Formation of alpha clusters in dilute neutron-rich matter

TECHNISCHE UNIVERSITÄT DARMSTADT

~ March 2019

SFB Workshop

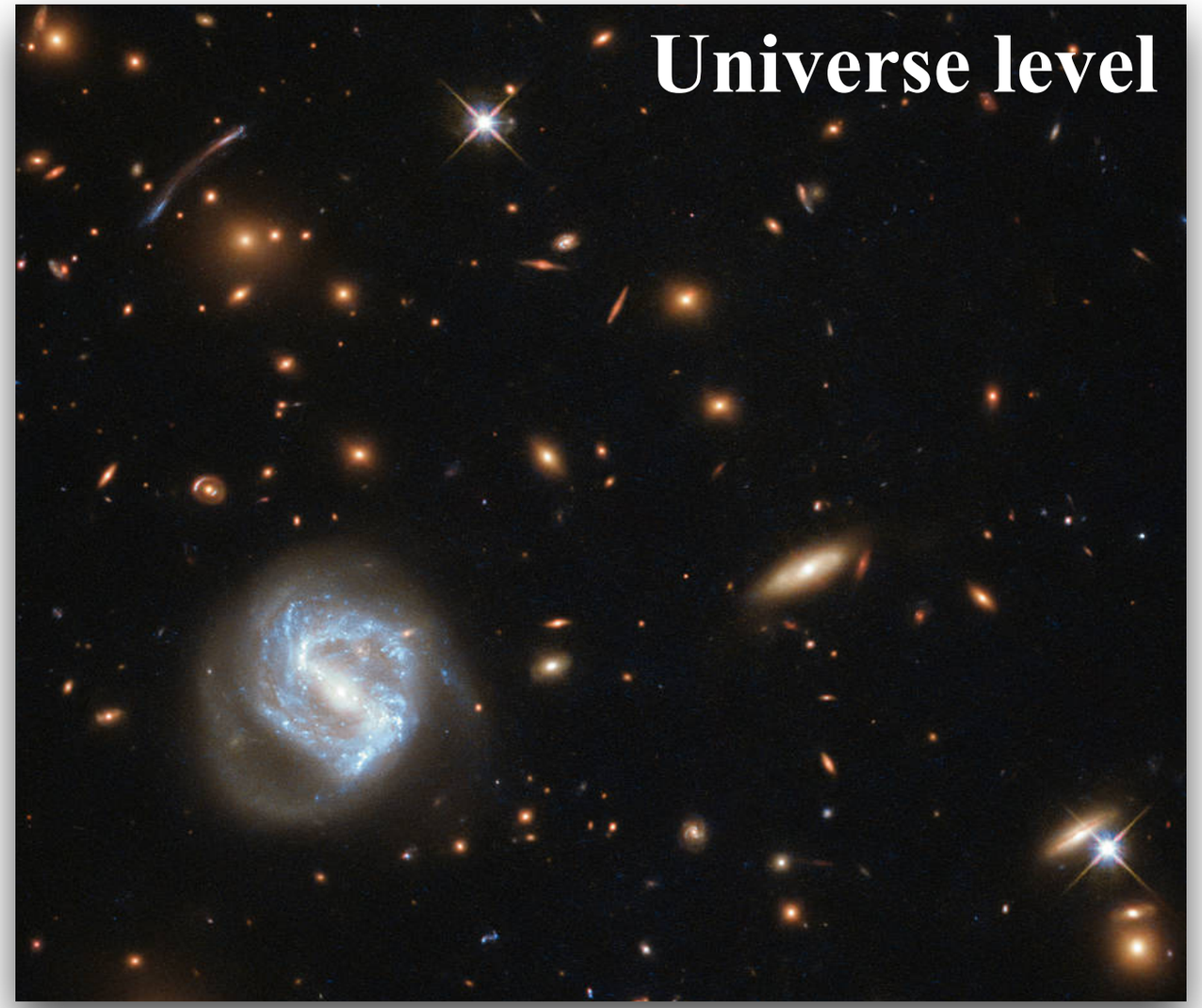
RIKEN NISHINA CENTER

April 2019 ~

Junki Tanaka

