International School of Nuclear Physics
45th Course
Nuclei in the Laboratory and in Stars
16–21, Septempber 2024

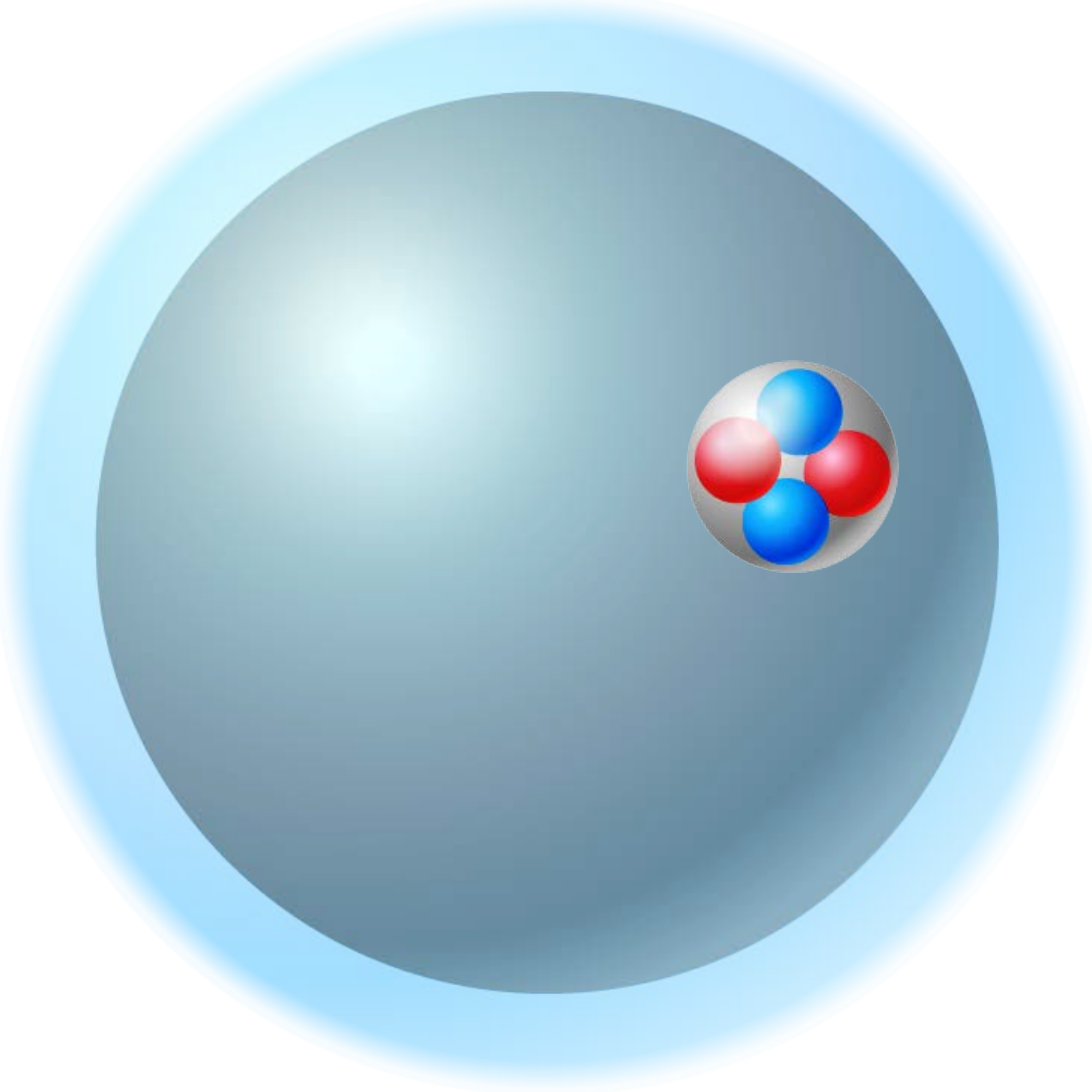
# Nuclear clustering
# – manifestations of nonuniformity in nuclei –

## + short story on nuclear physics in 1934

Tomohiro Uesaka (RIKEN)

Partly based on T. Uesaka & N. Itagaki, Phil. Trans. R. Soc. A 382:20230123 (2024).

**Does nucleonic/hadronic matter prefer nonuniformity rather than uniformity?**



**Manifestation of clusters**

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

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**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.**

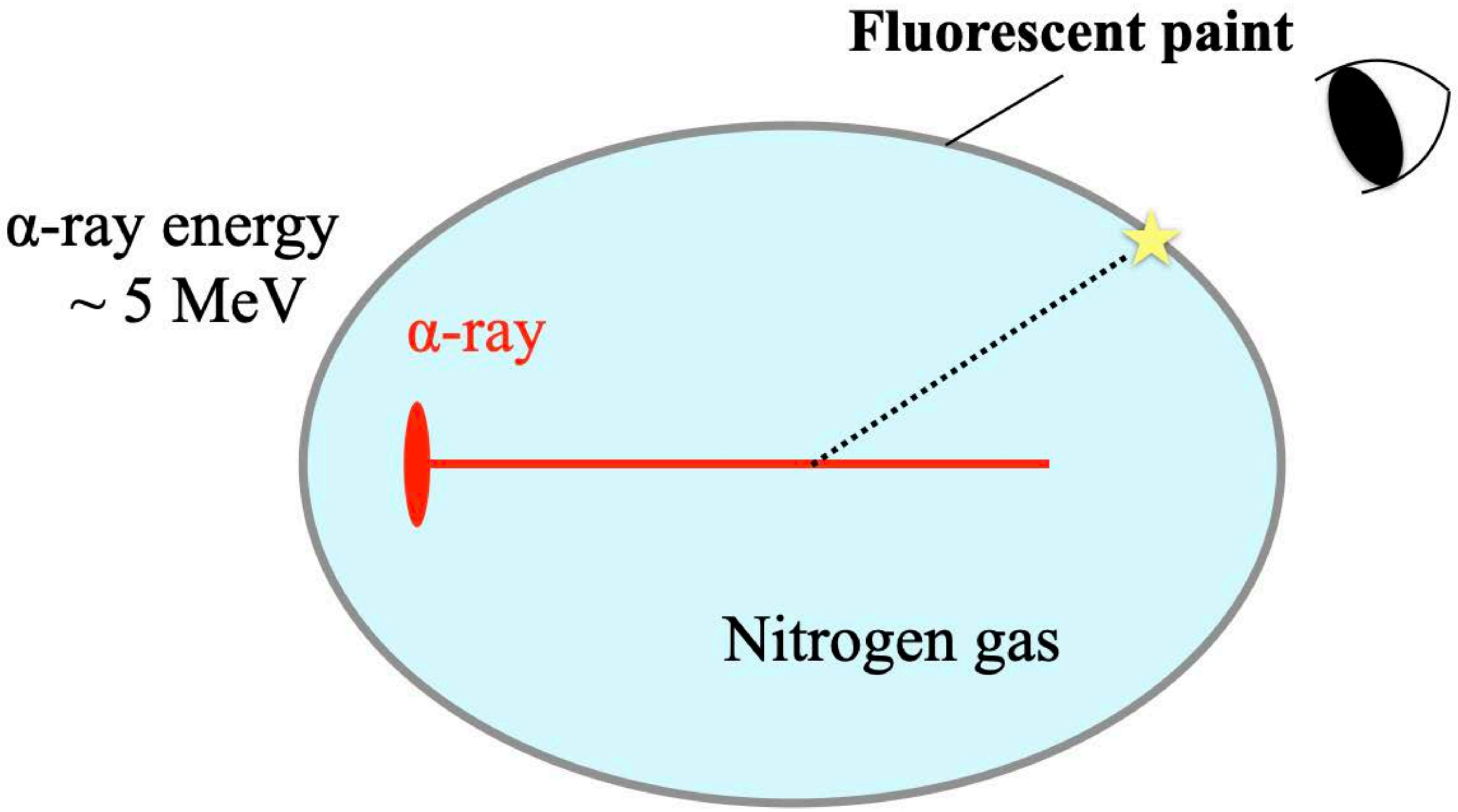
**The importance of light nuclei in supernova matter was also shown by a heavy-ion collision experiment.**

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

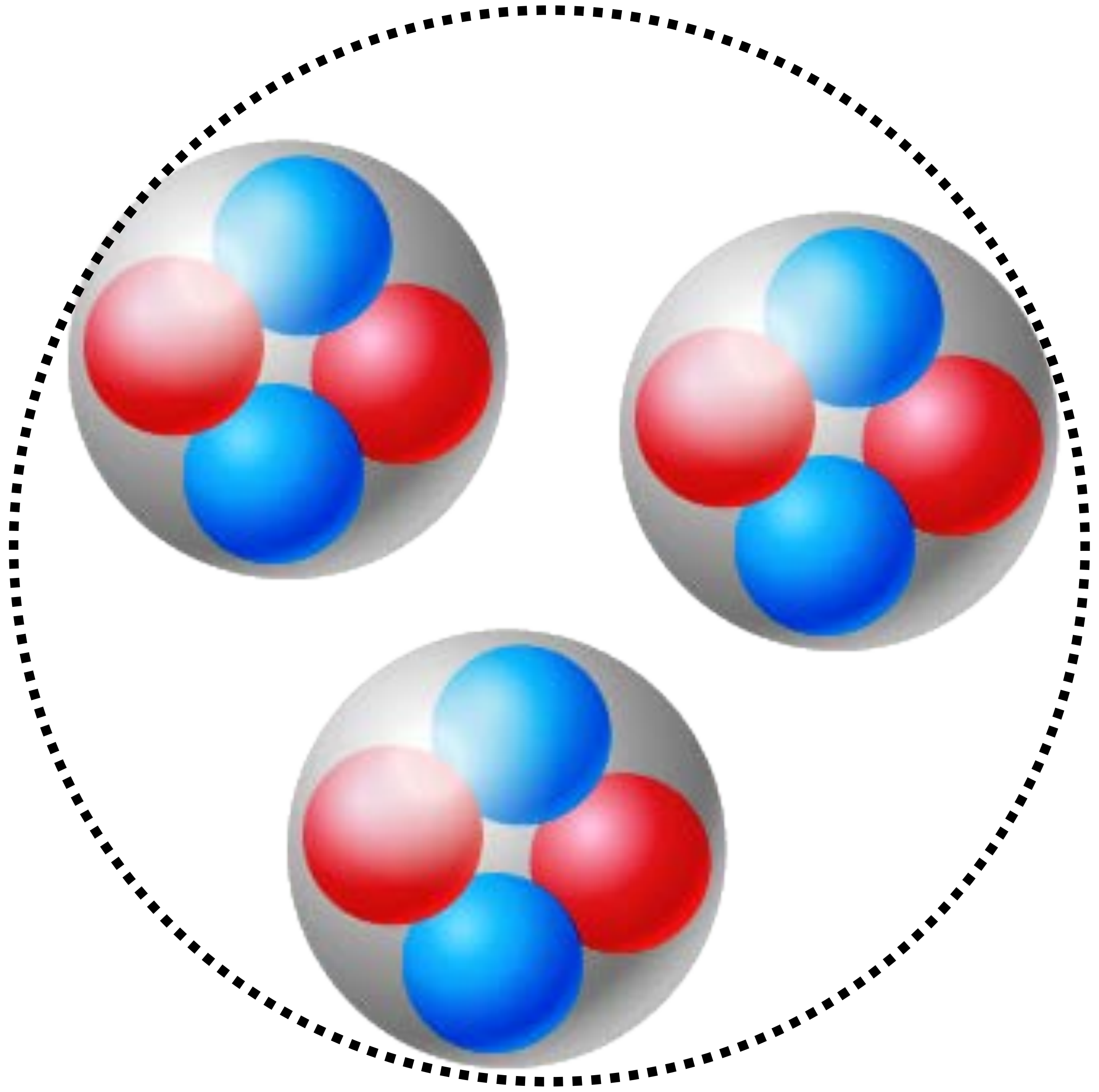
# Nuclear physics started with manifestation of Nonuniformity

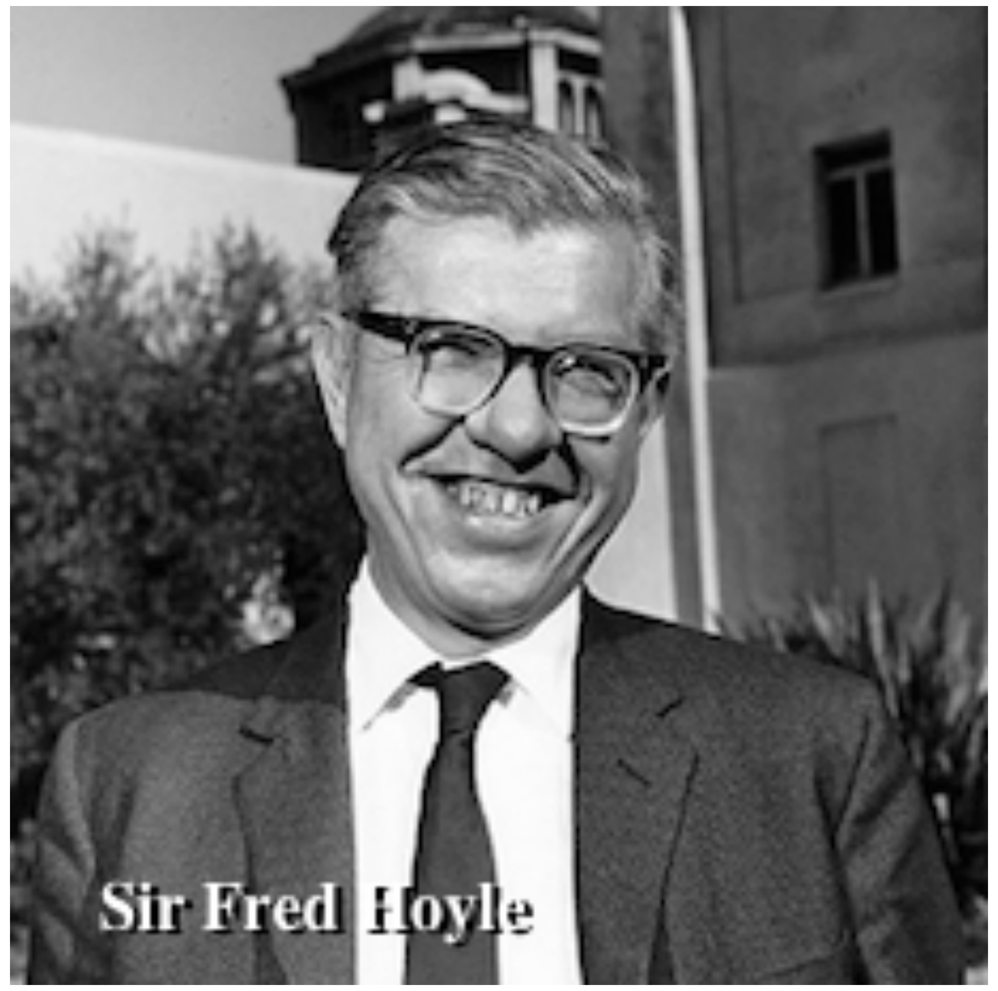
**α-decay: one of the radioactive decays first-observed in the late 19th century**

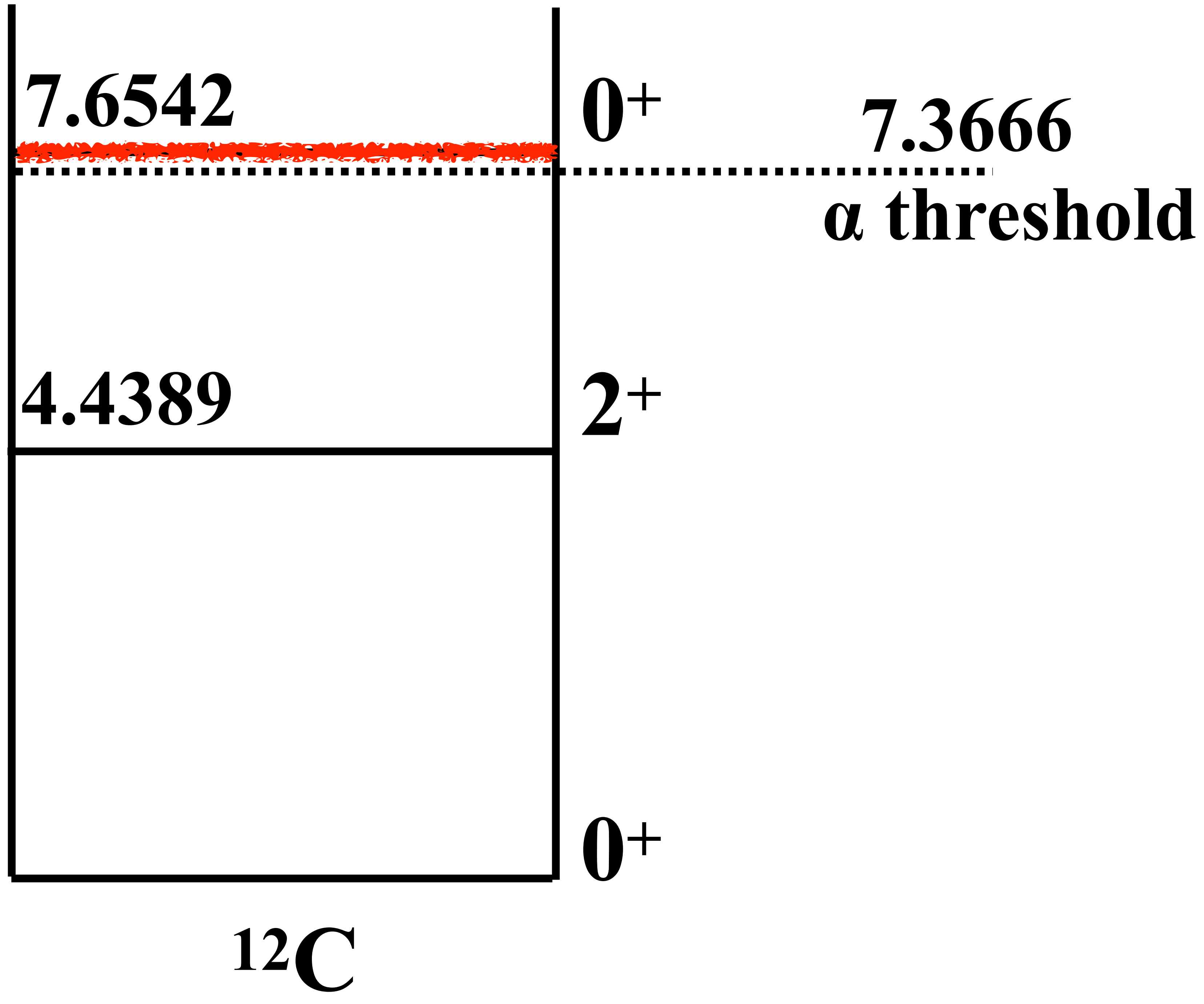
| | |
|---|---|
| 1895 (8th Nov.) | Discovery of X-ray by Röntgen |
| 1896 | Observation of radiation from Uranium by Becquerel |
| 1898 | Discovery of α- and β-rays by Rutherford |
| 1911 | Discovery of a nucleus via α scattering |
| 1919 | The first nuclear reaction transforming one element to the other using the $^{14}N(\alpha, n)^{17}O$ reaction |

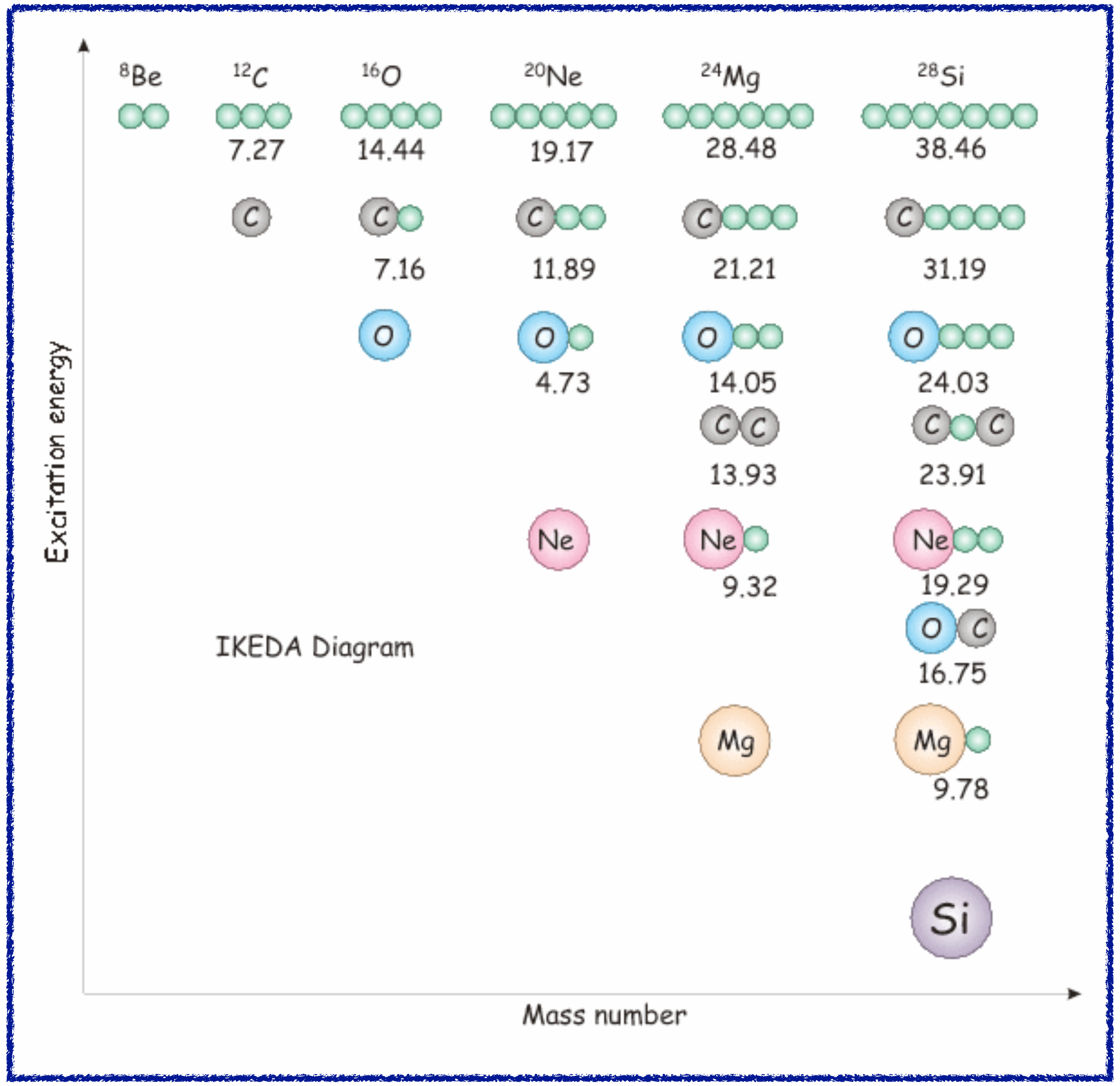


# Hoyle state and the Ikeda diagram





# Beyond the simple pictures of clustering

**Coexistence of clusters with shell-like (independent-nucleon) components**

**Occurrence of clusters**

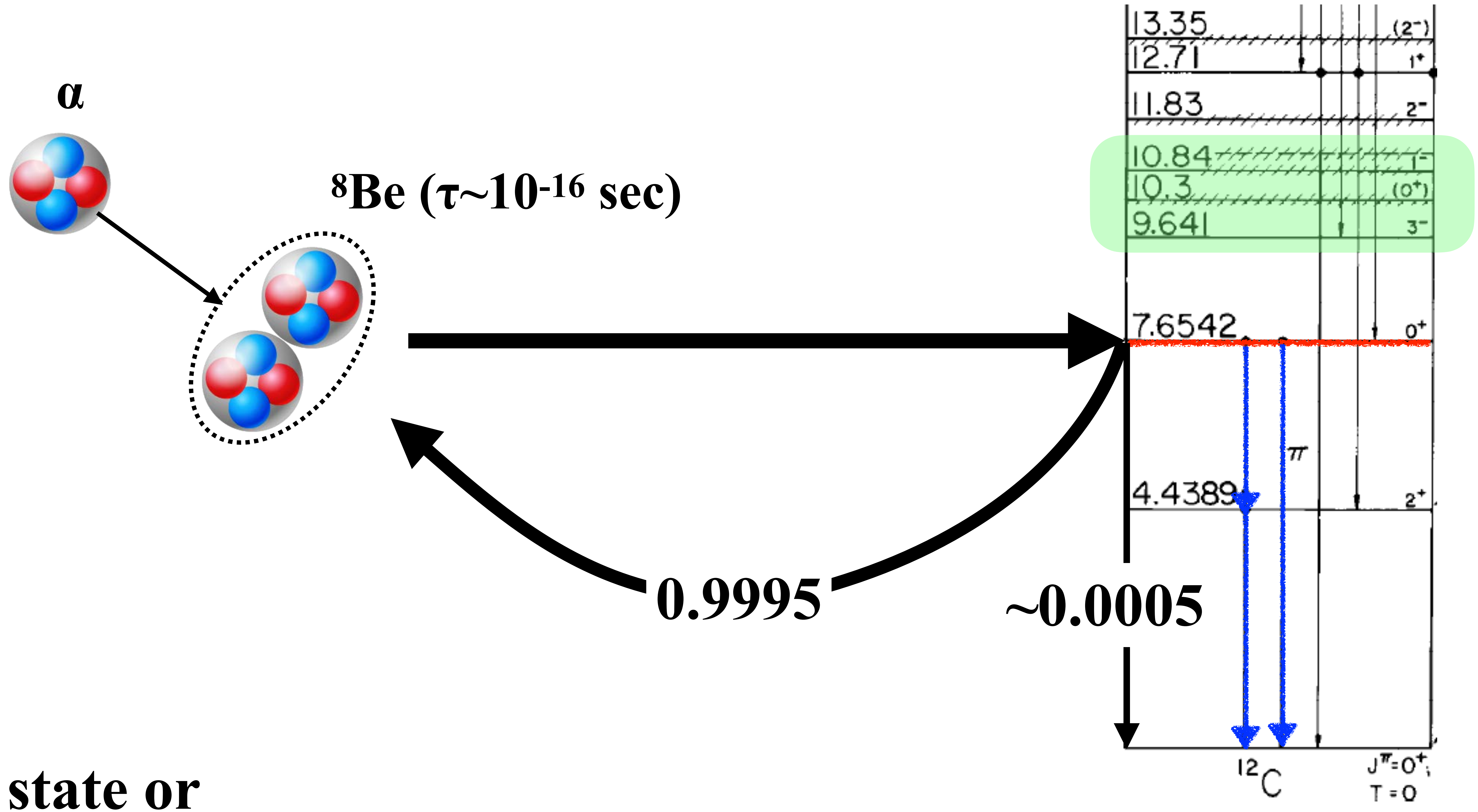
**in states other than those near the thresholds (e.g. ground states)**

**in *any* nuclei where the cluster development was not previously discussed.**

**"Cluster ubiquitousness"**

T. Uesaka & N. Itagaki, Phil. Trans. R. Soc. A **382**:20230123 (2024).

# Helium burning, origin of Carbon




No Hoyle state or

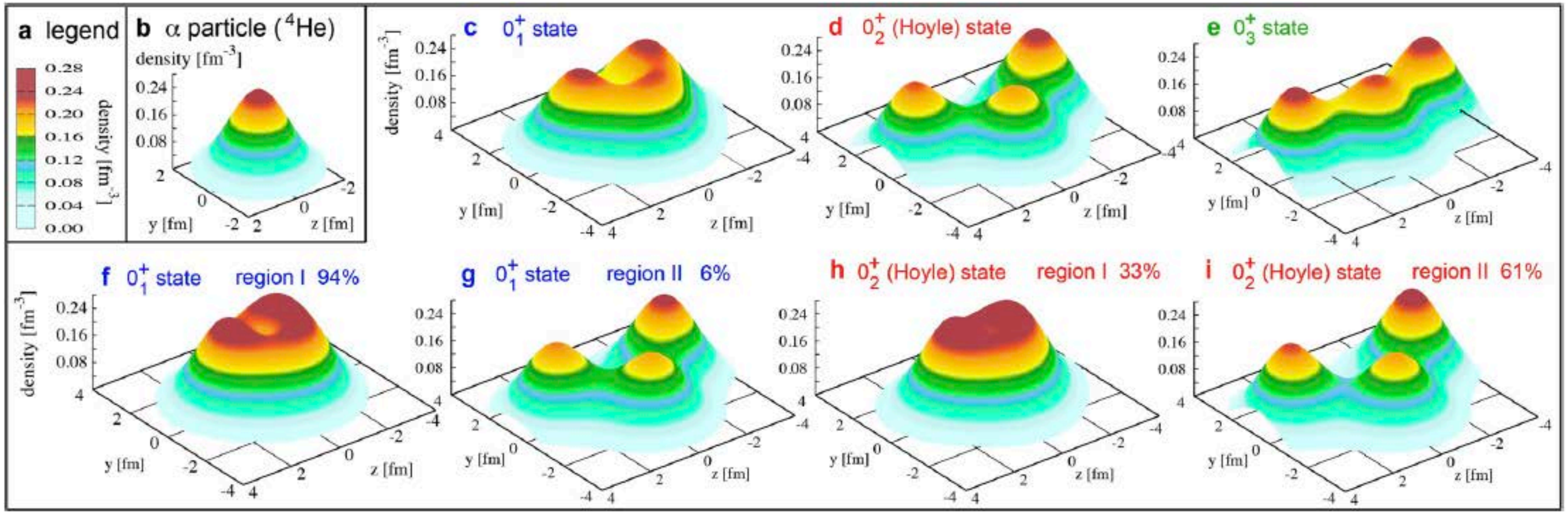
No electromagnetic decay from the Hoyle state (← cluster-shell mixture)

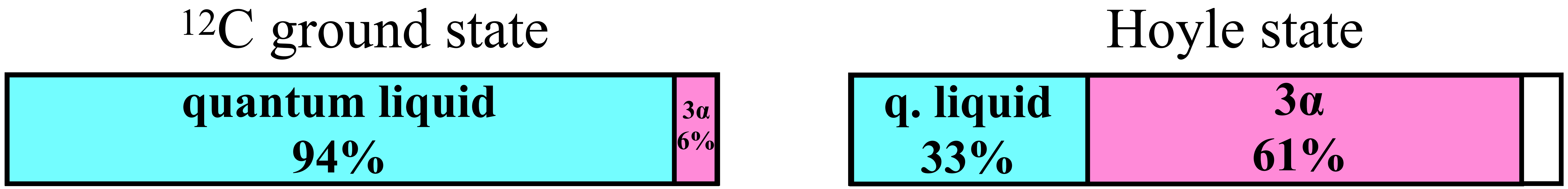
→ no (or much less) carbon and no life.

