Clustering and SRC

Recent topics from low energy nuclear physics

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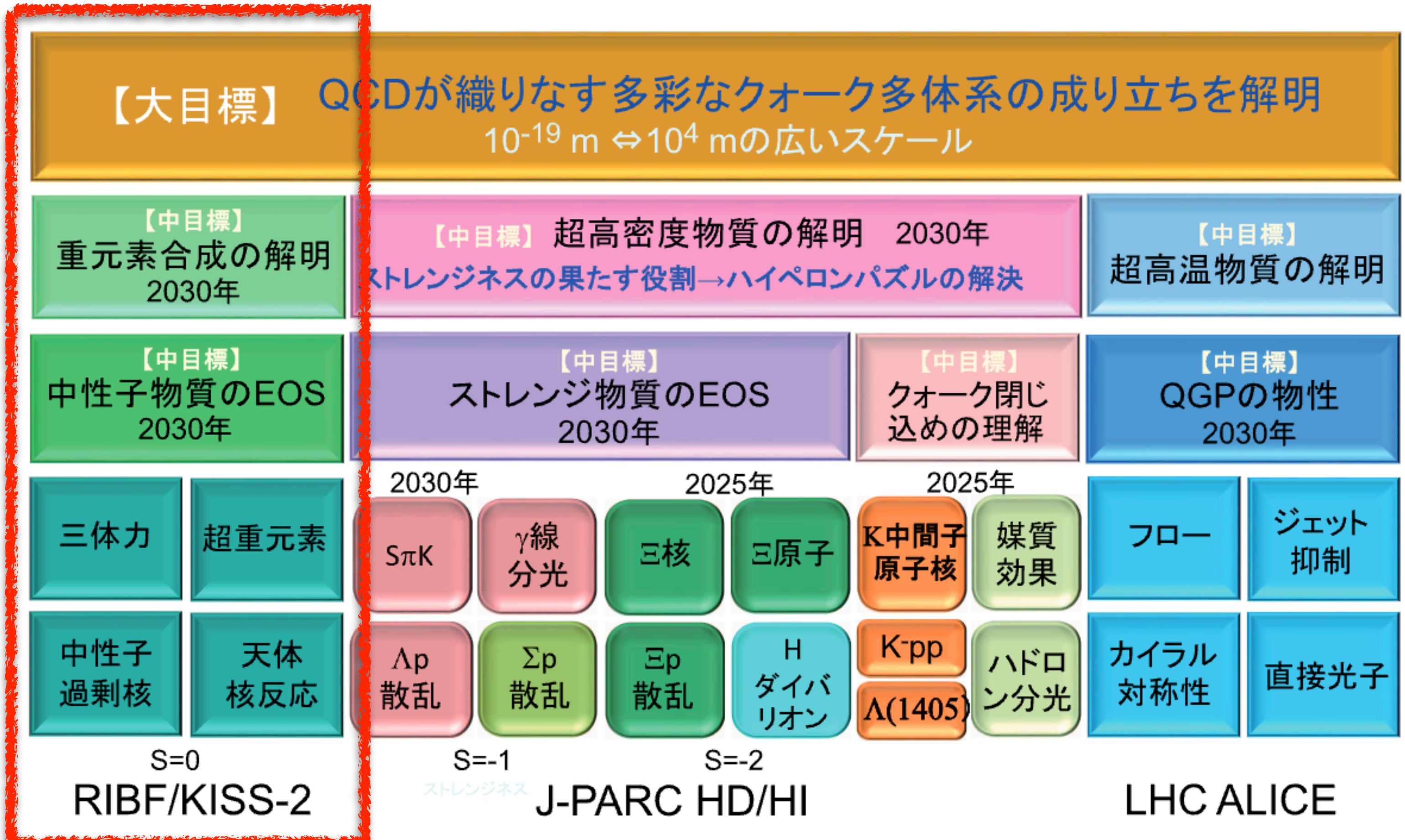
Low energy nuclear physics

日本の核物理の将来レポート（2021年版）



Low energy nuclear physics

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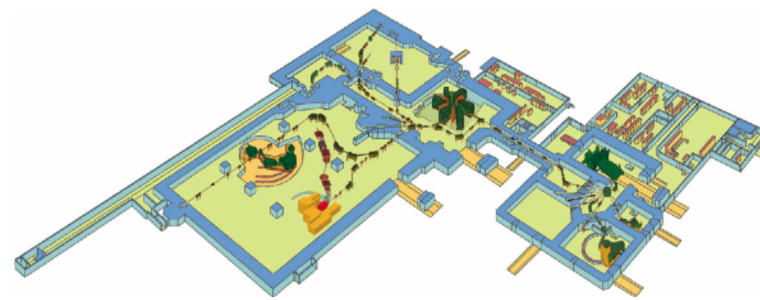
RCNP, Osaka

p: 392 MeV

Double-arm spectrometer Grand-Raiden & LAS

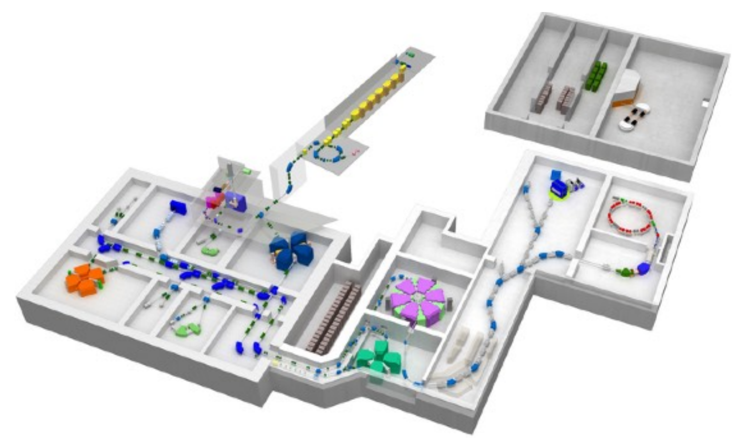


RIBF, RIKEN

^{238}U: 345 MeV/u
→ RI beam

3 spectrometers

- SAMURAI
- ZeroDegree
- SHARAQ/OEDO



Low energy nuclear physics

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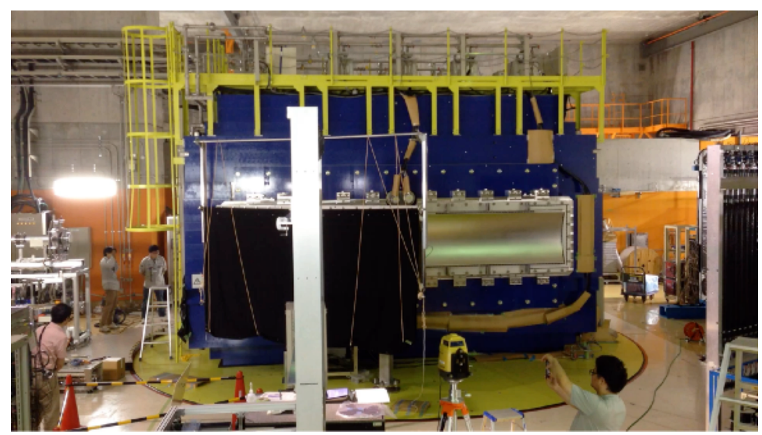
Lifecycle

Program Advisory Committee (PAC) meeting
- Once or twice per year
- Approved → expired in 4 years

Experiment
- Beam time: ~ a week
- Setup: scrap and build



Low energy nuclear physics

日本の核物理の将来レポート（2021年版）

Lifecycle

Pro

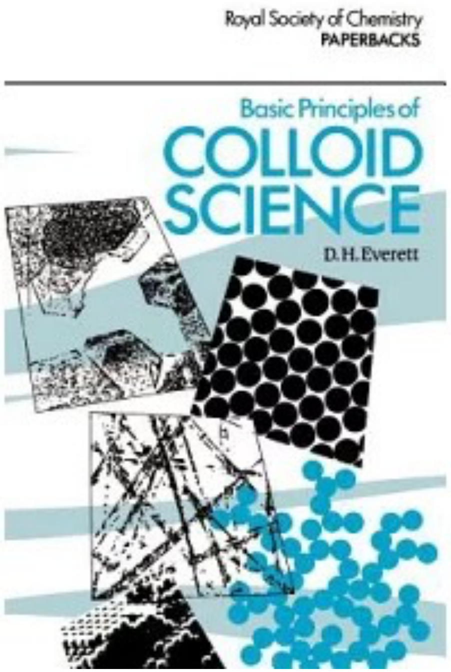
Exp

Variety of topics/programs in this field.

EIC gives us the opportunity for the physics we are interested in.

Hoping to increase momentum for further discussion.

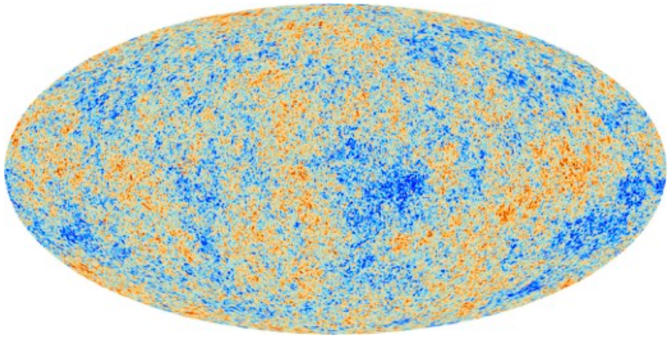
Does our material world prefer non-uniformity rather than uniformity?



Colloid

LLPS

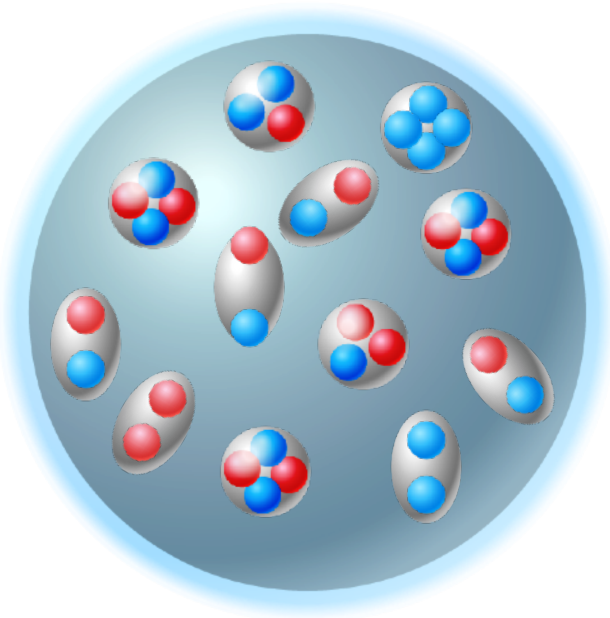
Nature (2018-03-15)



CMB

by Planck

Does our atomic nucleus prefer non-uniformity rather than uniformity?



Key ideas behind

- Nucleus is not a static, but a dynamic system even in the ground state.

- Minor components sometimes determine the nature of the system.

- Interplay of spin and isospin makes nucleus unique quantum system.

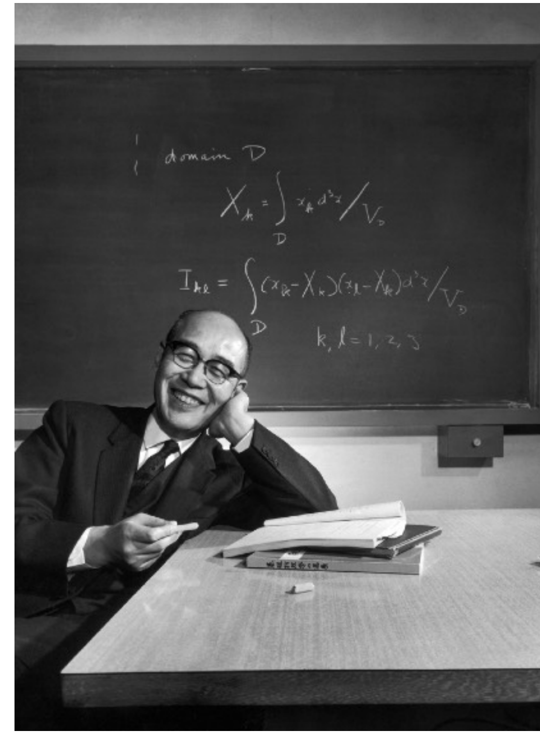
Nuclear force: pion exchange

On the Interaction of Elementary Particles. I.