Riken Nishina Center, Spin-Isospin

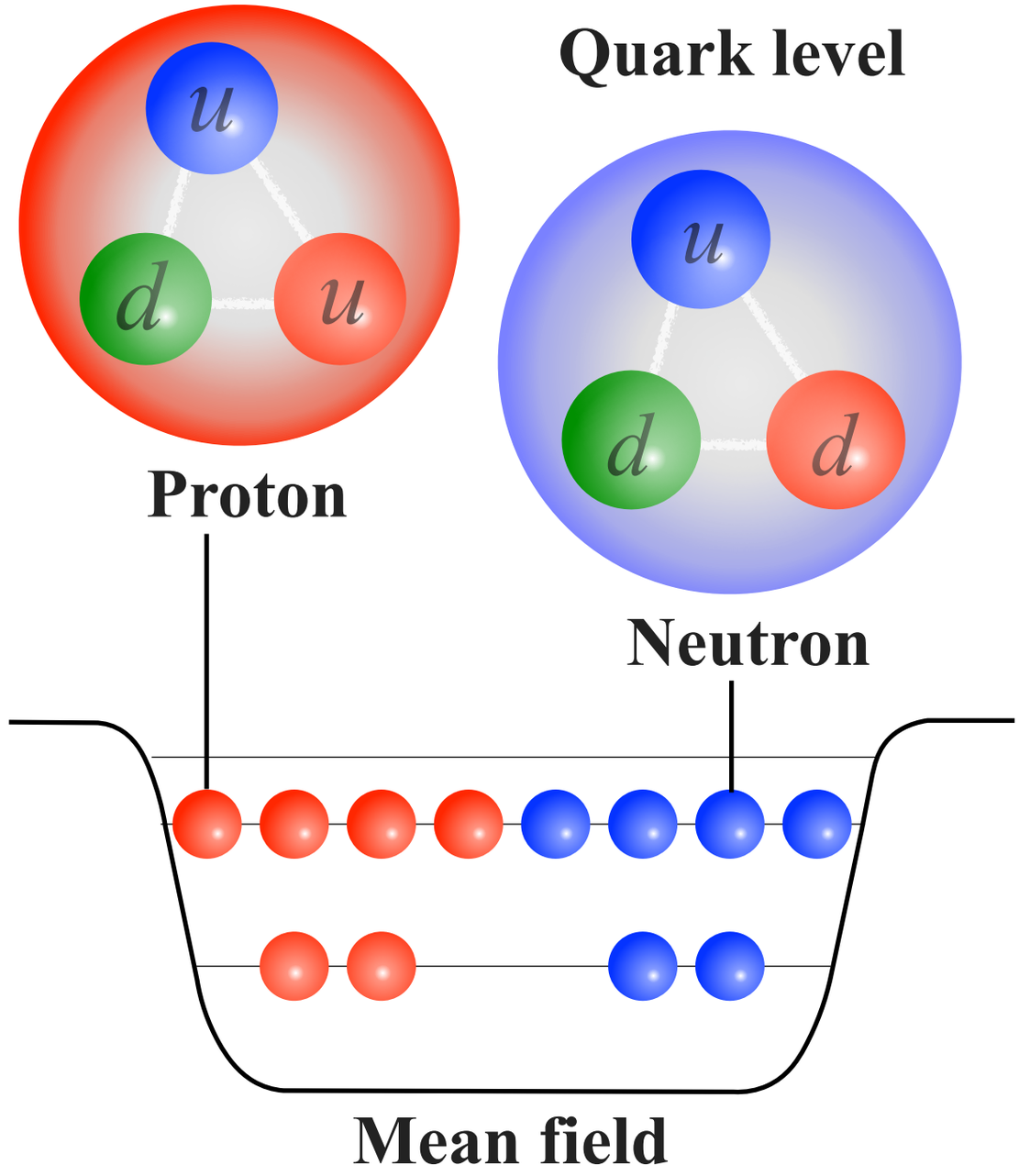
Correlation and Clustering



Hubble's Galaxy Cluster

Credit: ESA/Hubble & NASA

https://www.nasa.gov/image-feature/goddard/2018/hubbles-galaxy-cluster-cornucopia