# Ab-initio calculation of the $^{12}C$ ground and Hoyle states

T. Otsuka, T. Abe et al., Nature Comm. **13**, 2151 (2022).

**Large-scale shell model calculation with 12 active nucleons & Daejeon16 interaction (from χEFT N3LO)**

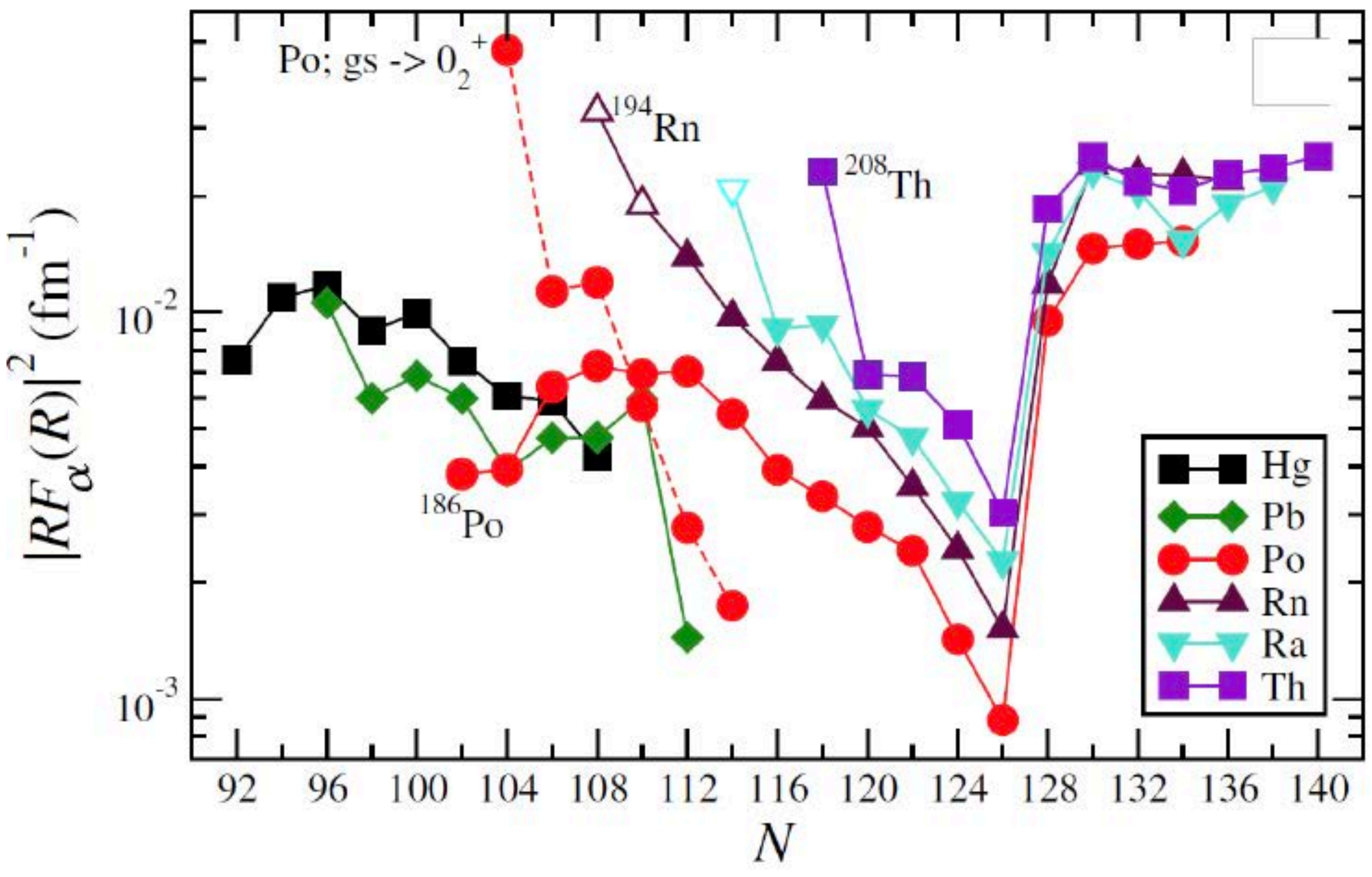


# Clustering at the north-east end of the nuclear chart

**Alpha preformation in α-decay nuclei homework since the discovery of α-decay and Gamow's model**

A. Andreyev et al., PRL **110**, 242502 (2013).

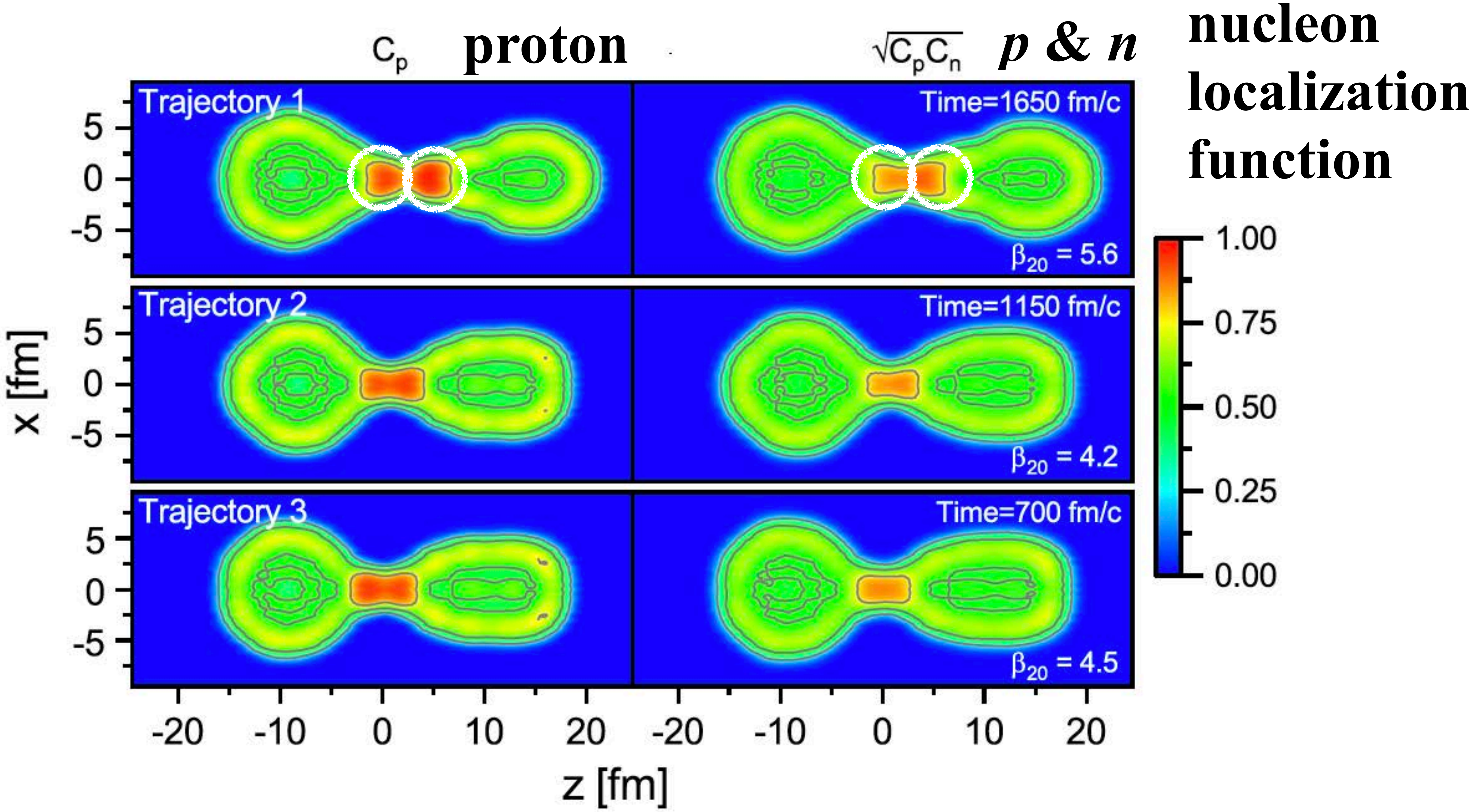



**Alpha clusters accelerate fission!**

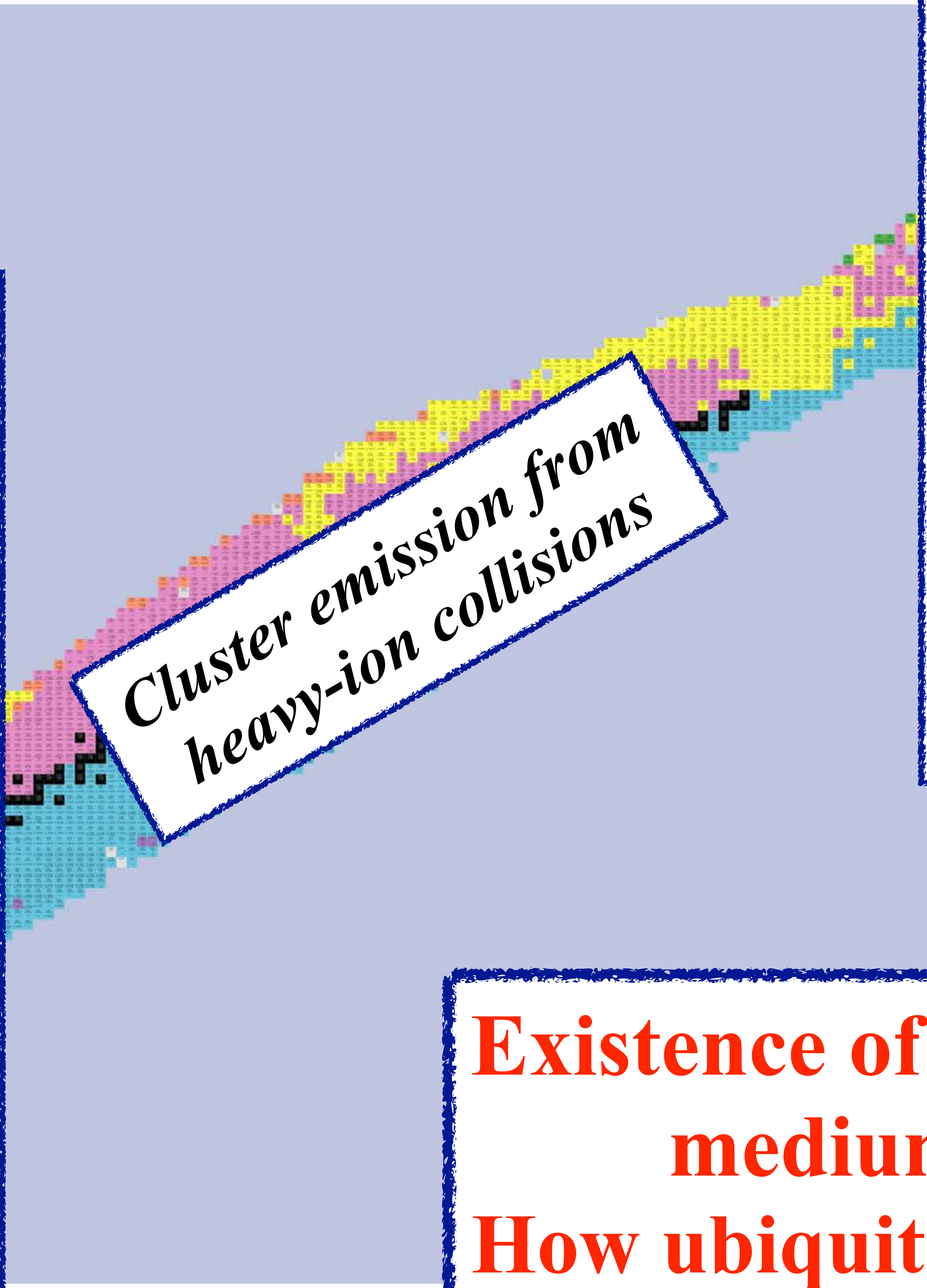
Z.X. Ren, D. Vretenar et al., PRL **128**, 172501 (2022).

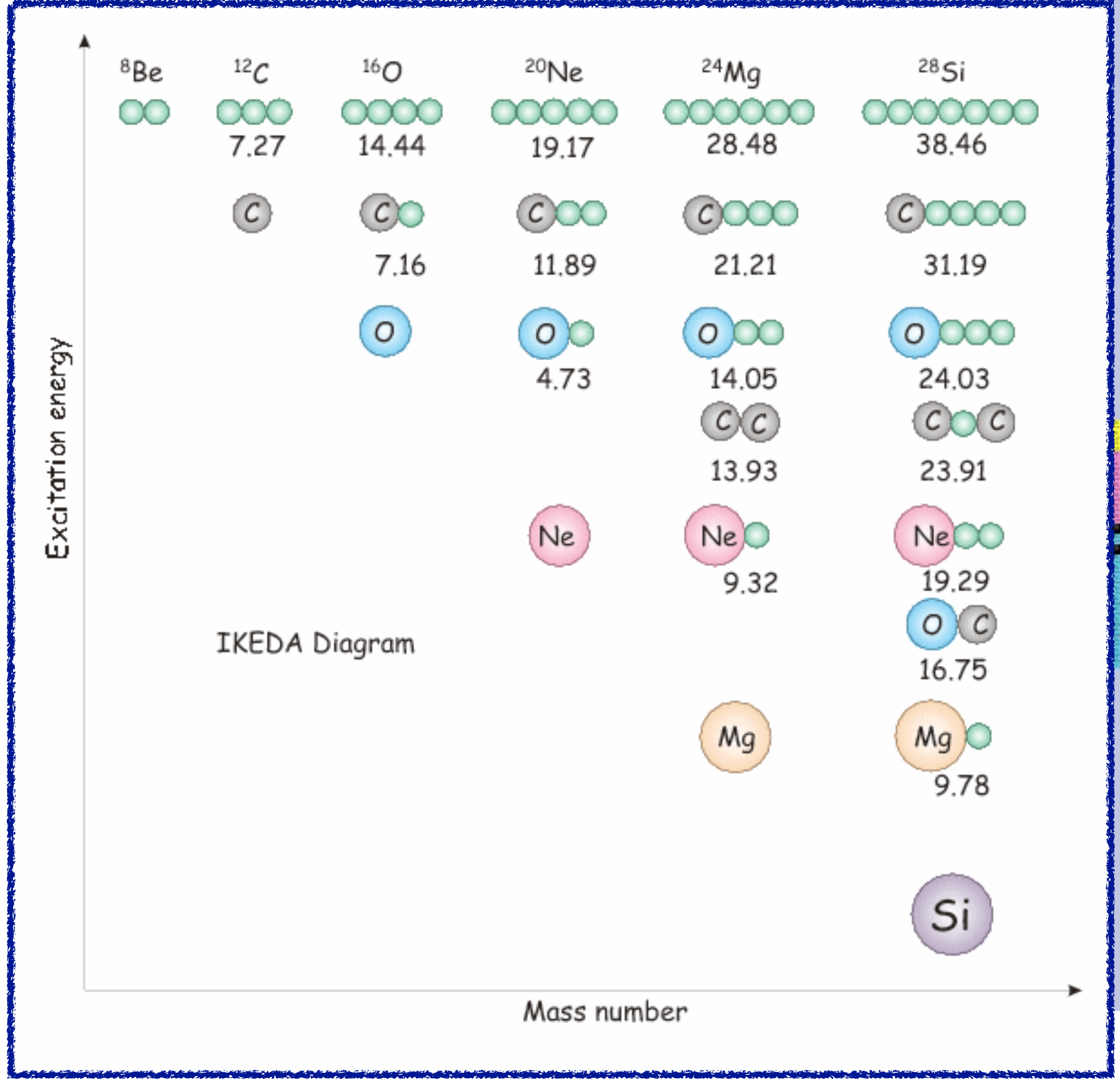
Time-dependent DFT predictions

**Two α clusters dynamically produced in the neck region accelerate the fission.**

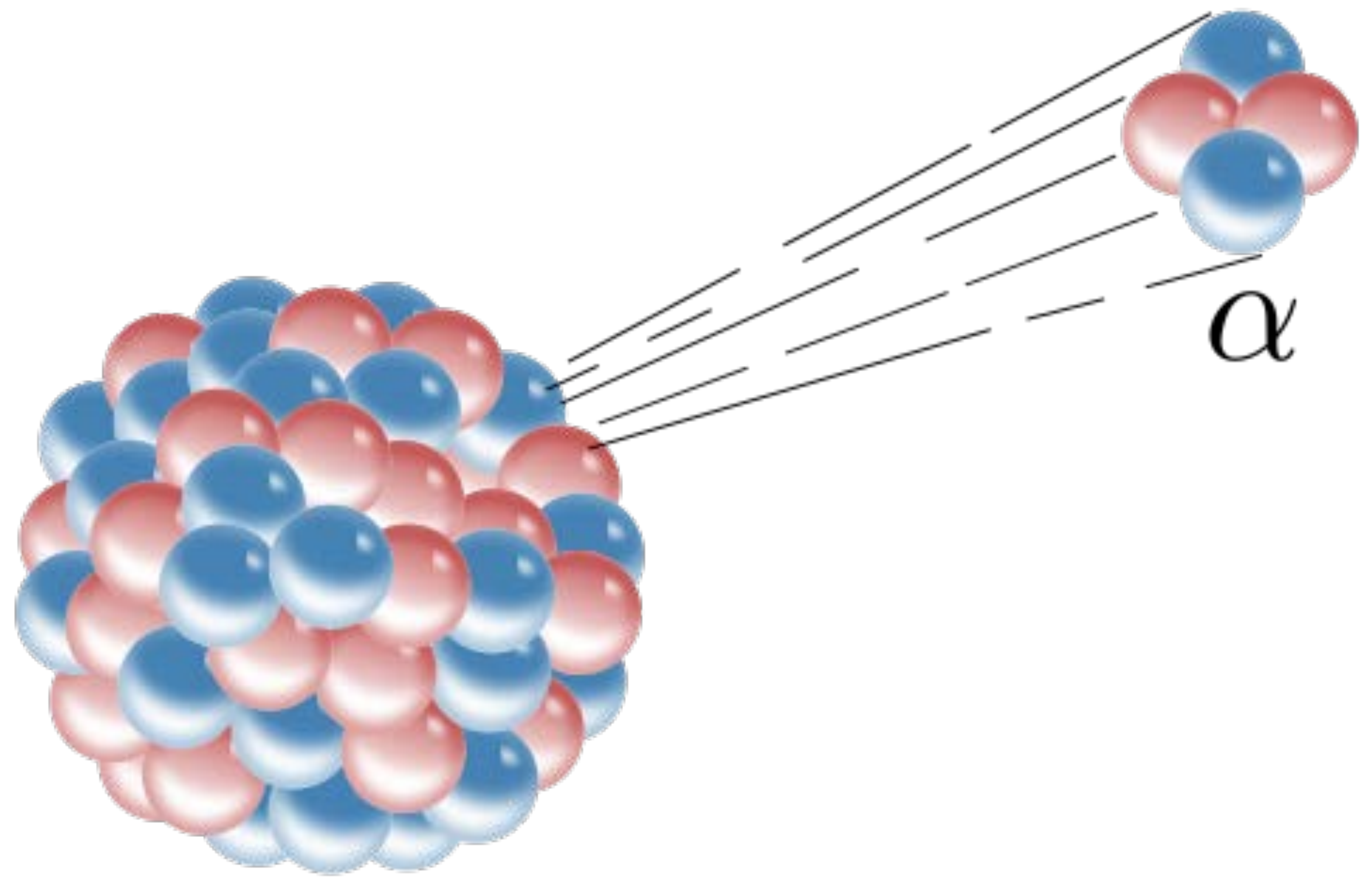


# Clusters are known to exist in light and heavy nuclei




*Cluster emission from heavy-ion collisions*




**QM tunneling**
**Preformation mechanism?**

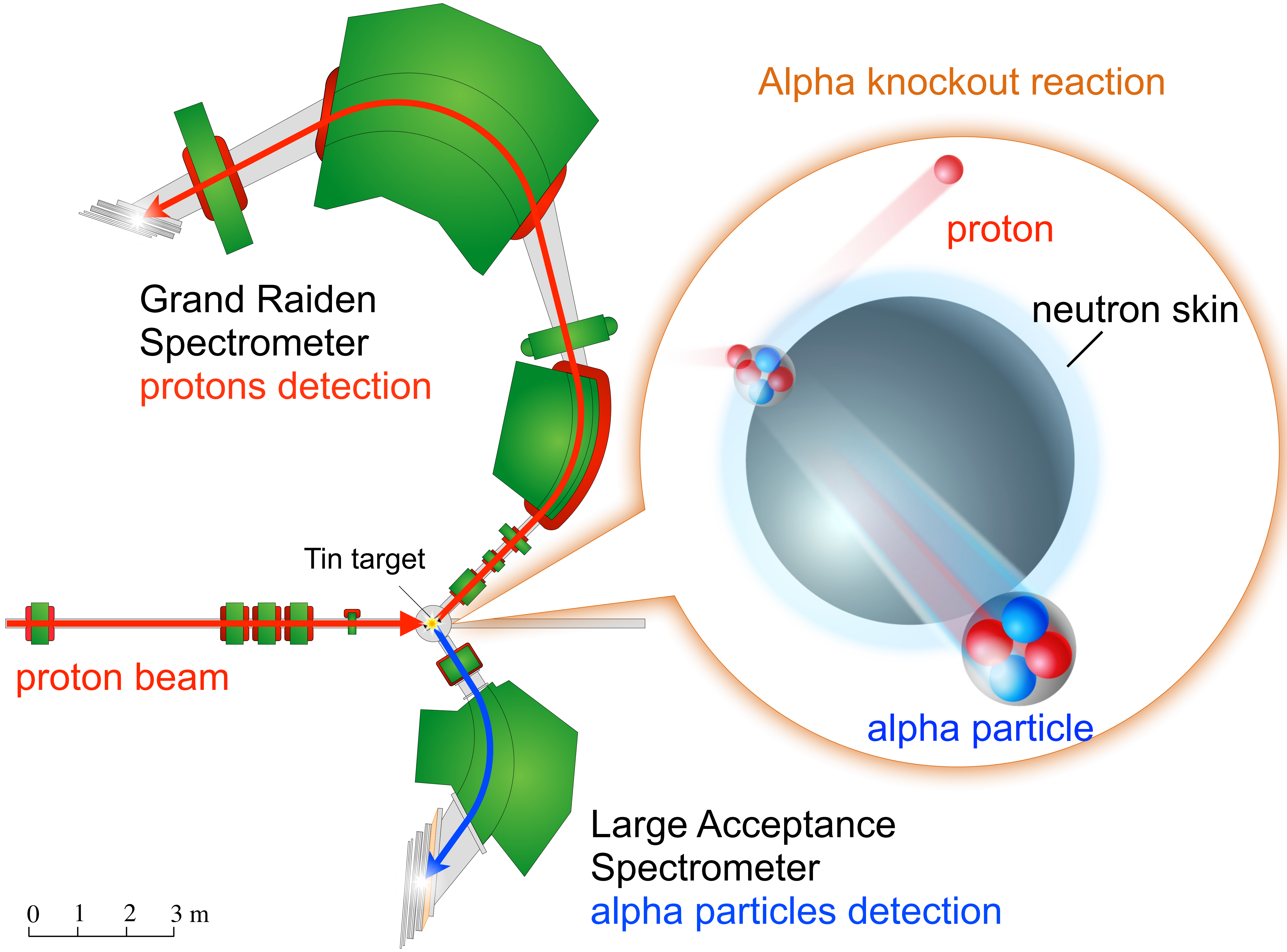
**Existence of clusters in medium to heavy nuclei?**
**How ubiquitous are clusters in nuclei?**

# α clusters in tin isotopes

REPORT

NUCLEAR PHYSICS

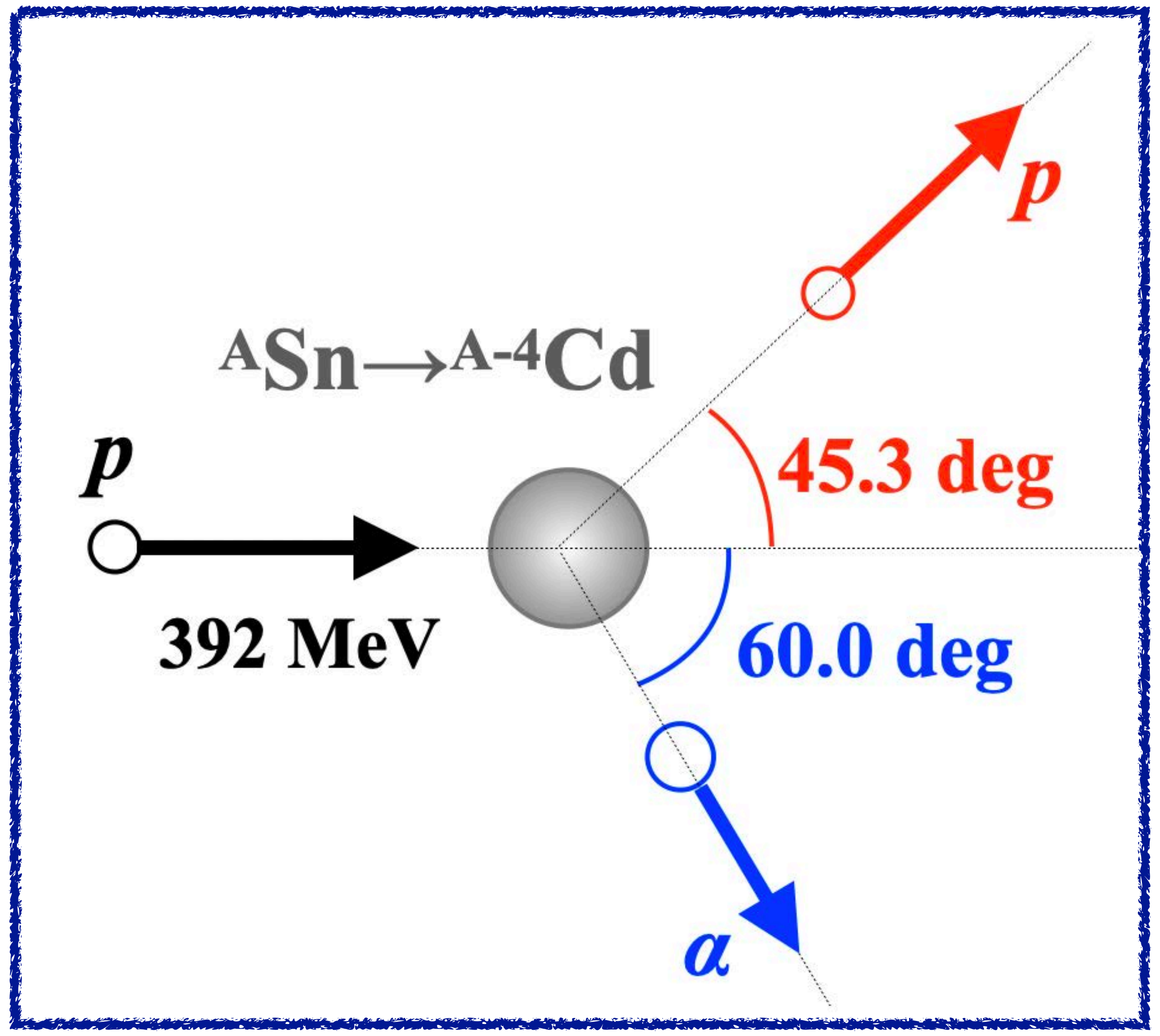
**Formation of α clusters in dilute neutron-rich matter**




$^{112,116,120,124}$Sn(p,pα)