By Hideki YUKAWA.

(Read Nov. 17, 1934)

§1. Introduction



Assuming $\lambda=5\times10^{12}\text{cm}^{-1}$., we obtain for m_U a value 2×10^2 times as large as the electron mass. As such a quantum with large mass and positive or negative charge has never been found by the experiment, the above theory seems to be on a wrong line. We can show, however, that, in the ordinary nuclear transformation, such a qnantum can not be emitted into outer space.

$$V_{12} = m_\pi c^2 \frac{f^2}{4\pi\hbar c}\frac{1}{3}(\tau_1\cdot\tau_2)$$

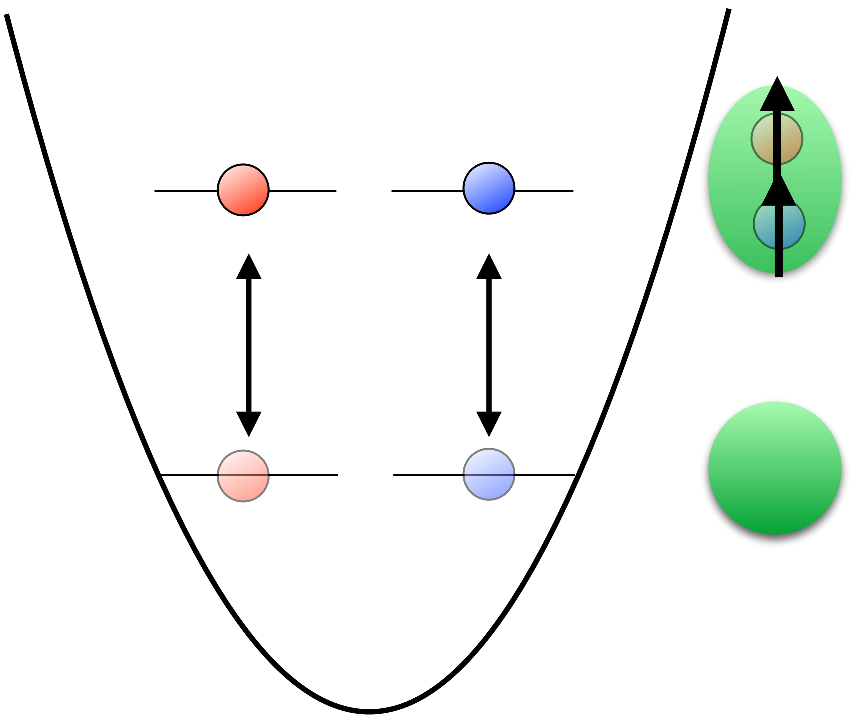
$$\times\left[\underbrace{(\sigma_1\cdot\sigma_2)\frac{e^{-\mu_\pi r}}{4\pi r}}_{\text{centralforce}} + \underbrace{S_{12}\left(1+\frac{3}{\mu_\pi r}+\frac{3}{(\mu_\pi r)^2}\right)\frac{e^{-\mu_\pi r}}{4\pi r}}_{\text{tensorforce}}\right]$$

Properties characterized by pion exchange

Nucleus is not a static, but a dynamic system even in the ground state.

Quantum mixing between the states above and below the Fermi surface.

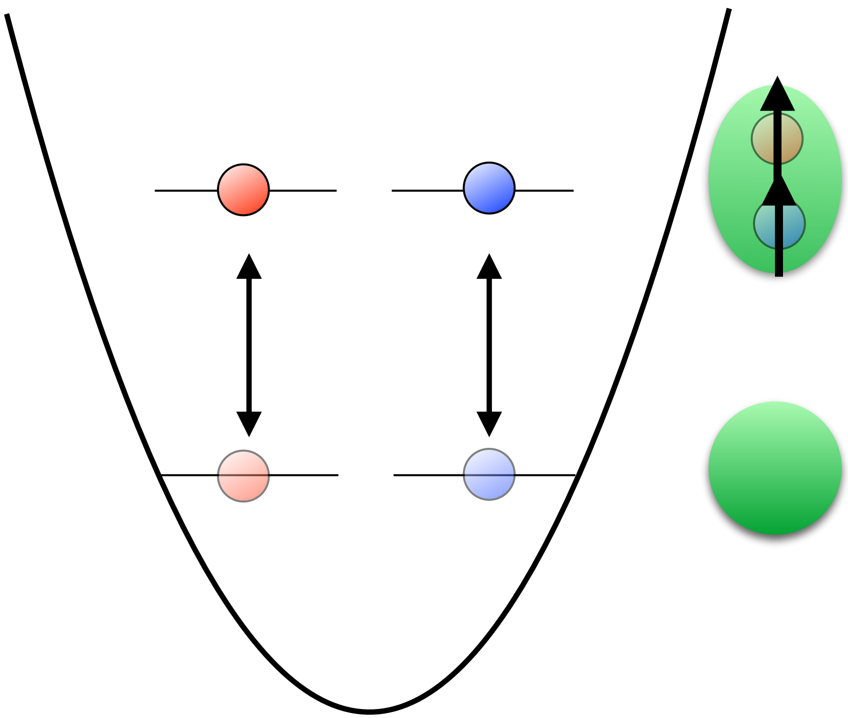
Stabilized through the off-diagonal terms of the Hamiltonian.



Properties characterized by pion exchange

Minor components sometimes determine the nature of the system.

States above the Fermi surface:
- D state in deuteron
- "High momentum component" in general

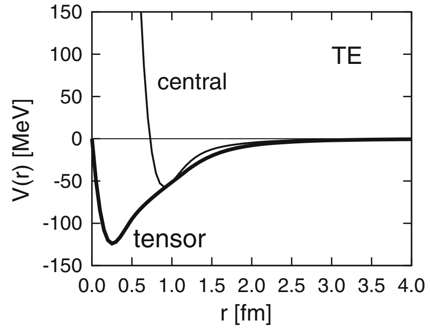


A mixture of a few accounts for as much as 50% of the binding energy.

Deuteron cluster plays a significant role.

Properties characterized by pion exchange

Minor components sometimes determine the nature of the system.



States above the Fermi surface:

- D state in deuteron
- "High momentum component" in general

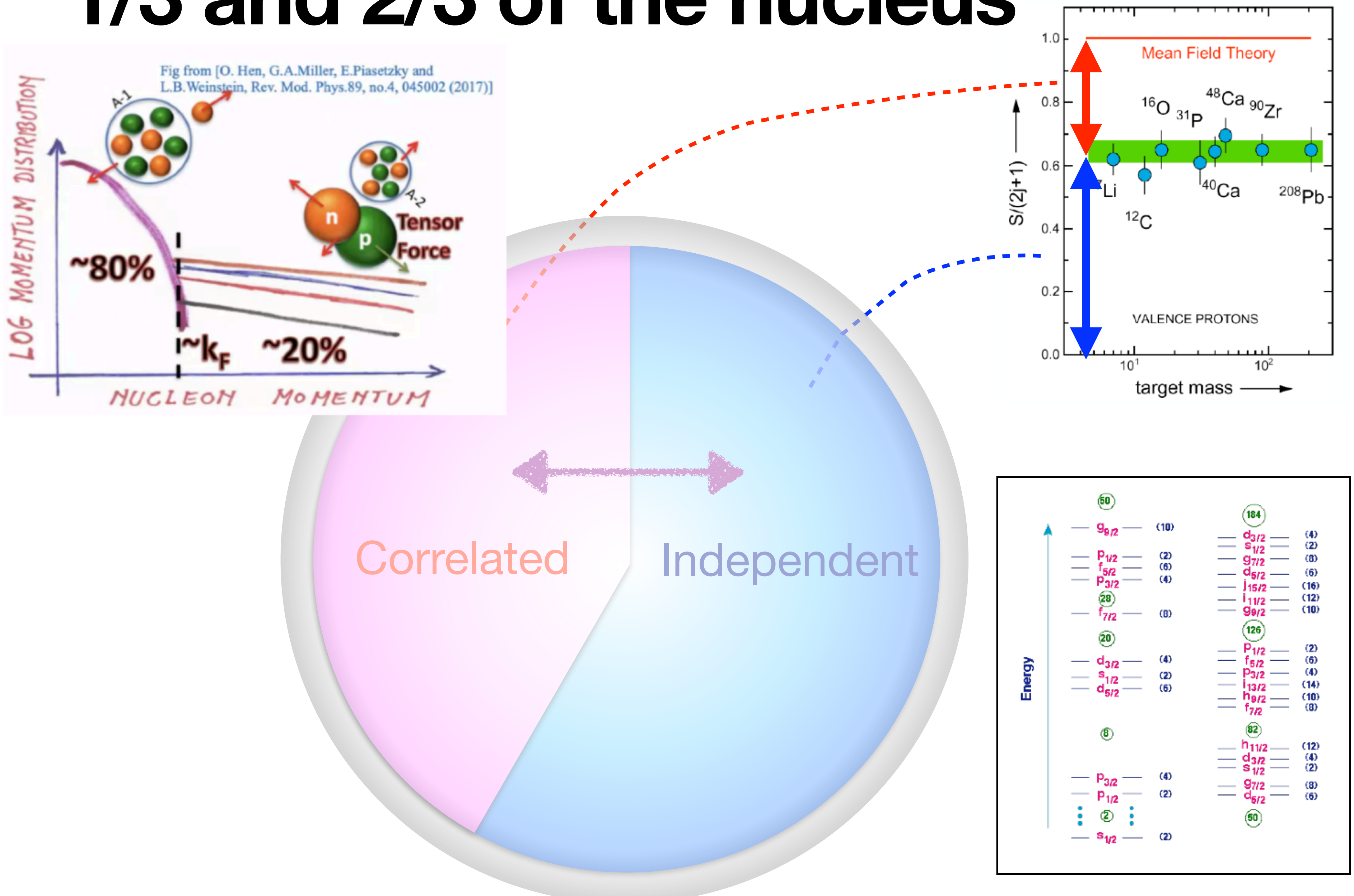
Table 2 Deuteron properties using the AV8' nucleon-nucleon potential.

Energy	−2.24 [MeV]
Kinetic	19.88
(SS)	11.31
(DD)	8.57
Central	−4.46
(SS)	−3.96
(DD)	−0.50
Tensor	−16.64
(SD)	−18.93
(DD)	2.29
LS	−1.02
P(*D*)	5.78 [%]
Radius	1.96 [fm]
(SS)	2.00 [fm]
(DD)	1.22 [fm]

A mixture of a few accounts for as much as 50% of the binding energy.