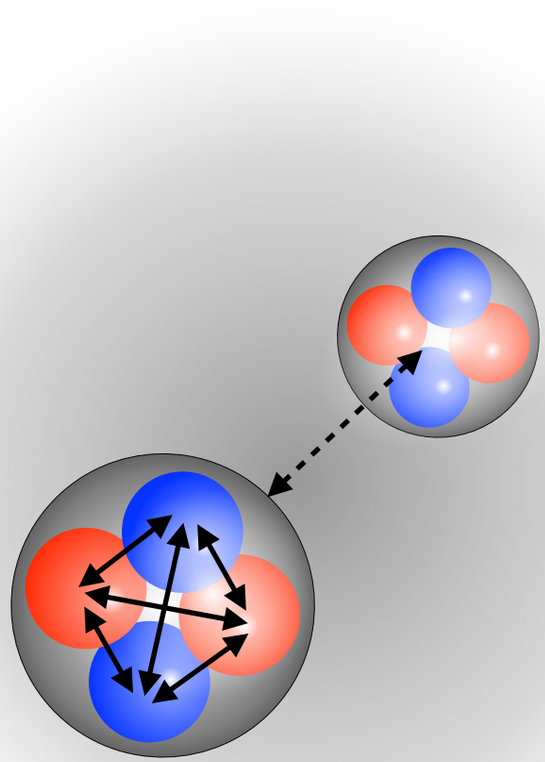


Clusters in Light Nuclei

Light nuclei

Prediction of α clusters

L.A. Hafstadt and E. Teller, Phys. Rev. 54, 681 (1937)
W. Wefelmeier, Z. Phys. **107** (1937)