@ $E_p$=392 MeV

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



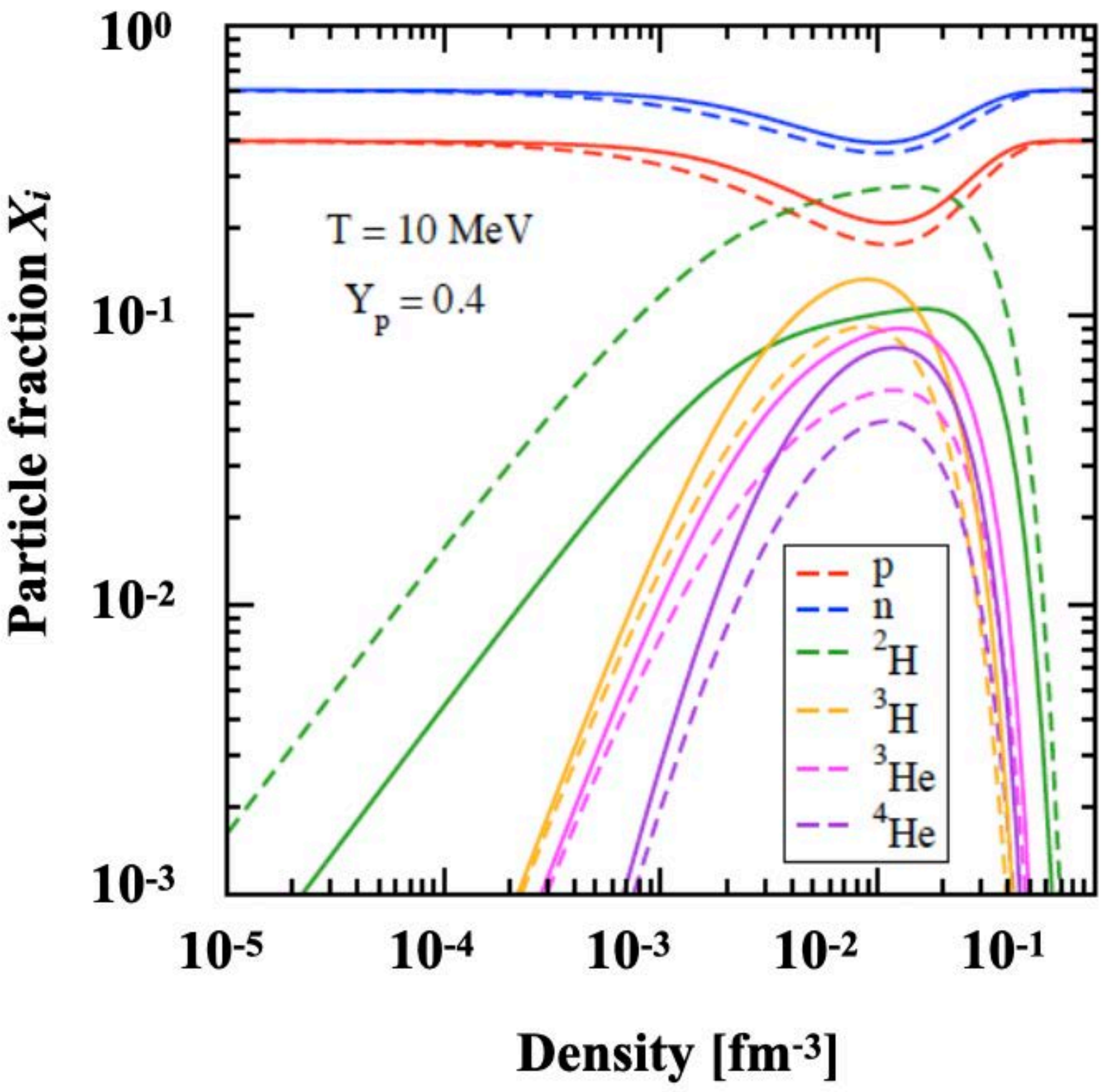
# Theoretical Background

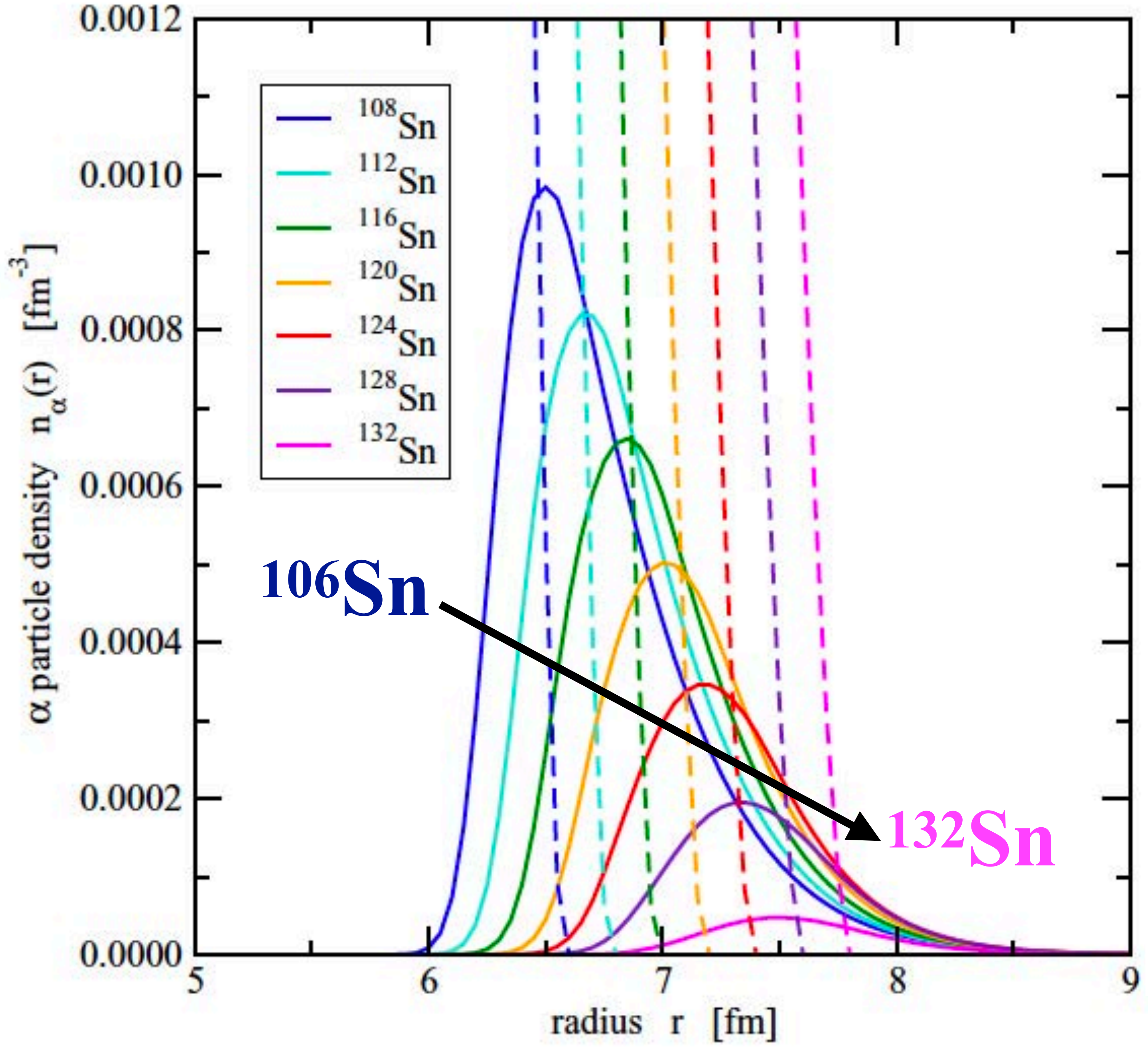
## Clustering in dilute nuclear matter

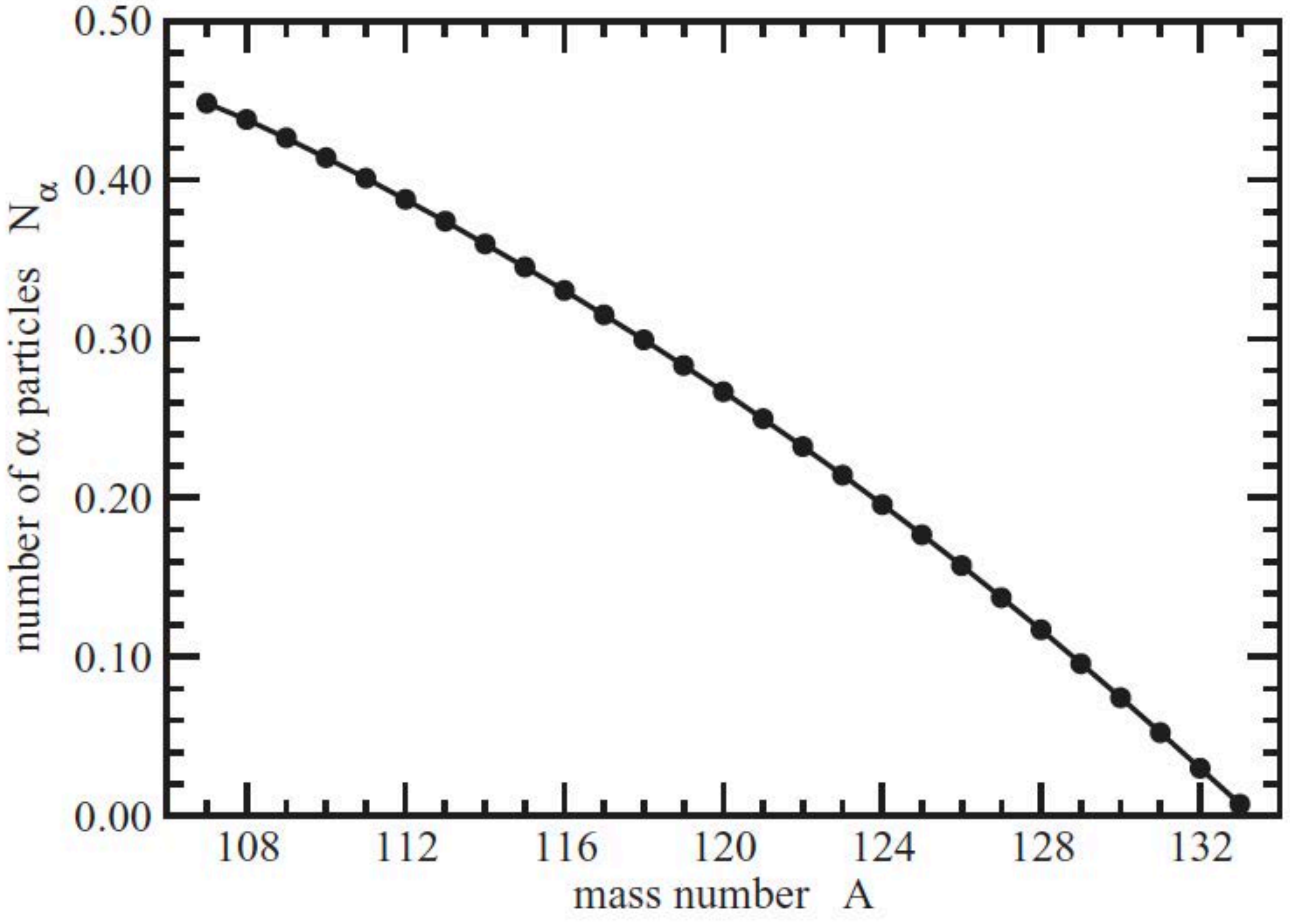
S. Typel,
J. Phys. Conf. Ser. 420, 012078 (2013)

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

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



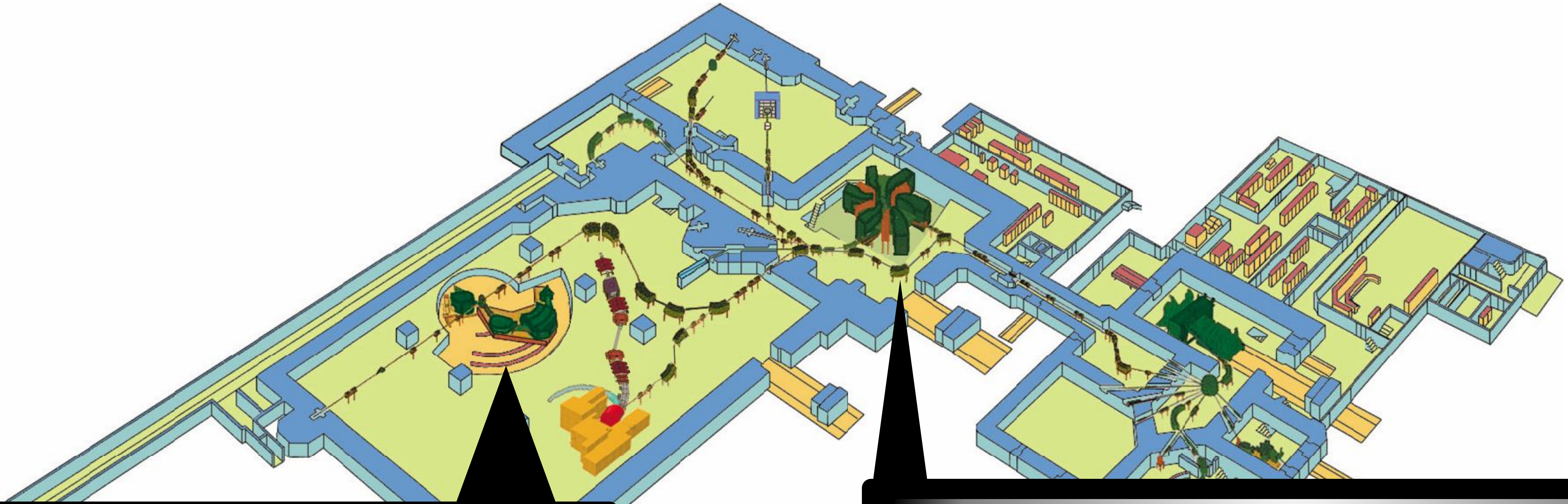



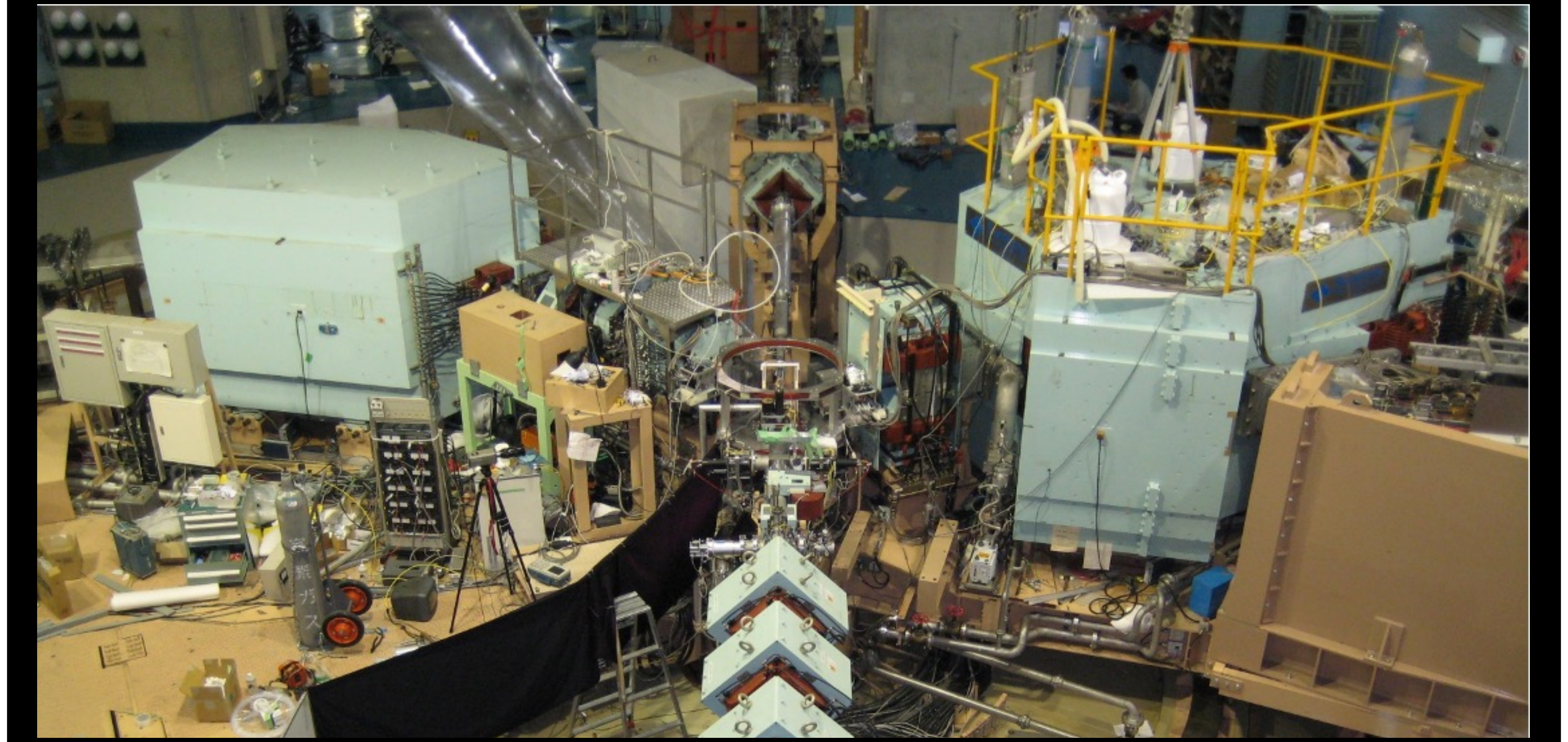

**Clusters grow at < 0.1 $\rho_{sat.}$**

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

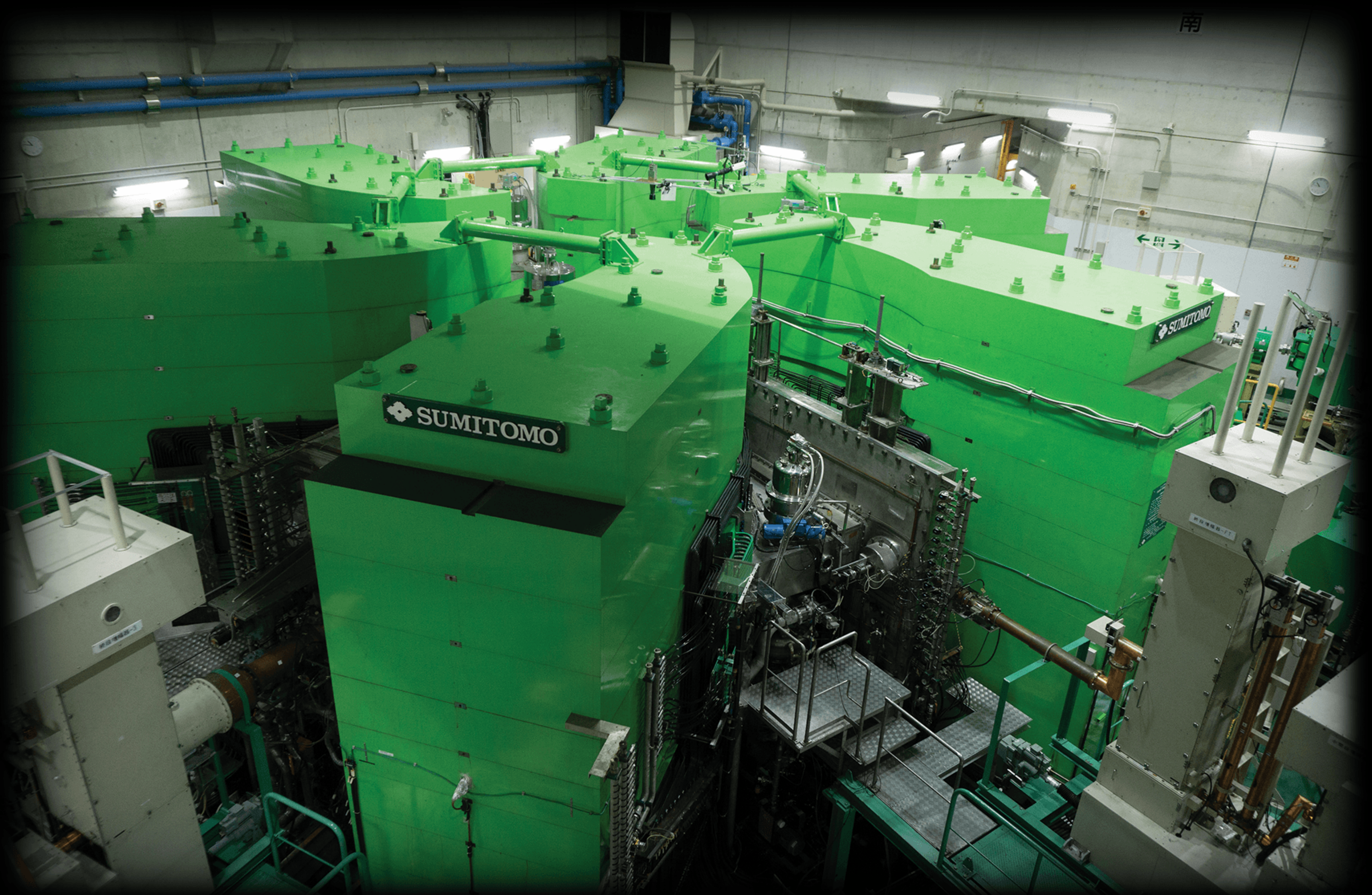
# Experiment at RCNP Osaka University



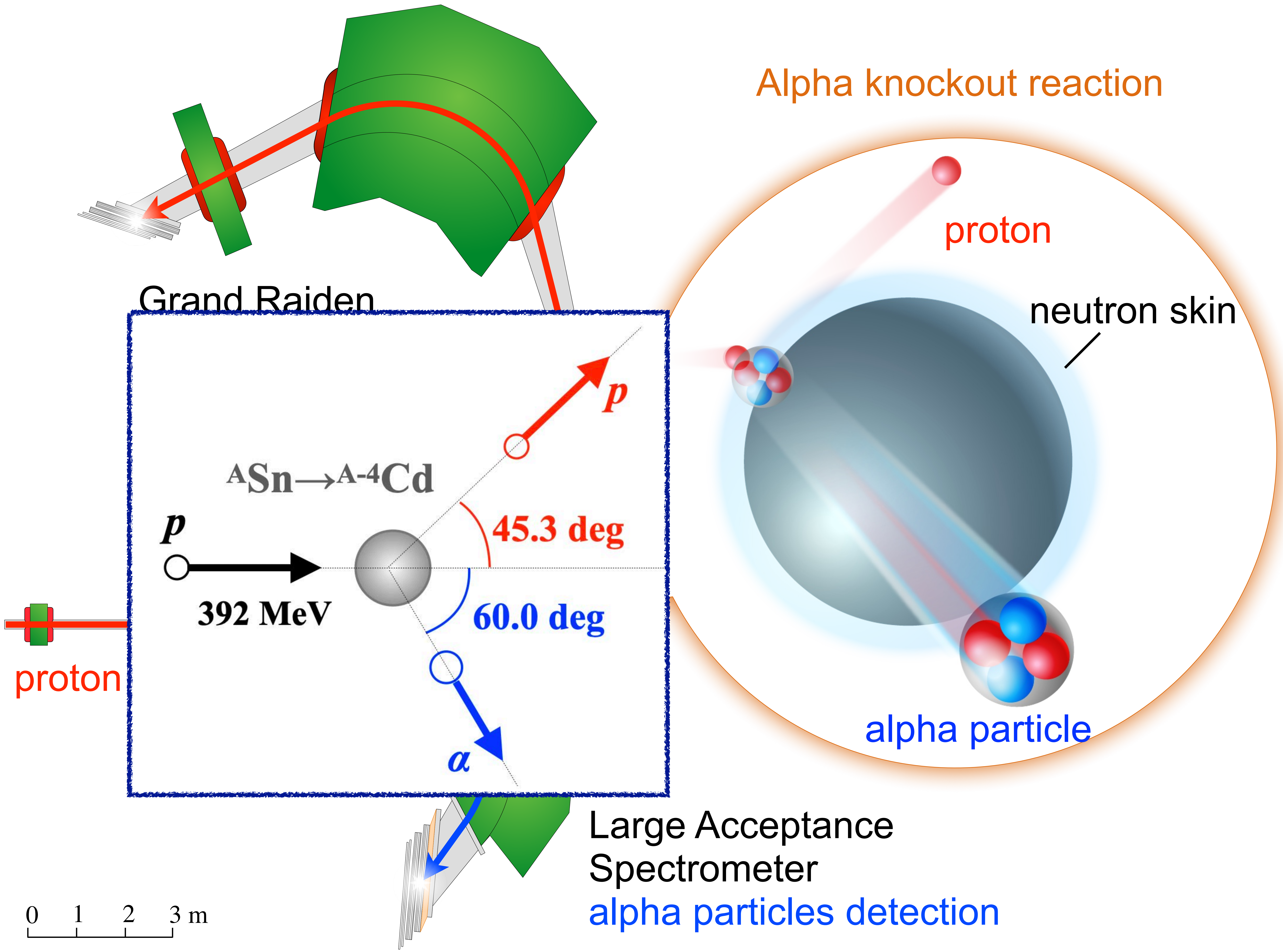
Grand Raiden and LAS spectrometers



Ring Cyclotron



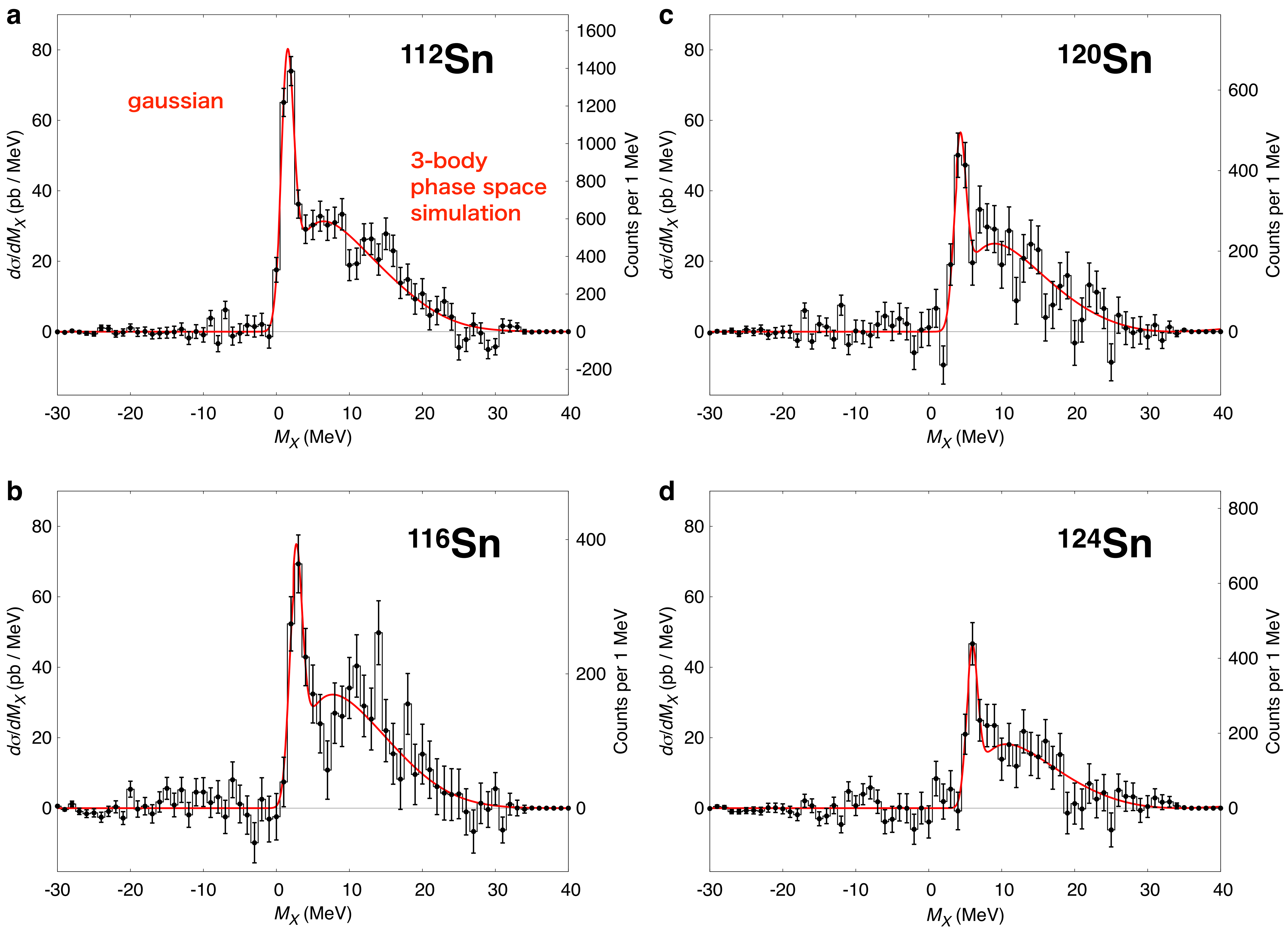
# $^{112,116,120,124}Sn(p,p\alpha)$ @ $E_p$=392 MeV