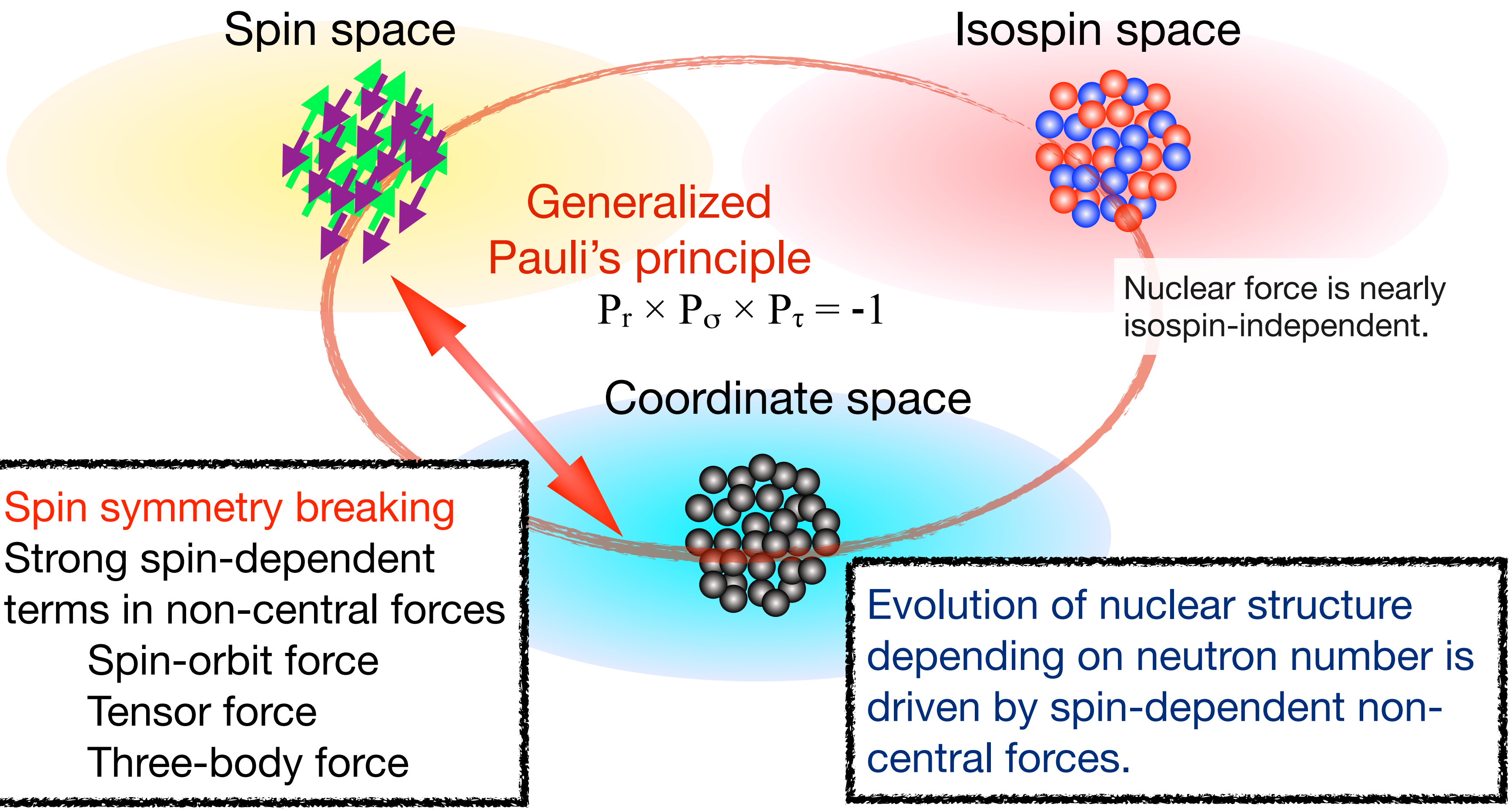
Deuteron cluster plays a significant role.

1/3 and 2/3 of the nucleus

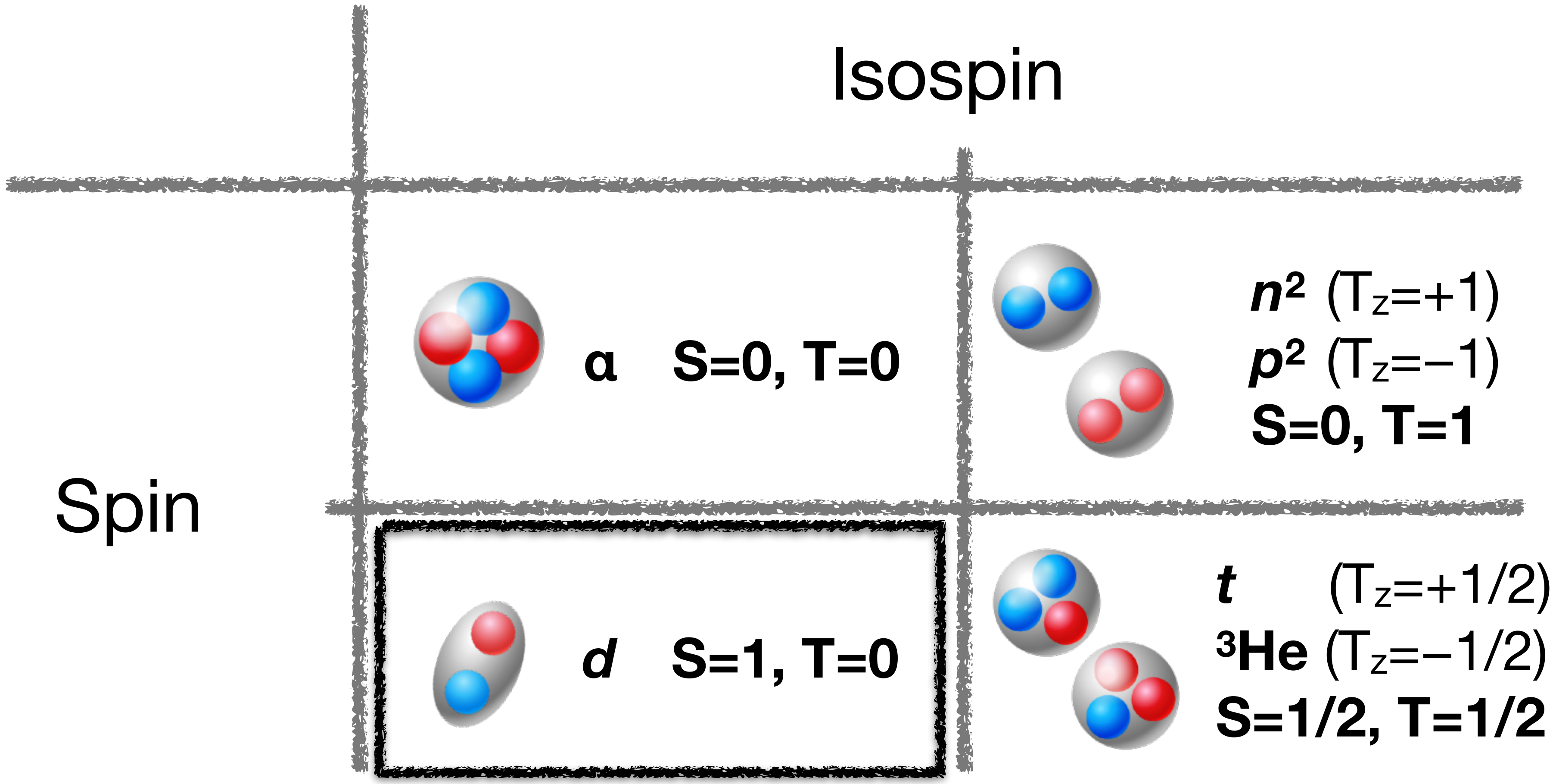


Properties characterized by pion exchange

Interplay of spin and isospin makes nucleus unique quantum system.

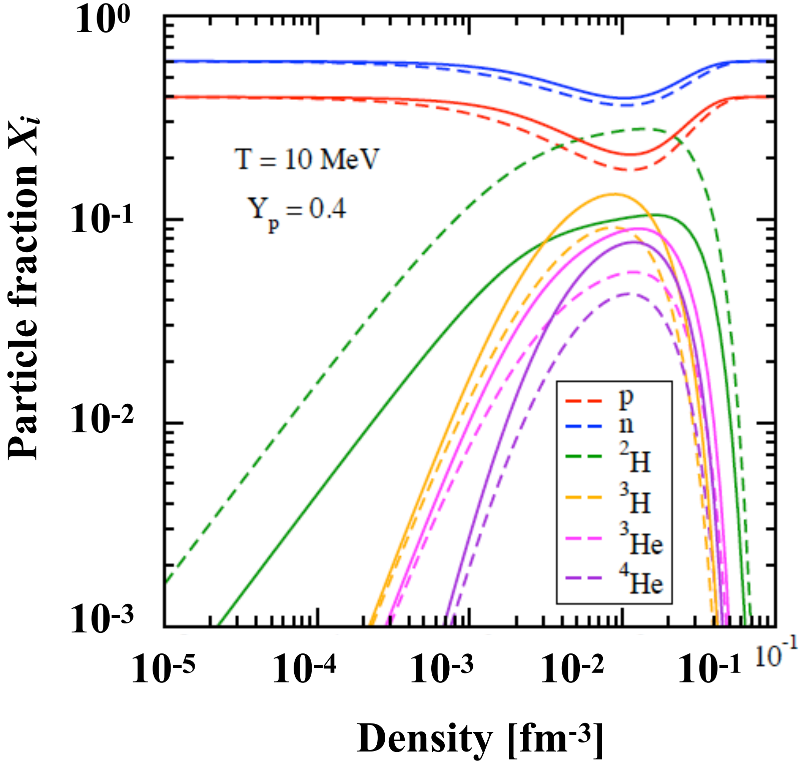


Looking at various clusters simultaneously

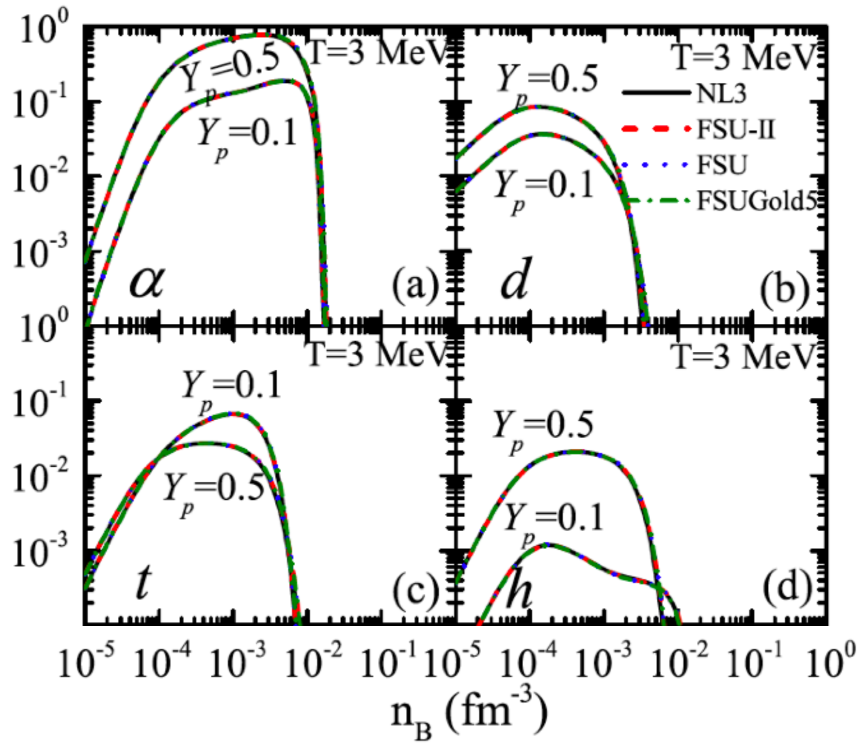


Progress in theory

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



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



Cluster develops at <1/10 of saturation density
Cluster formation strongly depends on isospin asymmetry

