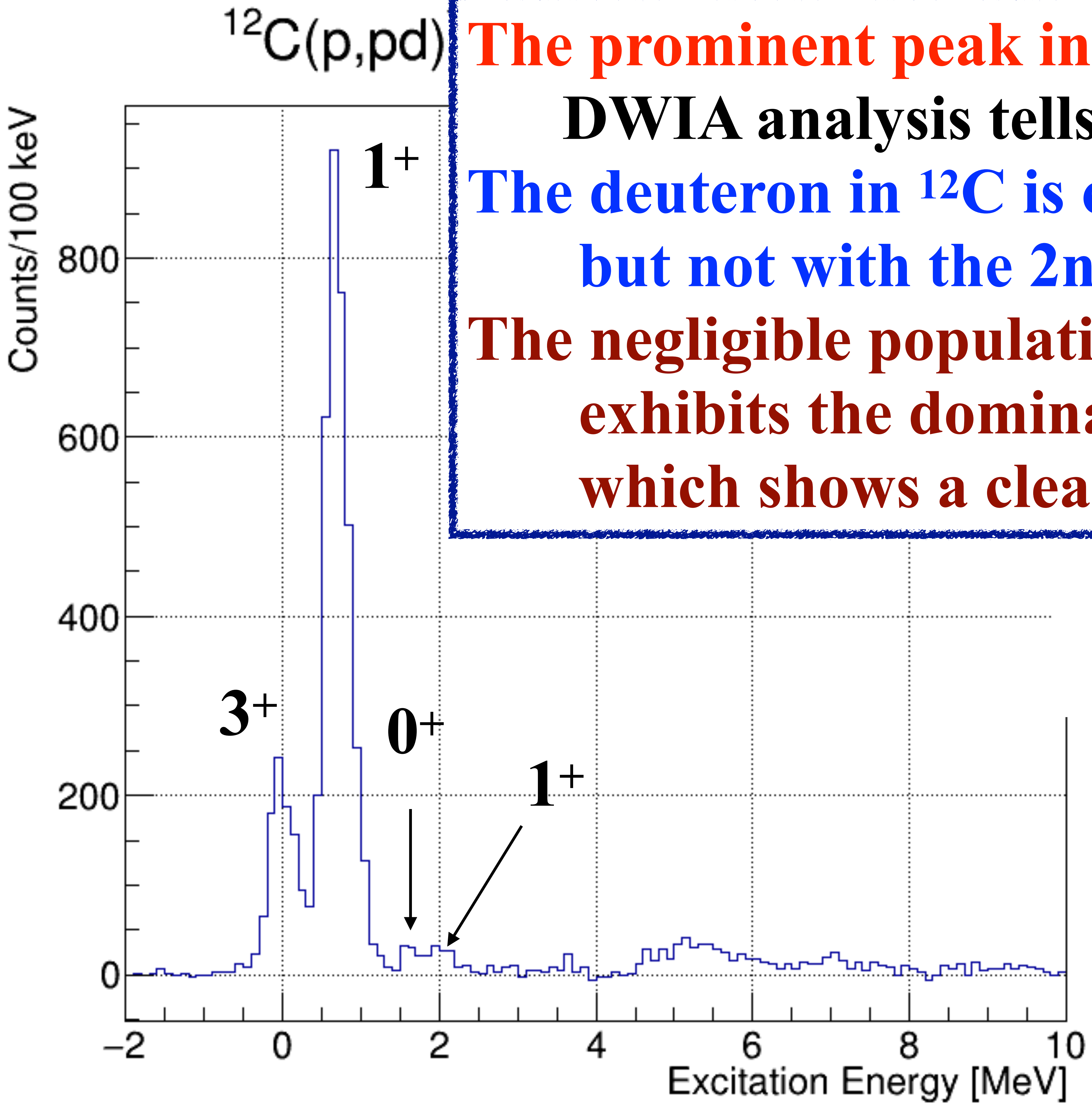
R. Tsuji, J. Zenihiro et al., Prog. Theo. Exp. Phys. **2026**, 053D01.



^{12}C(p,pd)^{10}B(0$^+$, T=1) @E_p=226 MeV

C.S. Lee, Y. Kubota, TU et al., Prog. Theo. Exp. Phys. **2026**, 053D01.

Recoilless (p_d~0) condition

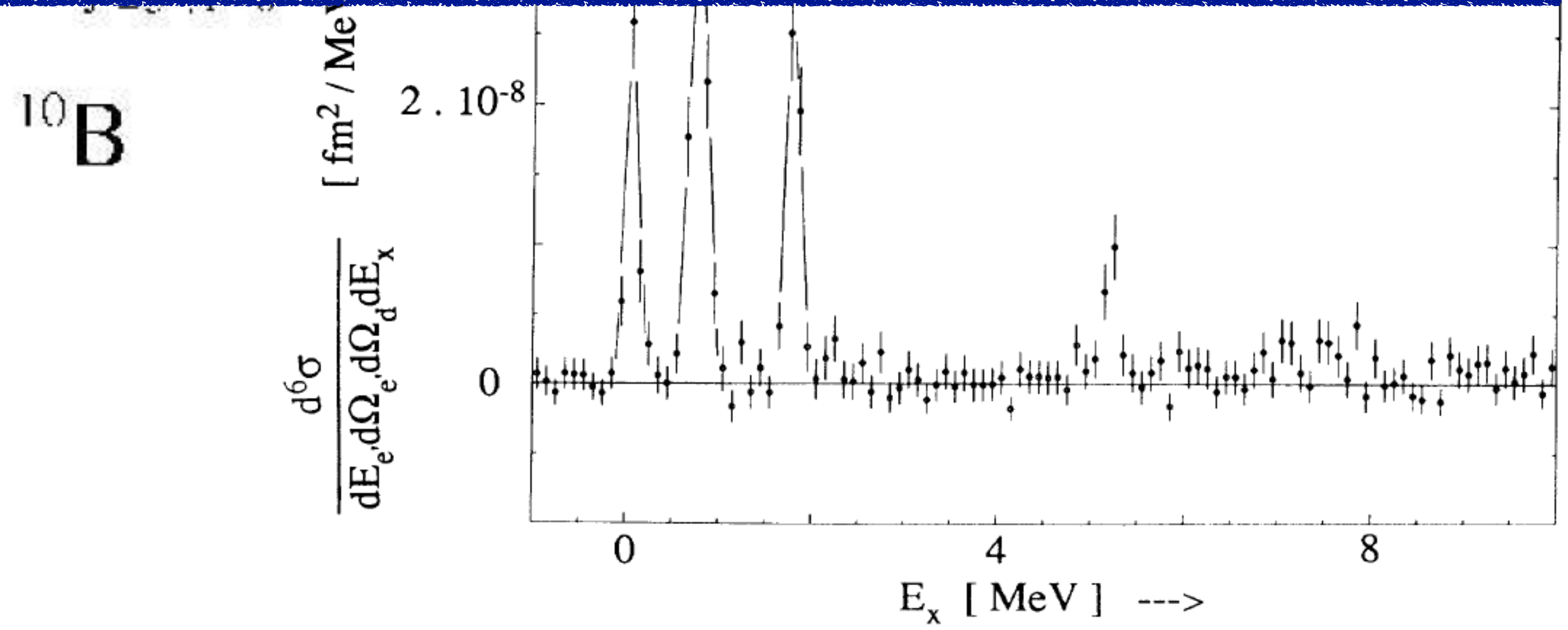


The prominent peak indicates the existence of "deuterons" in ^{12}C.

DWIA analysis tells us that the number of S-wave deuterons in ^{12}C is ~1.6.

The deuteron in ^{12}C is coupled with the 1st 1$^+$ state (0.718 MeV),
but not with the 2nd 1$^+$ state (2.154 MeV).

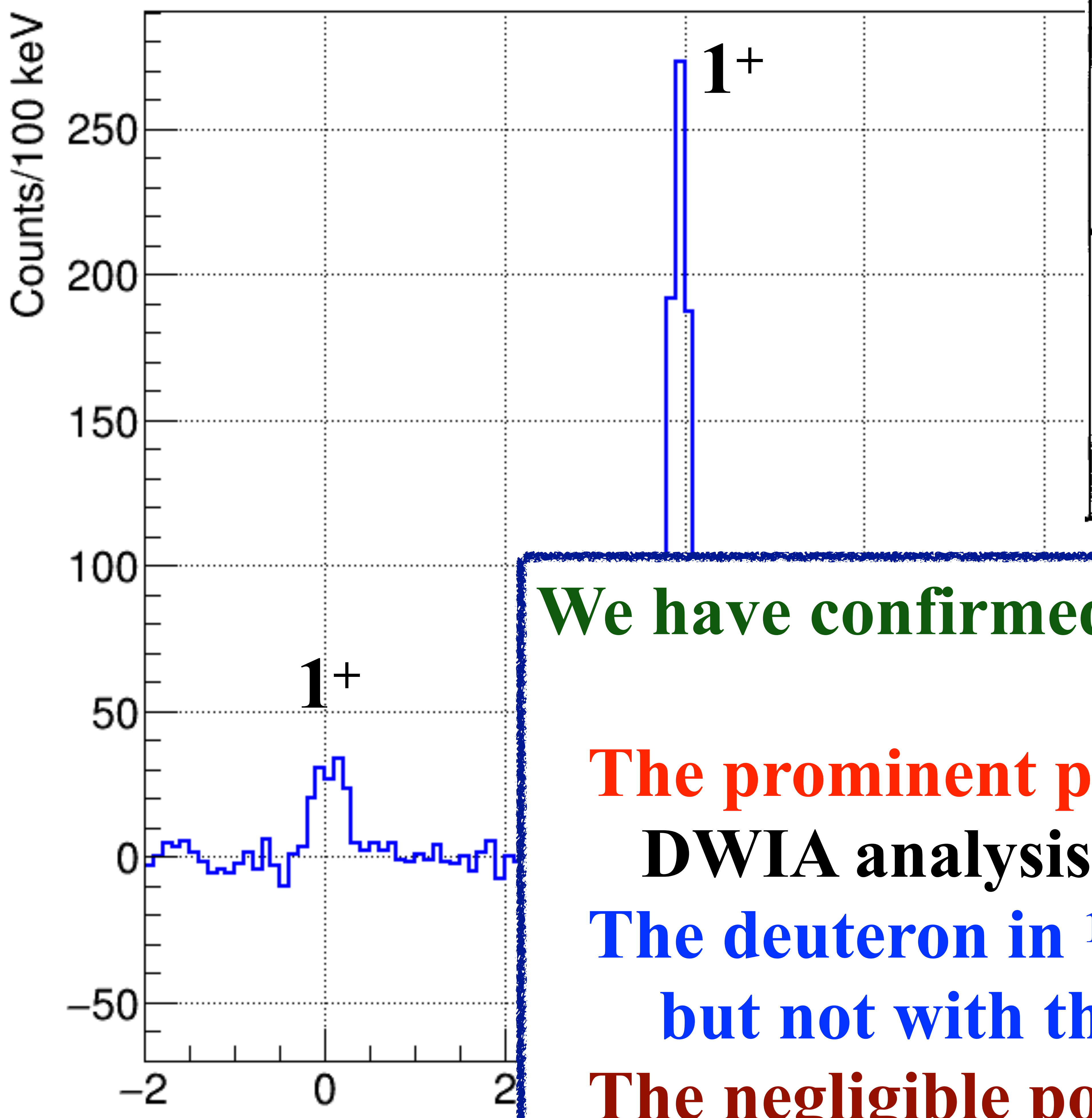
The negligible population of the 0$^+$ state (T=1) at 1.740 MeV
exhibits the dominance of the direct deuteron knockout process,
which shows a clear contrast to the (*e,e'd*) case.