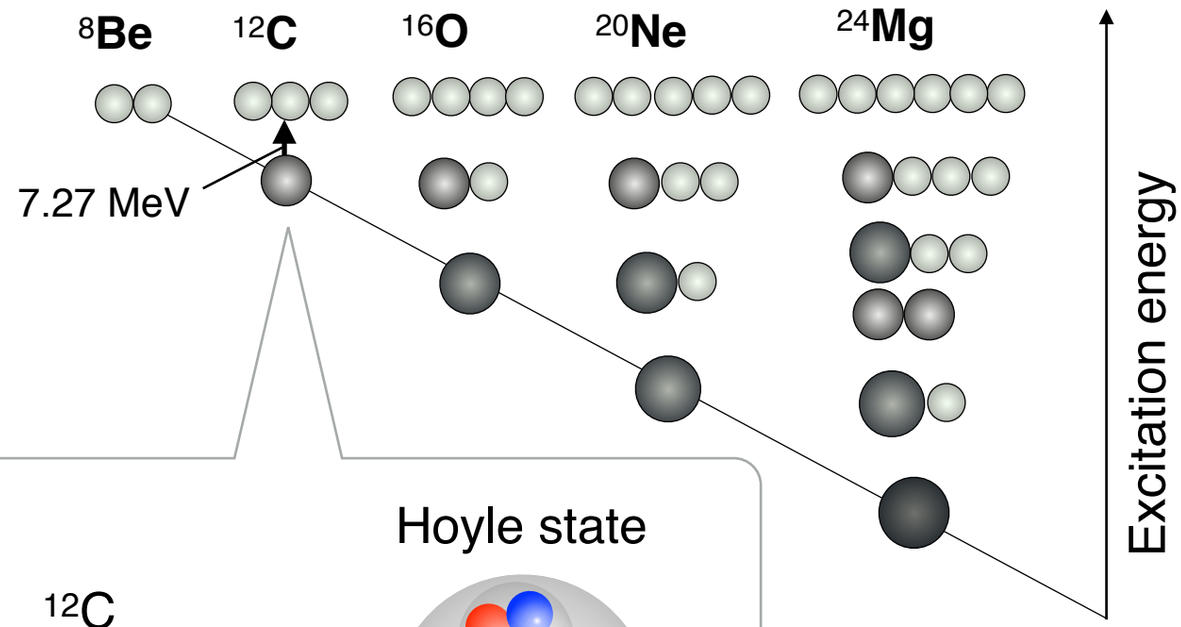


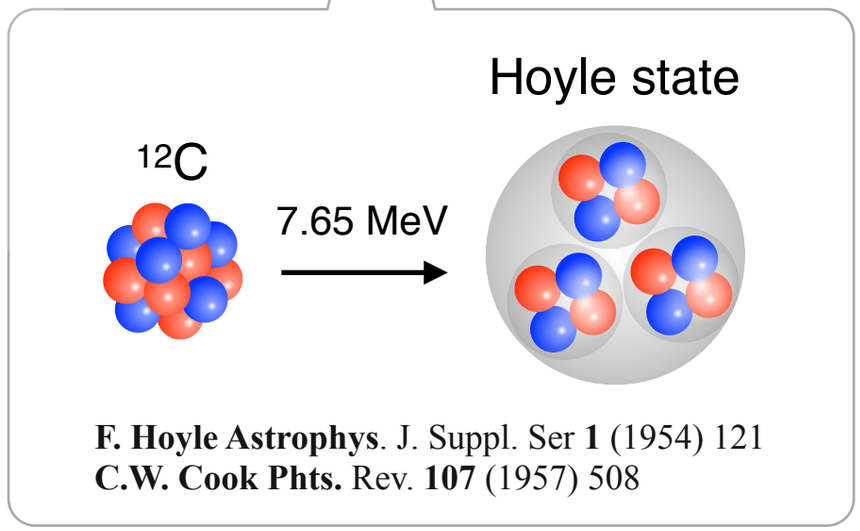
In dilute nuclear matter

Cluster structure

Ikeda Diagram

K. Ikeda Prog. Theo. Phys. Suppl. E**68** (1968) 464



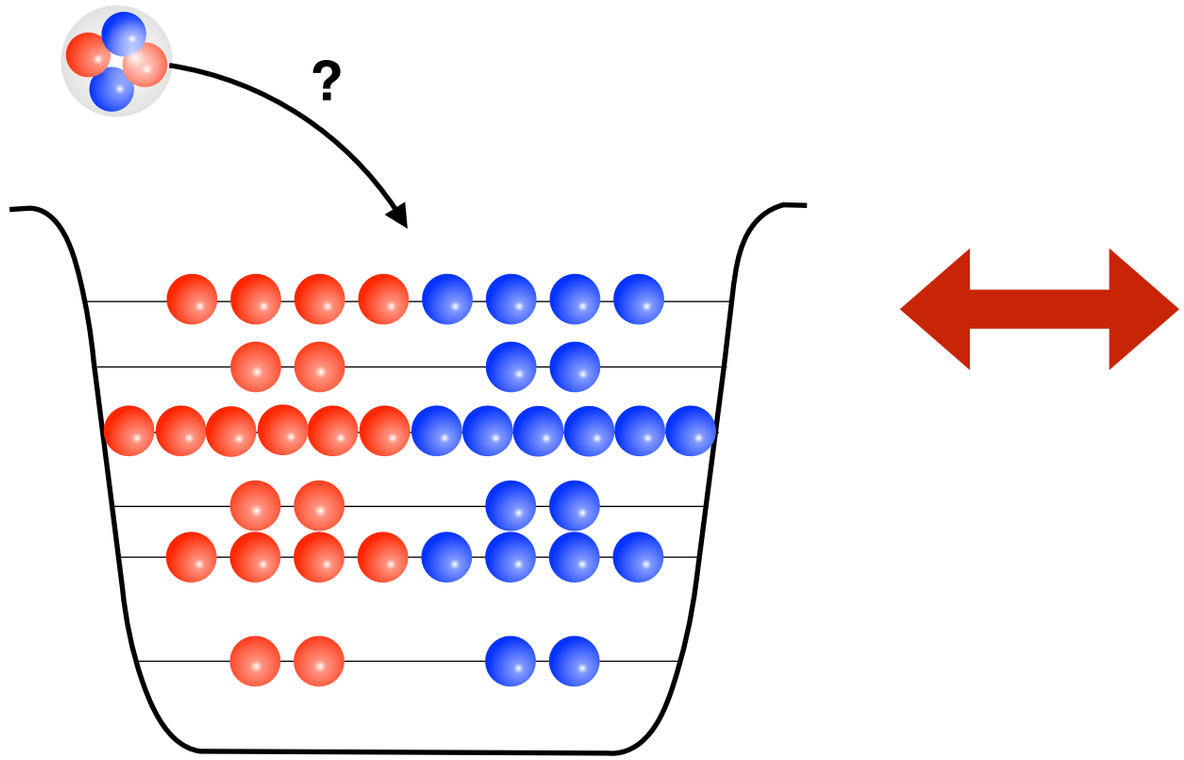


F. Hoyle Astrophys. J. Suppl. Ser **1** (1954) 121