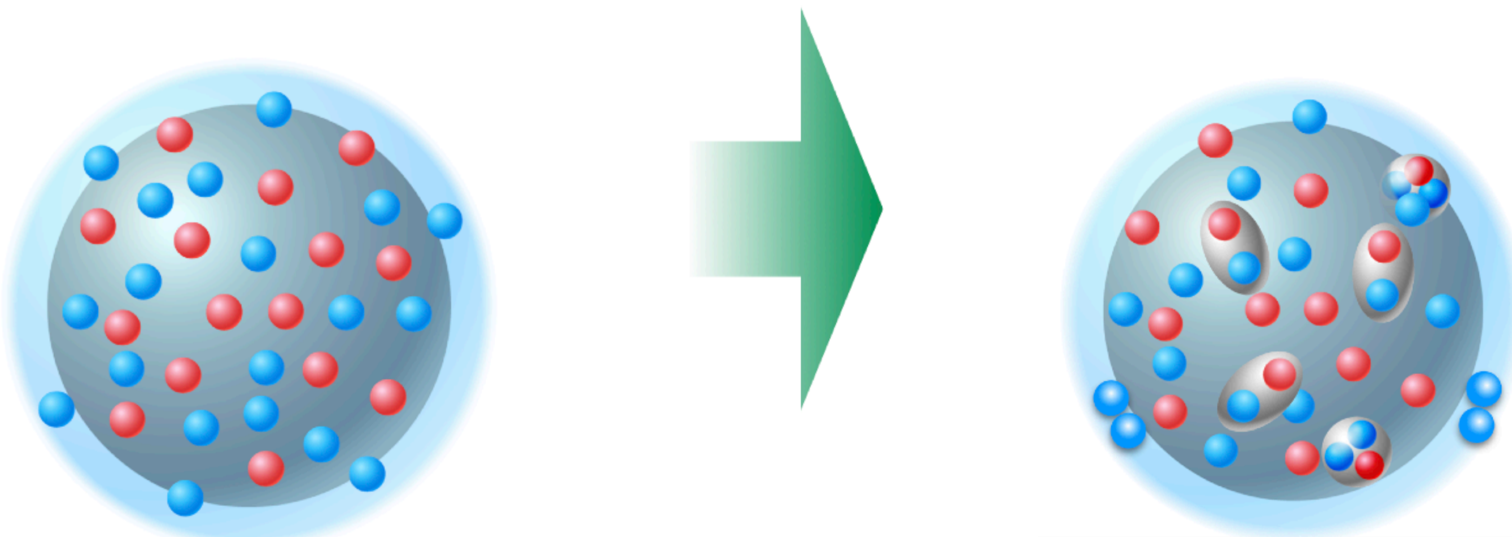
Modern view of atomic nucleus

Conventional picture

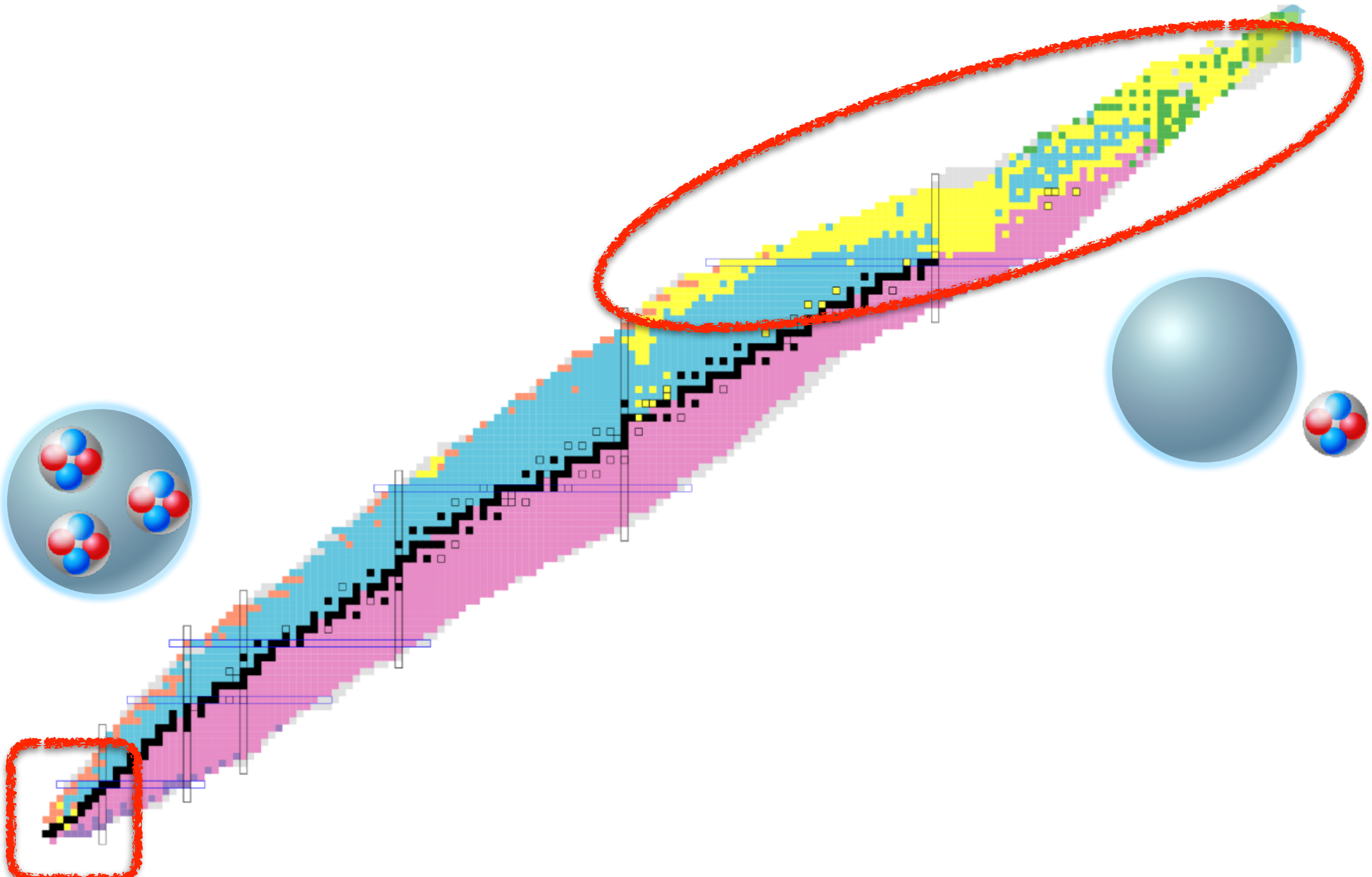
Uniform nuclei formed by independent neutrons and protons
Limited clusters (such as α) develop only in light and heavy nuclei

Modern picture

Various clusters (***d*, *t*, ^{3}He, *α*, ...**) develop in all nuclei
Non-uniform nuclei where nucleons and clusters coexist

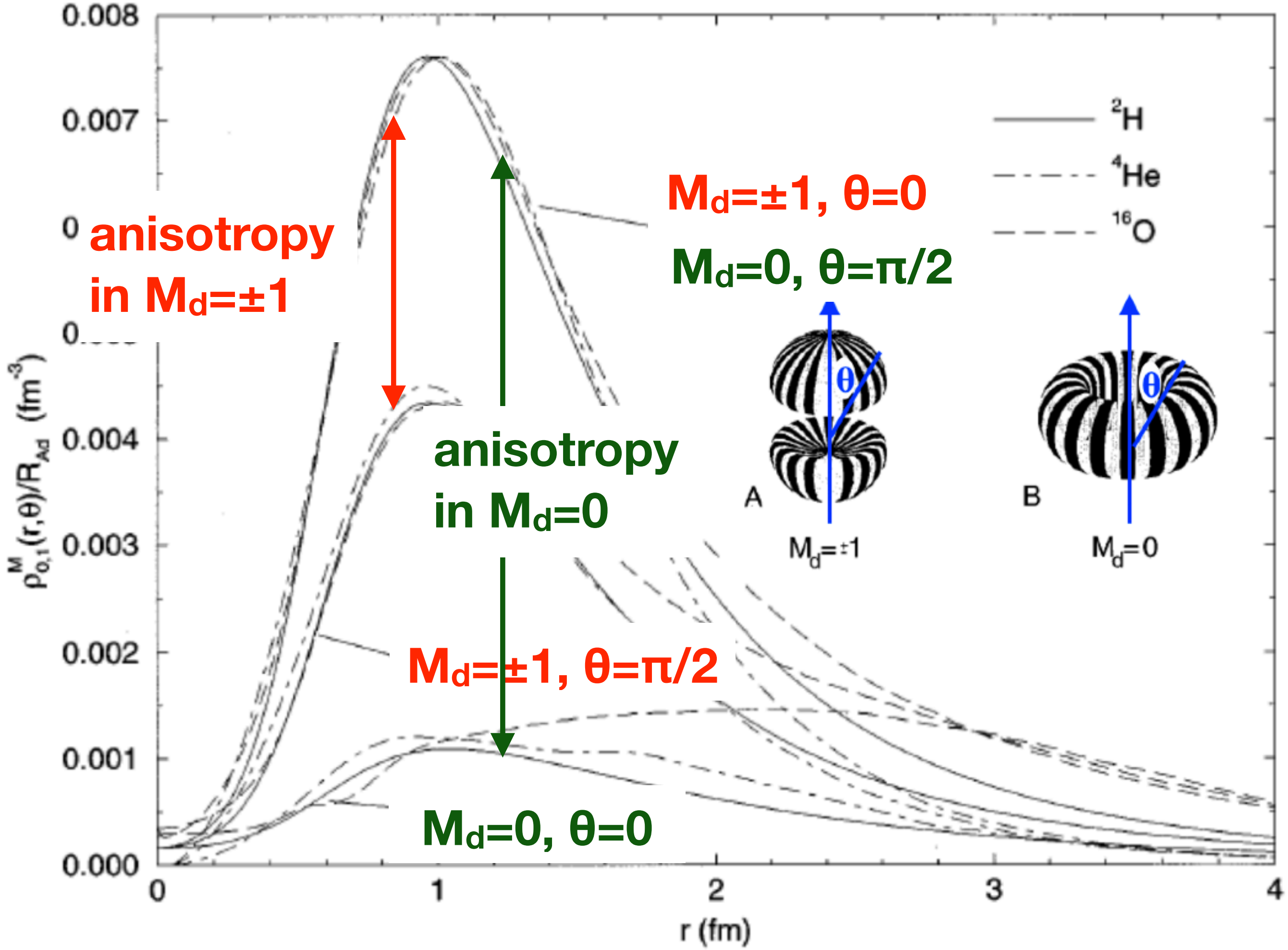


Is nuclear clustering universal?



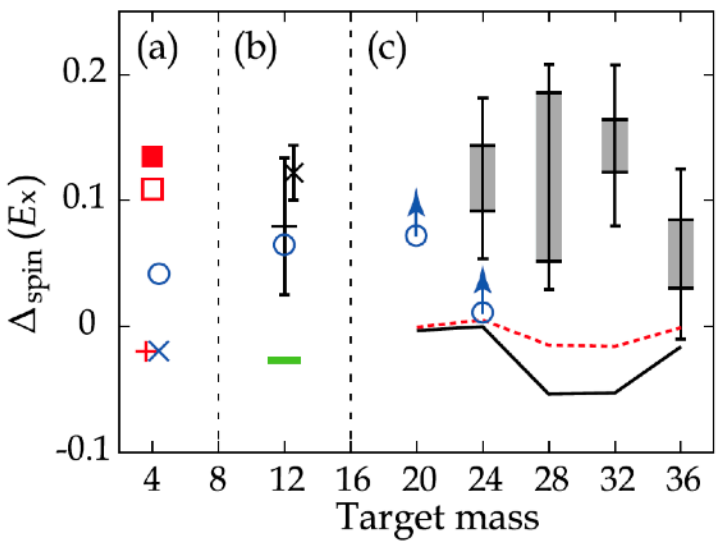
Deuteron-like spin-dependent anisotropy

“Femtometer toroidal structures in nuclei”
J. L. Forest et al., Phys. Rev. C **54**, 646 (1996)



Signature of the deuteron cluster?

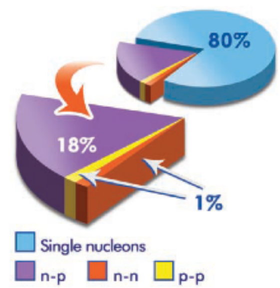
Finite spin expectation value

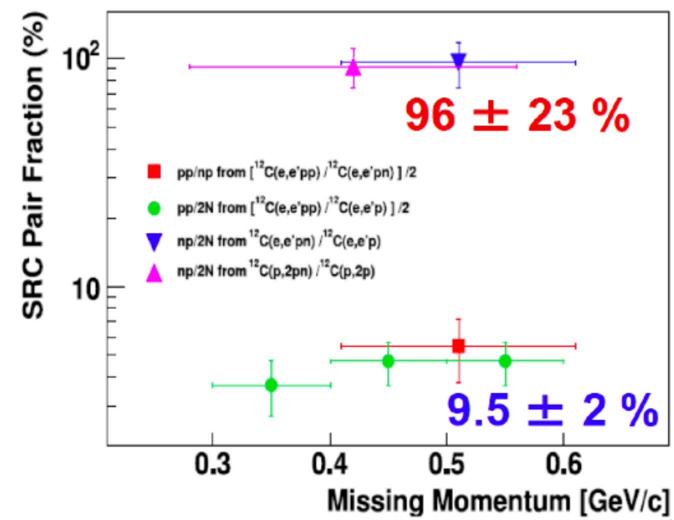


$$\lim_{E_x \to \infty} \Delta_{\rm spin}(E_x) = \langle \vec{S}_p \cdot \vec{S}_n \rangle$$

H. Matsubara et al., Phys. Rev. Lett. **115**, 102501 (2015).

Short range correlation





R. Subedi et al., Science **320**, 1476 (2008)

Knockout reaction $(e,e'p) \to (p,pN) \to (p,pX)$

Simple and clean reaction if the quasi-free condition is satisfied.