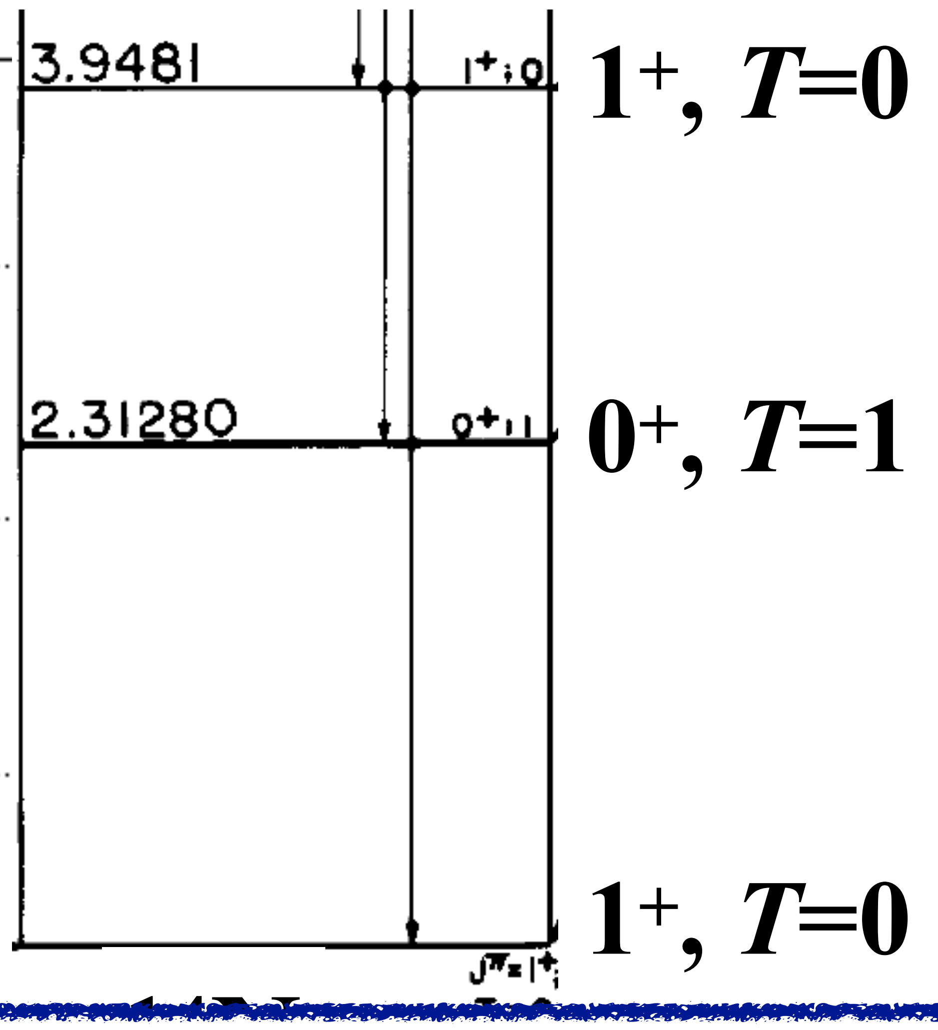


$^{16}O(p,pd)^{14}N(0^+, T=1)$ @E_p=226 MeV

Recoilless (p_d~0) condition

C.S. Lee, Y. Kubota, TU et al., Prog. Theo. Exp. Phys. **2026**, 053D01.





We have confirmed our conclusions for ^{12}C can also be applied to ^{16}O:

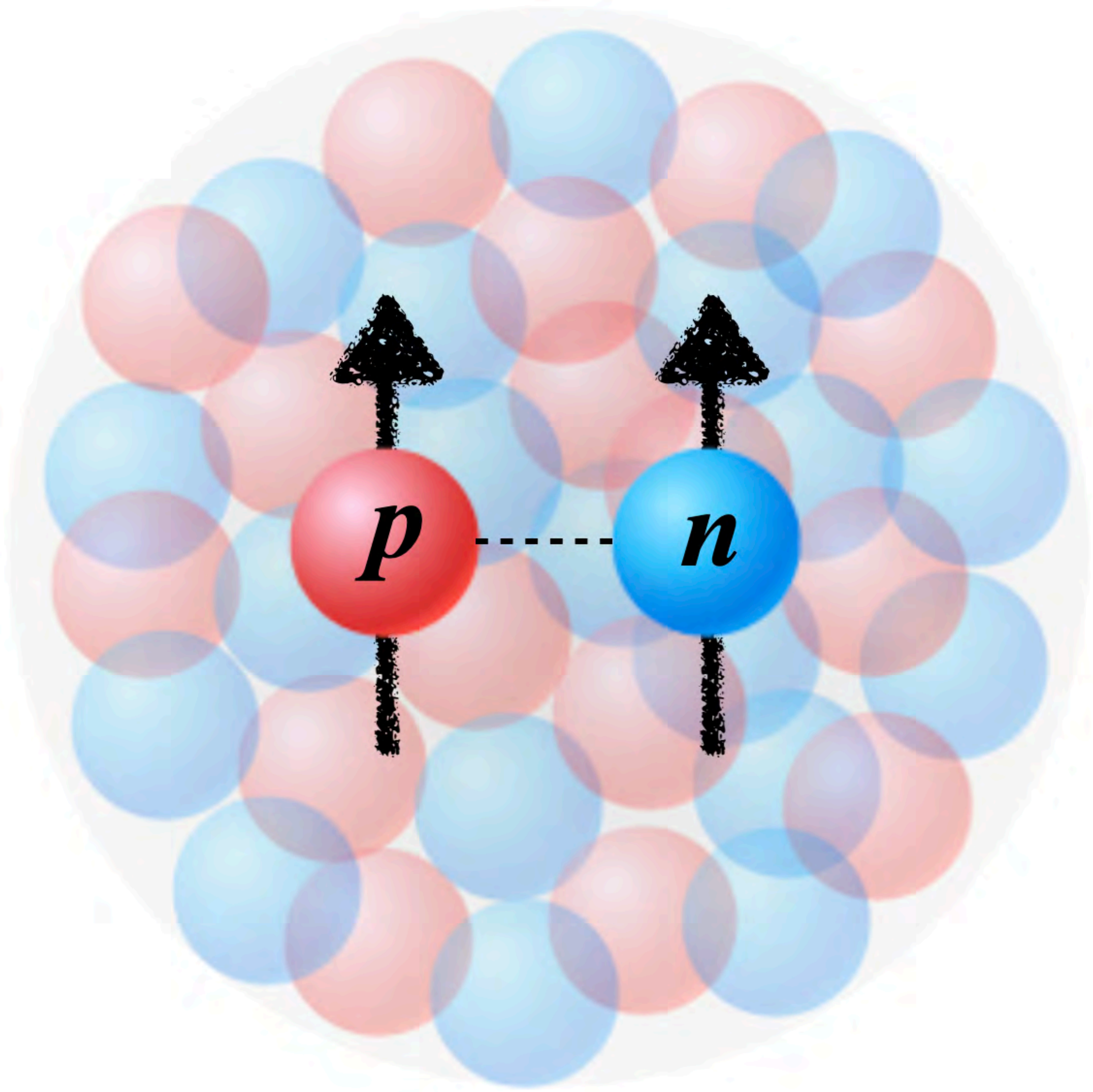
The prominent peak indicates the existence of "deuteron" in ^{16}O.

DWIA analysis tells us that the number of S-wave deuterons in ^{16}O is ~1.9.

The deuteron in ^{12}C is coupled with the 2nd 1^+ state (3.948 MeV), but not with the gnd 1^+ state (0 MeV).

The negligible population of the 0^+ state (T=1) at 2.313MeV exhibits the dominance of the direct deuteron knockout process.

Physics of deuteron-like *pn* correlation in nuclei



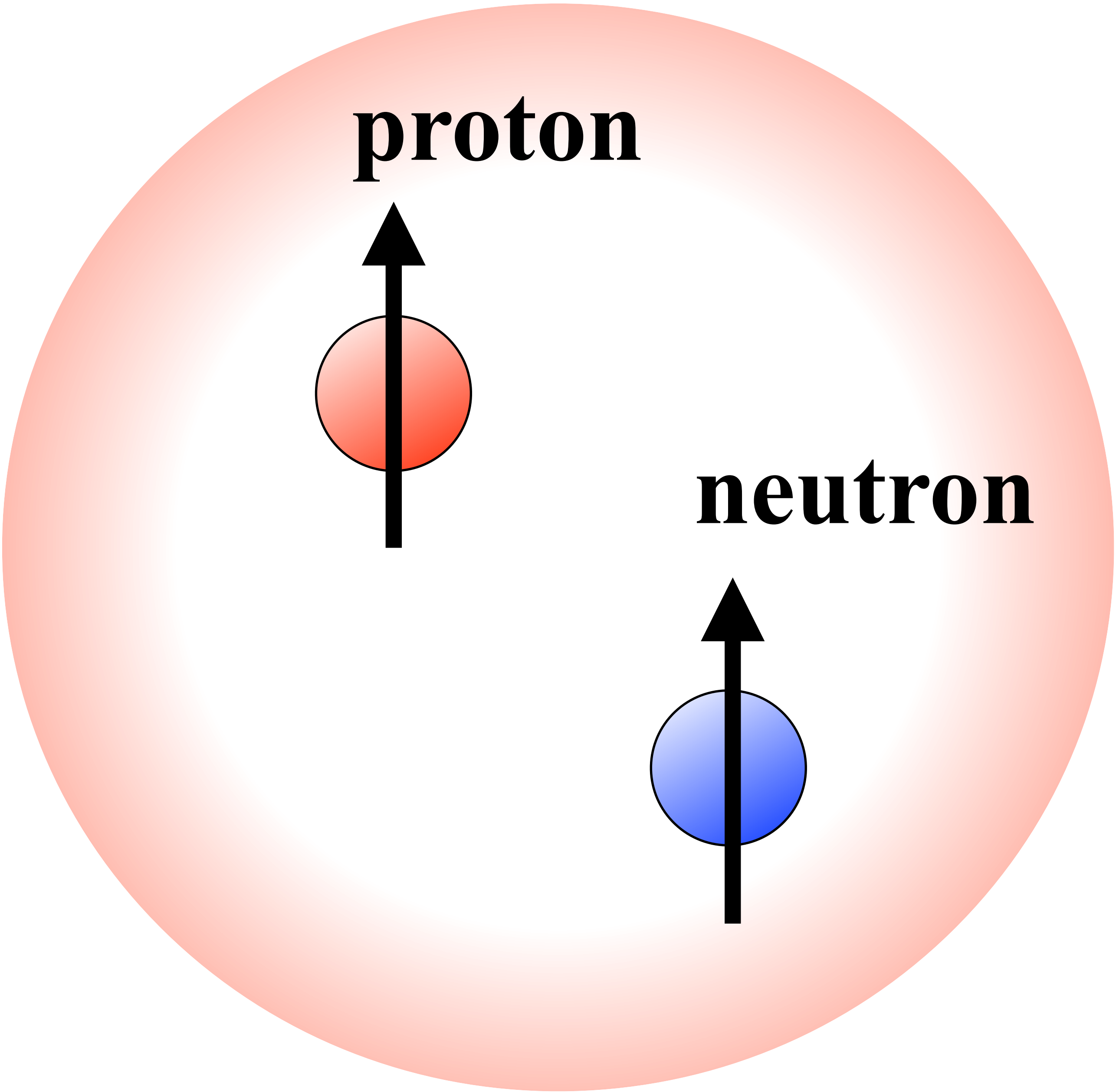
Major origin of the nuclear binding

May hint the change of quark-gluon structure of nucleons in nuclear medium.