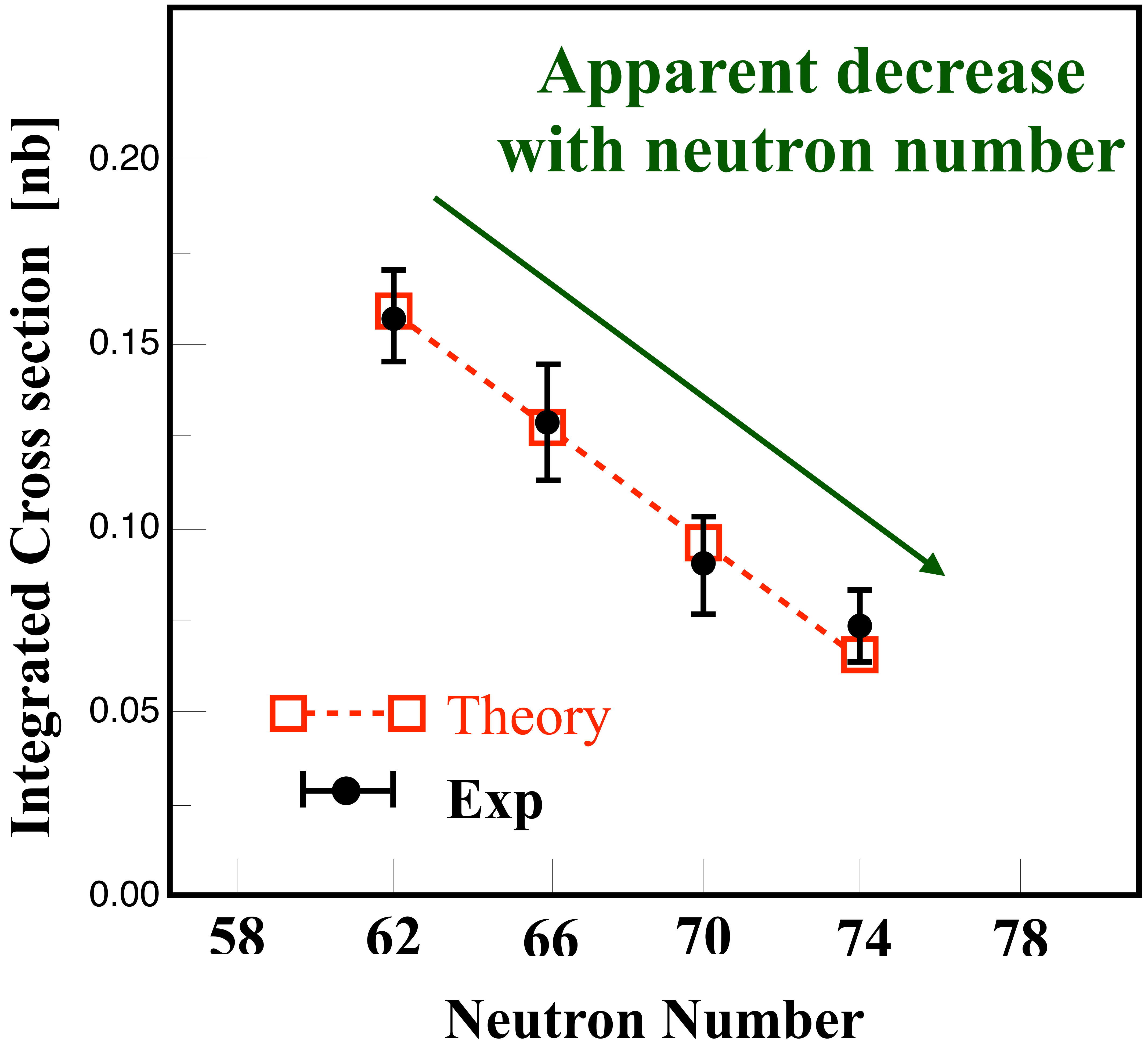
# What we observed

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

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

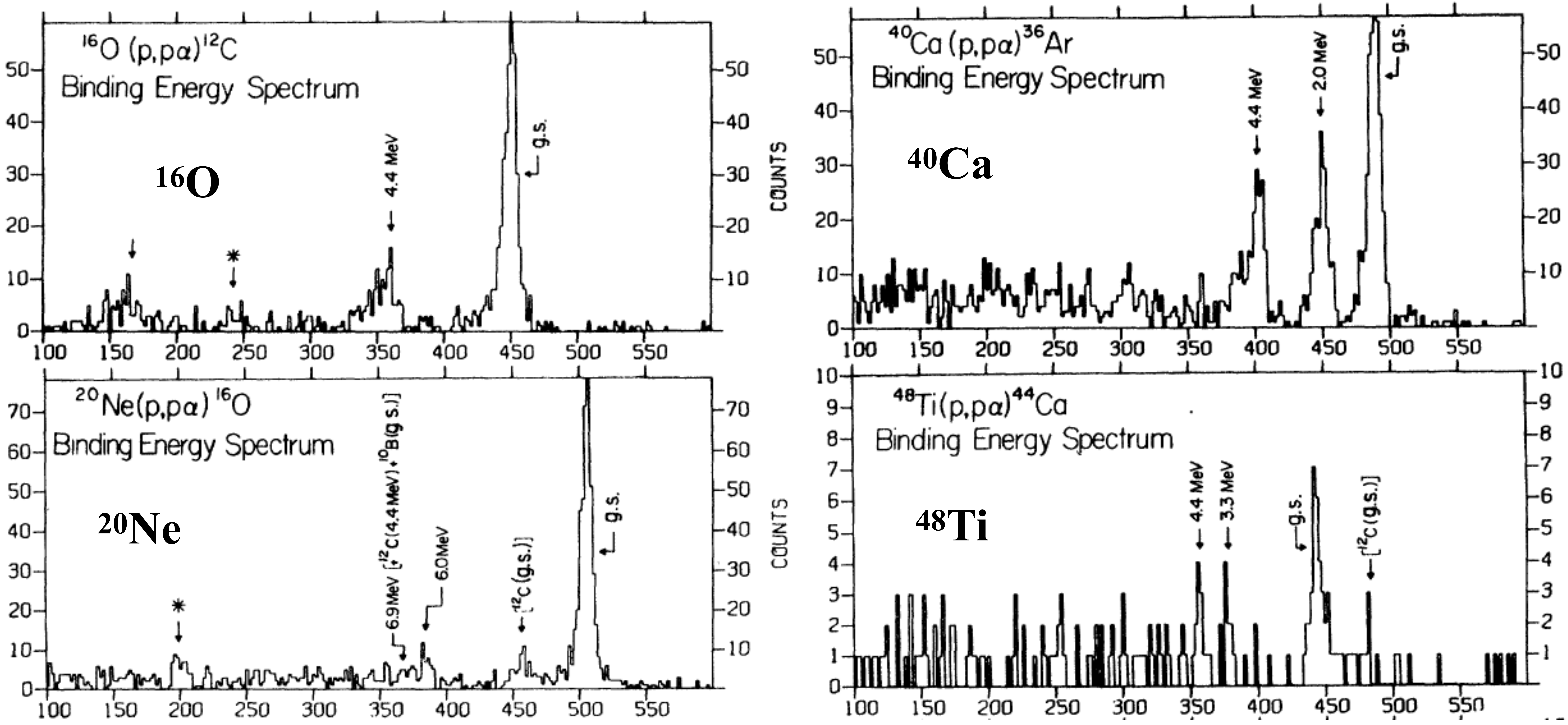



Excitation energy in Cd [MeV]



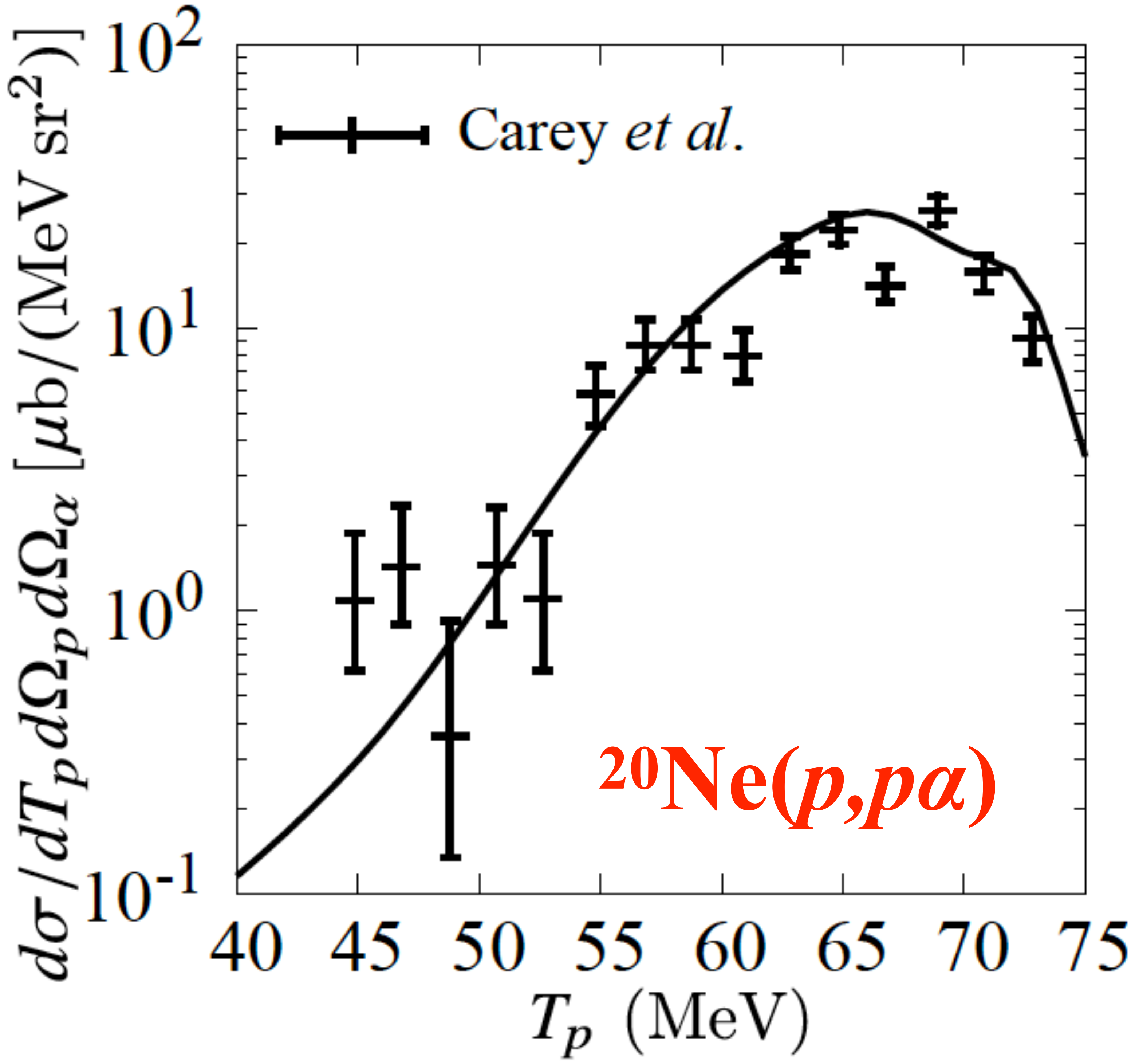
# Maryland results on (*p*,*pα*) at $E_p$ = 100 MeV

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



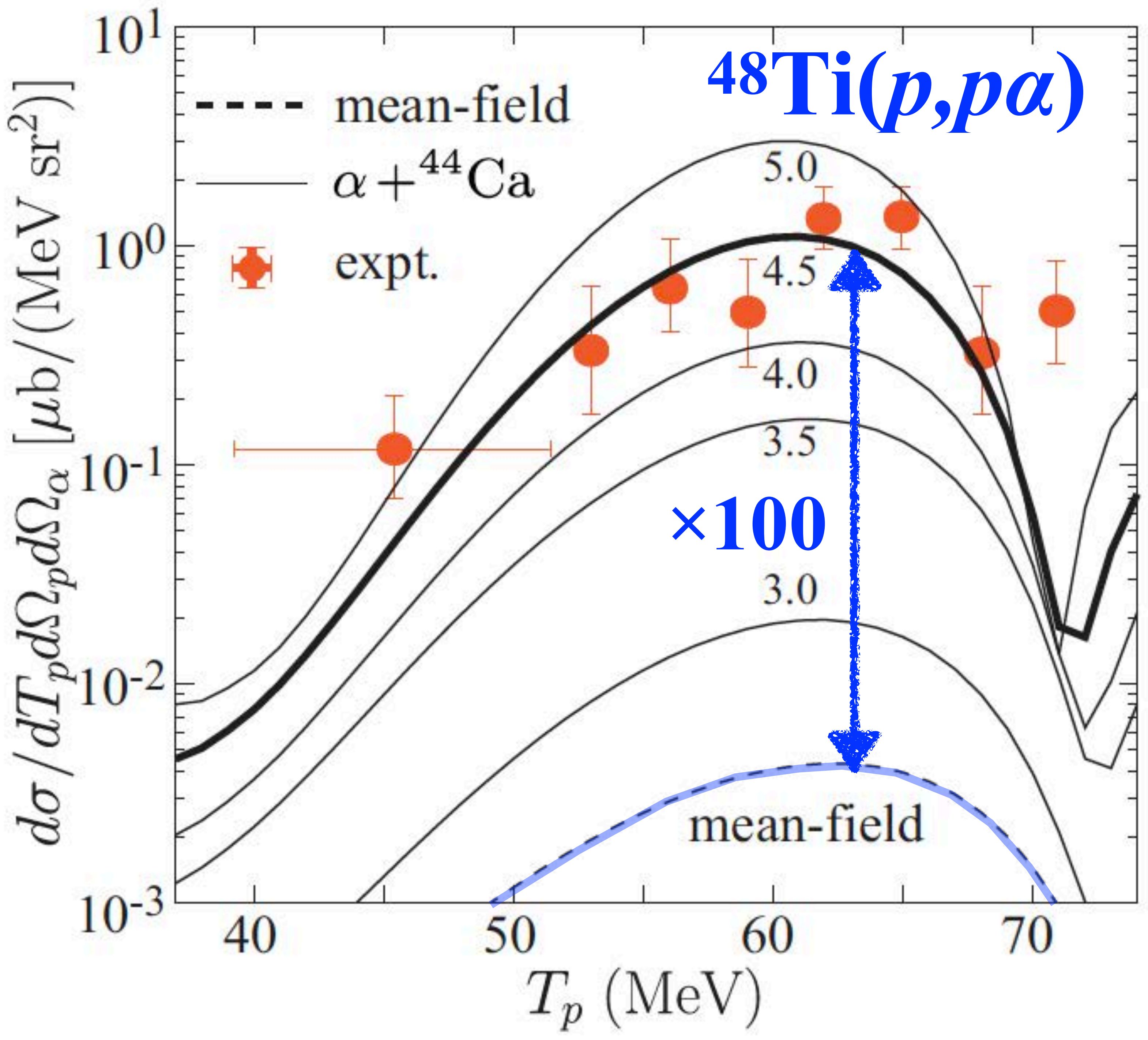
# Understanding the Maryland data

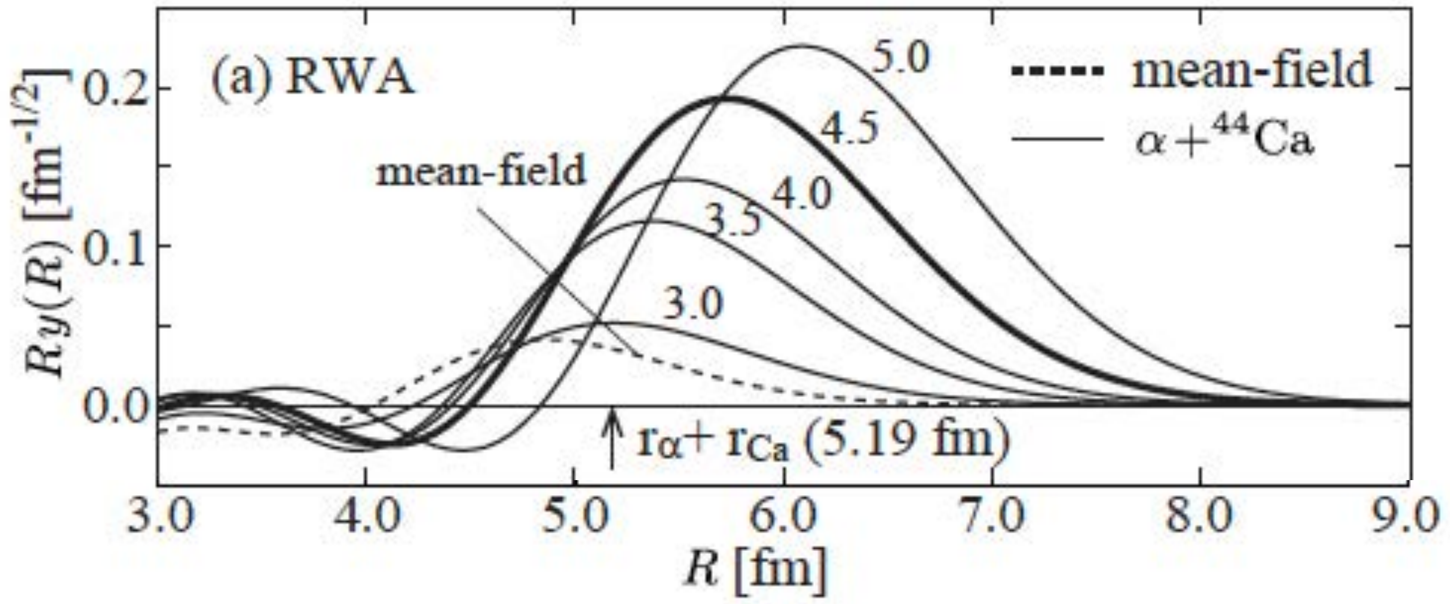
K. Yoshida et al.,
Phys. Rev. C 100, 044601 (2019).



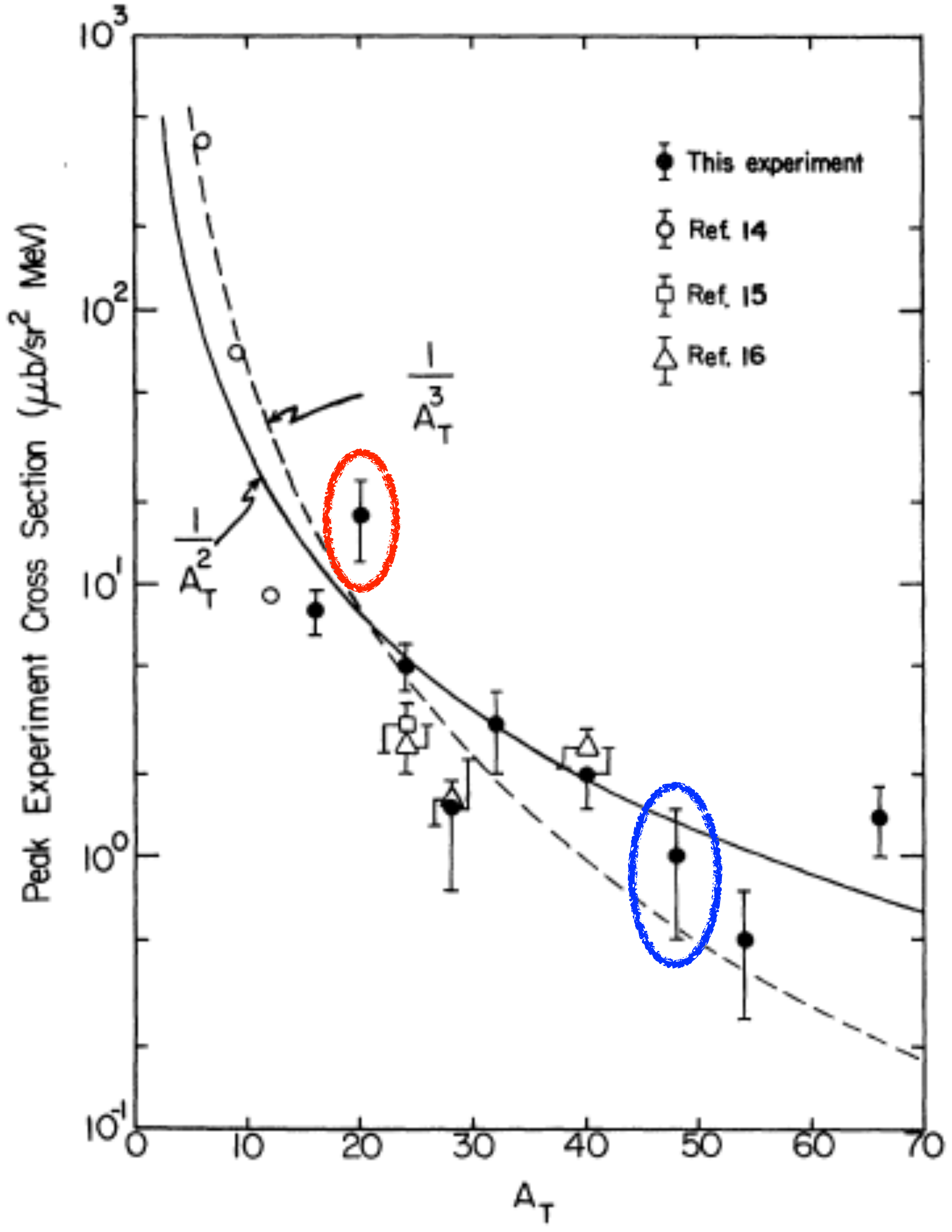

$S_\alpha$= 0.26

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



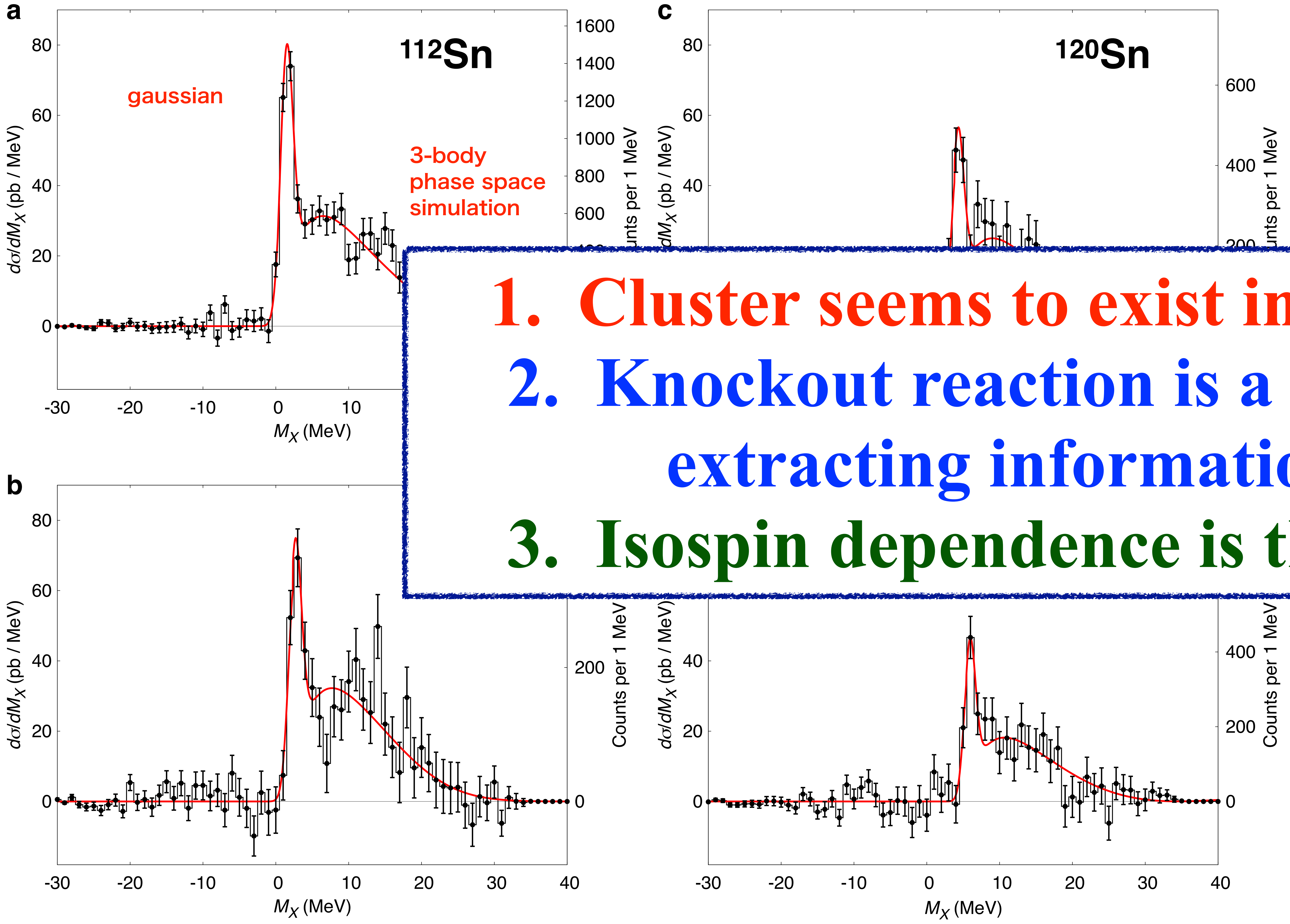

T.A. Carey et al.,
PRC **29**, 1273 (1984)




Missing mechanism?

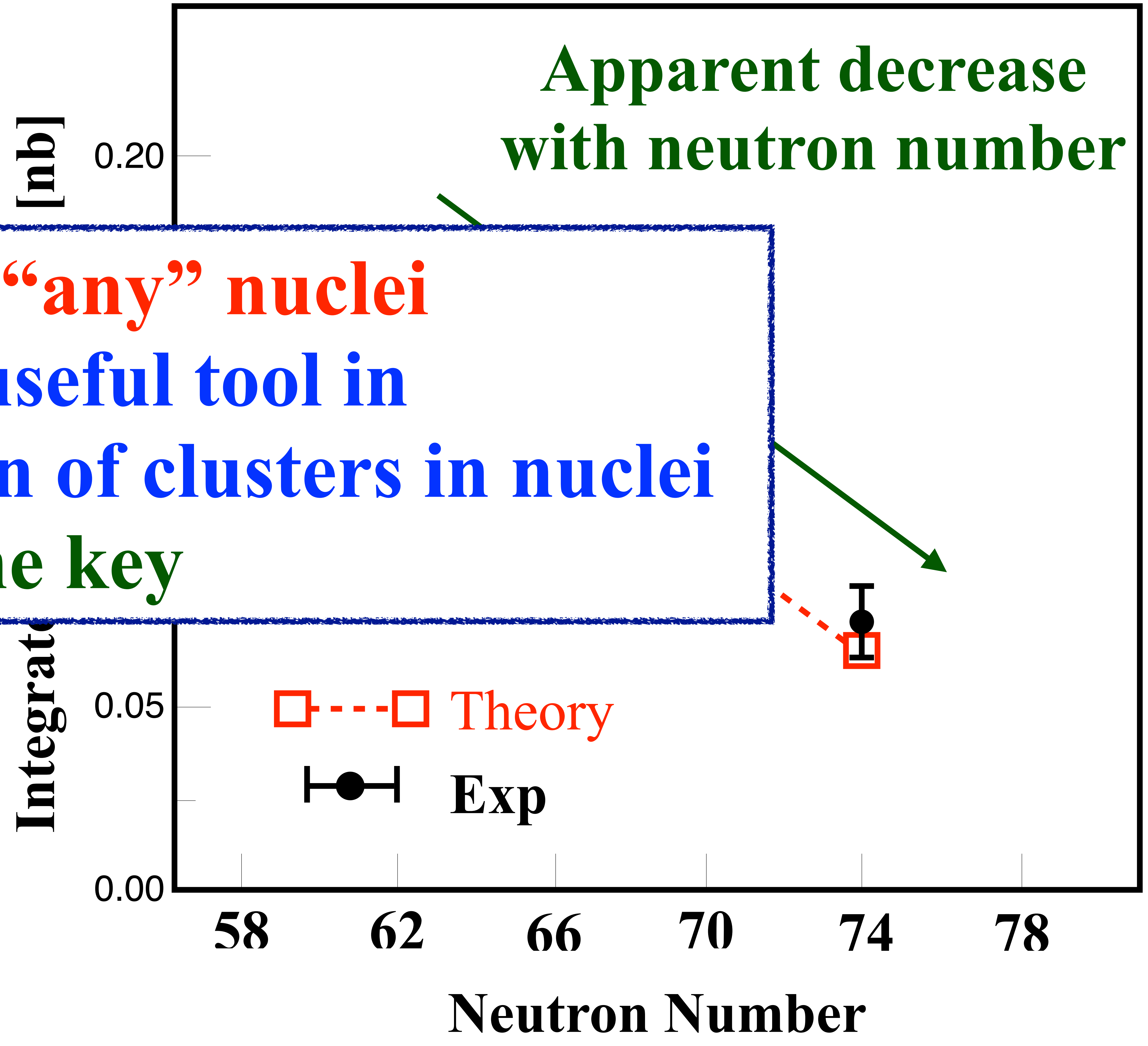
# Lessons from the Sn($p,p\alpha$) experiment

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




Excitation energy in Cd [MeV]