C.W. Cook Phts. Rev. **107** (1957) 508

Clusters in Heavy Nuclei ?

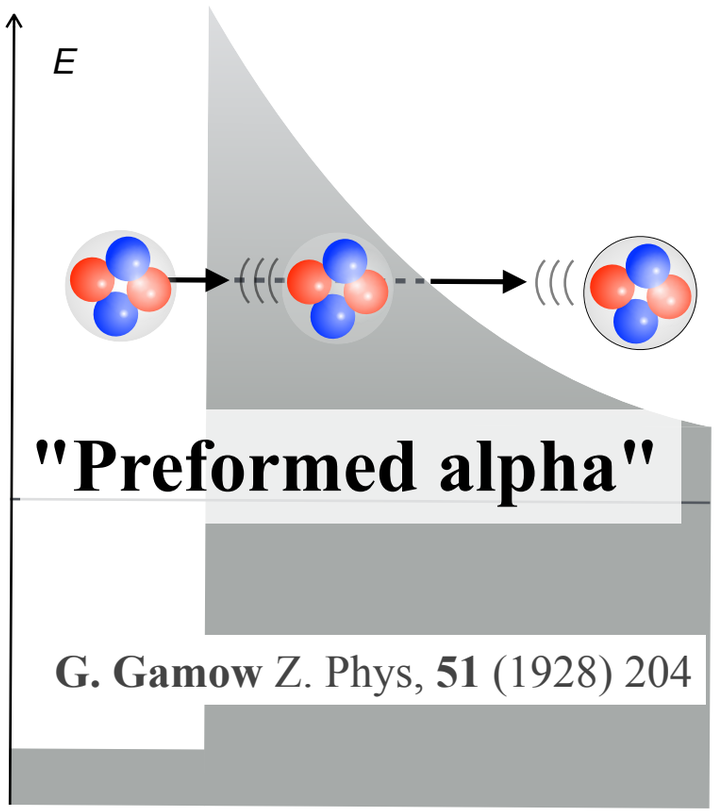
Heavy Nuclei ?

How to treat alpha clusters in mean field generated by nucleons ?



Mean-field Potential

Alpha clusters are essential ingredients for alpha decay !