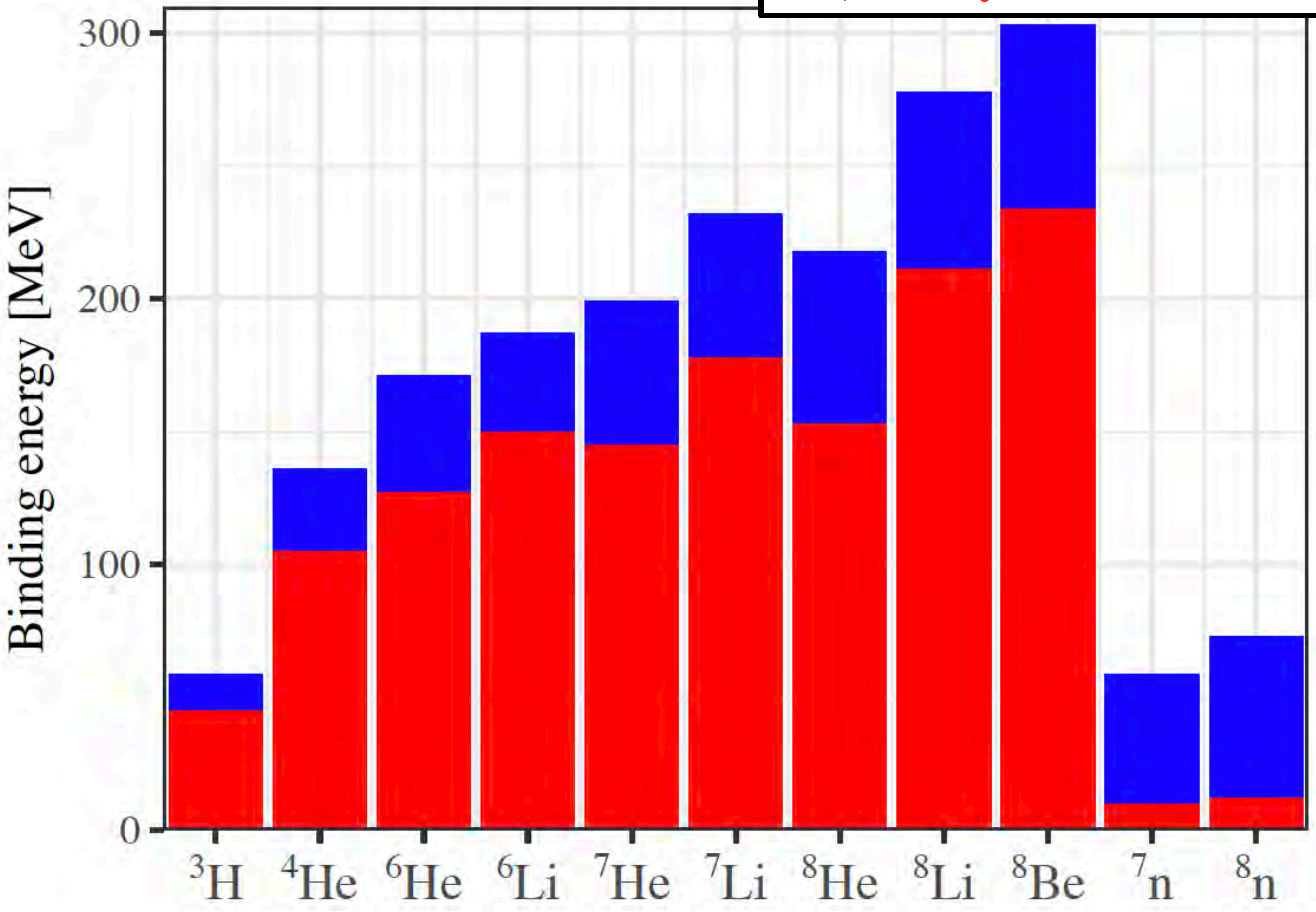
Tensor force and stabilities of deuteron and other nuclei

Deuteron is the only bound state of two nucleons.
70% of its binding energy originates from the tensor force driven by pion exchange.

Binding energy	2.225 MeV
RMS radius	1.9 fm
Spin-parity	1^+
Isospin	0

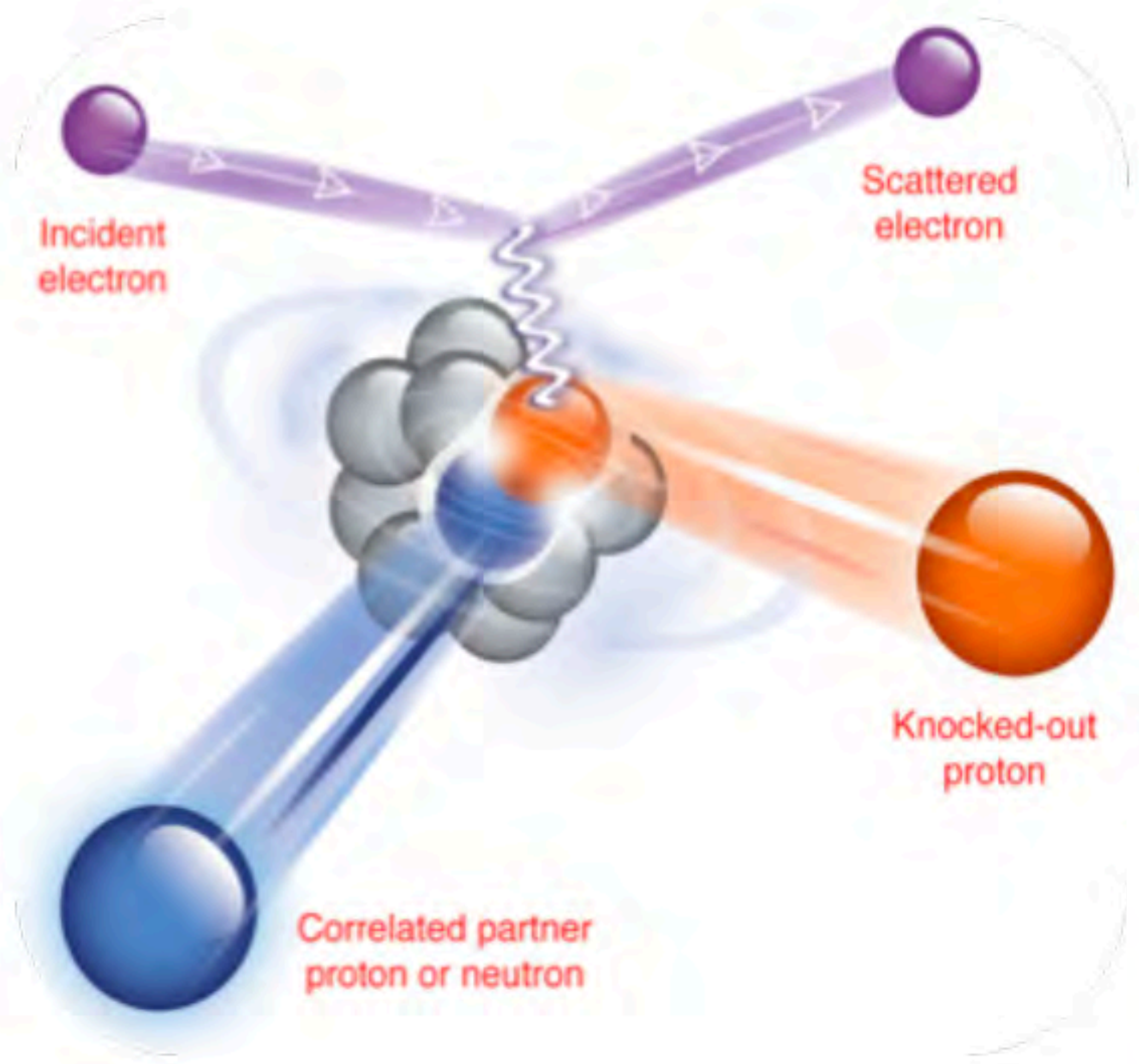


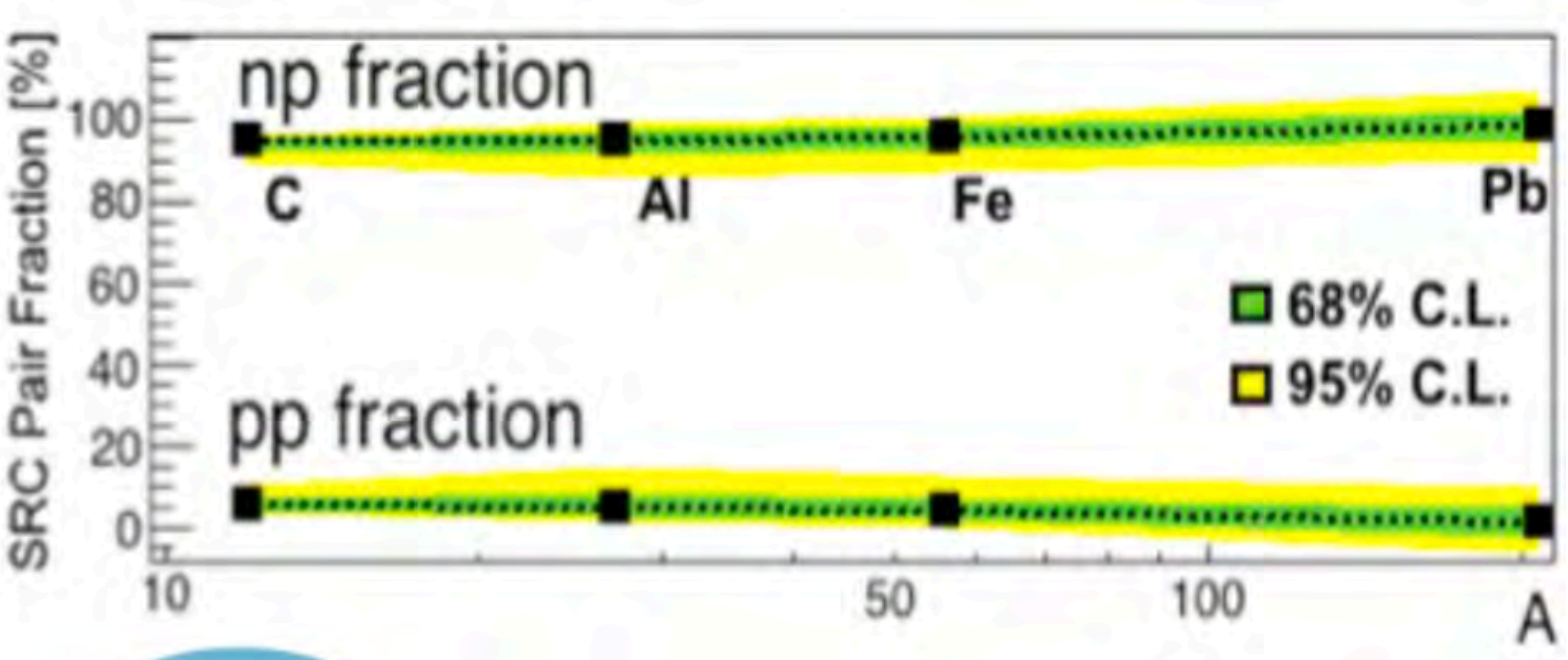
Total binding energy
π-exchange contribution (mainly tensor force effects)

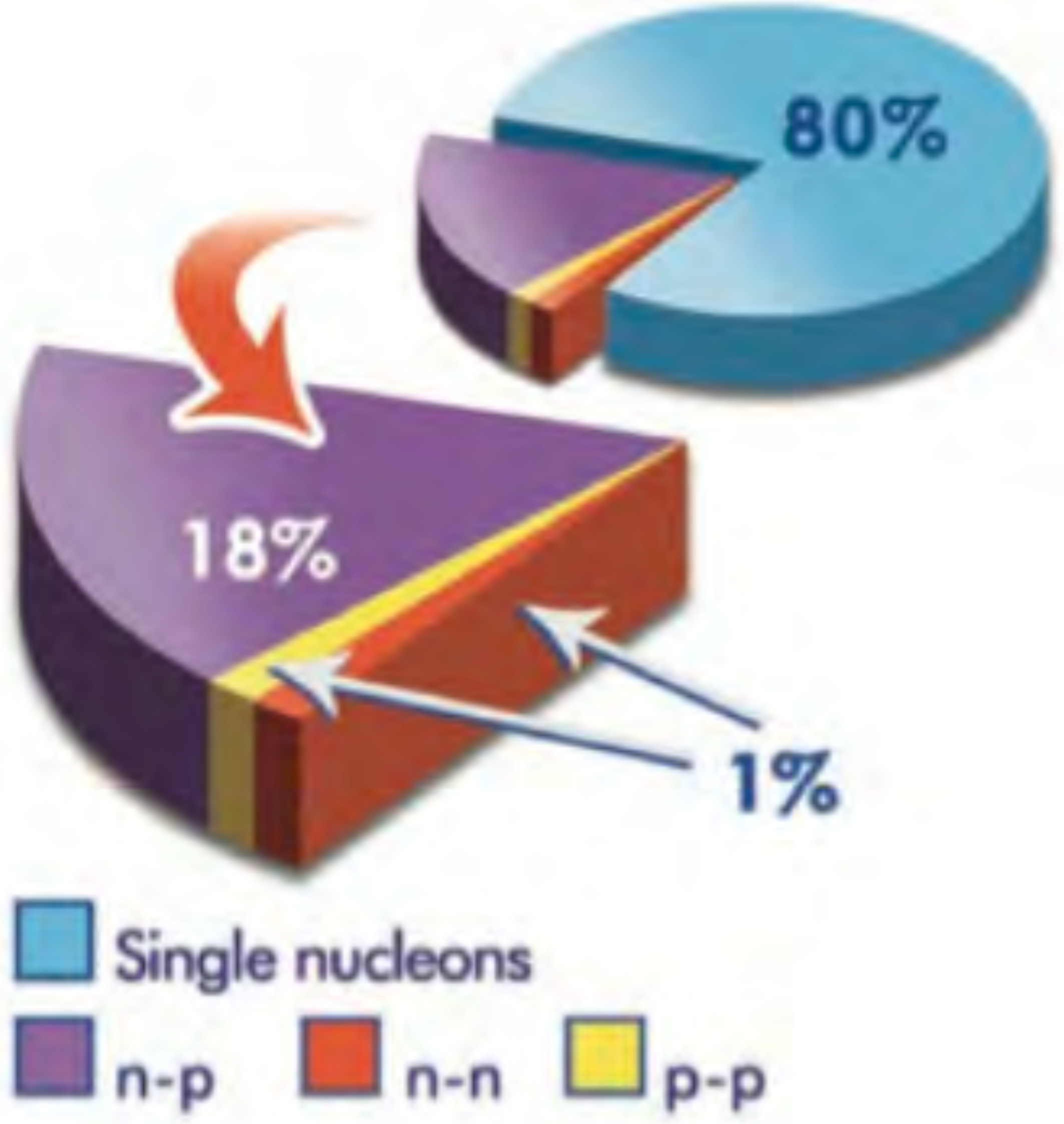


Values are from Pieper and Wiringa, Ann. Rev. Nucl. Part. Sci. 51, 53 (2001)