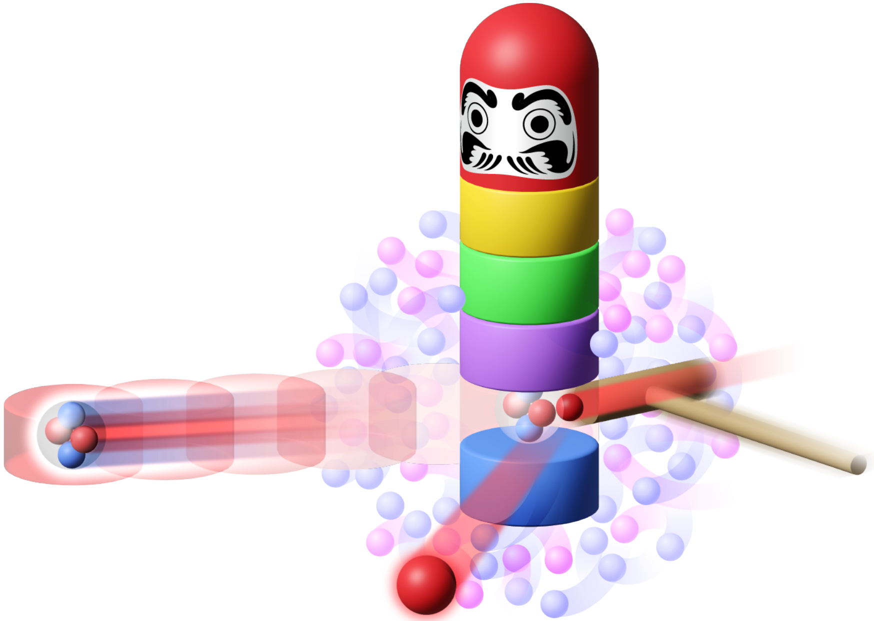
The final state interaction is minimized.

Cluster wave function, momentum distribution can be extracted.

Initial state Cluster Residue

$$|A\rangle = \sum_{i,j} |x\rangle_i \otimes |B\rangle_j$$

Knockout reaction cuts this entanglement instantly.



ONOKORO Project: cluster knockout

(p,pX) @ E/A = 200—300 MeV

X: (p,) d, t, ^{3}He, α

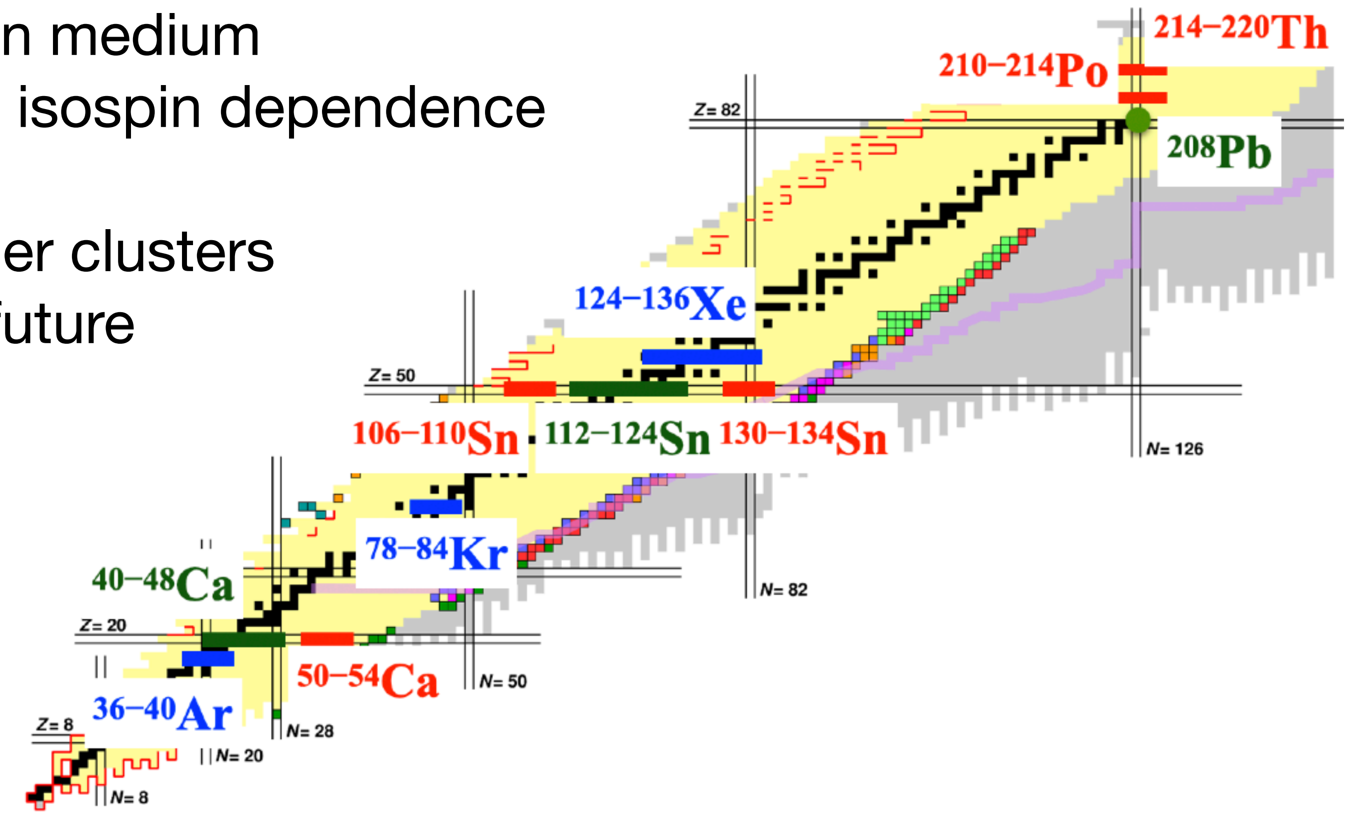
Relative abundance of each cluster and its isotopic dependence

α: Verification of alpha preformation on the surface

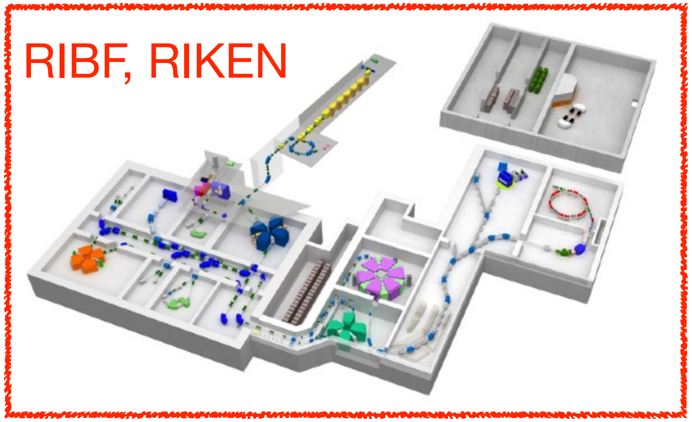
d: Tensor force in medium

t, ^{3}He: Opposite isospin dependence

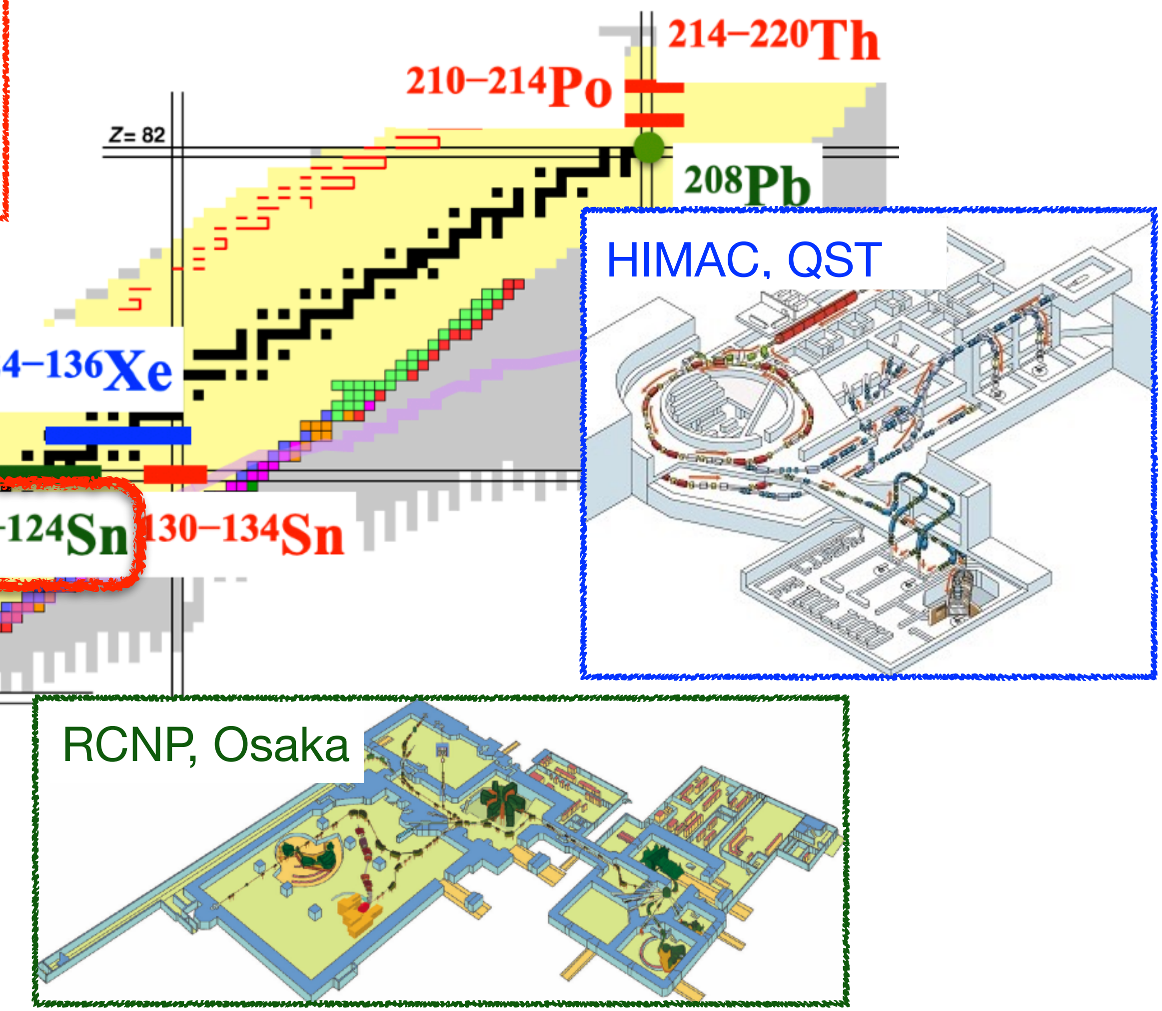
Extension to heavier clusters
(^{6}He, Li, Be, C) in future