Decay theoretical studies of surface alpha clustering

I. Tonozuka & A. Arima Nucl. Phys. A **323** (1979) 45

K. Varga, R. Lovas, R.J. Liotta, Phys. Rev. Lett. **69** (1992) 37

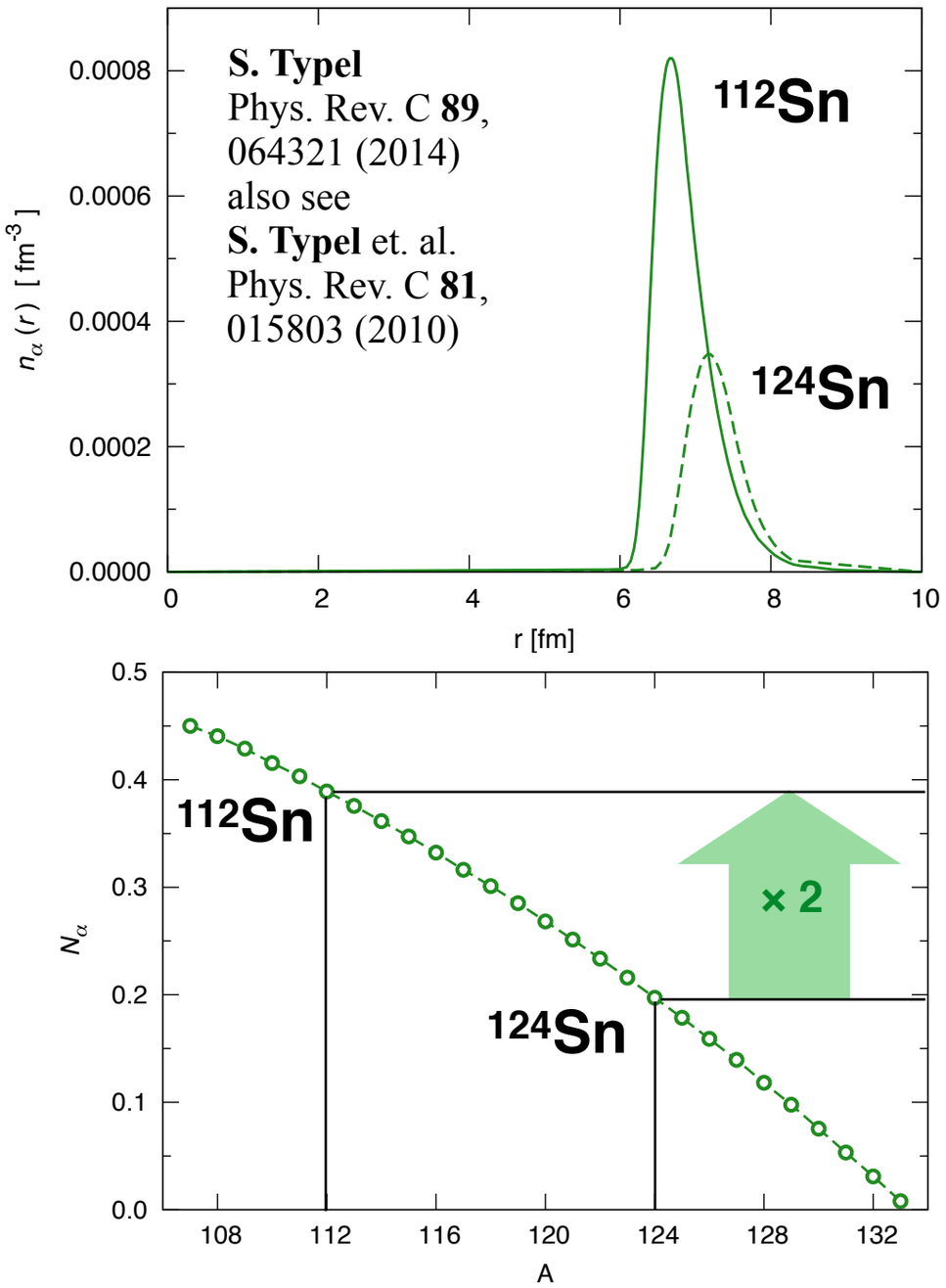
D. S. Delion, A. Dumitrescu, V.V. Baran PRC **97** (2018) 064303