Short-range correlation data from JLab







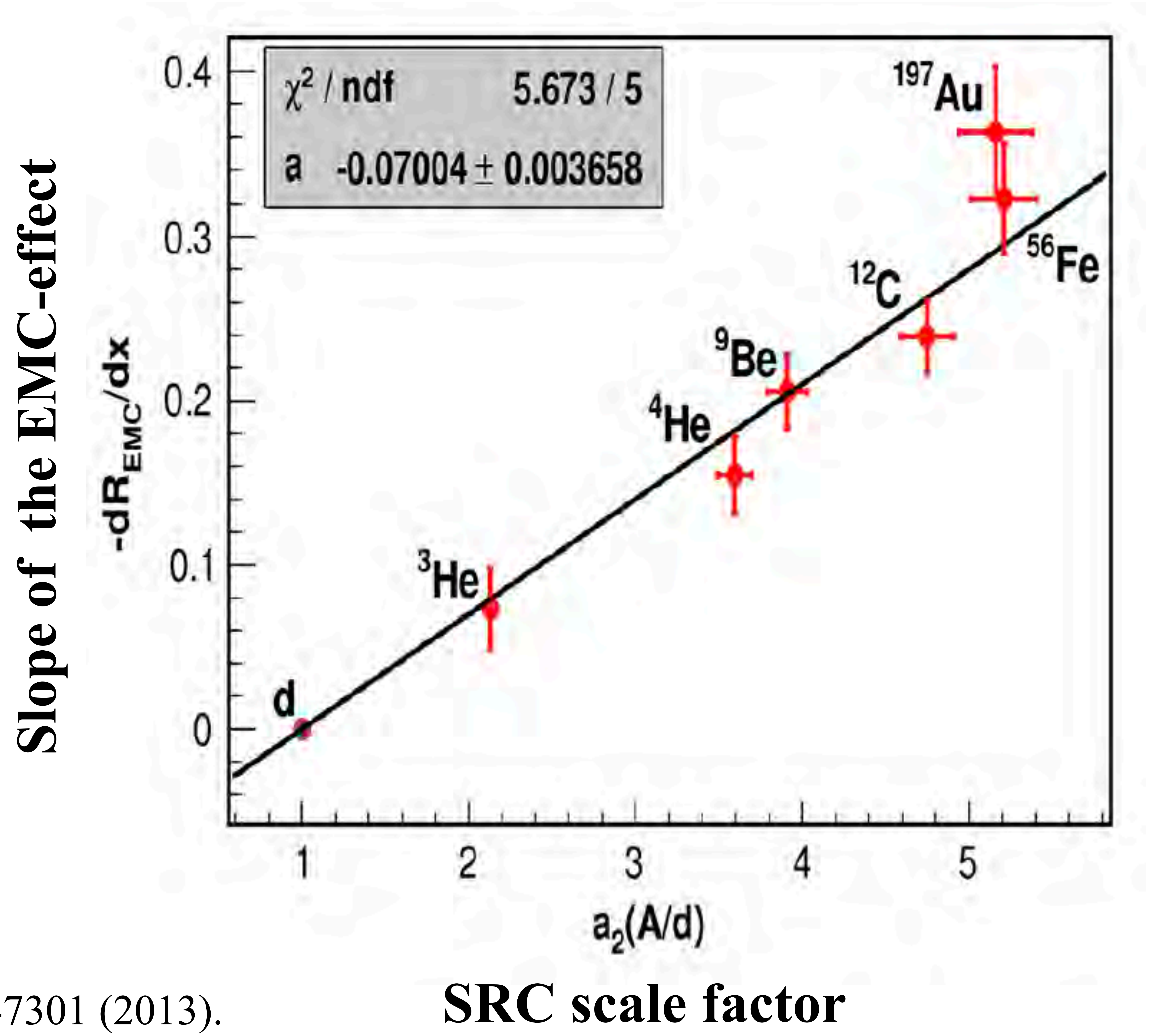
O. Hen et al., Science 364, 614 (2014).

N-N pairs at k_{rel} = 2 fm^{-1} (inter-nucleon distance of 0.5 fm) are >90 % likely to be proton-neutron pairs.

Short-range correlation (SRC)

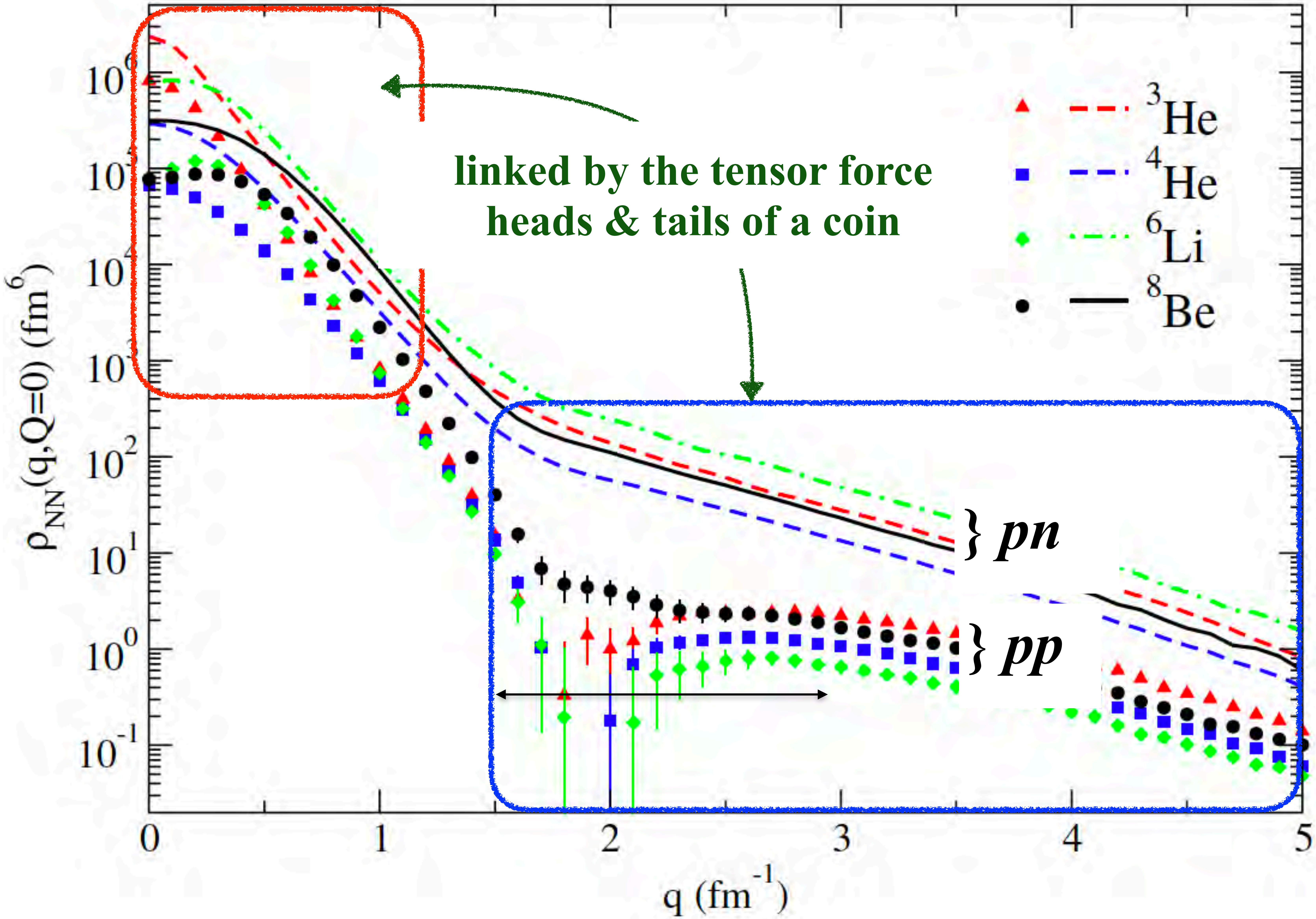
SRC and the change of the nucleon structure in nuclei

Short-range *p-n* correlation in nuclei may hint at the nuclear-medium effects on the nucleon parton distribution, known as the EMC effect.



O. Hen et al., Phys. Rev. C 85, 047301 (2013).

Physics of deuteron-like pn correlation in nuclei



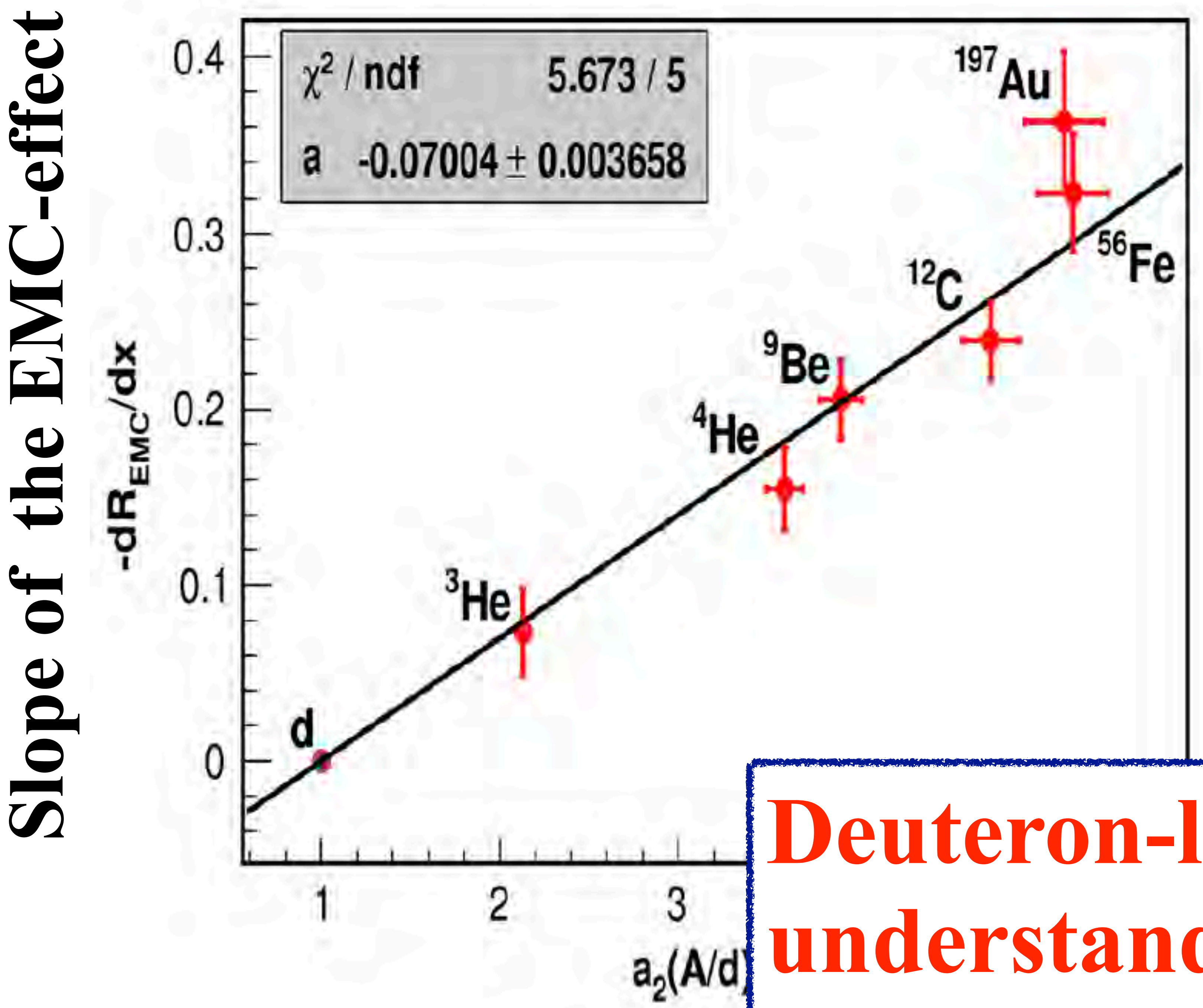
R. Schiavilla et al.,
Phys. Rev. Lett. 98, 132501 (2007).