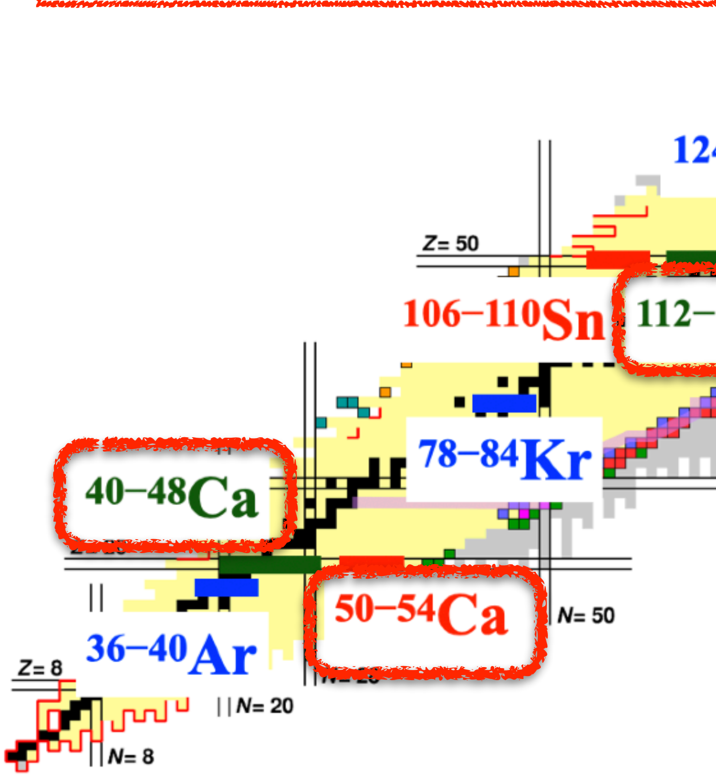


Full use of accelerator facilities in Japan

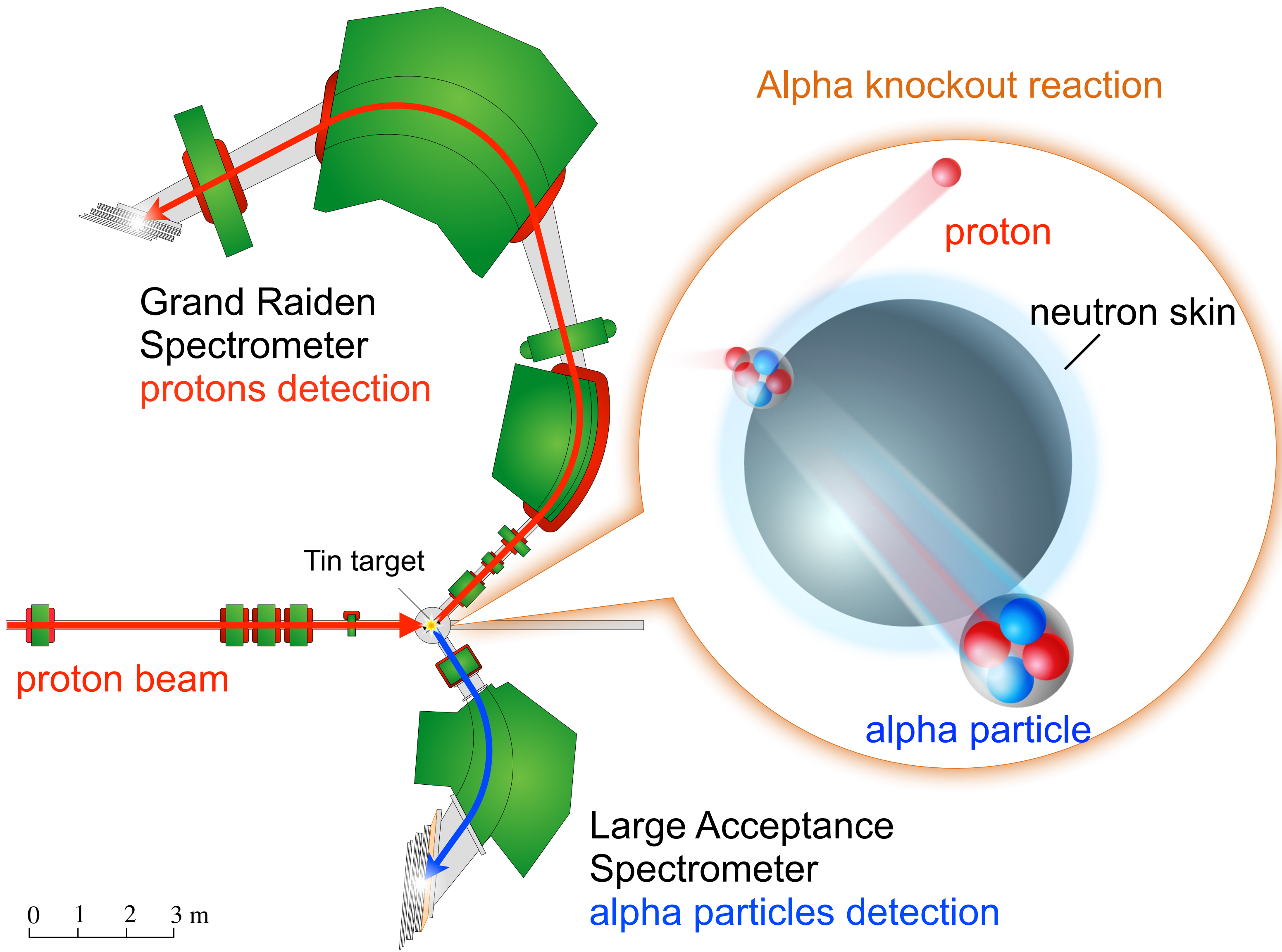


Wide mass range
Stable and unstable nuclei
Normal and inverse kinematics





α clustering in Tin isotopes



M. Fujiwara et al., Nucl. Instrum. Meth A **422,** 484 (1999).

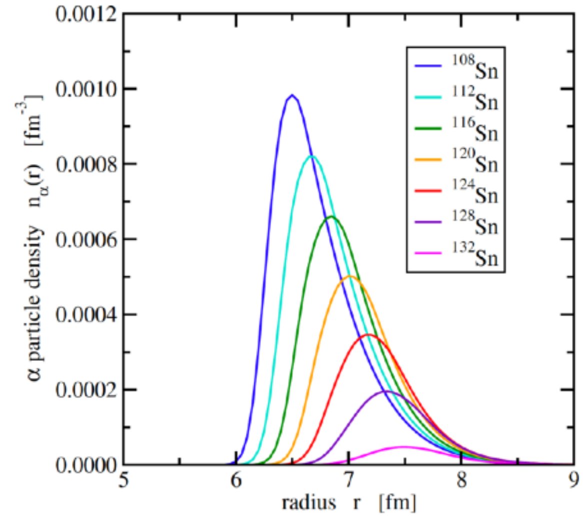
α clustering in Tin isotopes

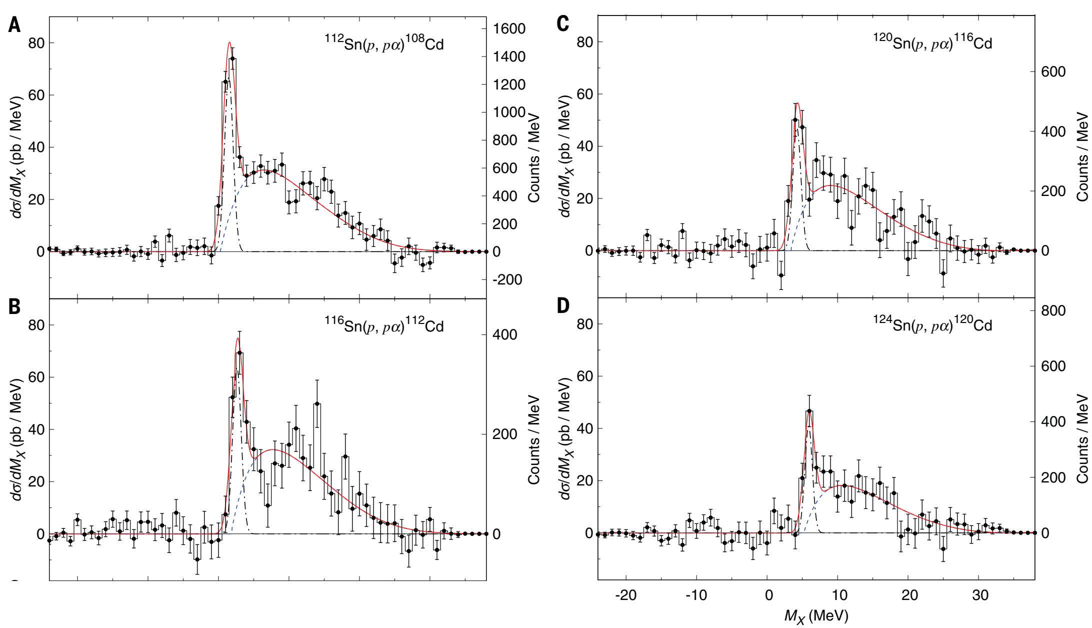

REPORT

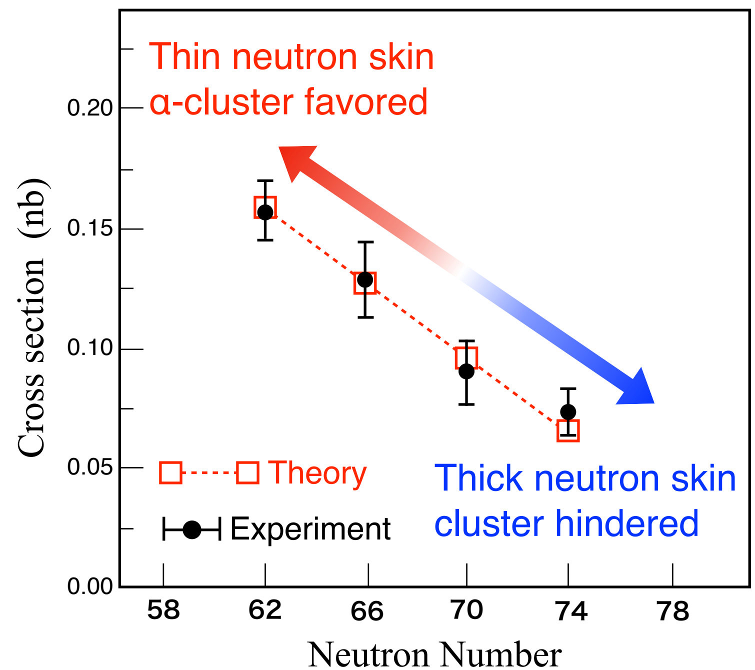
NUCLEAR PHYSICS

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]

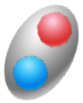






J. Tanaka et al., Science **371**, 260 (2021).

(p,pX) from Calcium isotopes



^{40}Ca(p,pd)

^{40}Ca(p,pt)

^{40}Ca in July 2023

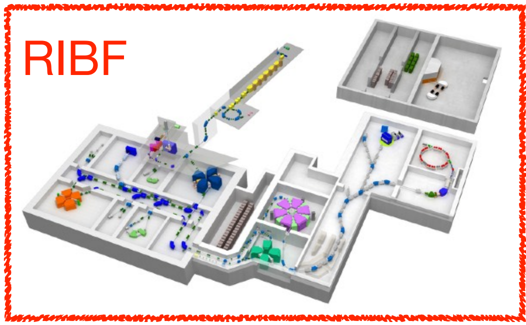
^{42,44,48}Ca in March 2024

S$_X$ [MeV]

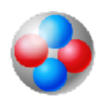
preliminary

S$_X$ [MeV]

$^{50\text{–}52}$Ca in Dec. 2024



^{40}Ca(p,p^3He)



^{40}Ca(p,$p\alpha$)

S$_X$ [MeV]

S$_X$ [MeV]

R. Tsuji et al.

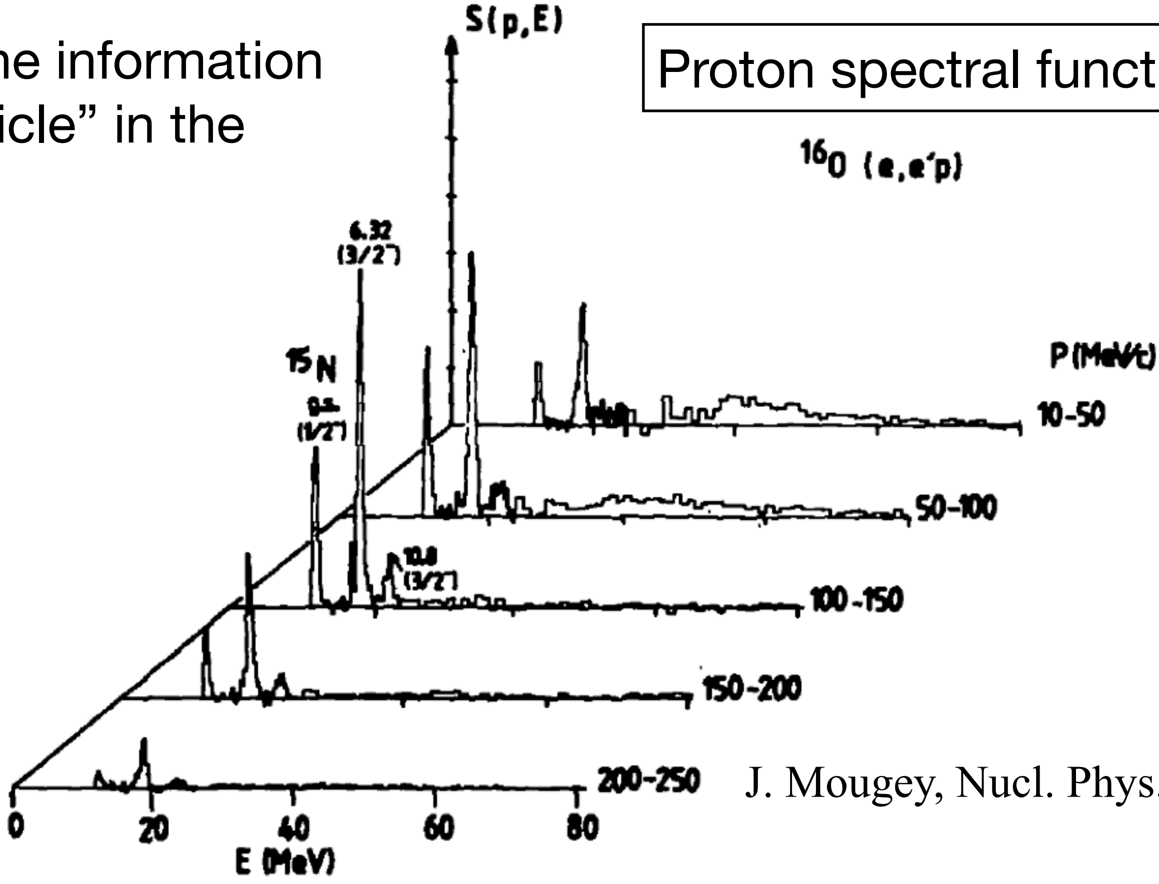
Generalization of the spectral function

Benhar, Fabrocini, Fantoni, Nucl. Phys. A 505 267 (1989)

$$P(S_X, k_F) = \Sigma_R \, |\langle R{:}X(S_X, k_F)|A\rangle|^2 \quad \delta(S_X - E_A - E_R - M_X)$$

It contains all the information about the “particle” in the nucleus.