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**



# Beyond the simple pictures of clustering

**Coexistence of clusters with shell-like (independent nucleon) components**

**Occurrence of clusters**

**in states other than those near the thresholds (e.g. ground states)**

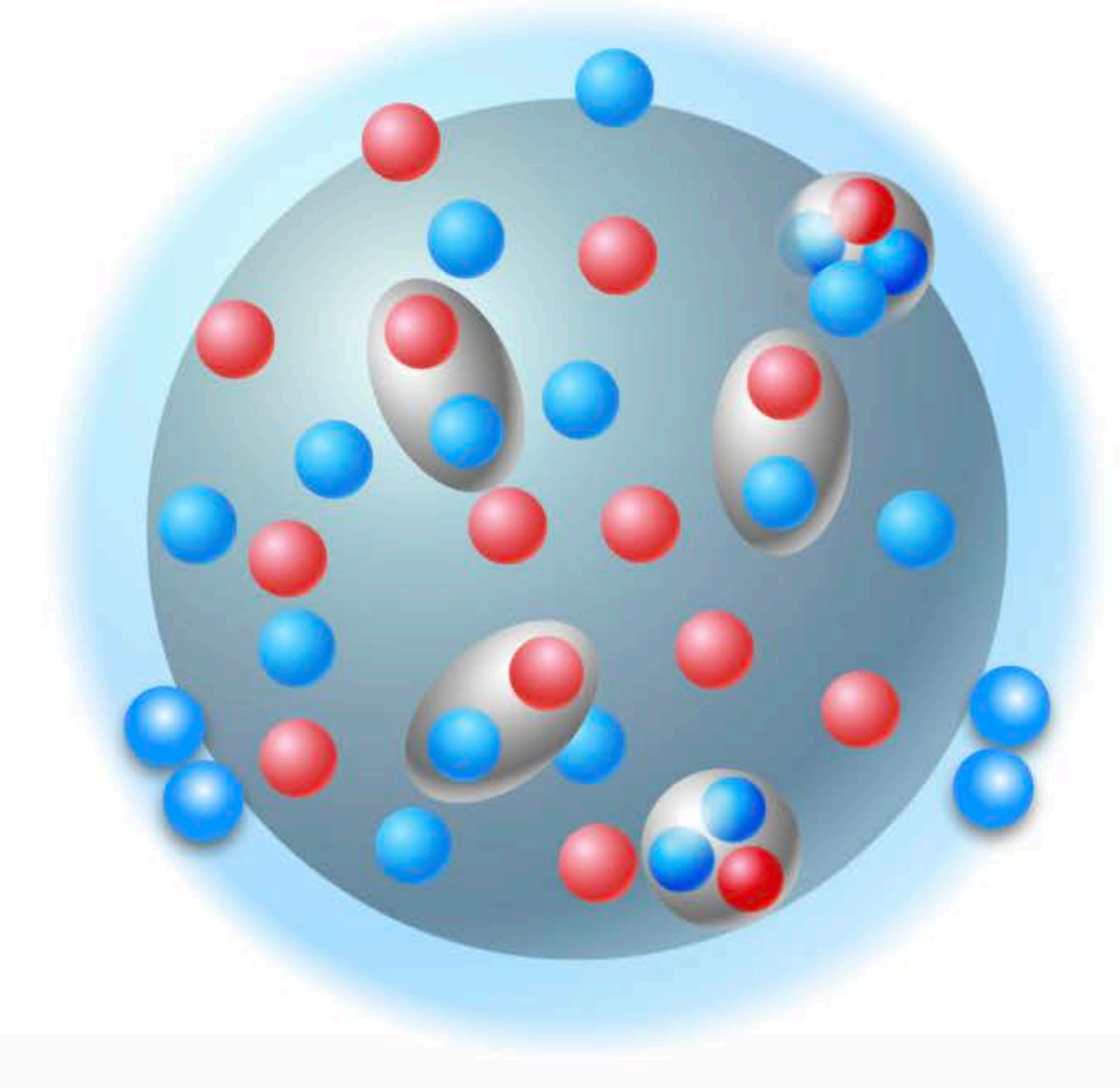
**in any nuclei where the cluster development was not previously discussed.**

**"Cluster ubiquitousness"**

**Existence of clusters more weakly bound than α particle**

**such as *d*, *t*, $^{3}$He, $^{2}n$, $^{4}n$ etc.**

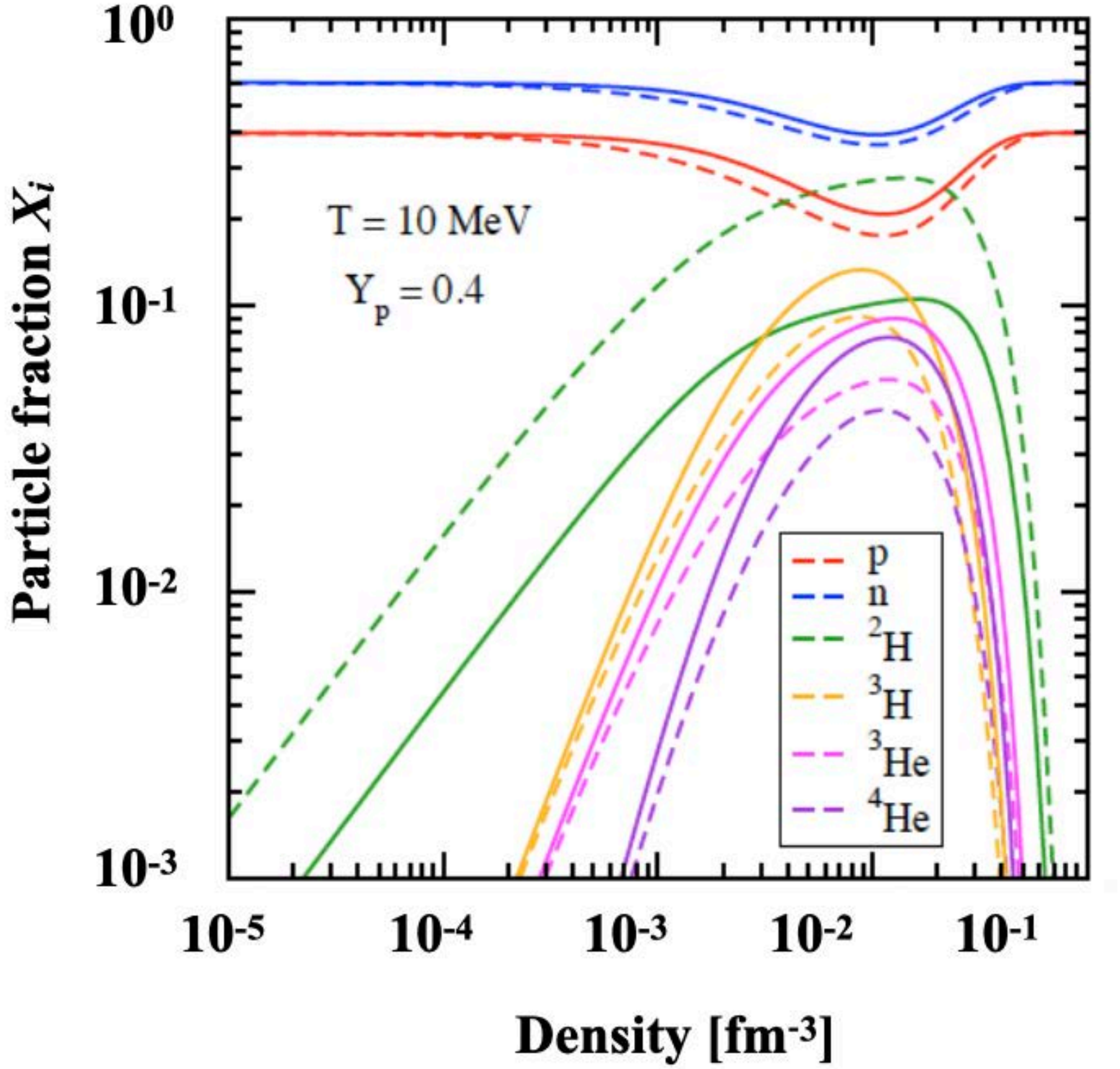
**"Generalized clusters"**



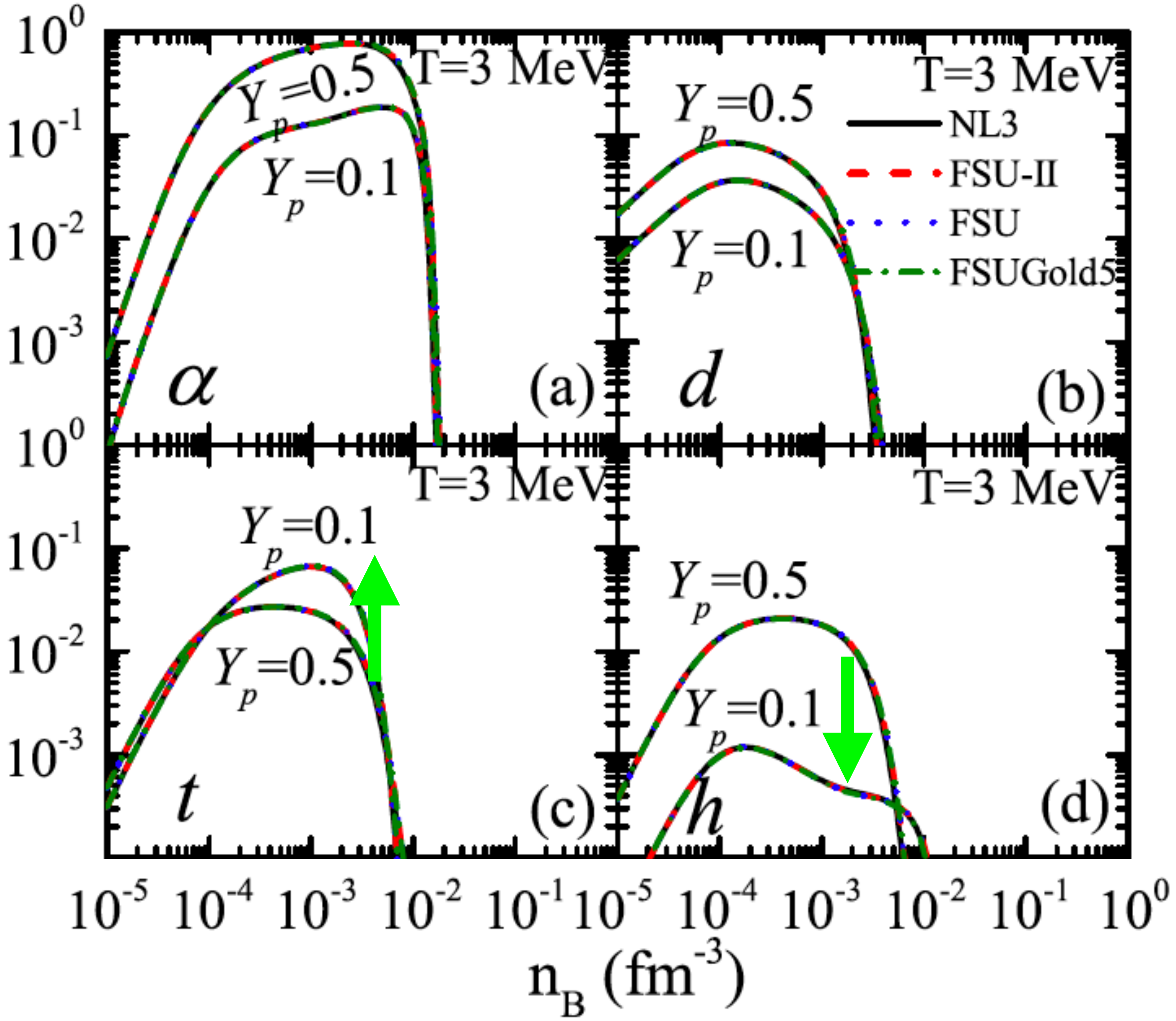
T. Uesaka & N. Itagaki, Phil. Trans. R. Soc. A **382**:20230123 (2024).

# Interests in clusters other than α

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




**Z.W. Zhang and L.W. Chen**
Physical Review C 95, 064330 (2017)




All the clusters grow at < 0.1 $\rho_{sat}$, but their relative abundances differ theory by theory.
Occurrence of clusters depends on the cluster's isospin and isospin asymmetry of the medium.

# Looking for all the clusters in stable and unstable isotopes

## ONOKORO Project

# Clustering in medium-heavy nuclei studied with knockout reactions

($p$,$p$<u>$X$</u>) @ E/A = 200—300 MeV
$X$: $d$, $t$, $^3$He, α

ONOKORO

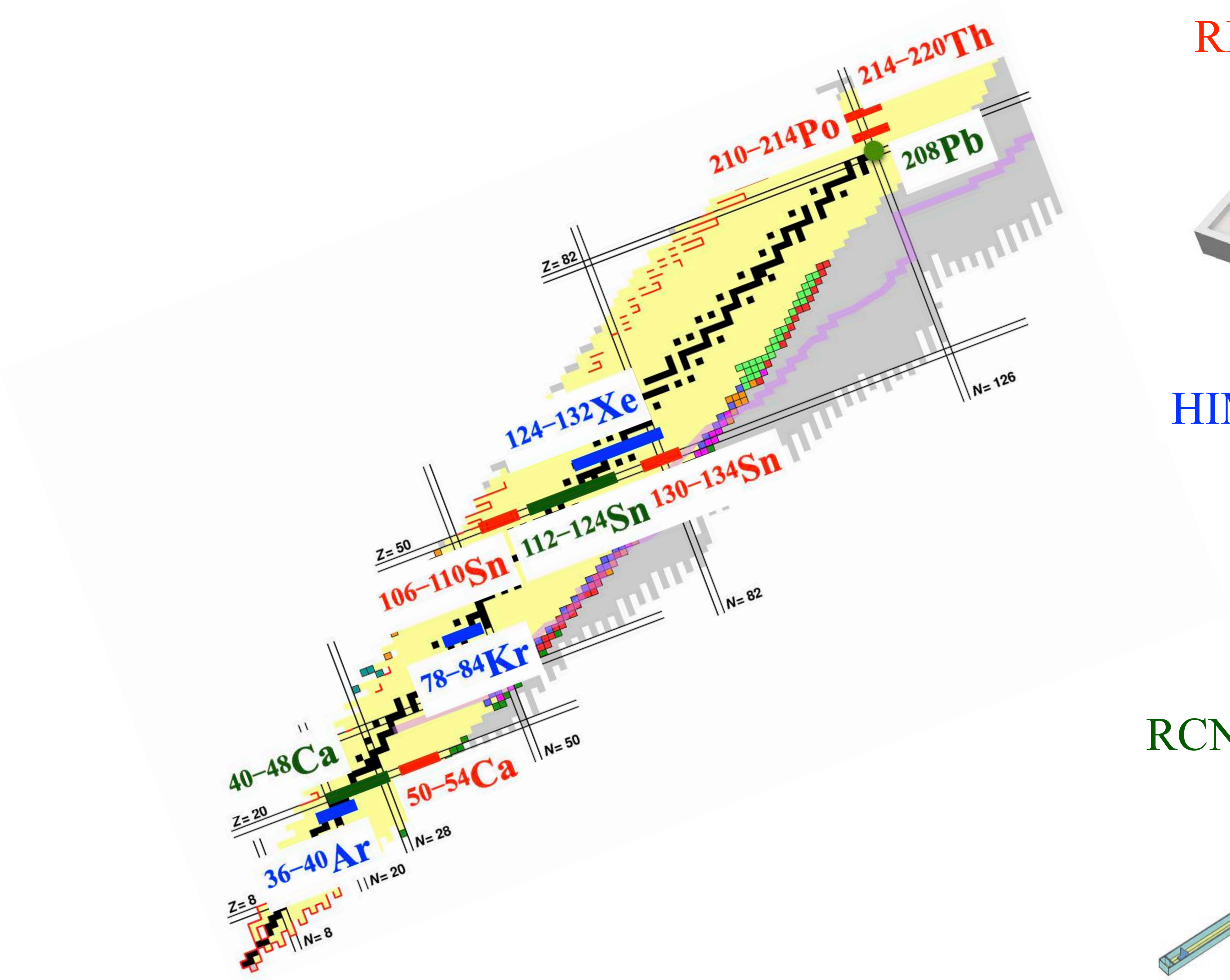
**Wide mass region**
**A=40−220**

×

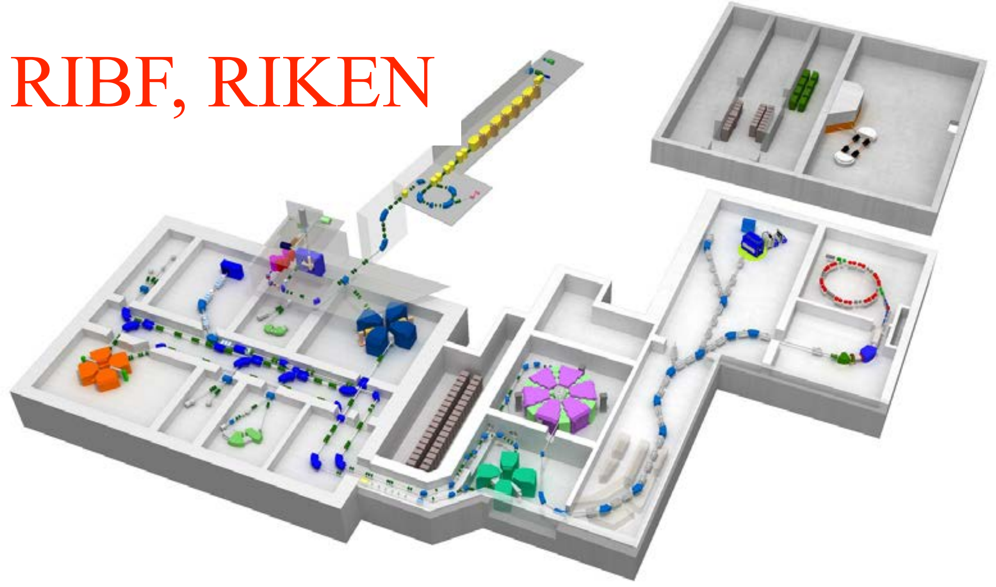
**Stable and unstable nuclei**

×

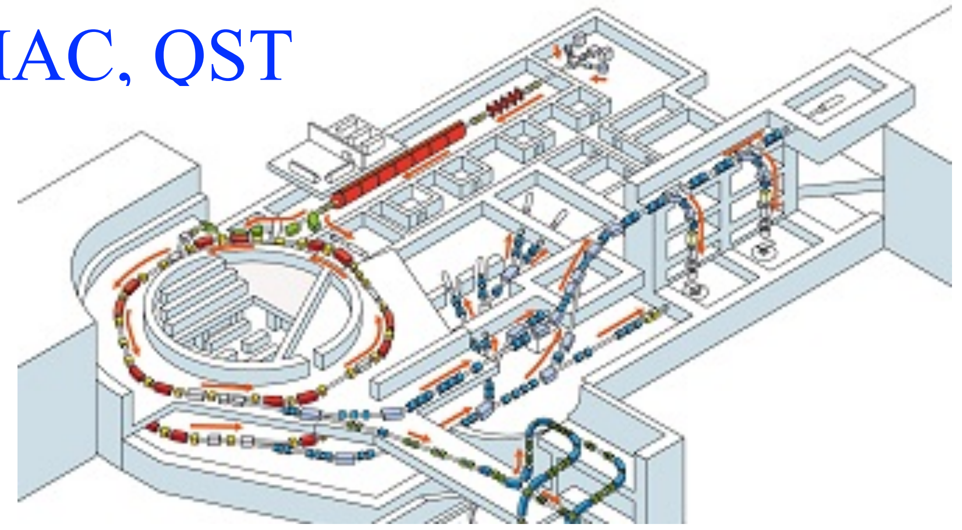
**All the light clusters**
**d, t, $^3$He, α …**



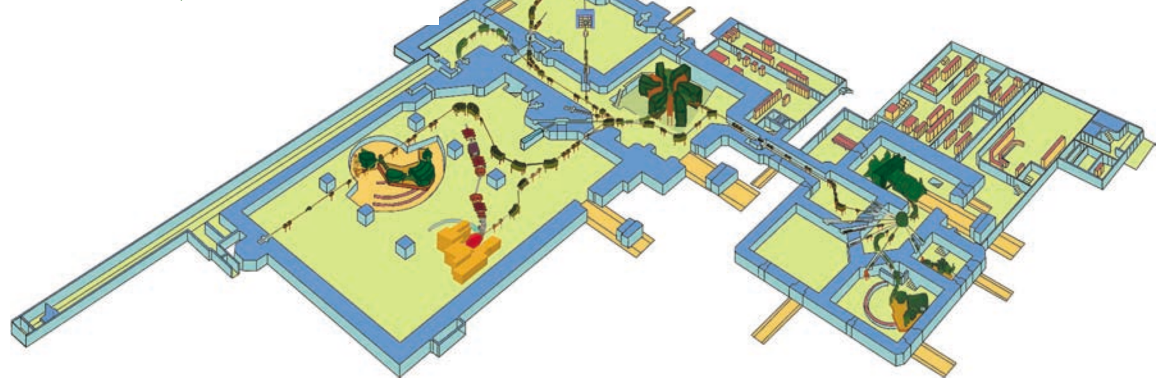

RIBF, RIKEN

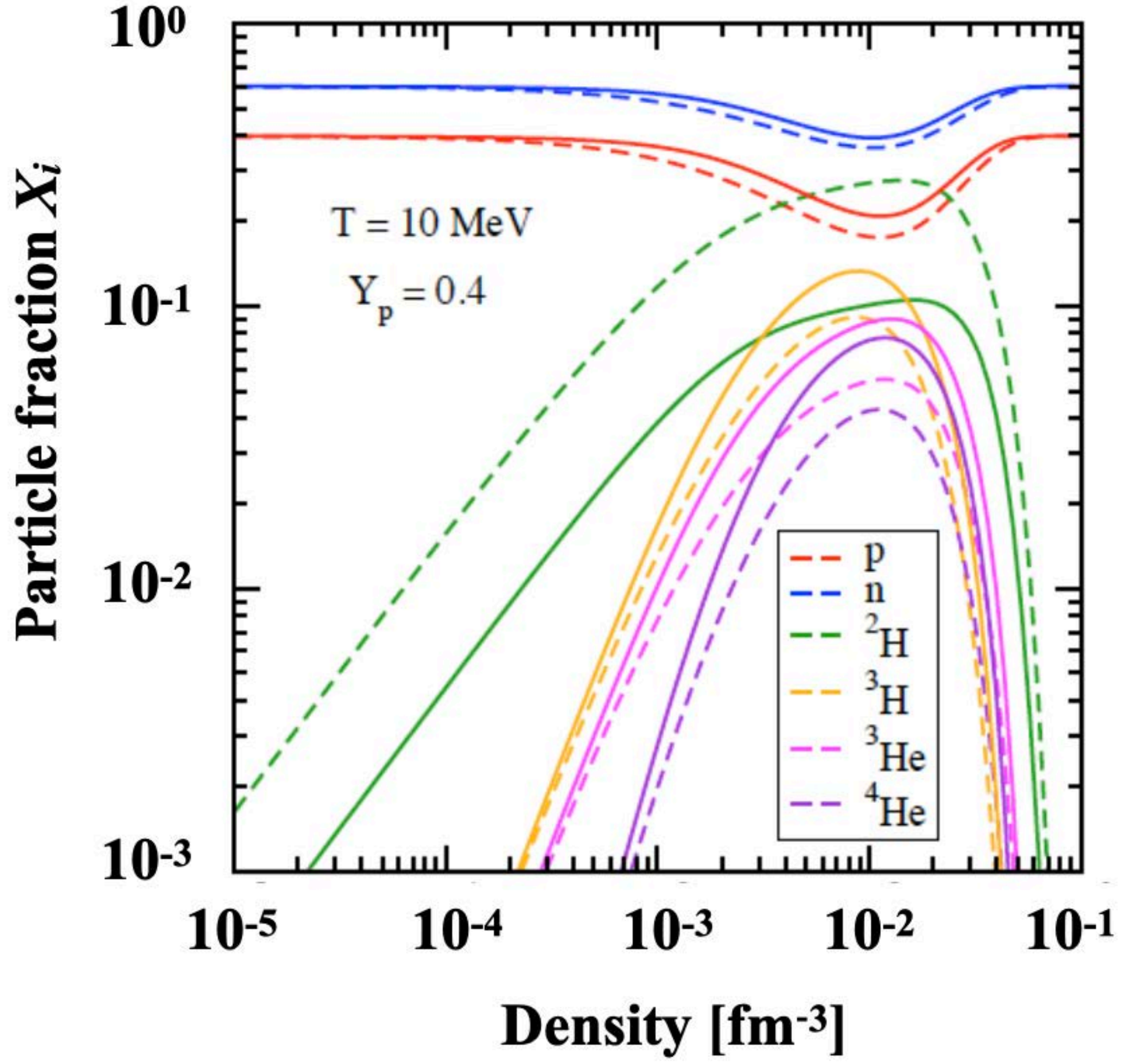


HIMAC, QST



RCNP, Osaka





# ONOKORO Project: study of clustering in medium to heavy nuclei

- Questions to be answered

  How can the mean-field picture be compatible with that with clusters?

  The peculiarity of low-density surface?

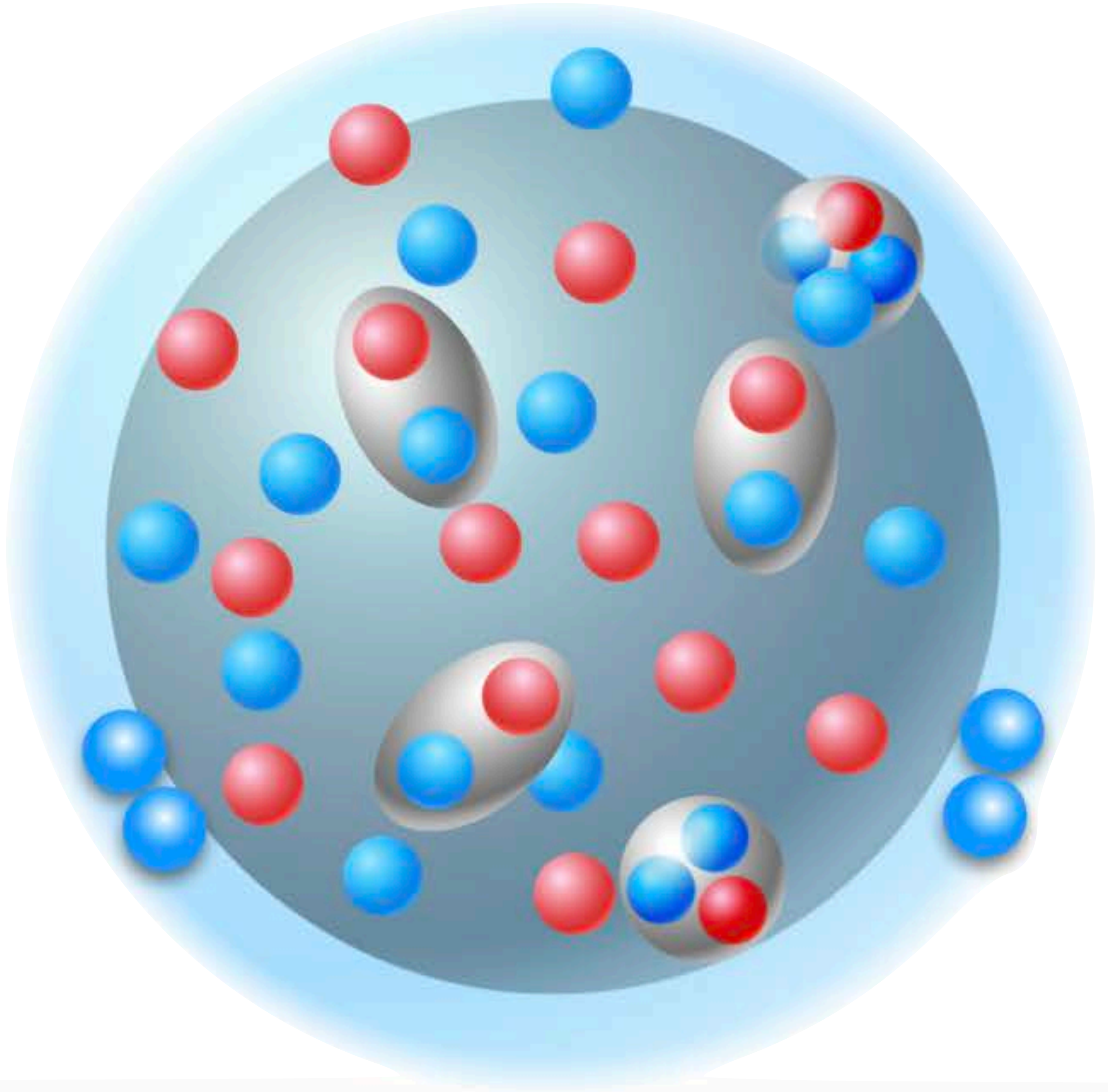
- Focus on the isospin dependences of the clustering

- Interests specific to each cluster

  Possible access to α preformed in α-decay nuclei

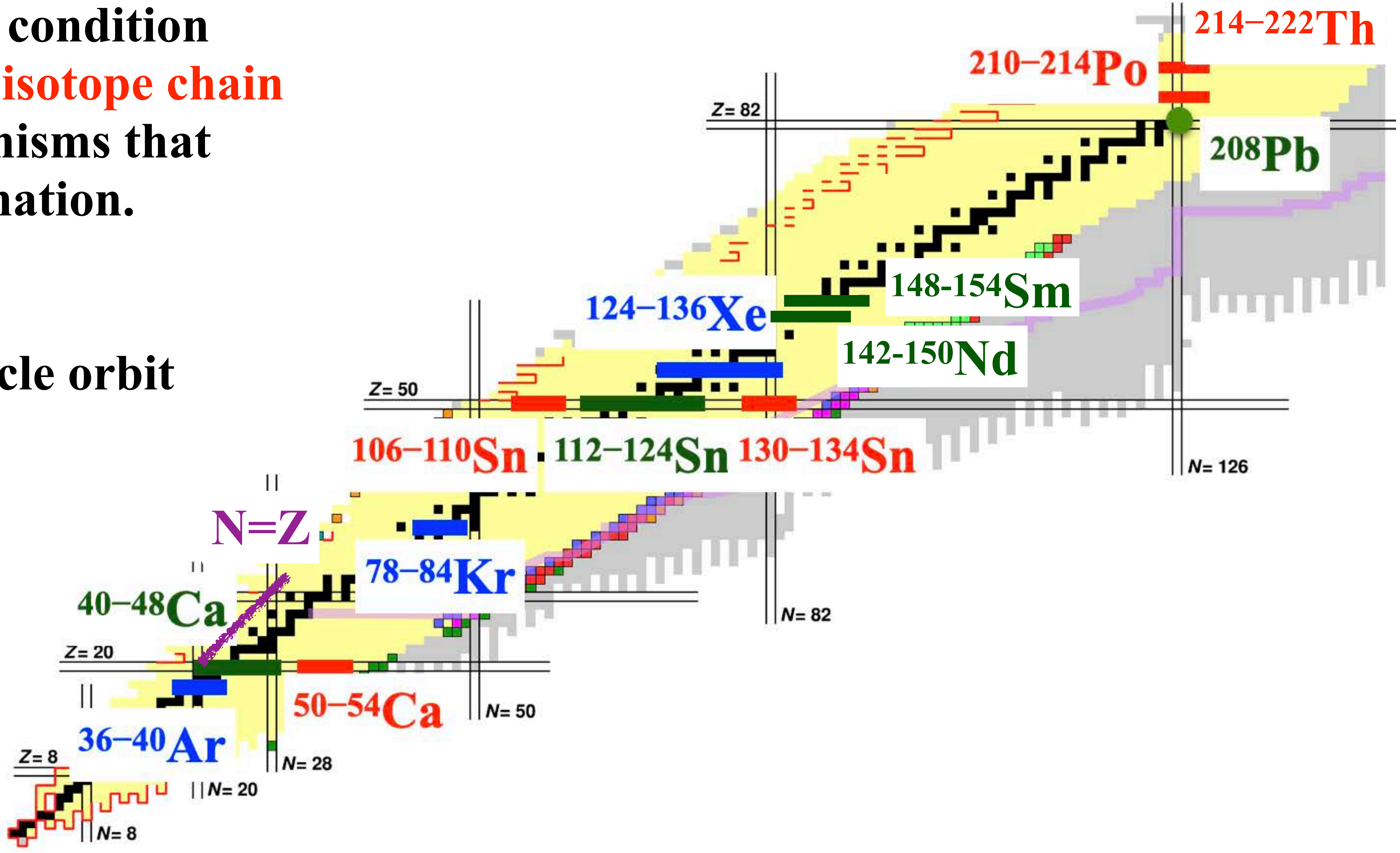
  Search for deuteron clusters which embody tensor-correlations in nuclei