The amount of SRC pairs at high momentum is one of the origins of quenching.

Short-range *p-n* correlation in nuclei hints at the nuclear-medium effects on the nucleon parton distribution.

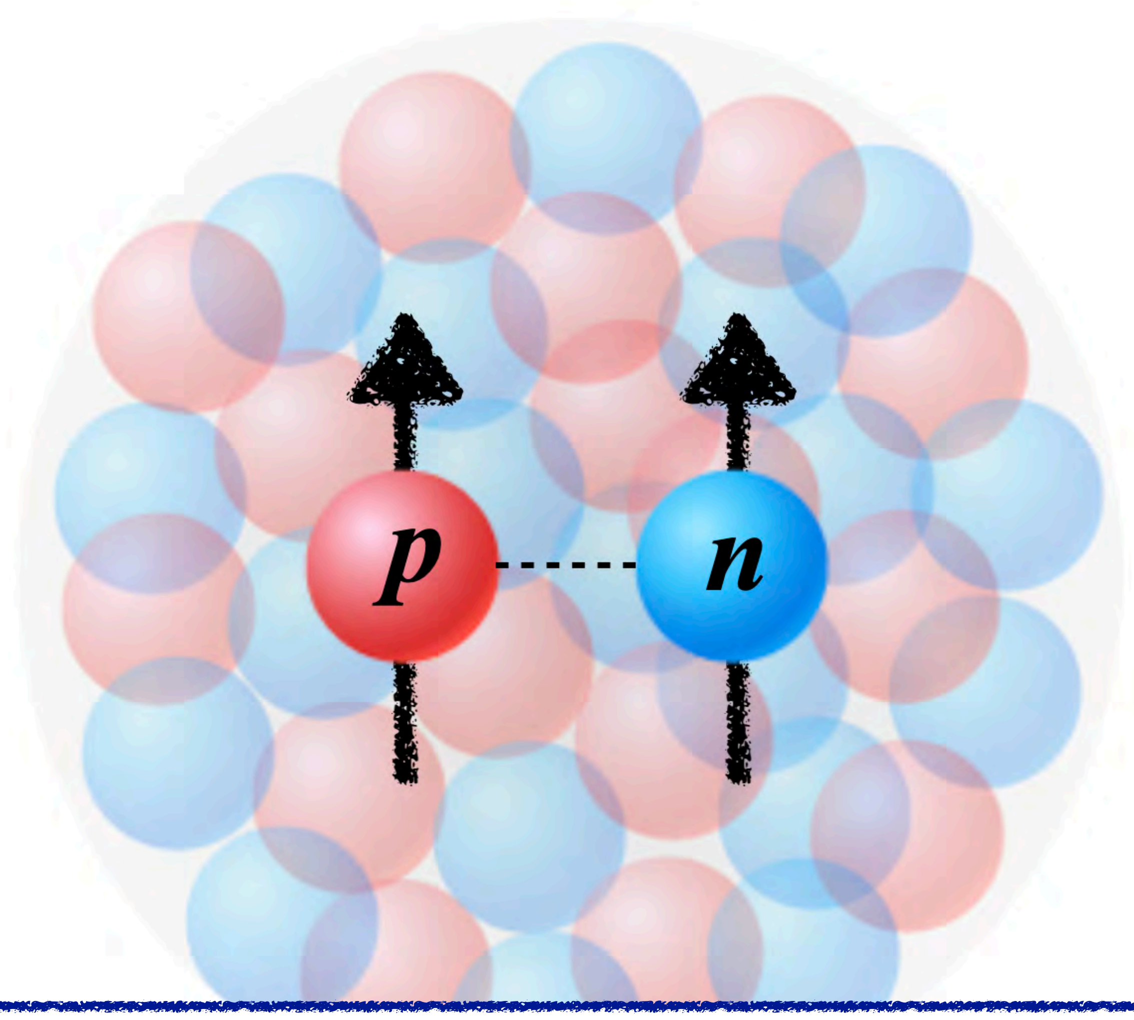
S=1 proton-neutron-pair in nuclei
← tensor interaction
(rank-2 tensor in spin space)

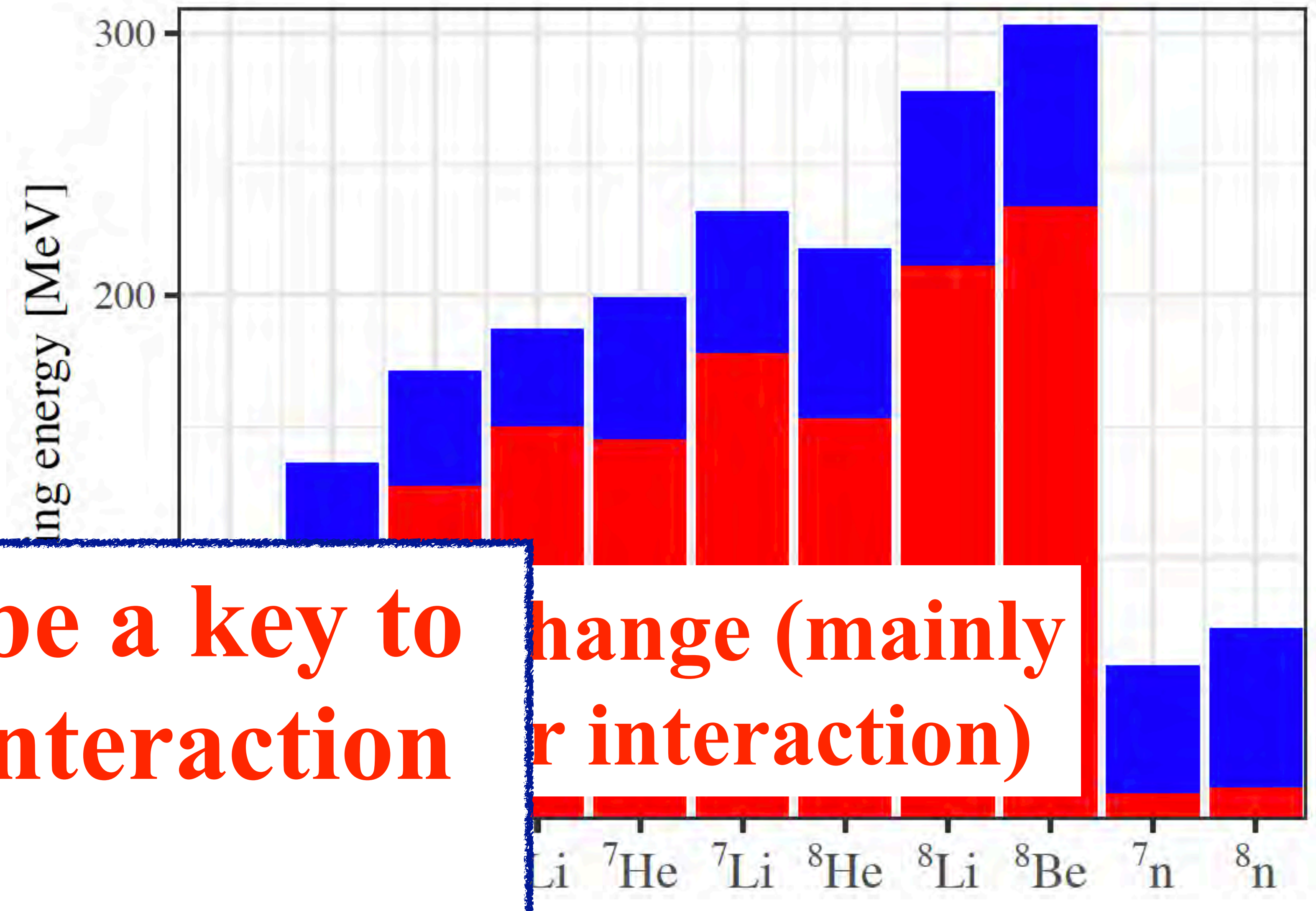
The tensor interaction is the major origin (≧50%) of nuclear binding.



SRC scal

O. Hen et al.,



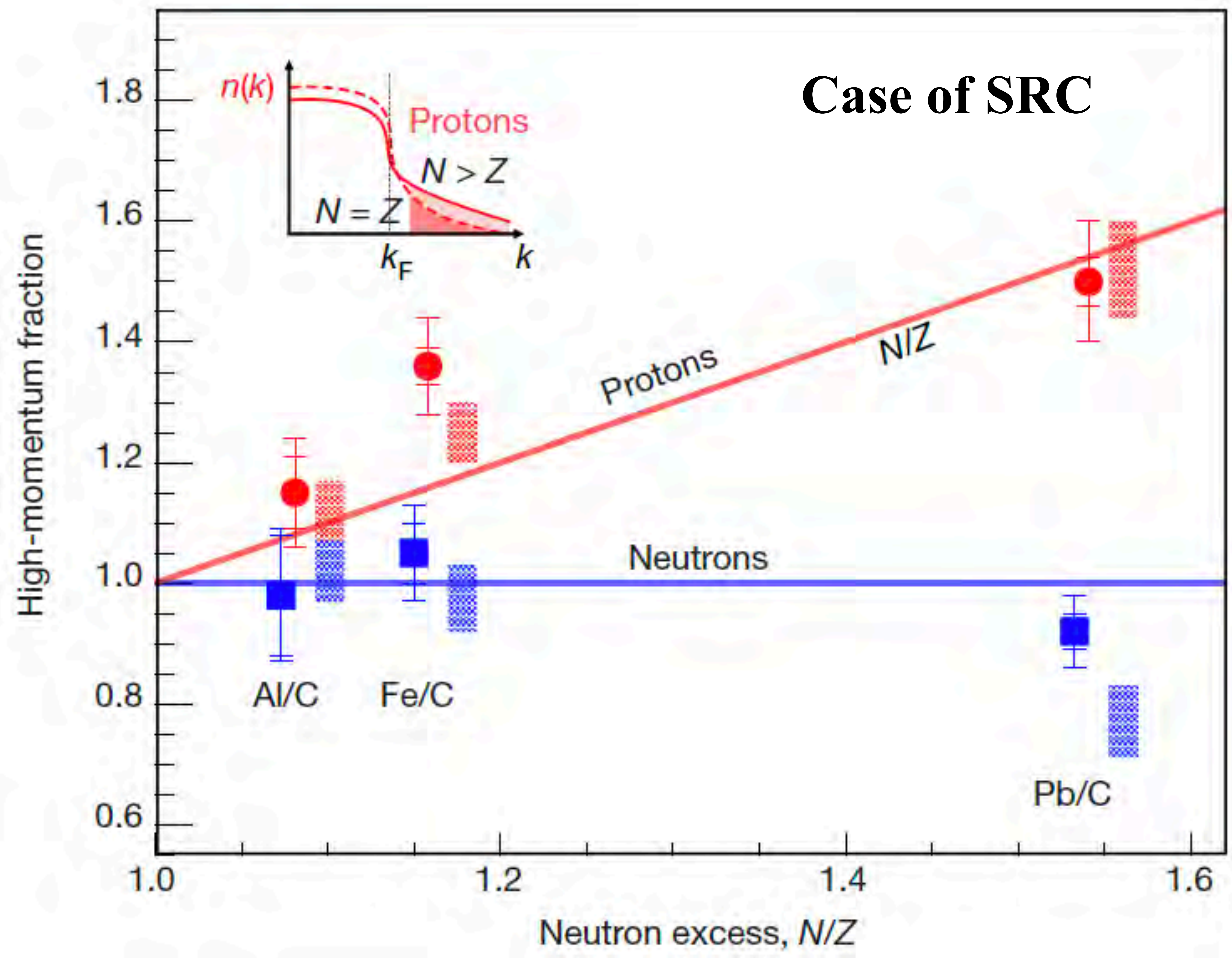


from Pieper and Wiringa, Nucl. Part. Sci. 51, 53 (2001)

Deuteron-like p-n correlation can be a key to understand how the quark-gluon interaction create nuclear binding.
This is one of the main topics in EIC physics.