Proton spectral function in ^{16}O

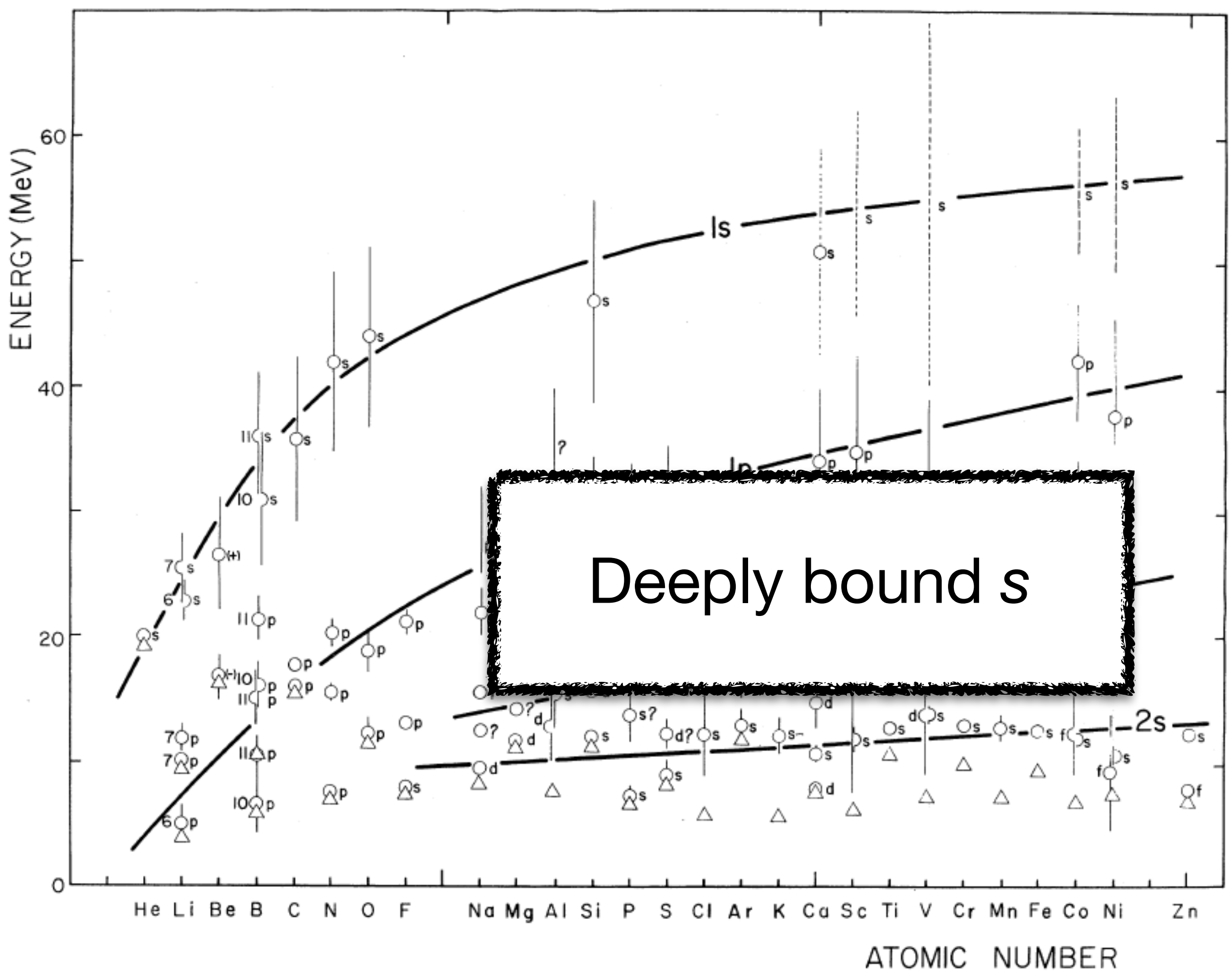


J. Mougey, Nucl. Phys. A 335, 35 (1980)

First determination of the spectral function for clusters

Do clusters form shell structures?

Shell structures seen in (*p*,2*p*) measurements



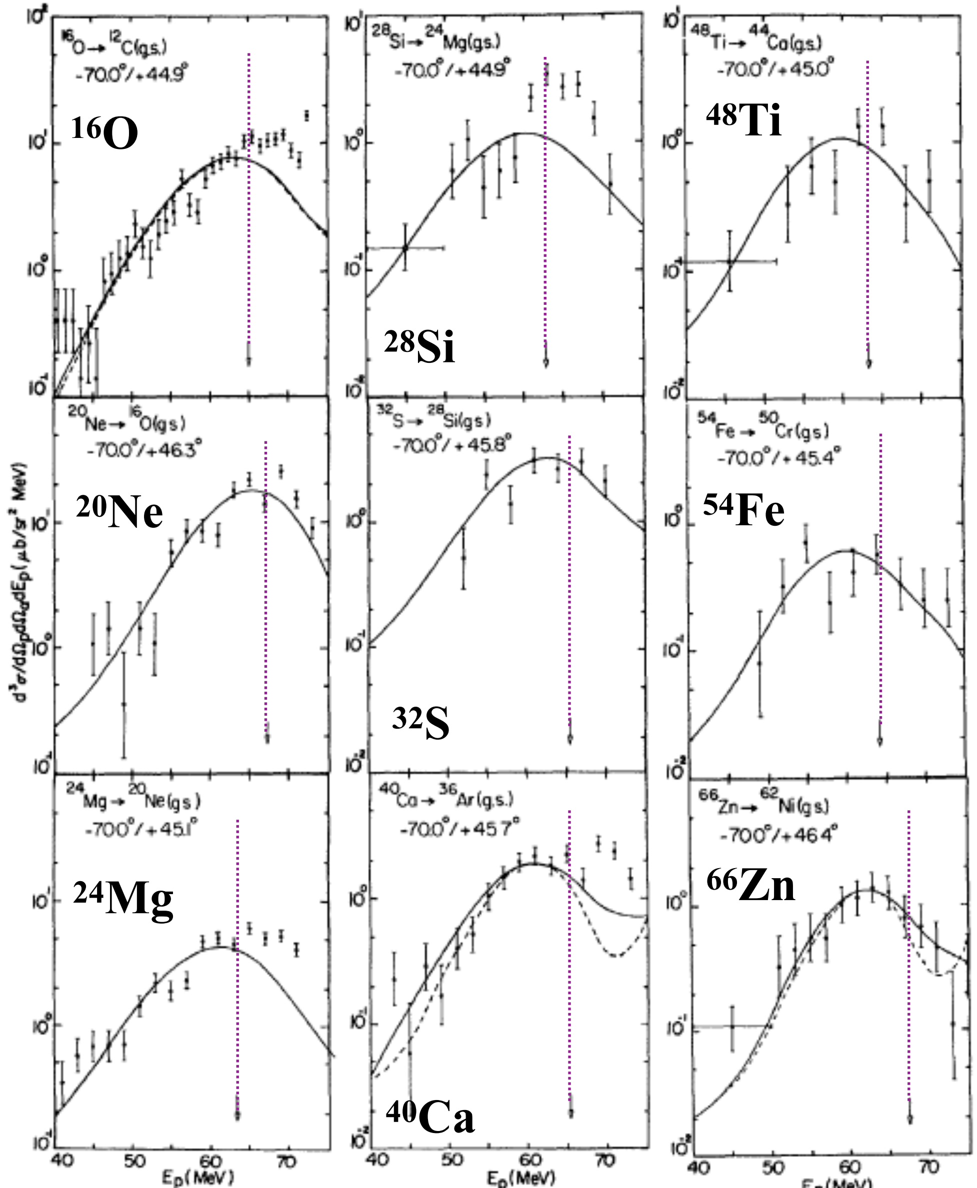
G. Jacob and Th. A. J. Maris, Rev. Mod. Phys. 45, 6 (1973)

Past (*p,pX*) data shows only *S* orbitals.

T.A. Carey et al., PRC **29**, 1273 (1984)
(p,pα) @ 101.5 MeV

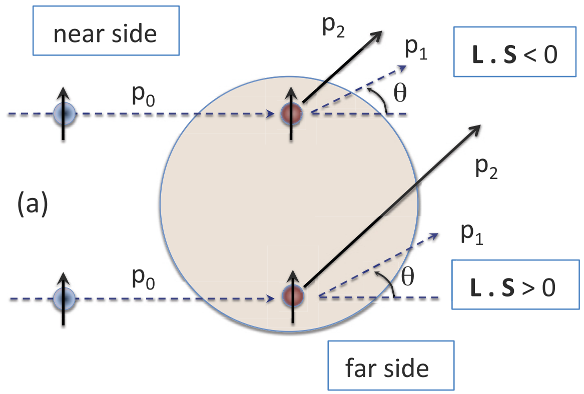
Why?

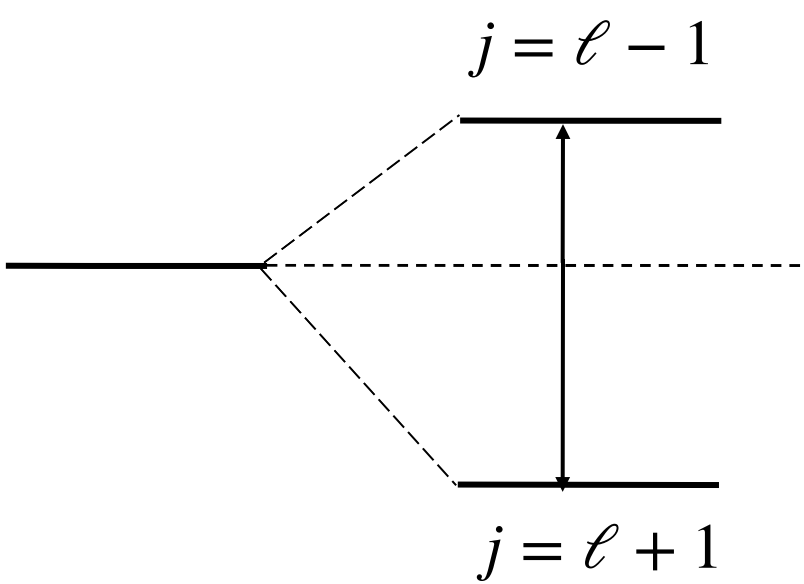
How about ***d***, ***t***, **³He**?