  First determination of t/$^3$He ratio



# Experiments under ONOKORO project

**Cluster knockout reactions at $E \sim 250$ MeV/u**
to fulfill the quasi-free condition
**Wide mass range & wide isotope chain**
to differentiate mechanisms that influence cluster formation.
- mass
- N/Z
- relevant single particle orbit

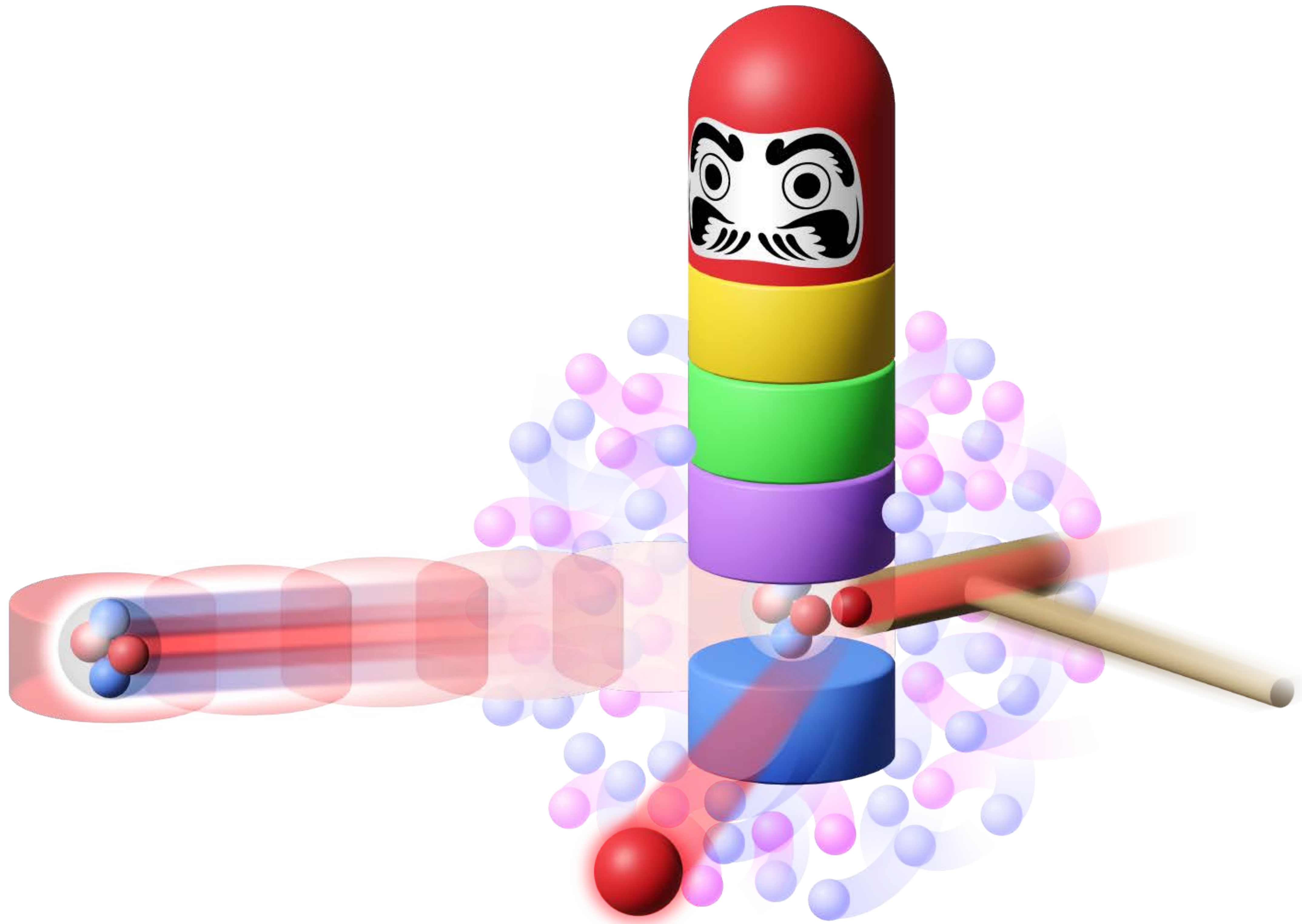


# Cluster knockout reaction

## Quantum-mechanical “Daruma otoshi”

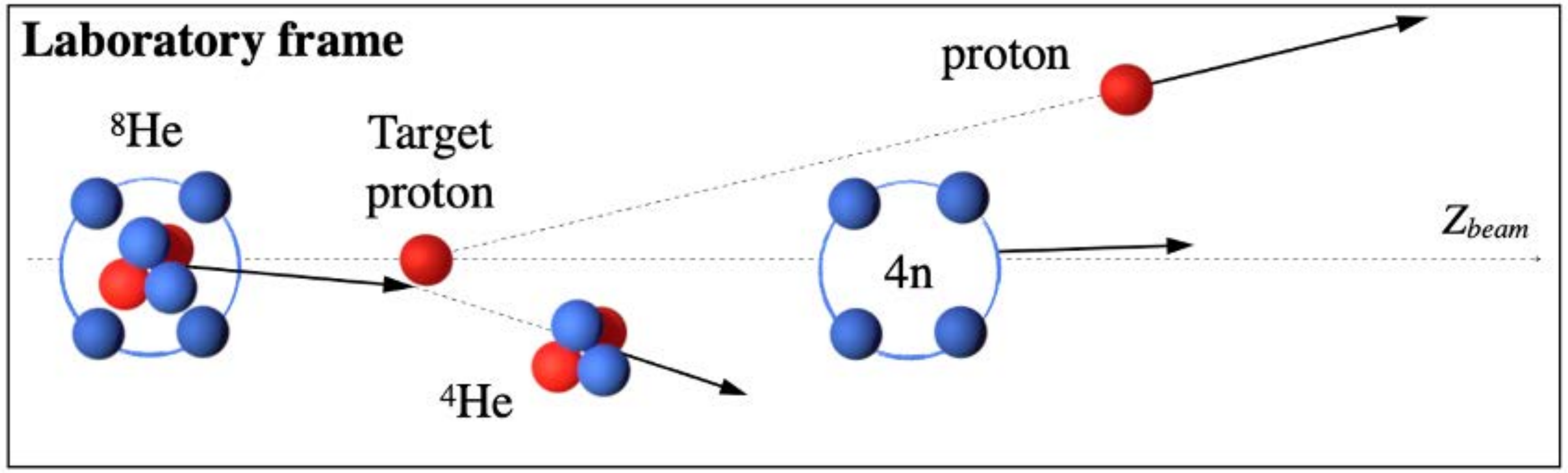
Knocking out a piece (⇔nucleon/cluster)
by a hammer (⇔high-energy proton)
with a large impact
(⇔large momentum transfer)

→ The other pieces (⇔the residual nucleus)
don’t realize that the piece is removed
(⇔initial-state information is kept).



**Extension of successful (p,pN)-reaction studies at RIBF/RCNP**
Tang et al. PRL 124, Kubota et al. PRL 125, Yang et al. PRL 126,
+ many SEASTAR papers

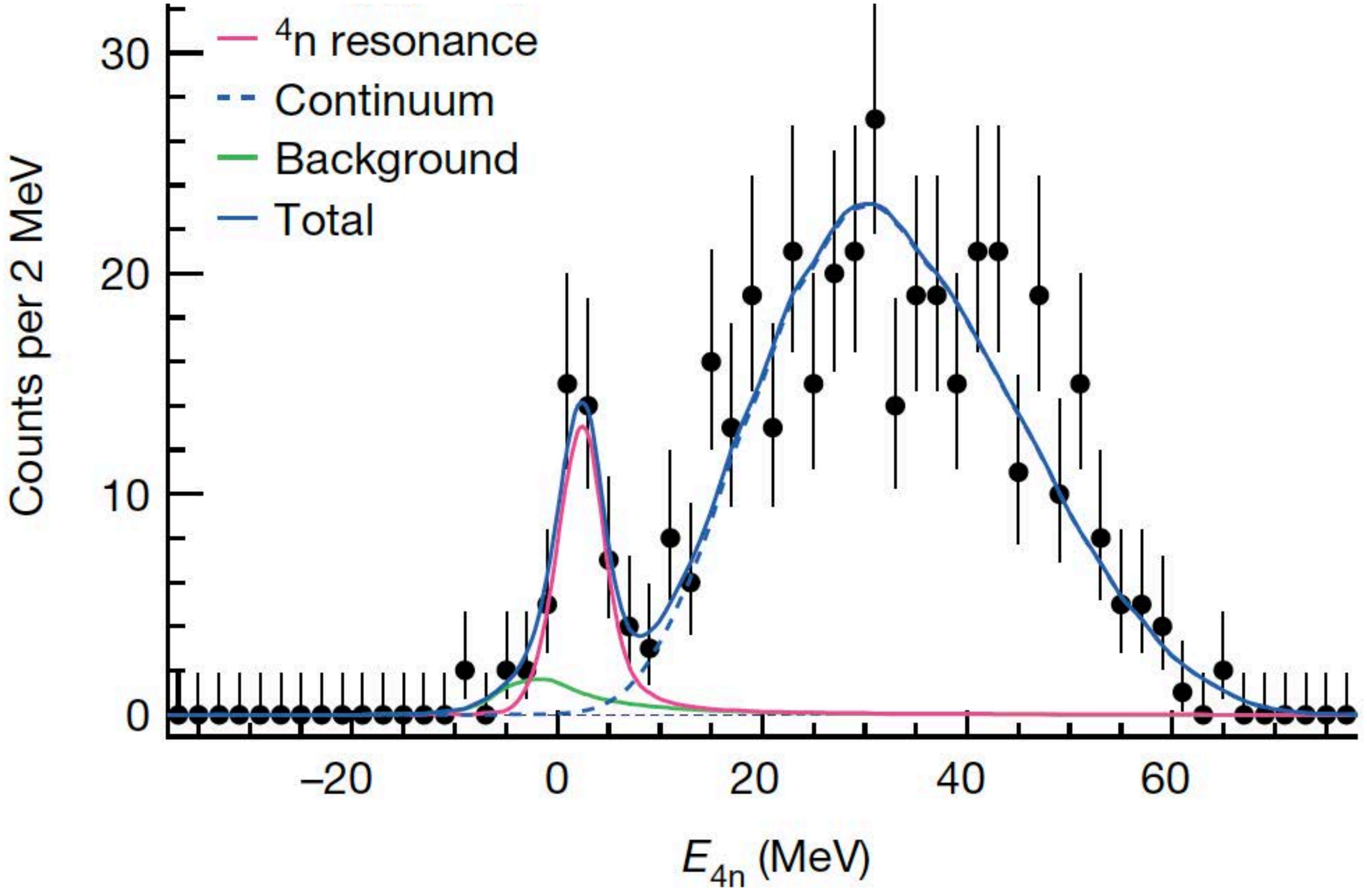
# Cluster knockout reaction studies @SAMURAI, RIBF




## Production of tetraneutron

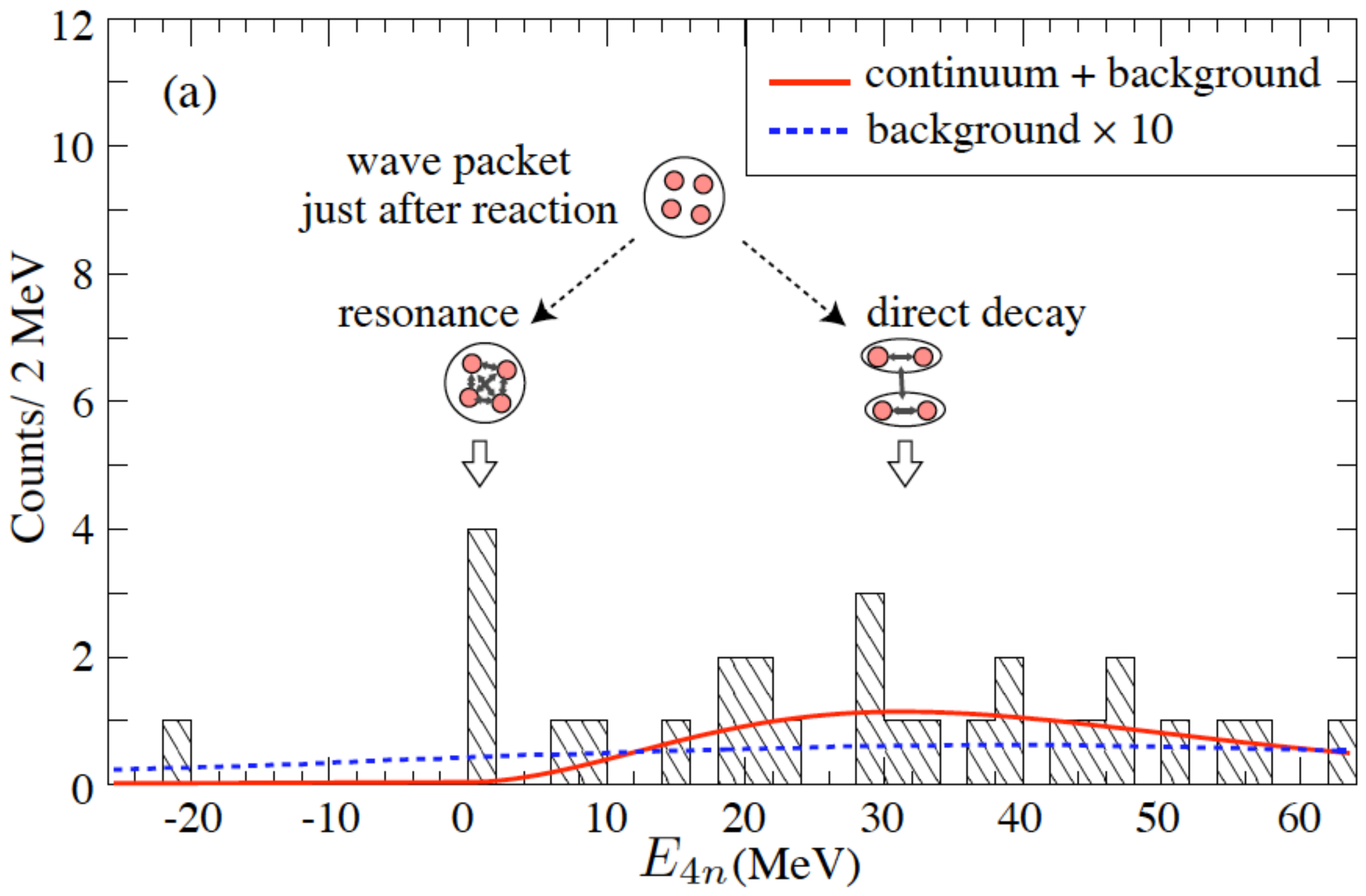
**M. Duer et al., Nature 606 (2022).**

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




**E= 2.37 ±0.38(stat.)±0.44(sys.) MeV**
**Γ = 1.75 ±0.22(stat.)±0.30(sys.) MeV**

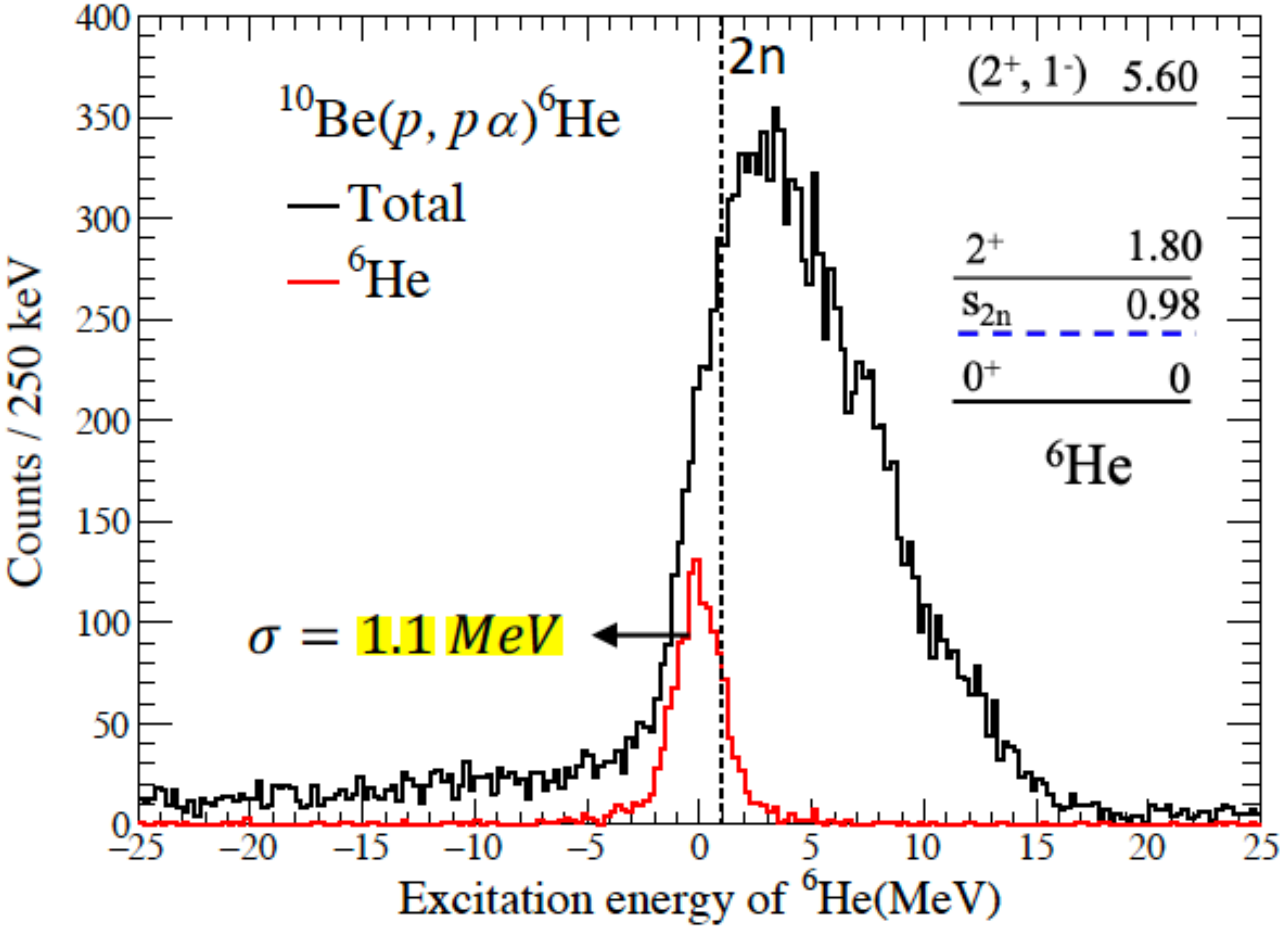
**K. Kisamori, et al., PRL 116 (2016).**
**$^4$He($^8$He,$^8$Be)$^4n$**
**@SHARAQ**

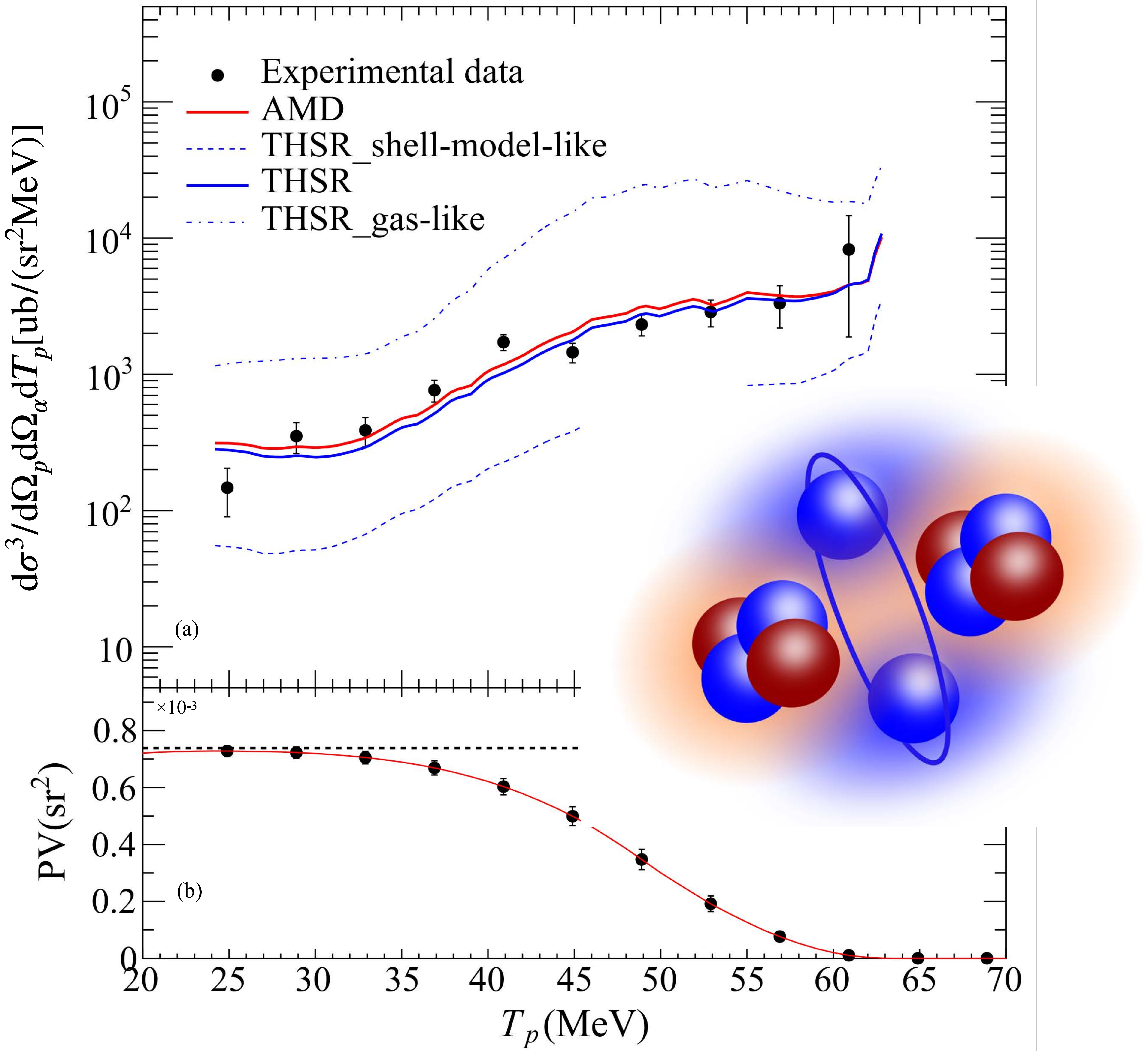



**$E_{4n}$ = 0.83 ± 0.65 (stat.) ± 1.25 (syst.) MeV**

# Molecular structure of $^{10}$Be (α-α-2n)

## $^{10}$Be($p$,$p\alpha$)



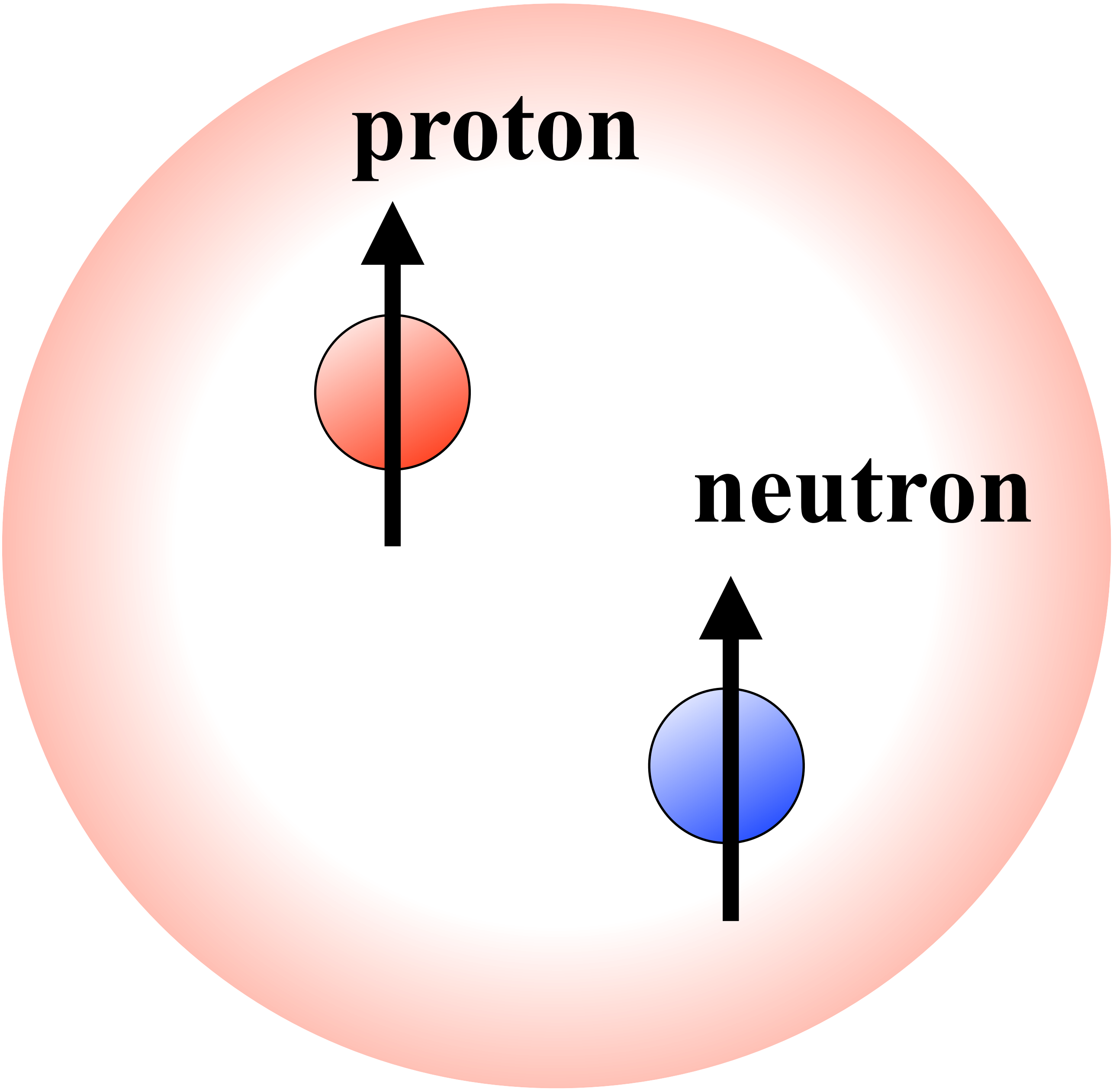




**Pengjie Li, D. Beaumel et al.,**
**Physical Review Letters 131, 212501 (2023).**

# Deuteron-like *p-n* correlation in nuclei

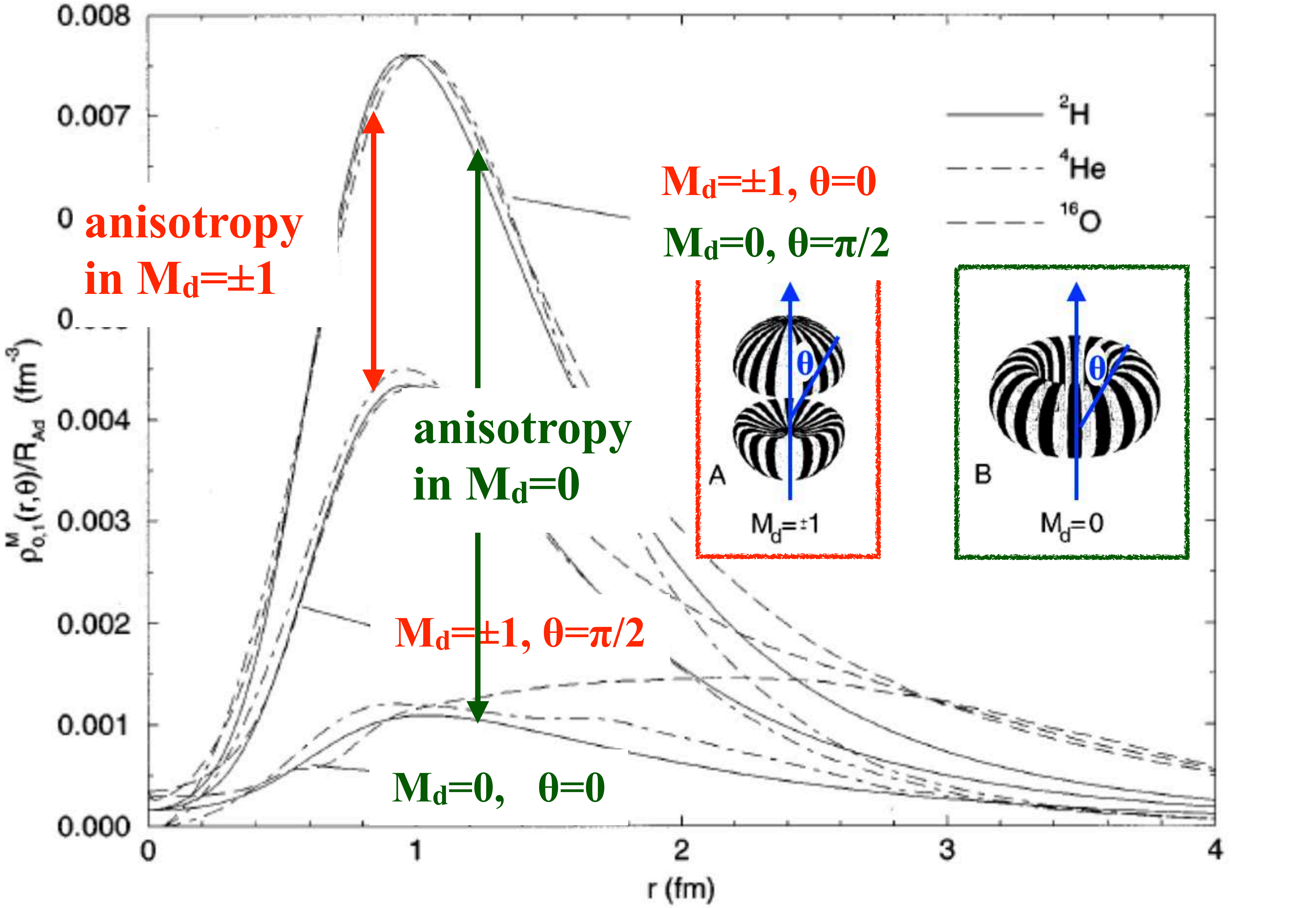
**Deuteron is the only bound state of two nucleons.**
**70% of its binding energy originates from the tensor force driven by pion exchange.**