Long-range correlations should be studied at low-energy facilities.

Isospin dependence of deuteron-like correlation



M. Duer et al., Nature 560, 617 (2018).

Indication of stronger SRC for proton in neutron-abundant environment.

Deuteron-like correlation in nuclear far from the stability line should be studied with RI beams

How do S=1 *pn*-pair correlation emerge with isospin?

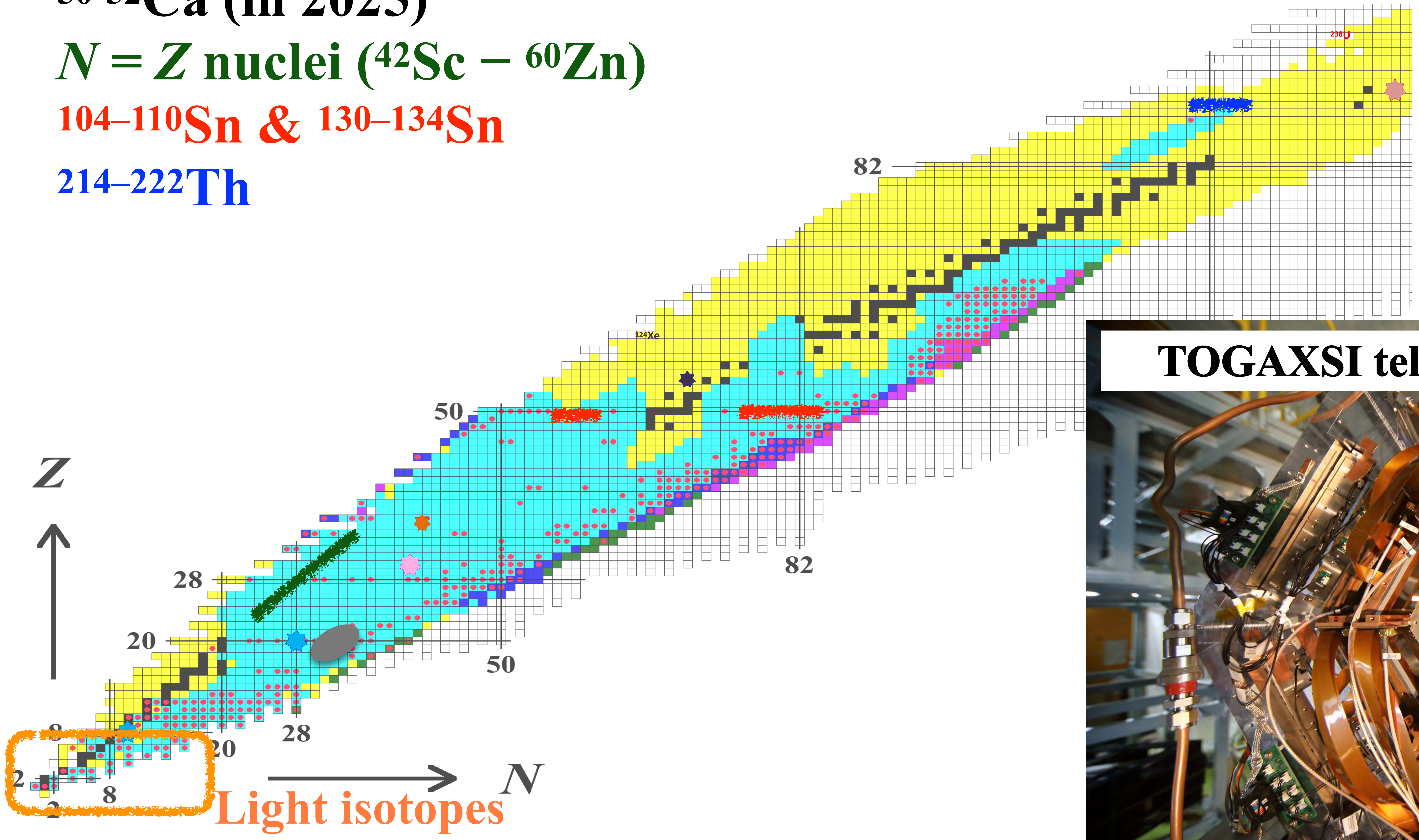
ONOKORO @ RIBF

$^{50\text{-}52}$Ca (in 2025)

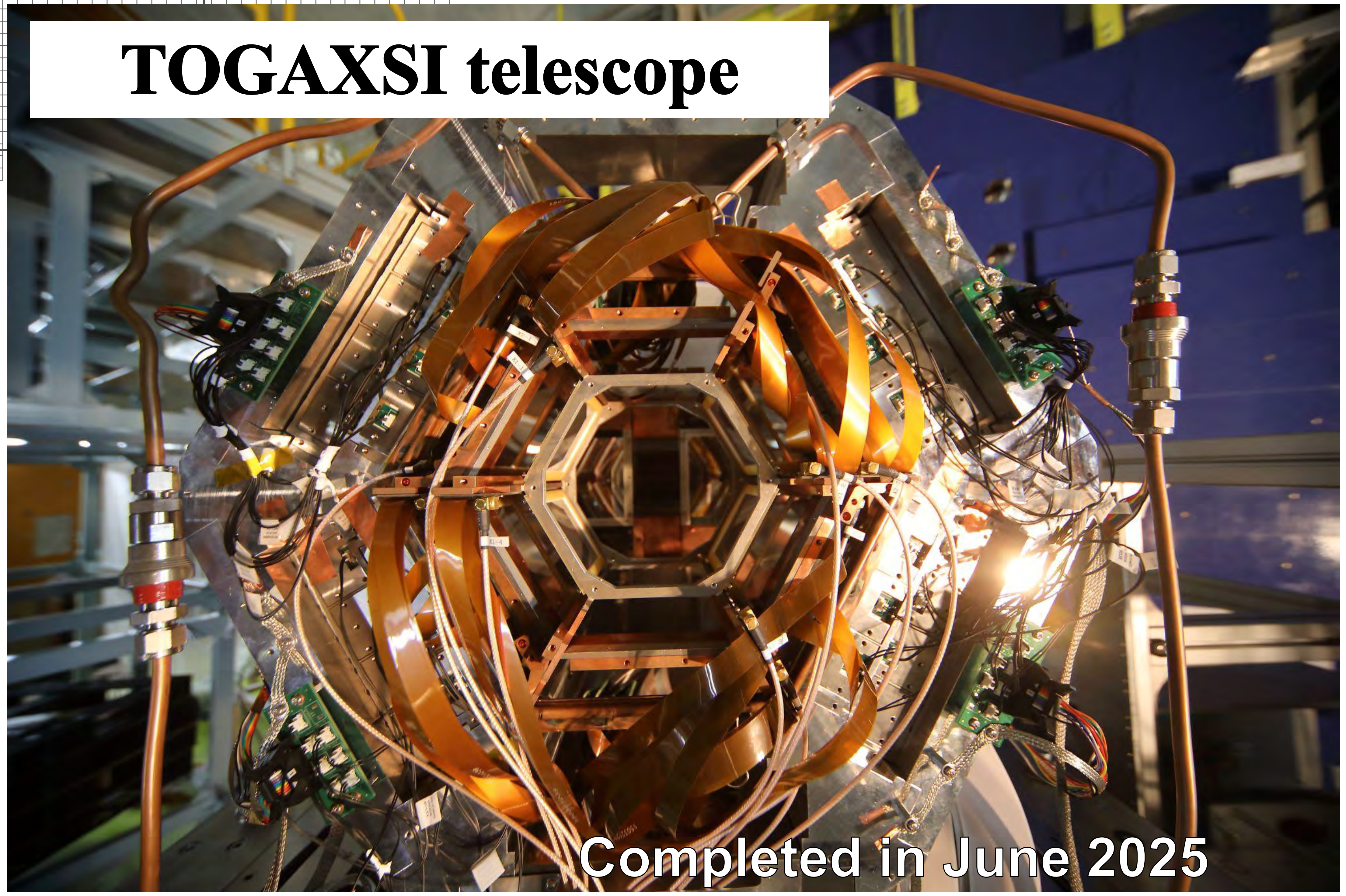
N = *Z* nuclei (^{42}Sc – ^{60}Zn)