C.Qi, R. Liotta, W. Ramon, Prog. Part. Nucl. Phys. **105** (2019) 214

D. S. Delion, R. Liotta Phys. Rev. C **87**, 041302(R) (2013)

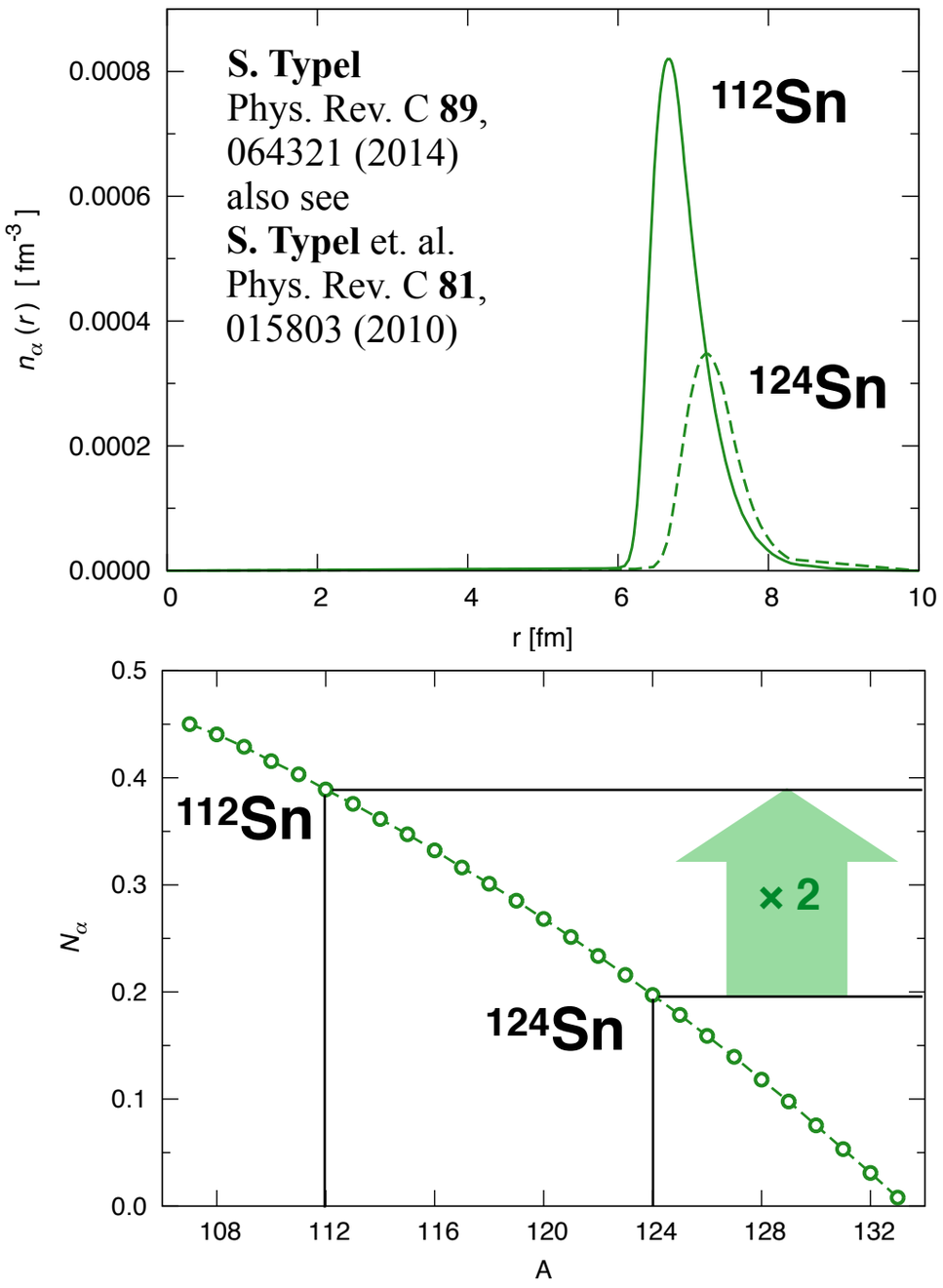
Clusters in Heavy Nuclei ?

alpha clusters in nuclear surface!?