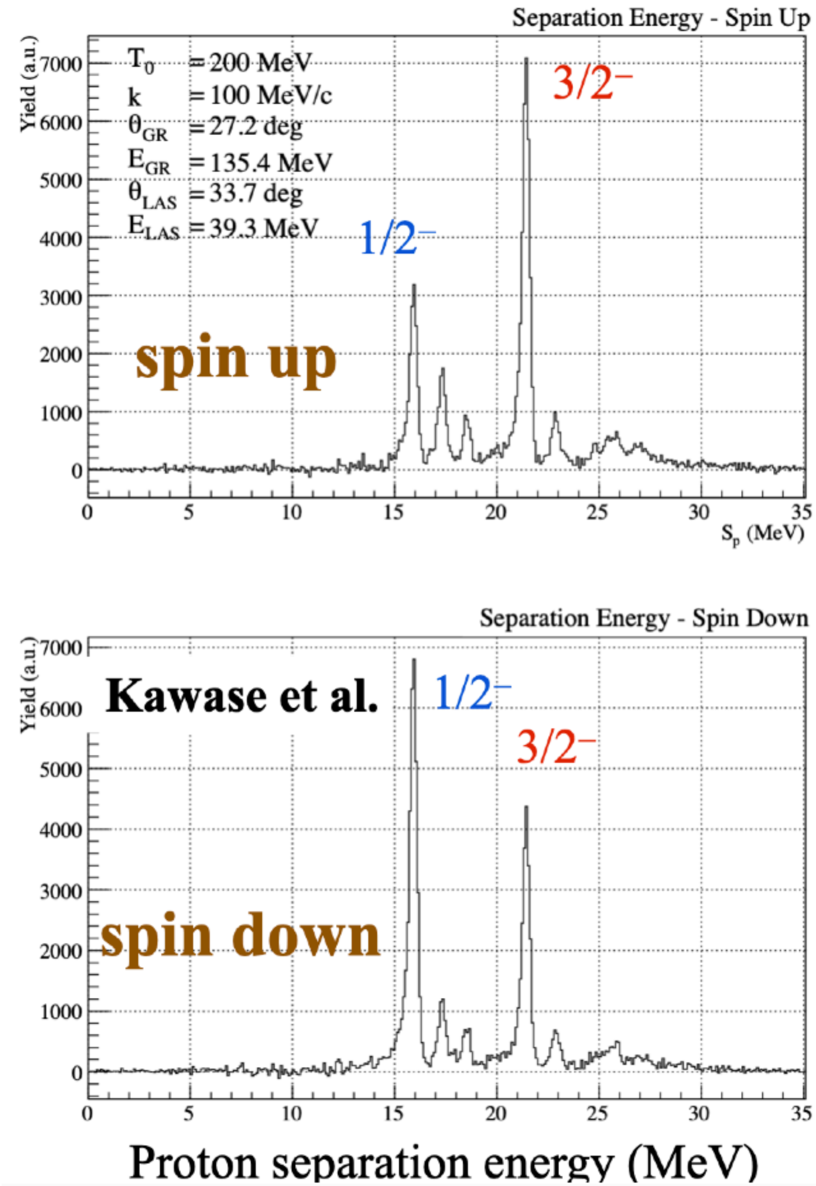


Separation of $J_>$ and $J_<$

Maris effect

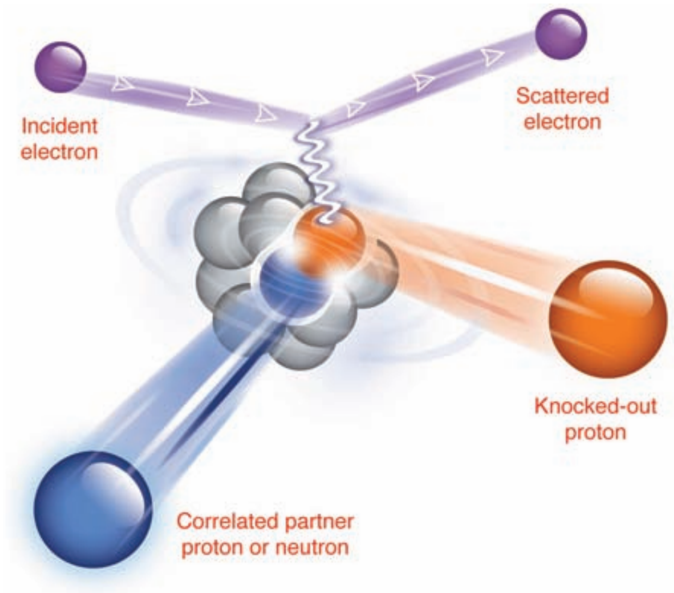


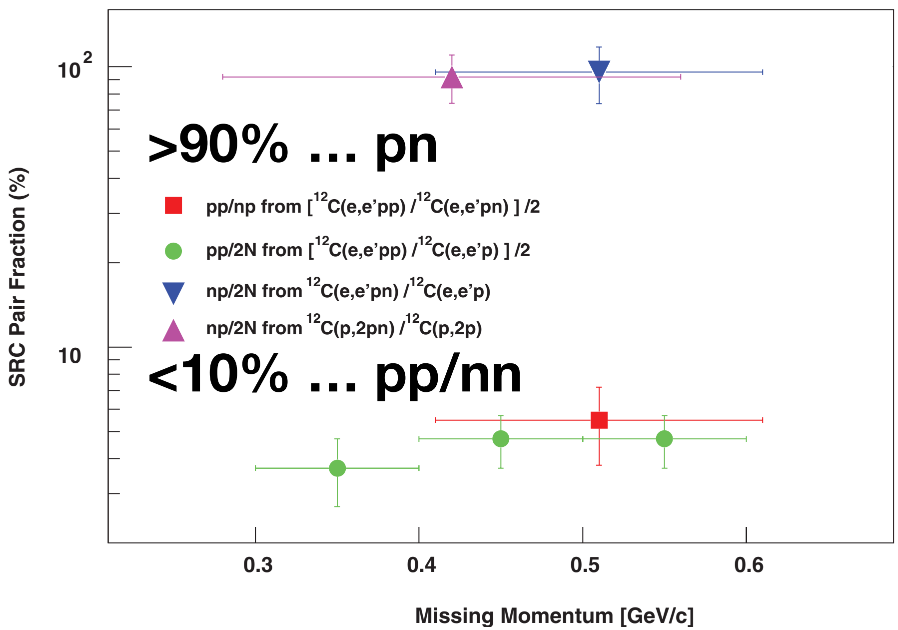




Hot topic: short range correlation

R. Subedi et al., Science **320** 1476 (2008).



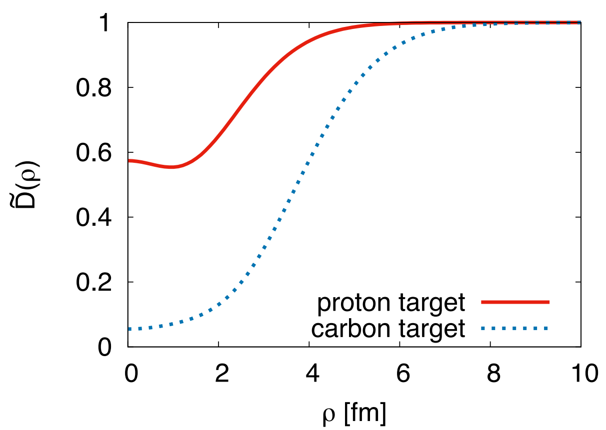


→ **Deuteron (cluster) knockout using electron**

☺ Transparent probe

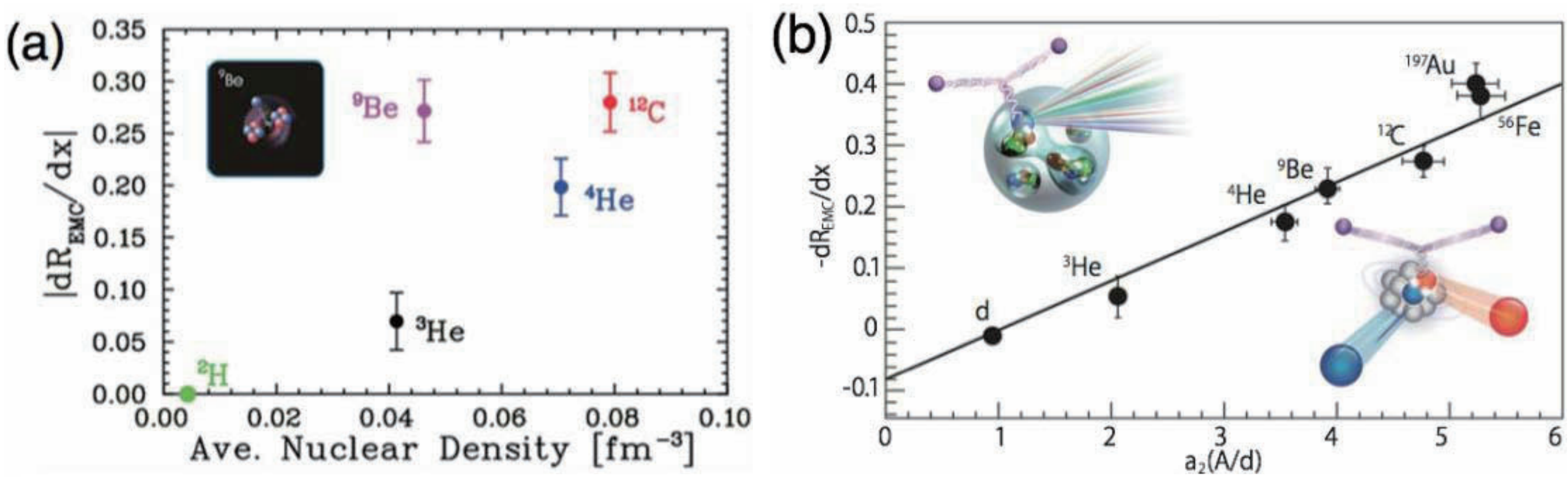
☹ Only applicable to stable nuclei

c.f. SCRIT



Cluster “size” and EMC effect

EMC effect is determined by the local density, not the average density.

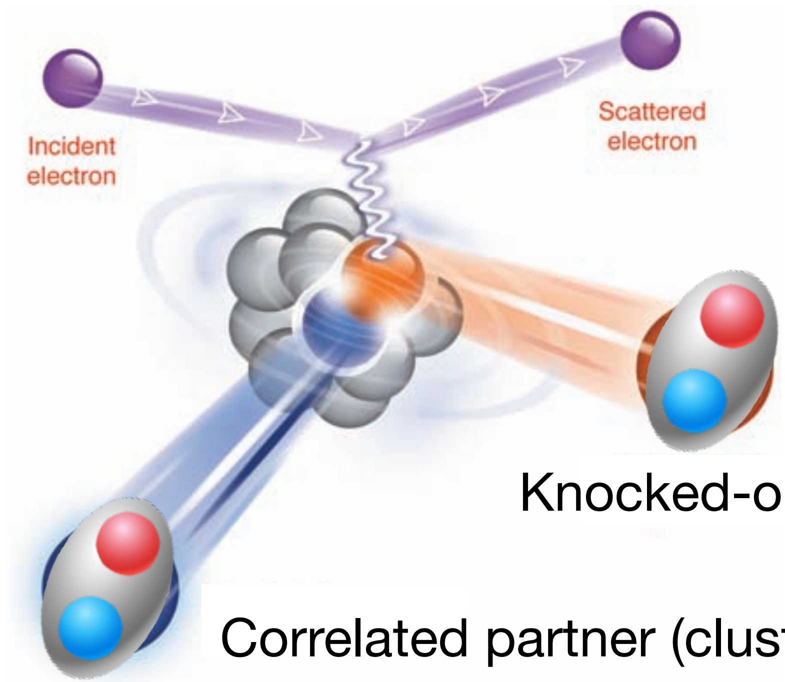


Cluster size and amount play a role.

→ **EM form factor of the cluster**

“Clusters” made of clusters

(*e*,*e’XX*)



Clusters may form larger subsystems:
“clusters” made of clusters.

A clean electron probe is ideal for studying such “weak” structure.

Summary

- Variety of topics/programs in the field of low energy nuclear physics.
- EIC gives us the opportunity for the physics we are interested in.
- We hope to increase momentum for further discussion.
- Possible physics cases at EIC:
    - Deeply bound *s* state.
    - SRC / cluster knockout: (*e,e'X*)
    - EMC effect / EM form factor of the cluster.
    - Cluster-cluster correlation: (*e,e'XX*).