$^{104–110}$Sn & $^{130–134}$Sn

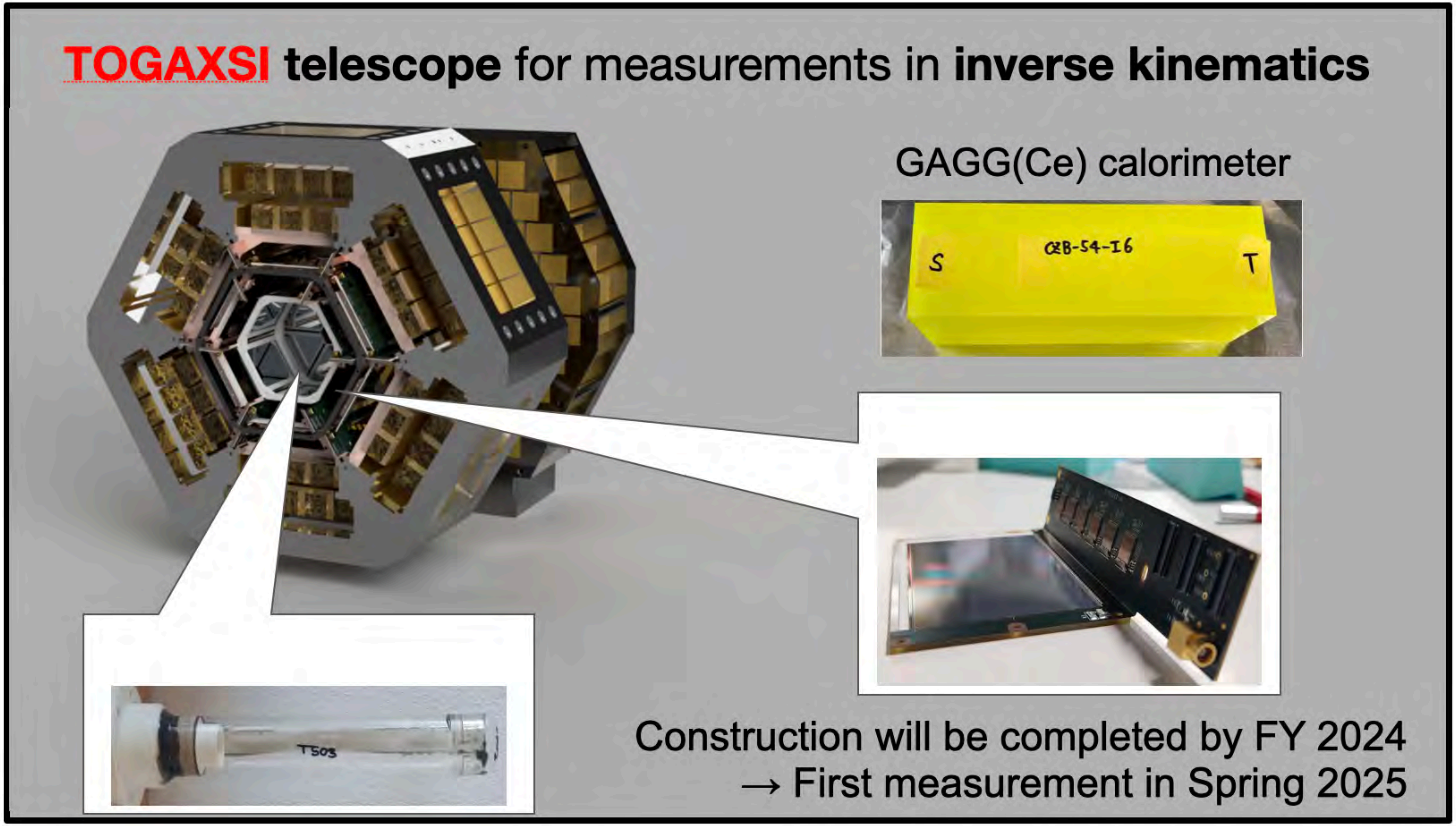
$^{214–222}$Th



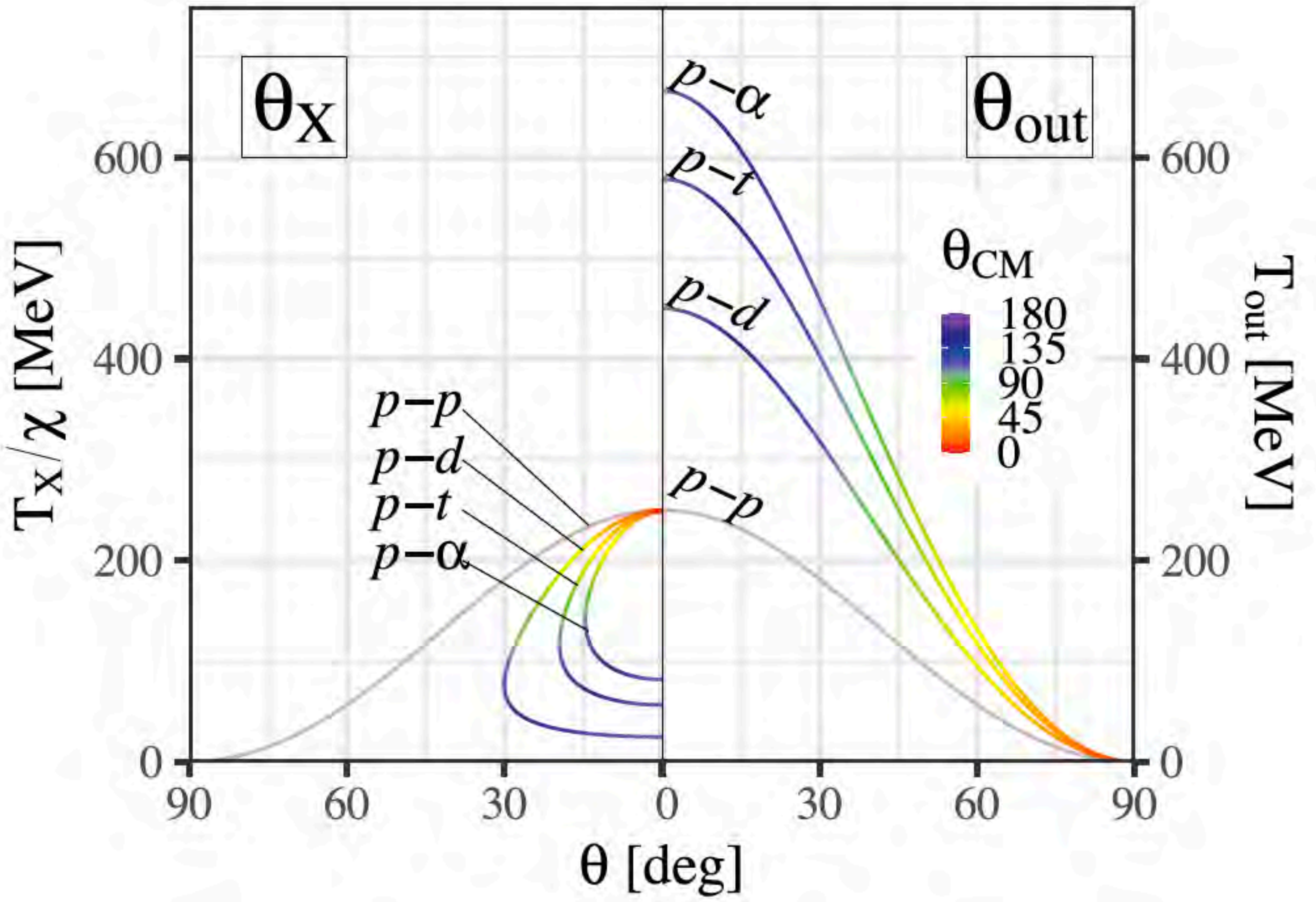
Yuki Kubota



ONOKORO @ RIBF



Kinematics of the (*p,pX*) reaction in inverse kinematics



TU, PTEP **2024**, 083D01.

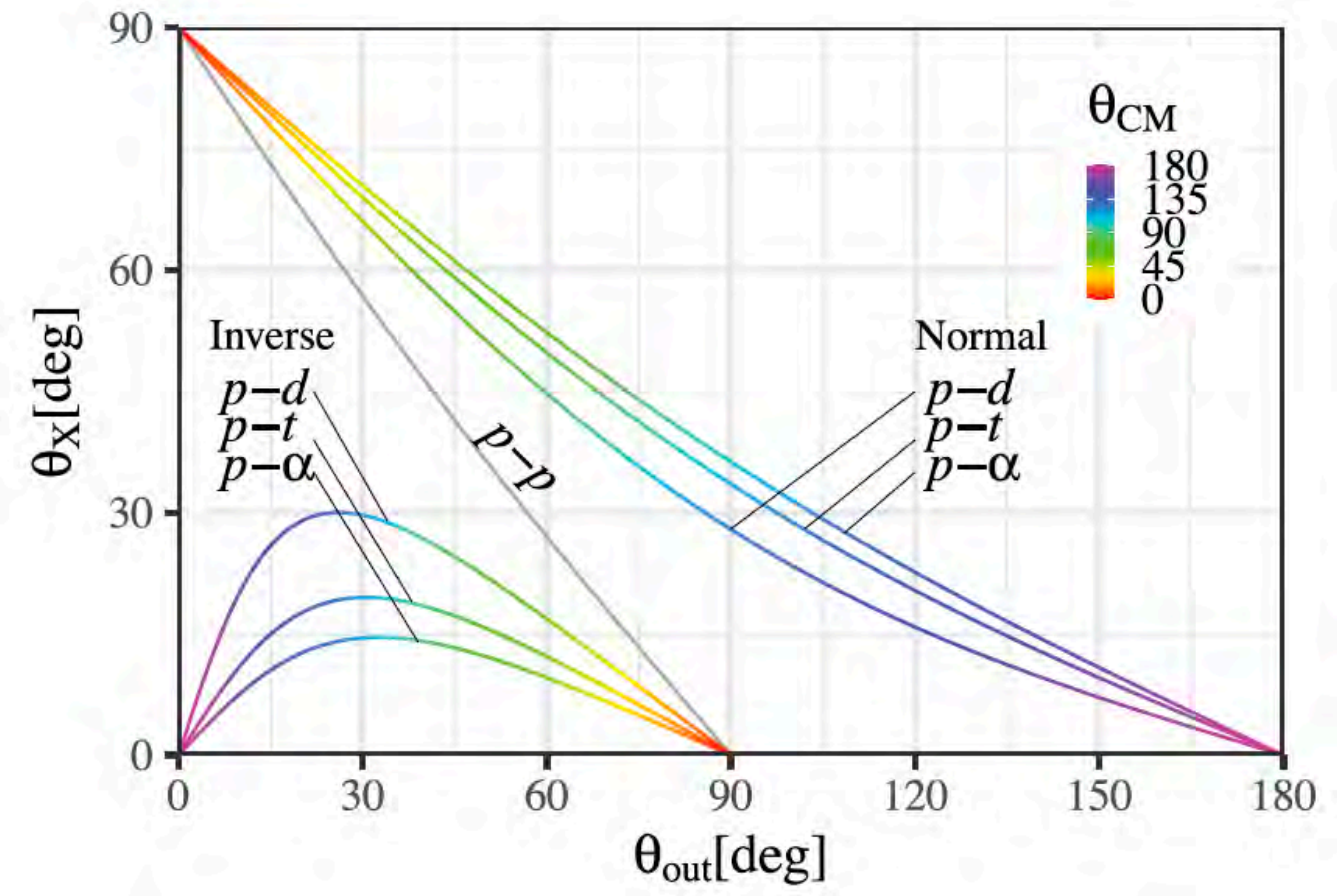
$$\sin(\theta_{\max}) = \frac{m_p}{m_X}$$