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



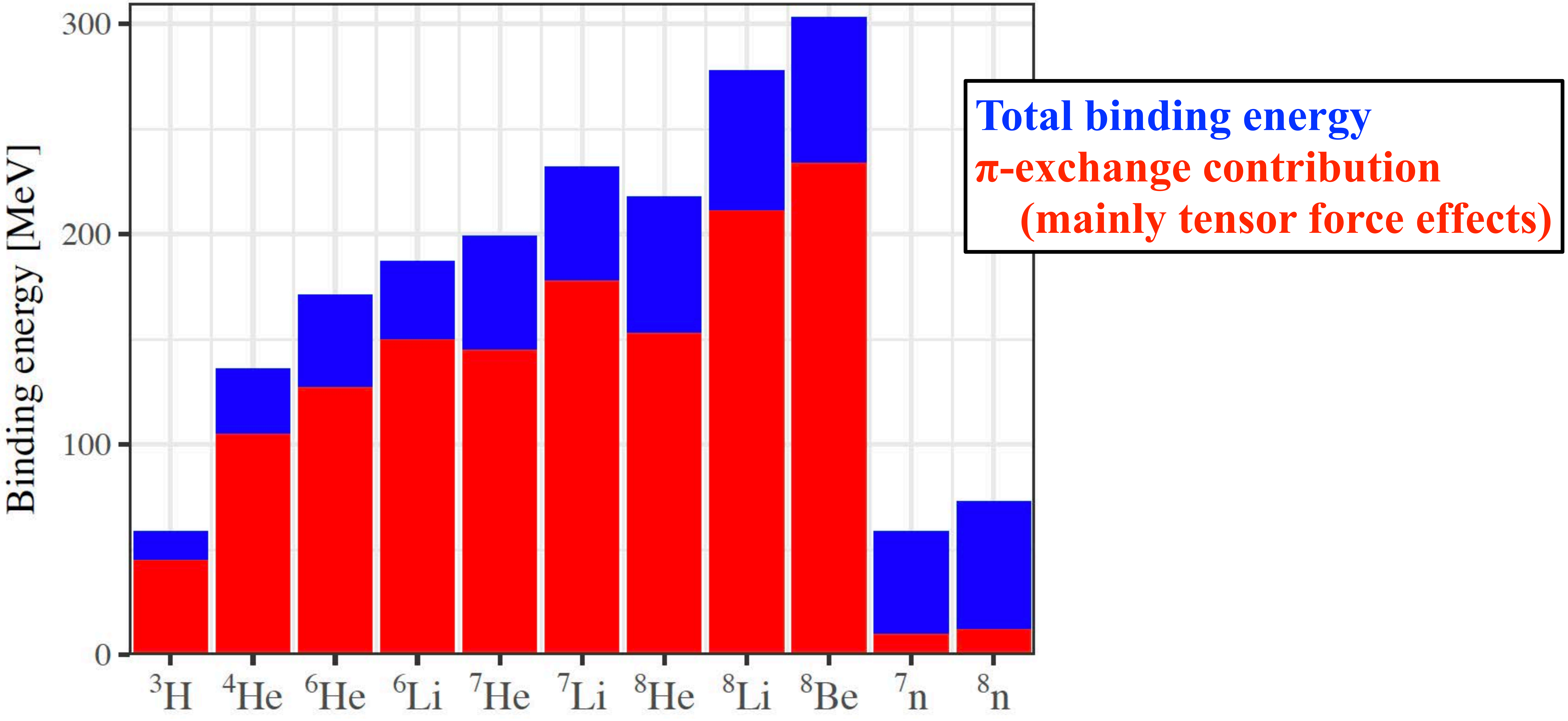

**"Femtometer toroidal structure in nuclei"**
Forest et al., Phys. Rev. C 54, 646 (1996)

**Density distribution for T=0, S=1 pairs in $^2$H, $^4$He, $^{16}$O**



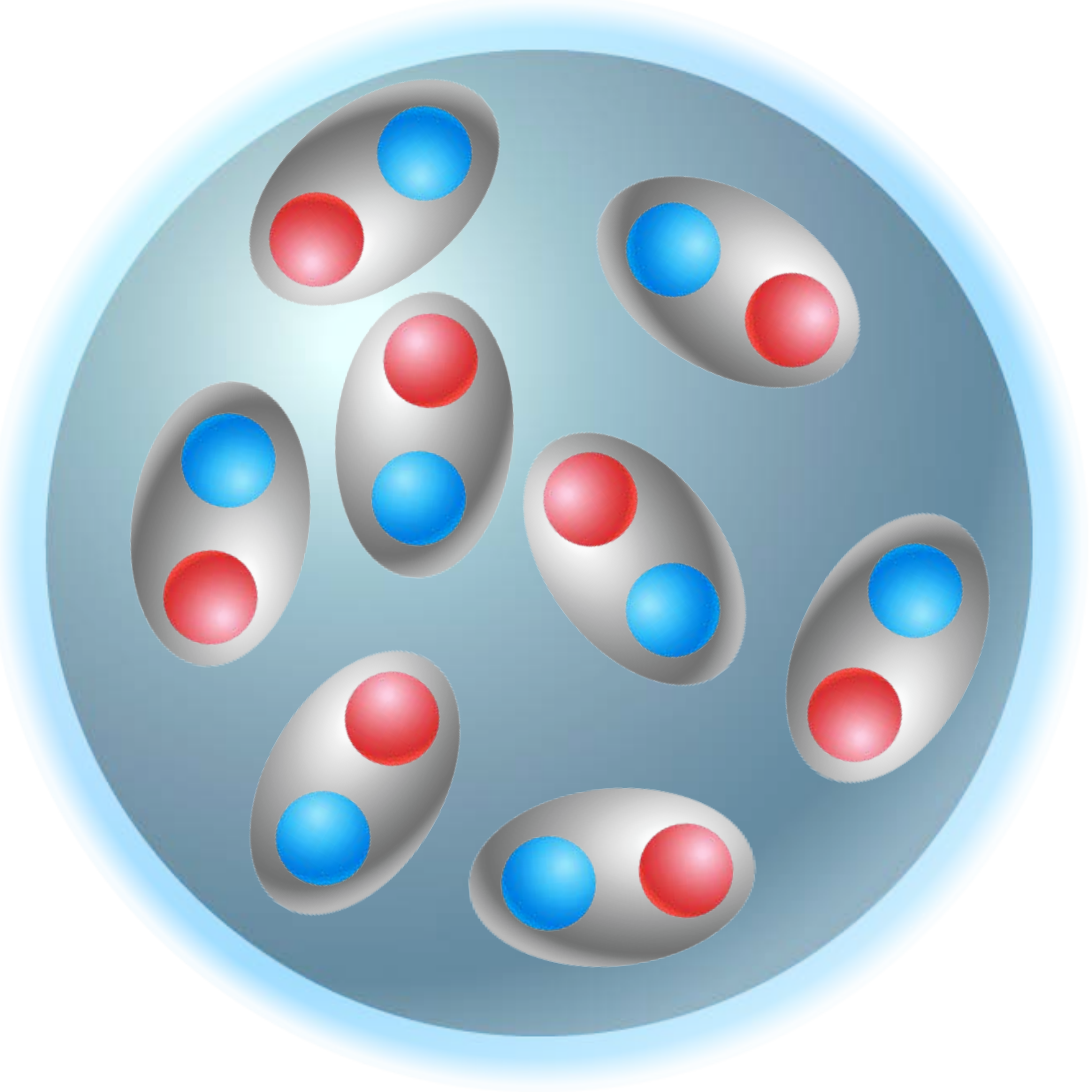

**"Deuteron-like" spin-dependent anisotropy is persistent in nuclei**

# Tensor force binds the deuteron and other nuclei




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

# Is a nucleus made of deuterons (spin-1 bosons)?



PHYSICAL REVIEW C VOLUME 54, NUMBER 2 AUGUST 1996

**Femtometer toroidal structures in nuclei**

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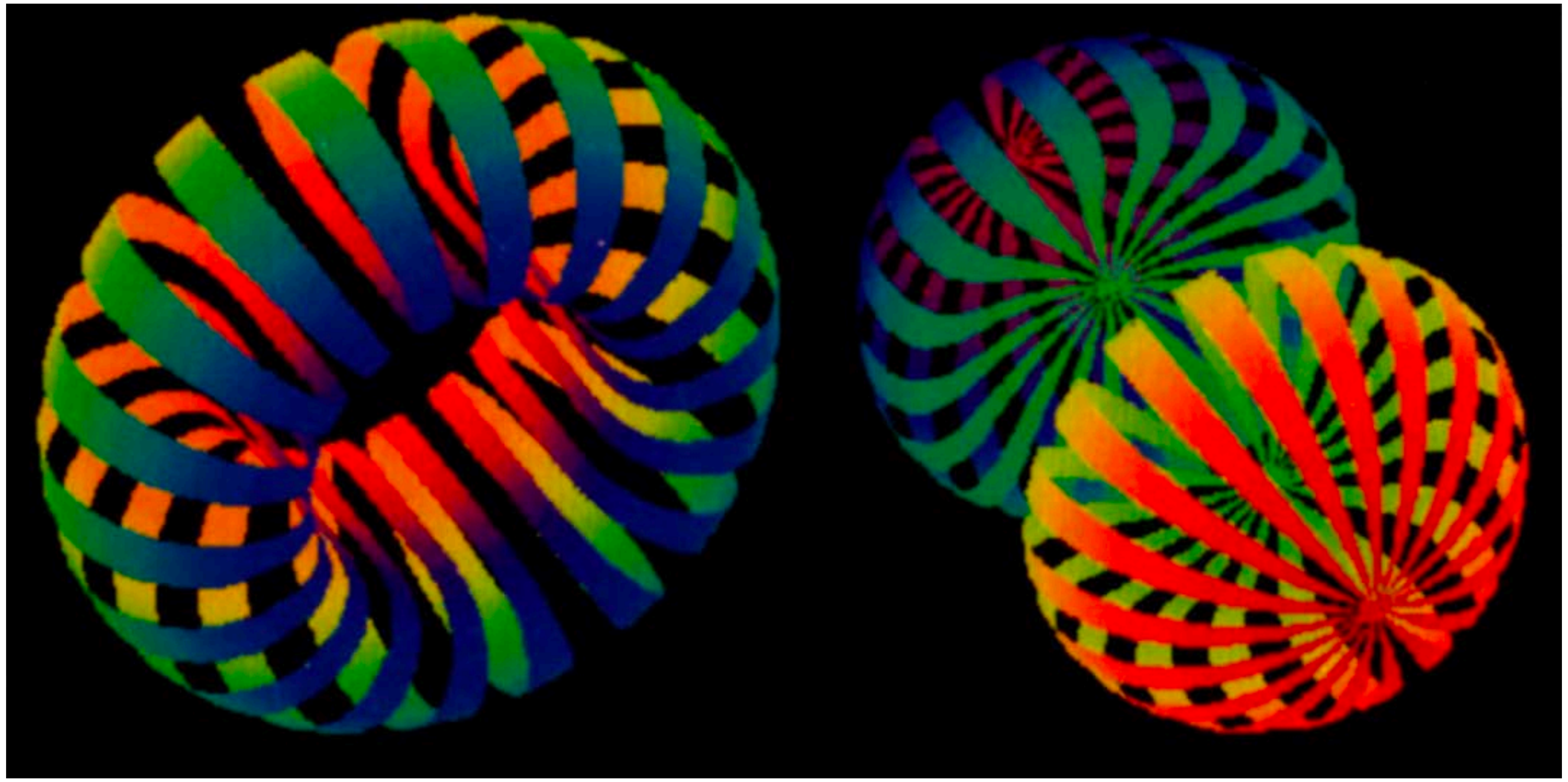
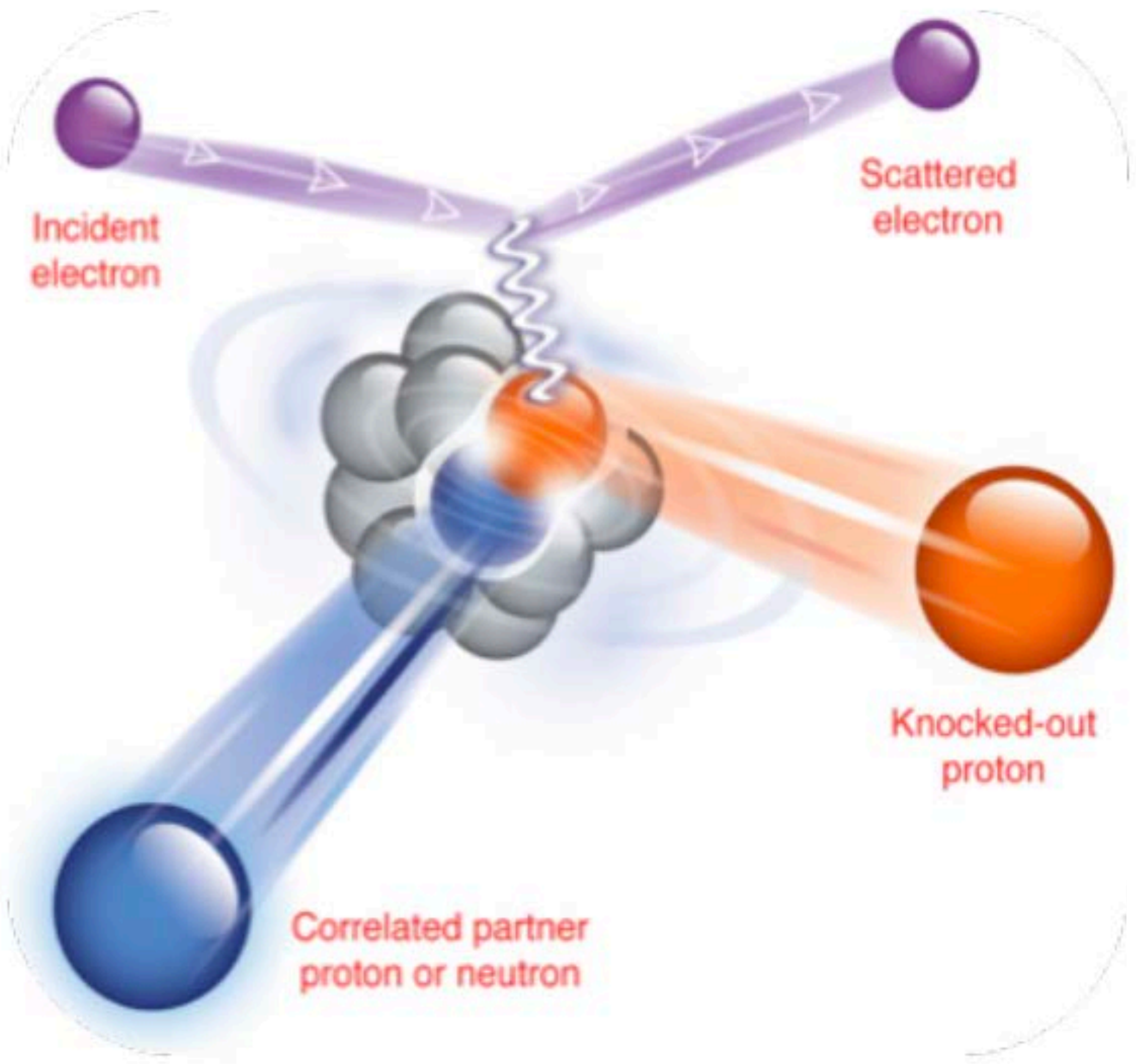
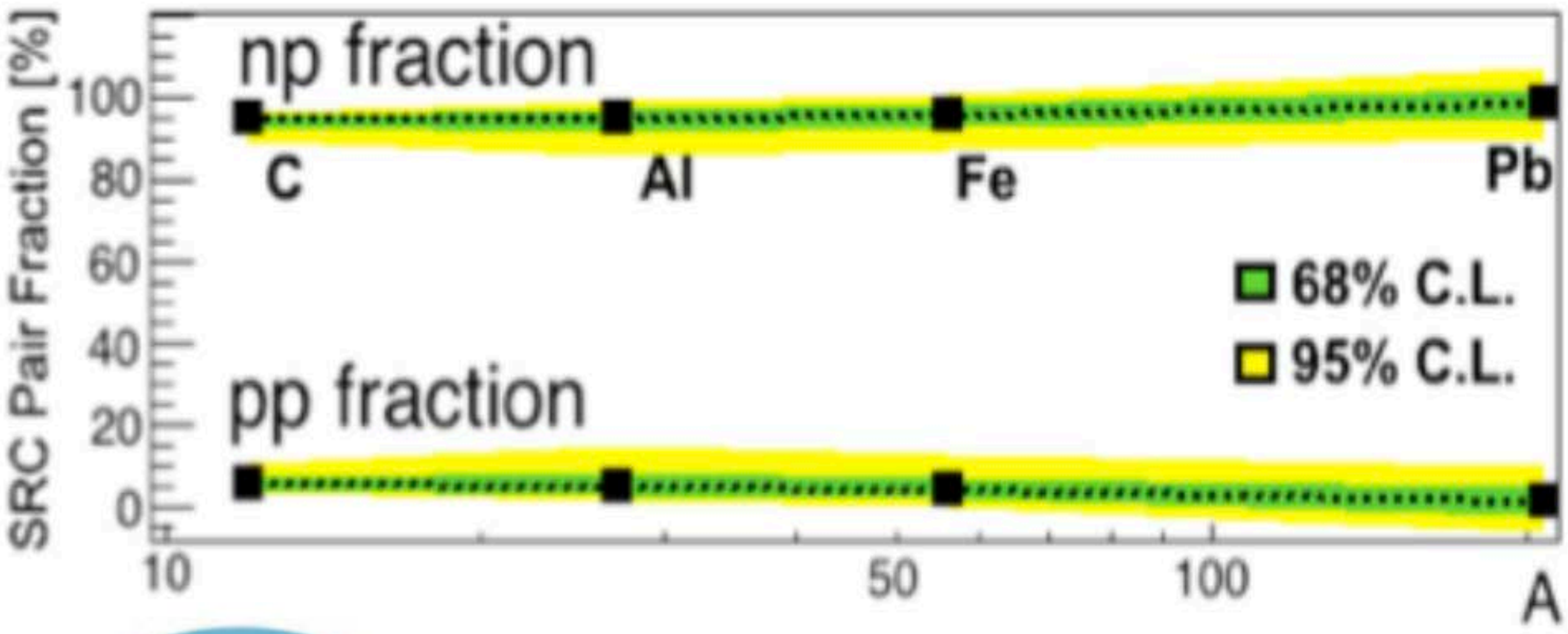
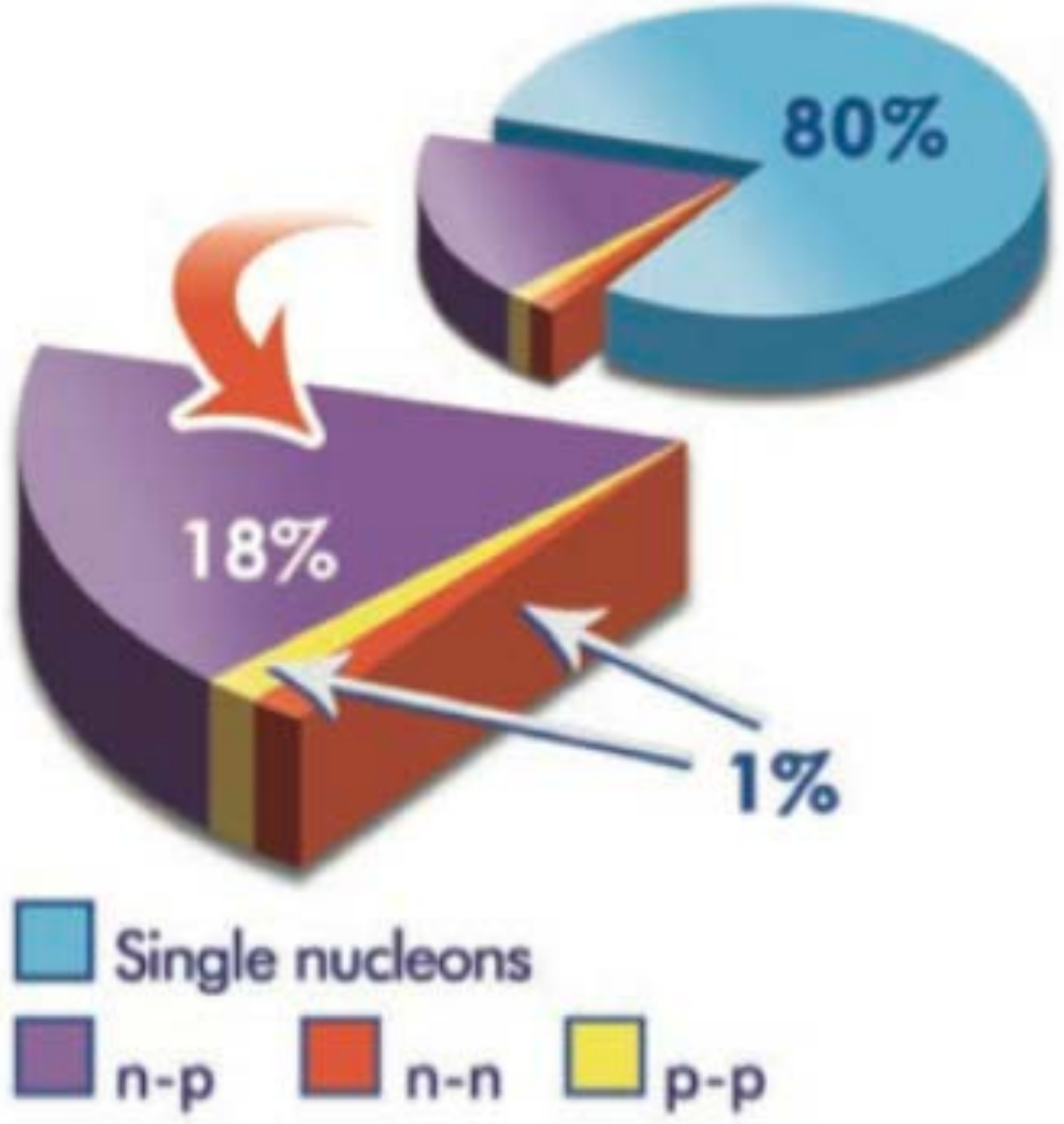