***d*: θ_{max}=30.02 deg**

***t*/[3]He: θ_{max}=19.51 deg**

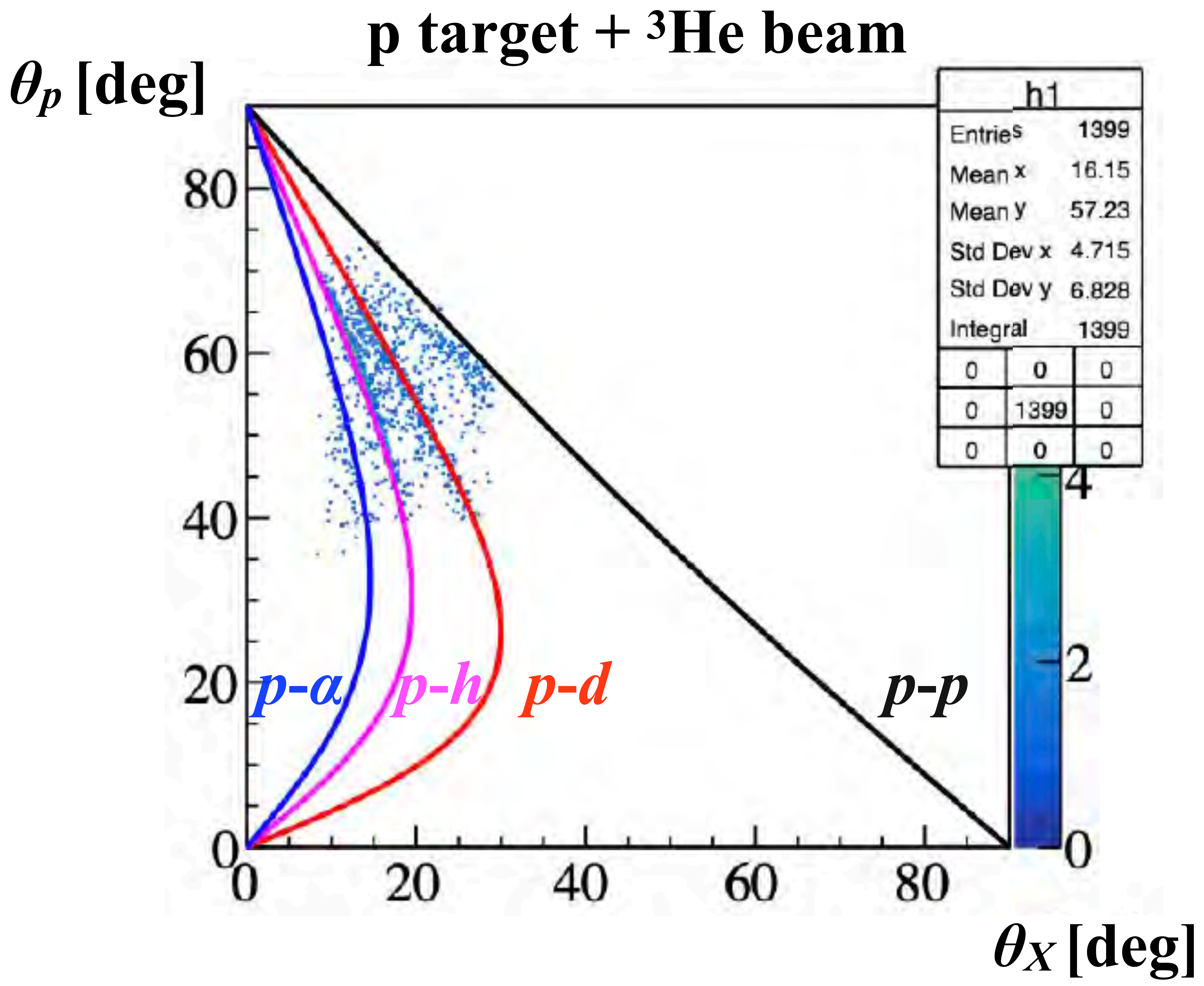
α: θ_{max}=14.58 deg

Angular correlation is a fingerprint of the reaction



Snapshot from ONOKORO @ RIBF

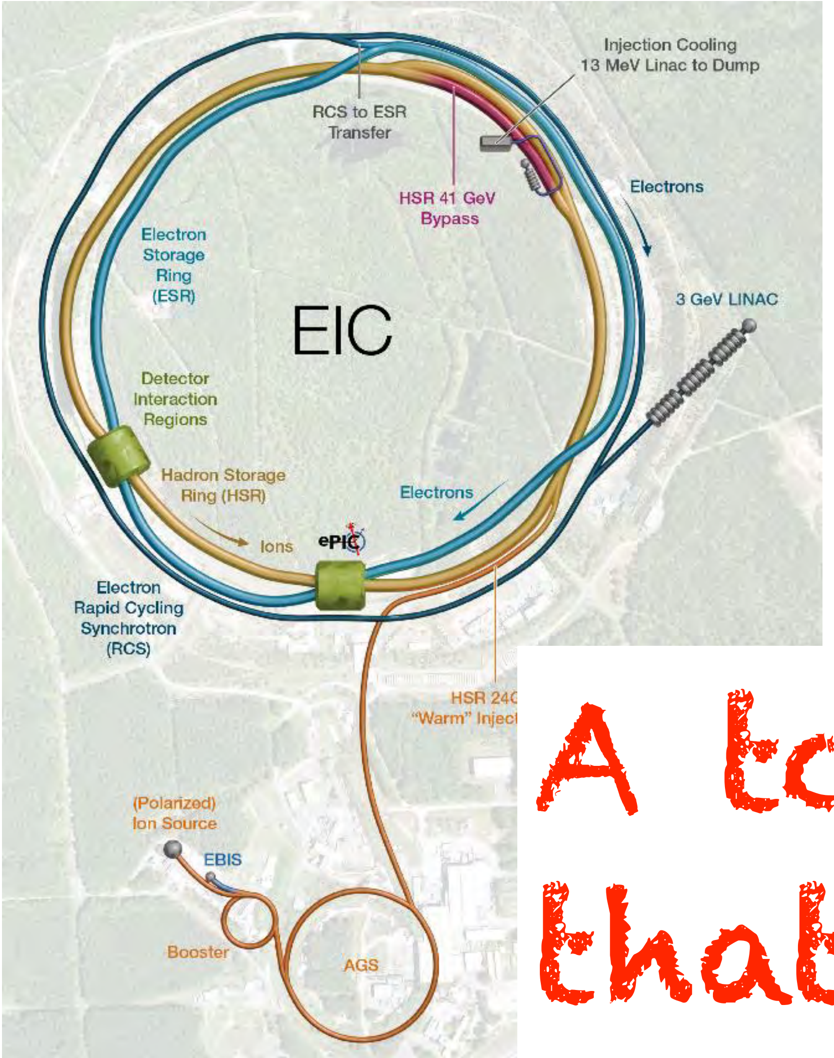
Courtesy of S. Koyama and Y. Kubota

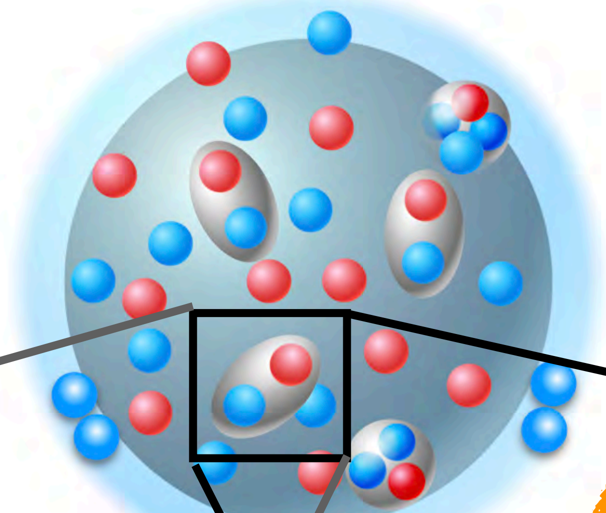


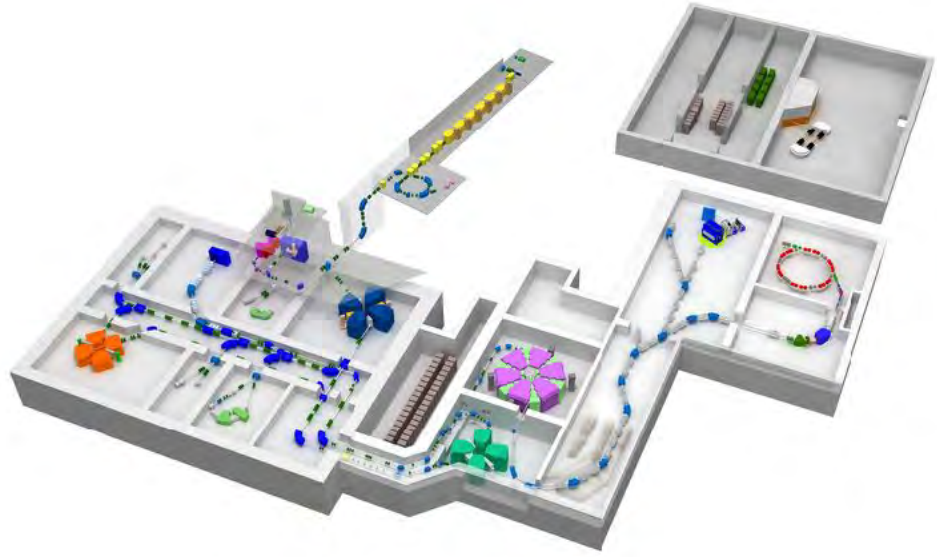
Kinematical correlation between scattered proton and knocked-out cluster is the key in identifying the (*p*,*pX*) reaction

Clear locus corresponding deuteron knockout.

Looking at *p-n* correlation on a wide scale

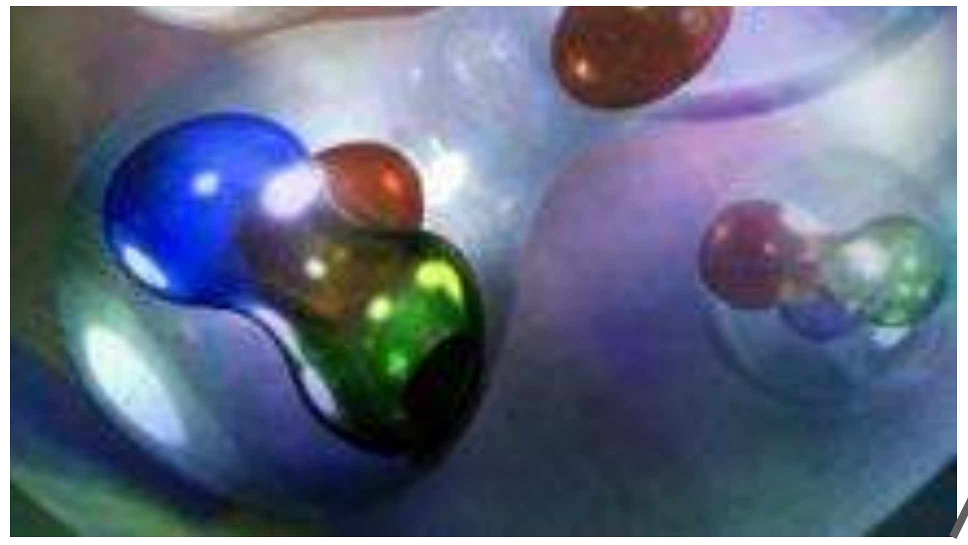






ONOKORO

A topic of the "multi-scale nuclear physics" that links RIBF and EIC.



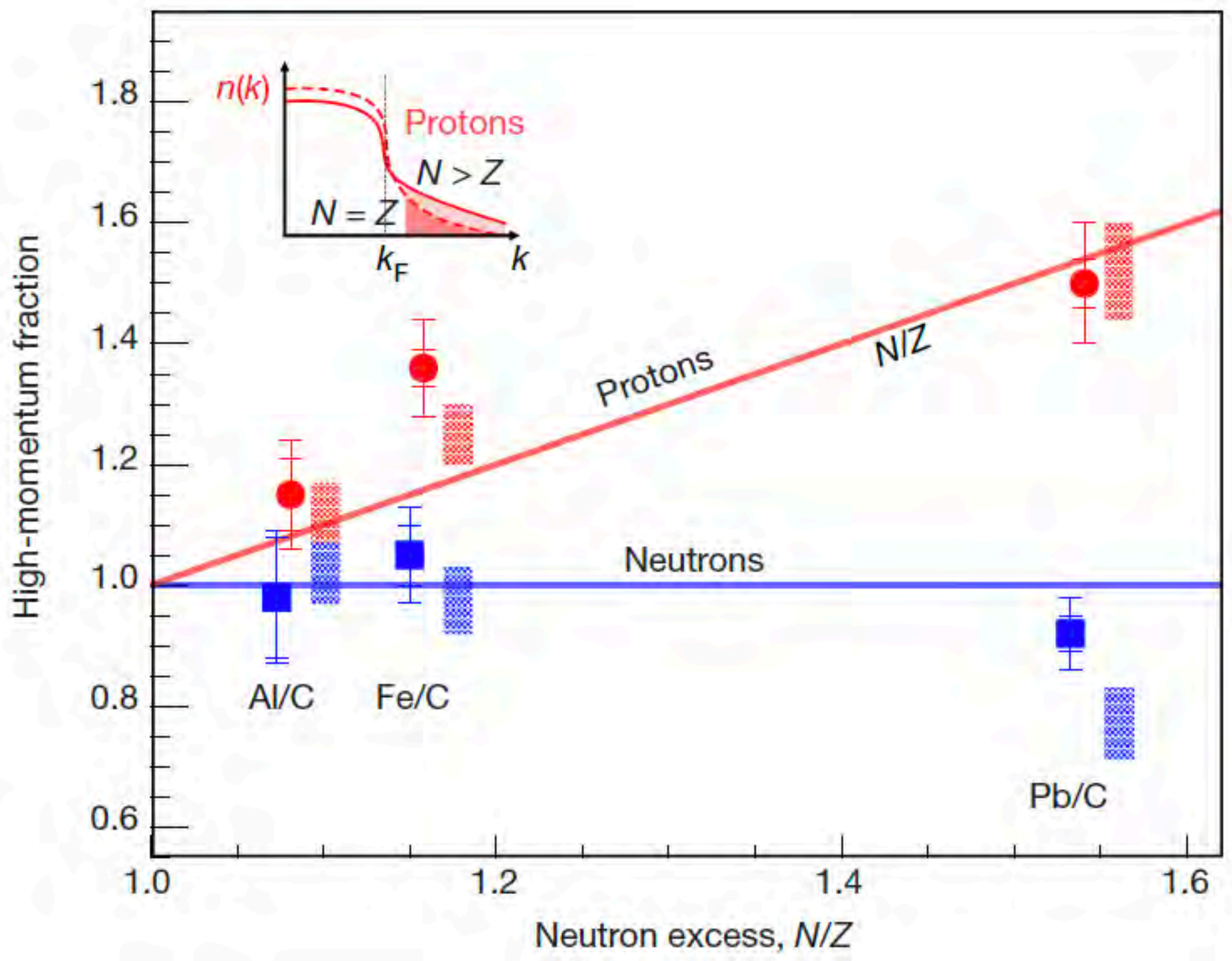
small p-n distance

Proton radius (~0.8 fm)

large p-n distance

quark-gluon dynamics

nucleon-meson dynamics



M. Duer et al., Nature 560, 617 (2018).

Summary of the part 3

The Ikeda diagram (threshold rule) has been a guiding principle in nuclear cluster physics. More general views of nuclear clustering, such as clustering in nuclear ground states and their coexistence with independent particle structure, remain to be understood.

The cluster knockout (*p*,*pX*) reactions can be good experimental probes of clustering in ground states. What you have learned about the nucleon knockout (*p*,*pN*) reaction can apply to the (*p*,*pX*) reactions, almost as it is.

The (*p*,*pα*) data for medium to heavy nuclei clearly show that our understanding of the clustering is far from satisfactory.
Sn(*p*,*pα*) data sheds new light.

The ONOKORO project aims to clarify the mechanisms of clustering by extending the cluster knockout reaction studies to all the light clusters in stable and unstable nuclei.