# Experimental signatures of deuteron in nuclei



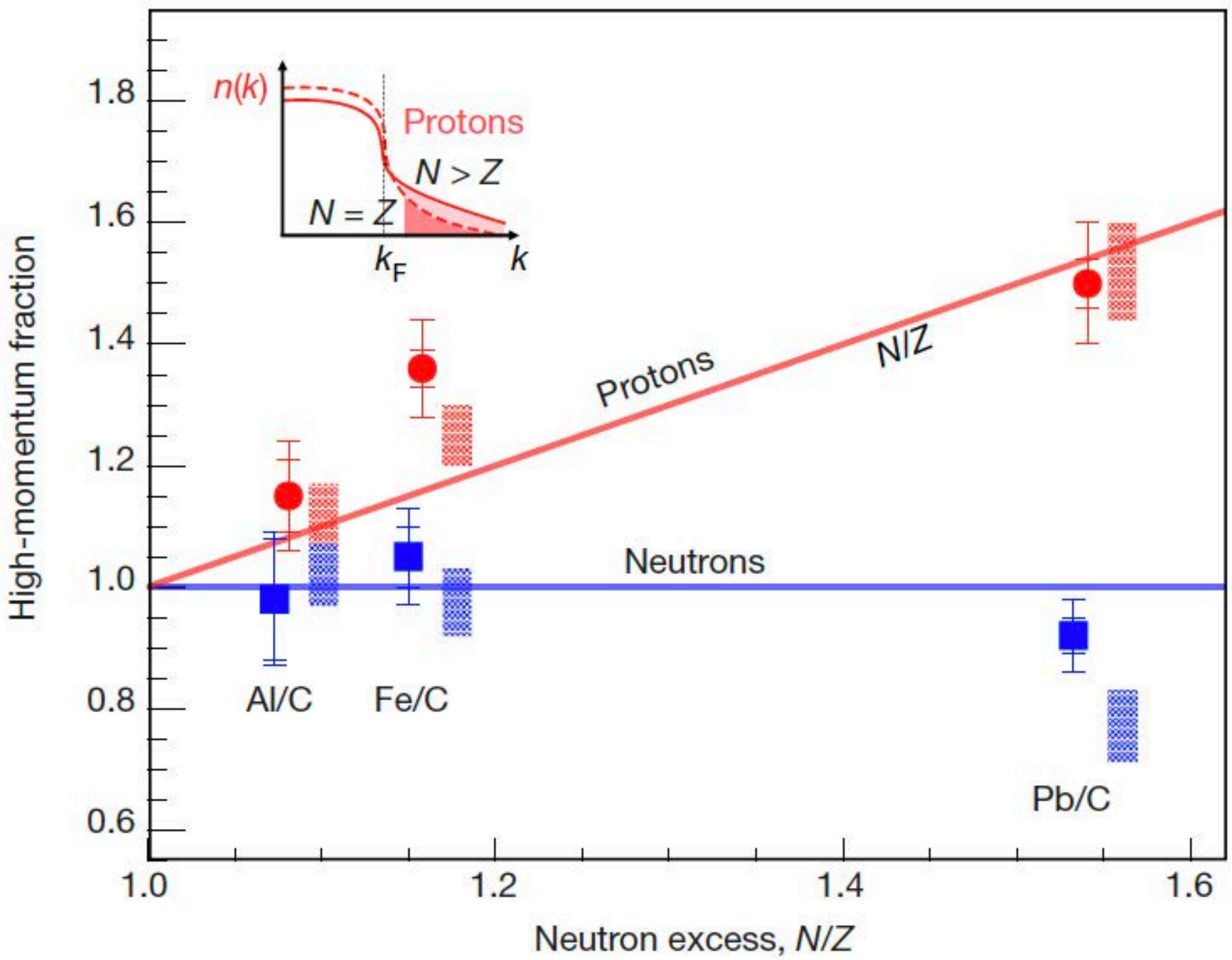

O. Hen et al., Science 364, 614 (2014).




***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)**

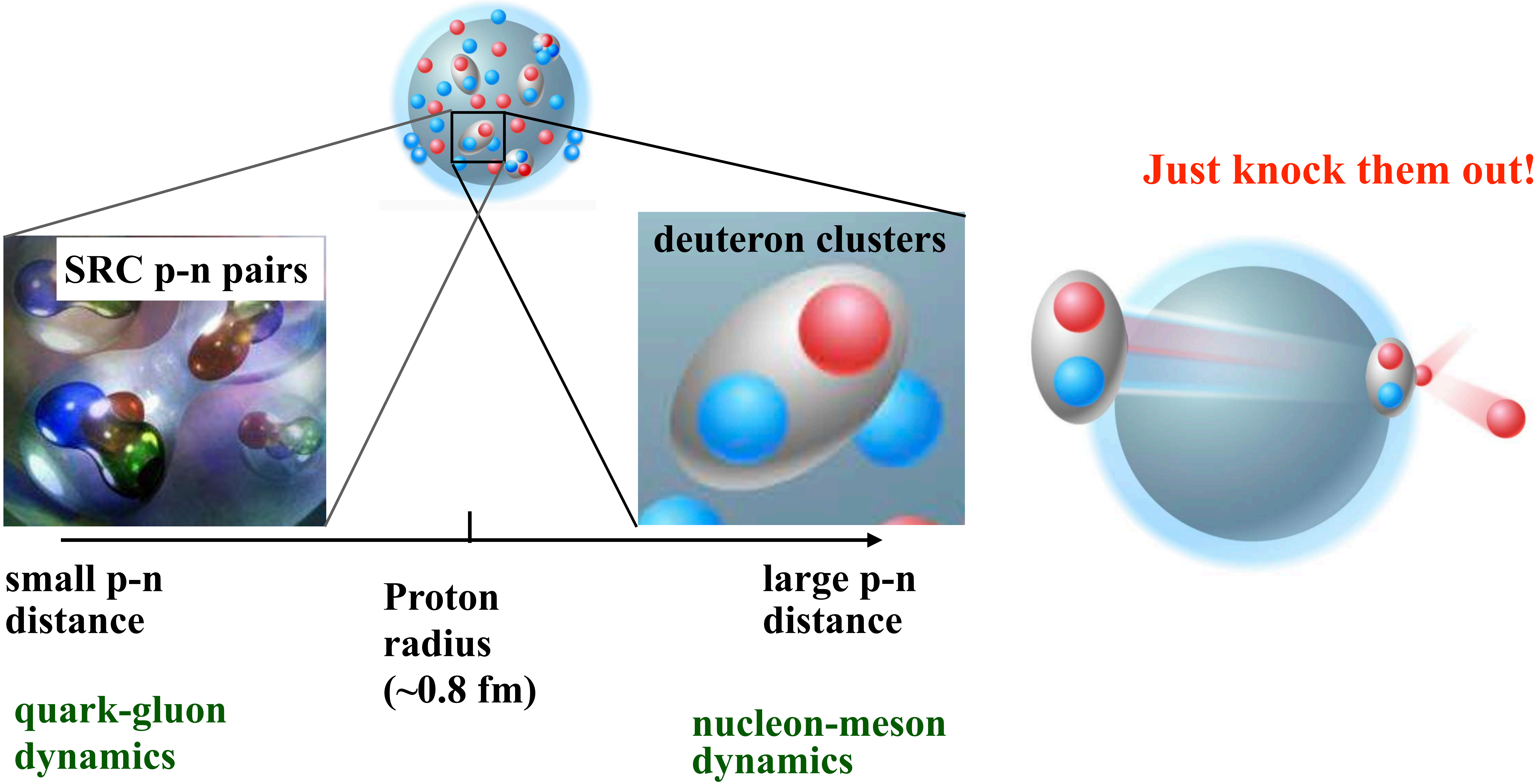
# Isospin dependence of SRC




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

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

# Direct observation of deuterons using the (*p*,*pd*) reaction



# $^{40-48}$Ca($p$,$pd$) @ 226 MeV

ONOKORO

**Indication of decreasing trends with the excess neutron in the deuteron formation probability.**

**Reaction analyses (DWIA) to extract the deuteron formation probability are ongoing.**

Unpublished data removed

shade: $^{16}$O background

R. Tsuji et al.

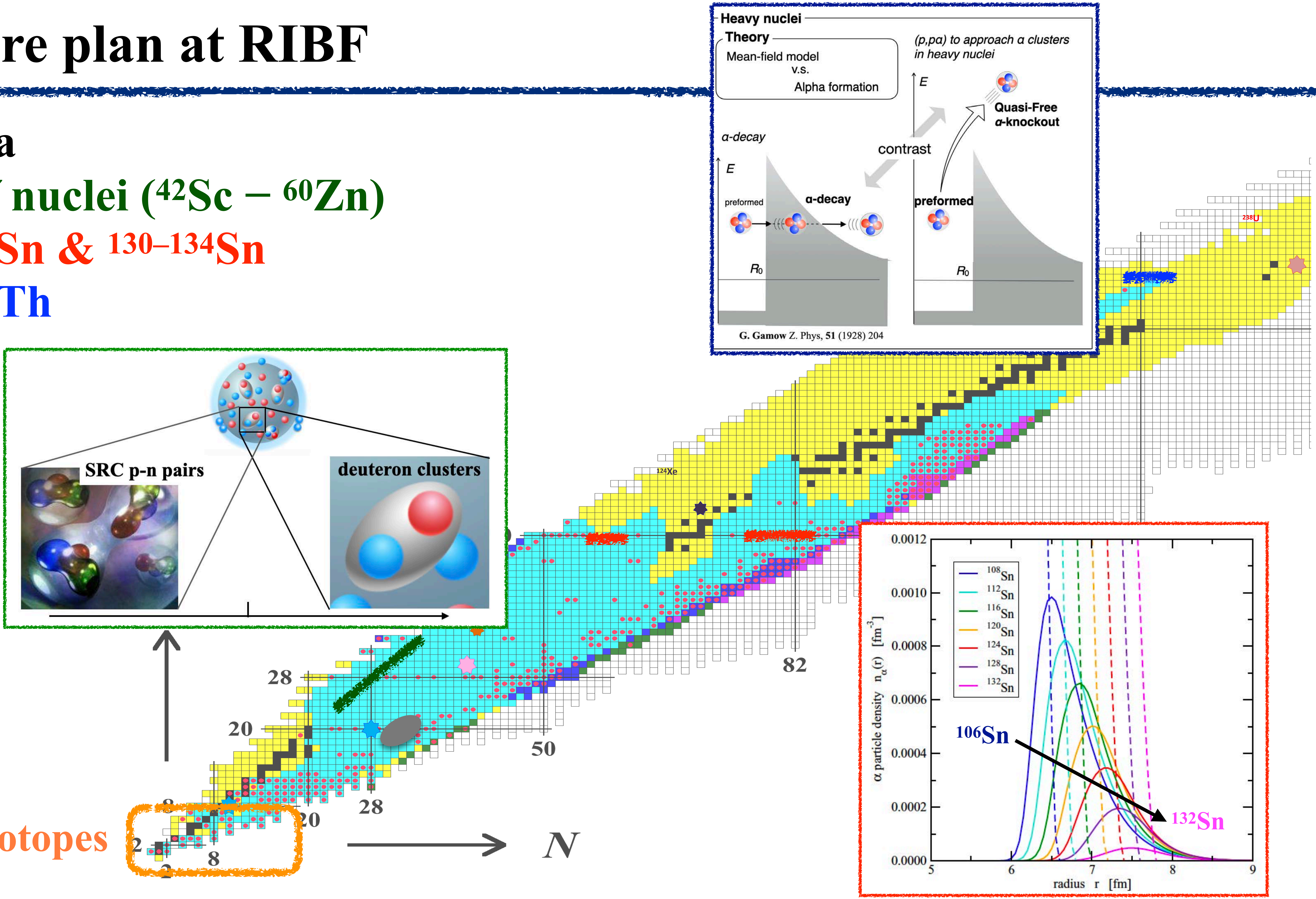
# Future plan at RIBF

$^{50\text{-}52}$Ca

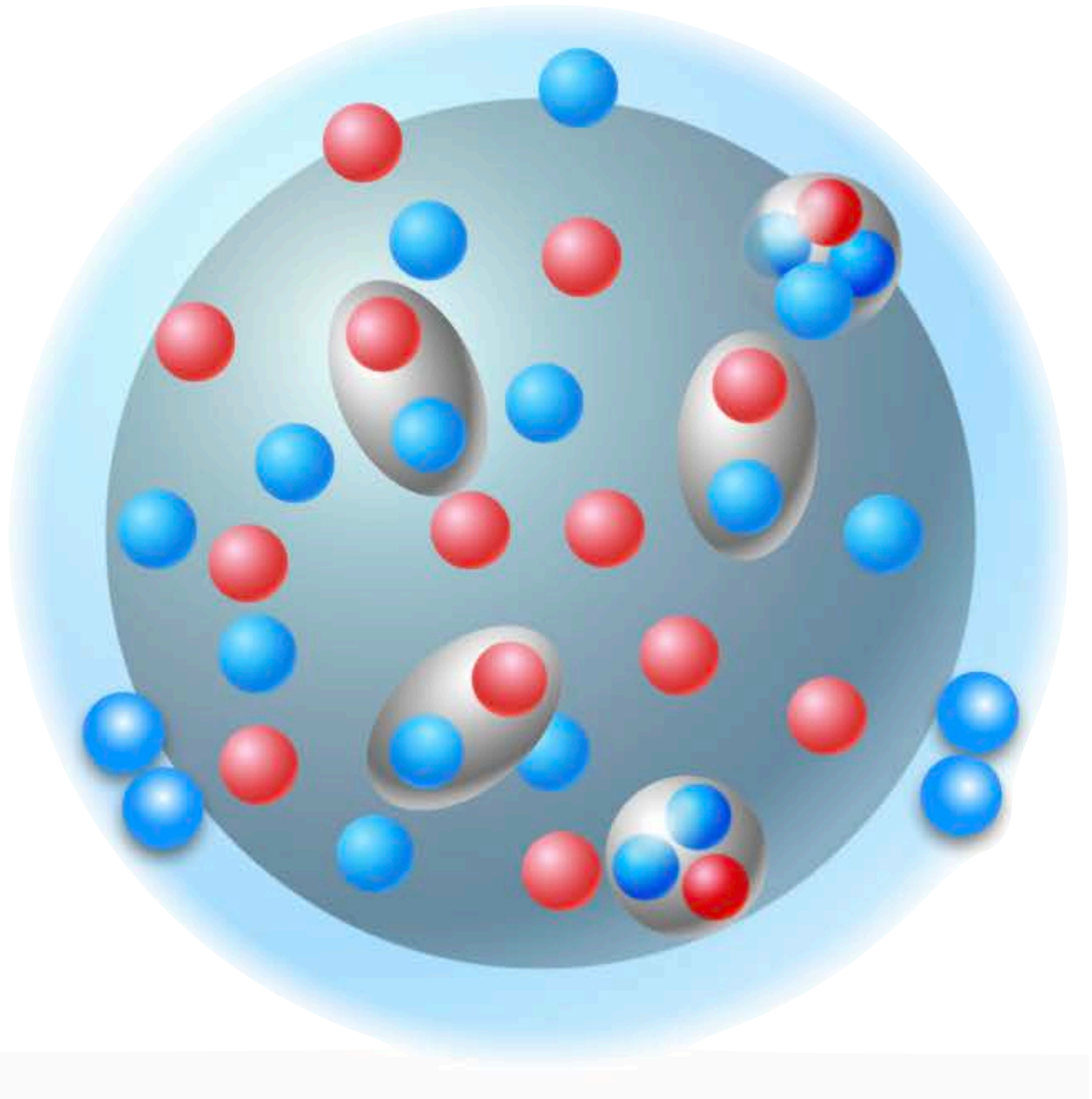
$N = Z$ nuclei ($^{42}$Sc – $^{60}$Zn)

$^{104\text{–}110}$Sn & $^{130\text{–}134}$Sn

$^{214\text{–}222}$Th



**Does nucleonic/hadronic matter prefer non-uniformity rather than uniformity?**



We try to answer this question using knockout reactions.

# The first paper of “the nuclear chart”

# The first paper of "the nuclear chart"

REMARQUES SUR LA CONSTITUTION DES NOYAUX ATOMIQUES. I.

Par K. GUGGENHEIMER.

**Sommaire.** — Limites de stabilité des diverses catégories d'atomes. Existence probable à l'intérieur des noyaux de couches indépendantes de neutrons et de protons.

Remarks on constitution of atomic nuclei I
Kurt Guggenheimer, Phys. Radium, 56 (1934) 253-256.

**Forgotten paper and it hardly appears in recent nuclear-physics textbooks. However, several important inventions and discoveries that are relevant to modern nuclear physics have been made in the paper.**

**Invention of the nuclear chart**
**Concept of "isotone" (and naming)**
**Limit of stability**
**Discovery of shell closures at N=50 and 82**

# The first nuclear chart by Guggenheimer in 1934

**Most of data are from F. Aston's mass measurements**

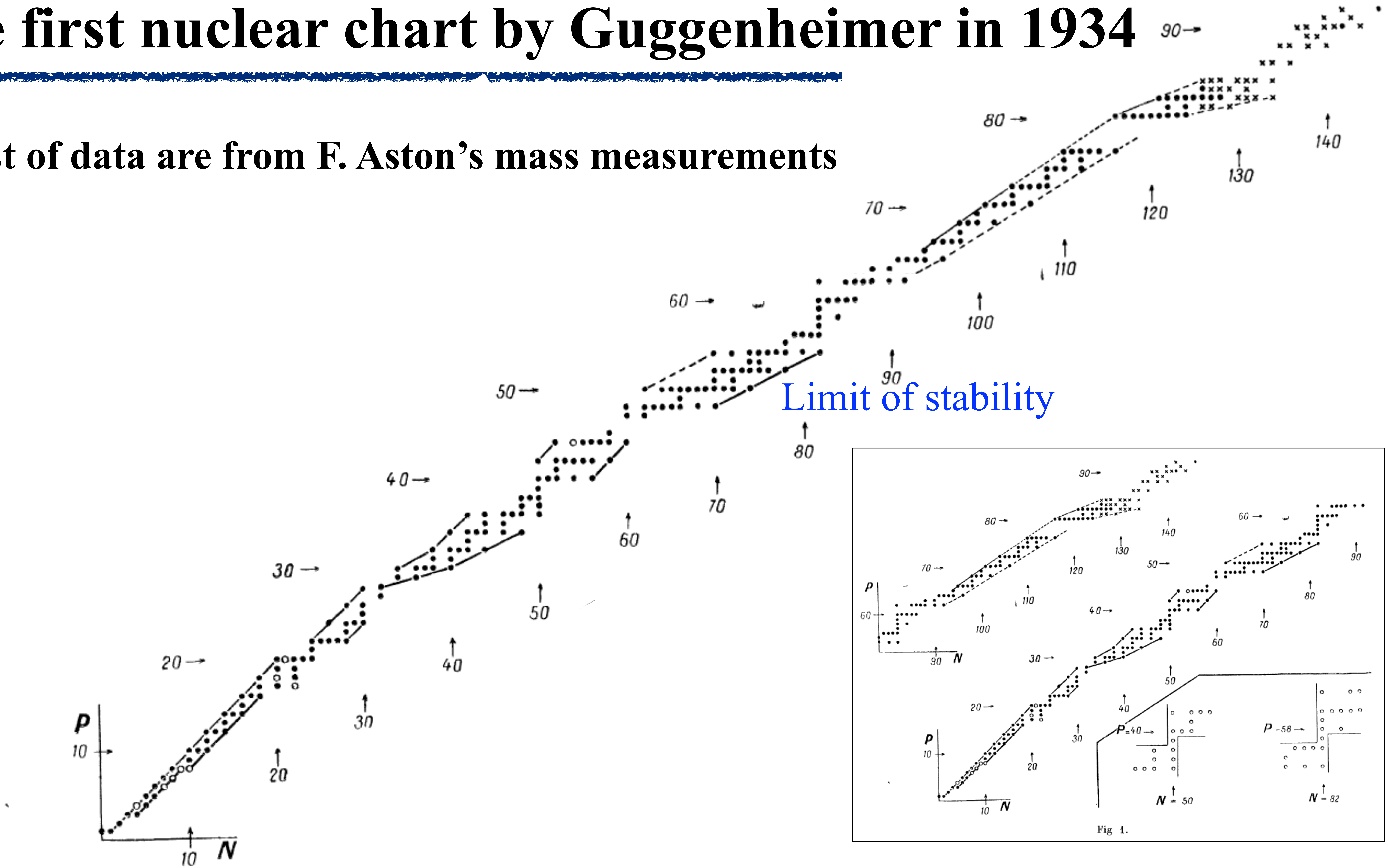


Fig. 1.

# The first nuclear chart by Guggenheimer



## Table of nuclides



Contents hide



From Wikipedia, the free encyclopedia

A **table** or **chart of nuclides** is a two-dimensional graph of isotopes of the elements, in which one axis represents the number of neutrons (symbol *N*) and the other represents the number of protons (atomic number, symbol *Z*) in the atomic nucleus. Each point plotted on the graph thus represents a nuclide of a known or hypothetical chemical element. This system of ordering nuclides can offer a greater insight into the characteristics of isotopes than the better-known periodic table, which shows only elements and not their isotopes. The chart of the nuclides is also known as the **Segrè chart**, after the Italian physicist Emilio Segrè.[1]

### Description and utility [ edit ]

*See also: Valley of stability*

A chart or table of nuclides maps the nuclear, or radioactive, behavior of nuclides, as it distinguishes the isotopes of an element. It contrasts with a periodic table, which only maps their chemical behavior, since isotopes (nuclides which are variants of the same element) do not differ

neutrons and along the Y axis by their numbers of protons, out to the limits of the neutron and proton drip lines. This representation was first published by Kurt Guggenheimer in 1934[2] and expanded by Giorgio Fea in 1935,[3] Emilio Segrè in 1945 or Glenn Seaborg. In 1958, Walter

Seelmann-Eggebert and Gerda Pfennig published the first edition of the Karlsruhe Nuclide Chart. Its 7th edition was made available in 2006. Today, there are several nuclide charts, four of which have a wide distribution: the Karlsruhe Nuclide Chart, the Strasbourg Universal Nuclide Chart, the Chart of the Nuclides from the Japan Atomic Energy Agency (JAEA), and the Nuclide Chart from Knolls Atomic Power Laboratory in the United States.[4] It has become a basic tool of the nuclear community.

# Concept of "Isotone"

"isotope" proposed by Frederick Soddy (a famous nuclear chemist)

Frederick Soddy

isoto*n*e
$p \leftrightarrow n$

**Guggenheimer:**

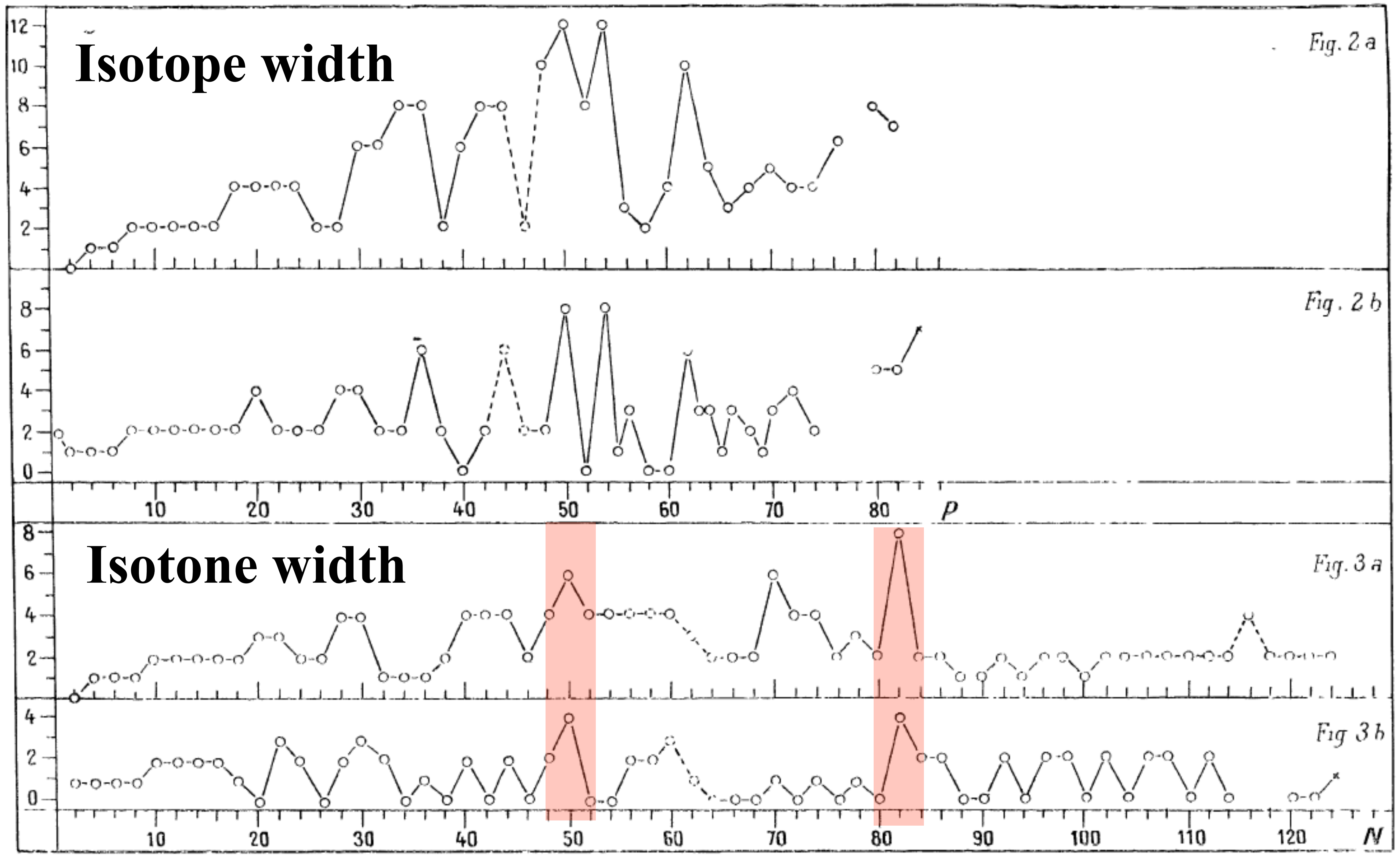
**The isotopes are found on the same horizontal, P(Z) = const, the atoms containing the same number of neutrons on the same vertical line , N = const. This last mode of grouping will play an important role in this work and in those which will follow. This is why I have taken the liberty of proposing a new name: as these atoms of the same number N are in some way isotopes with respect to the number of neutrons, we shall call them, to abbreviate the language, isoto*n*es.**

# Discovery of shell closure (magicity) at N=50 and 82

The most pronounced discontinuities are at the points N =50 and N = 82.

The isotopic width reaches its maximum values (6 and 8). (left figure)

The isotones N = 50 and N = 82 are also the only ones where there are two distinct nuclei of odd charge. In both cases, the upper and lower stability limits are vertical at the same place, (right figure).



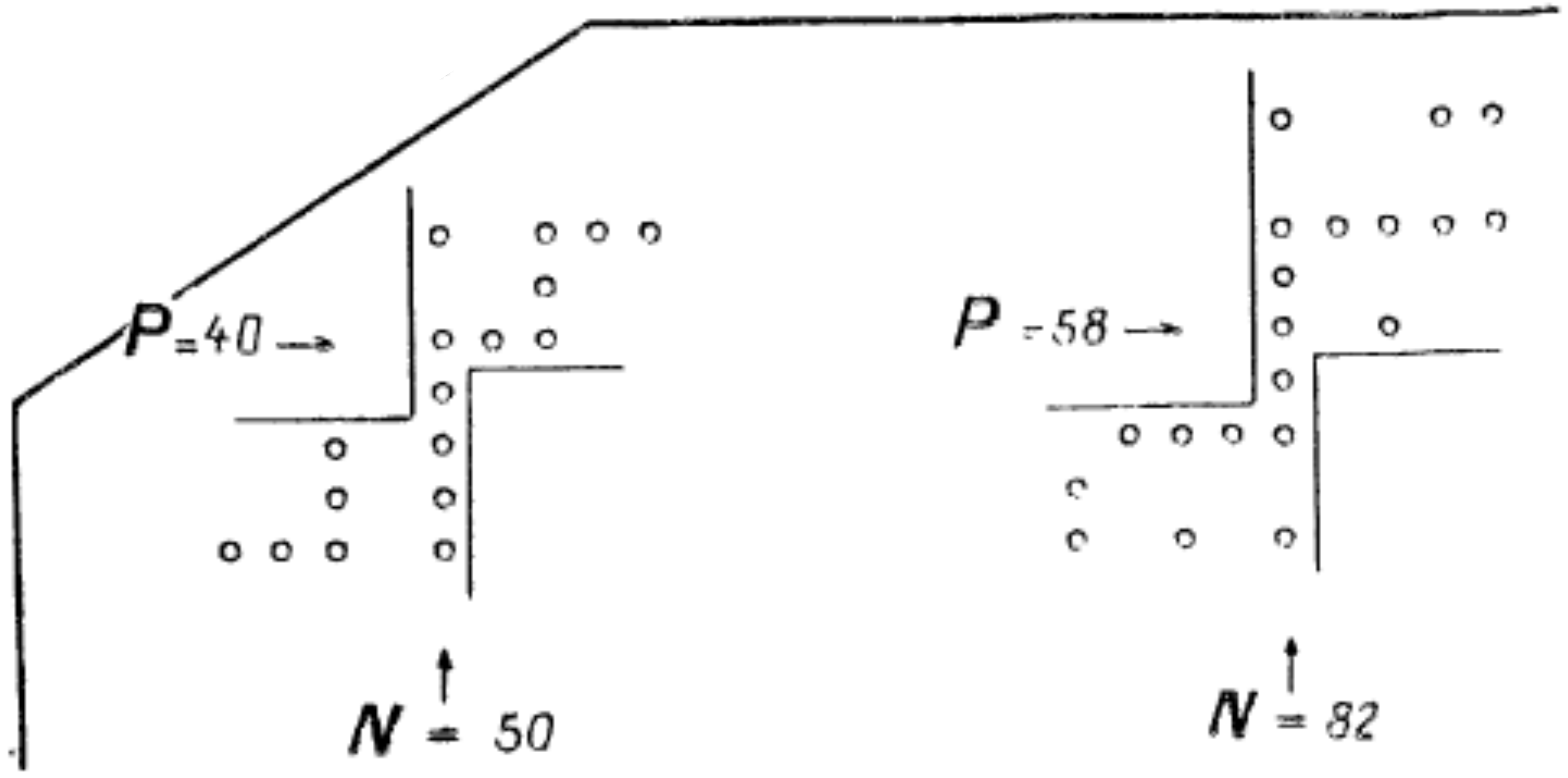




Fig 1.

# Discovery of shell closure (magicity) at N=50 and 82

For it shows clearly that neutrons and protons are attached to the nuclei - at least in these places - as primordial constituents and independent of each other.
If nuclei consisted essentially of α and neutrons, one would expect the stability limit to never takes a steeper inclination than that of the diagonal, because then the maximum excess of free neutrons would decrease when the number of α particles increases.

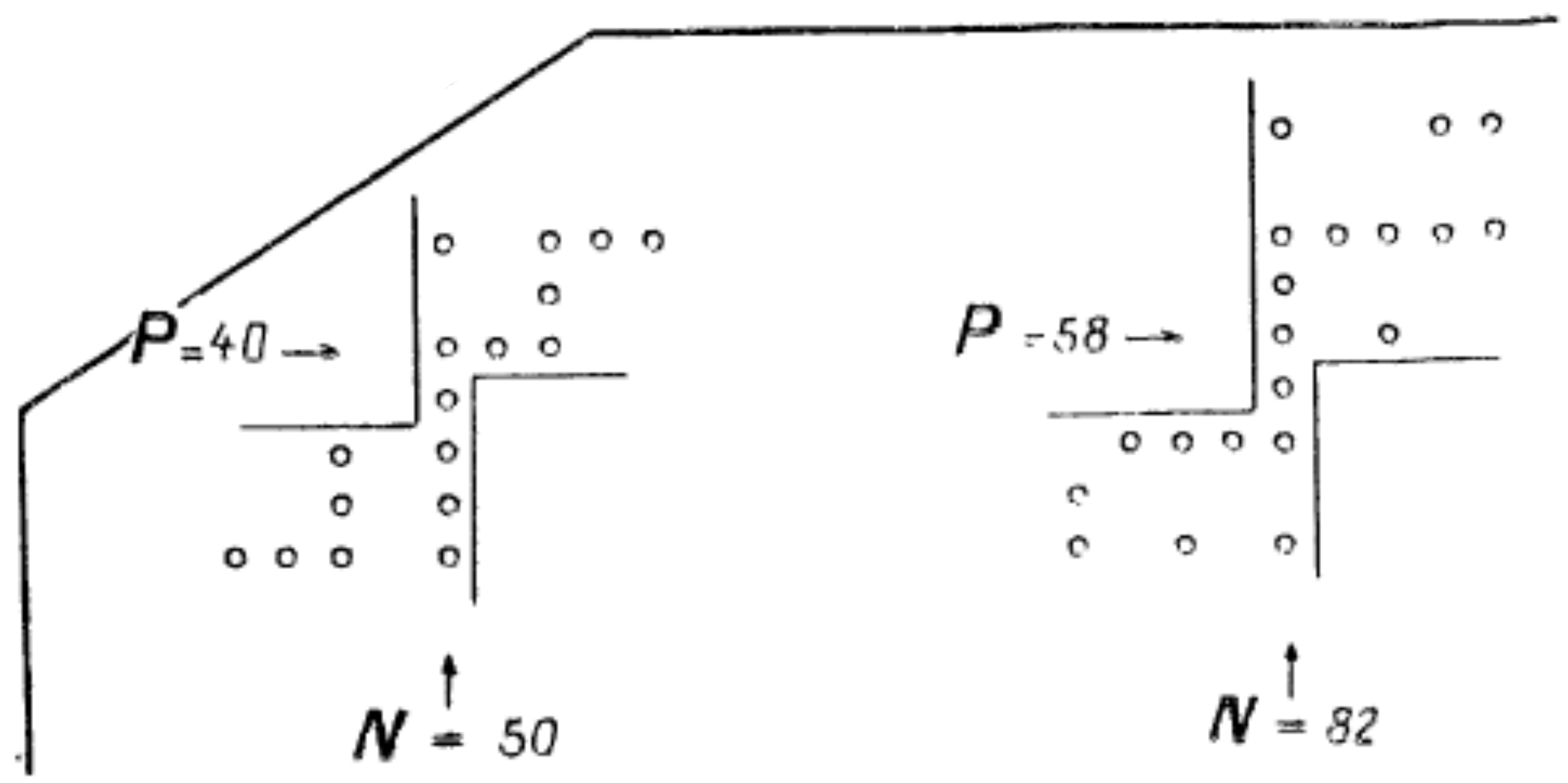


Fig 1.

**Protons and neutrons are fundamental constituents of nuclei.**
**Shell closures take place at N=50 and 82.**

**The discovery was forgotten after Bohr's theory of compound nucleus.**
**Guggenheimer's paper is not referred even in Mayer's paper in 1948.**

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