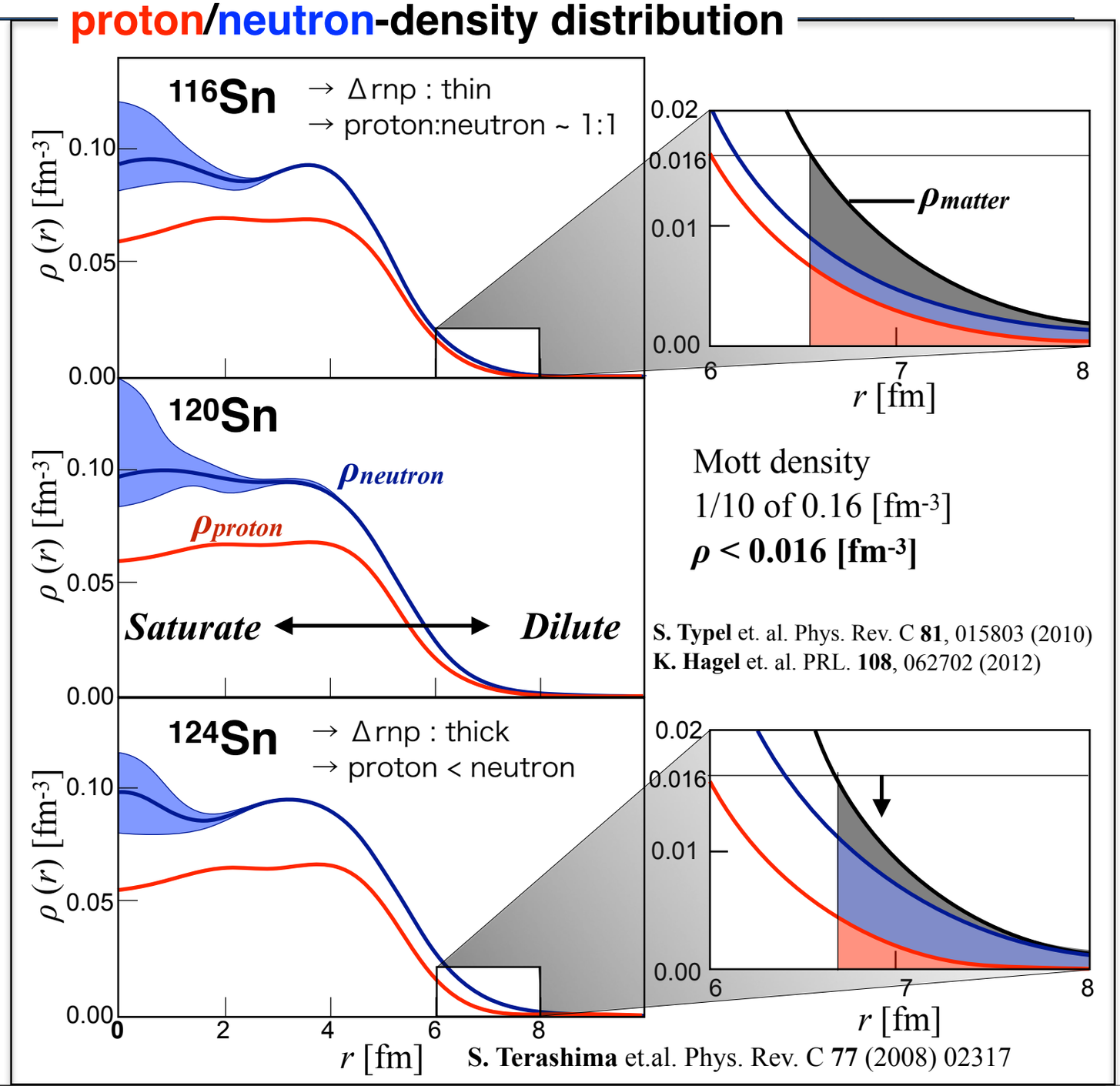


Clusters in Heavy Nuclei ?

alpha clusters in nuclear surface!?

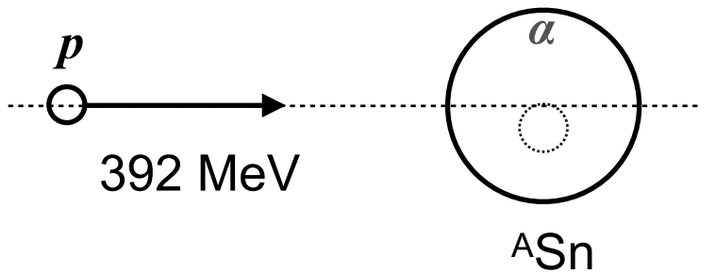


proton/neutron-density distribution

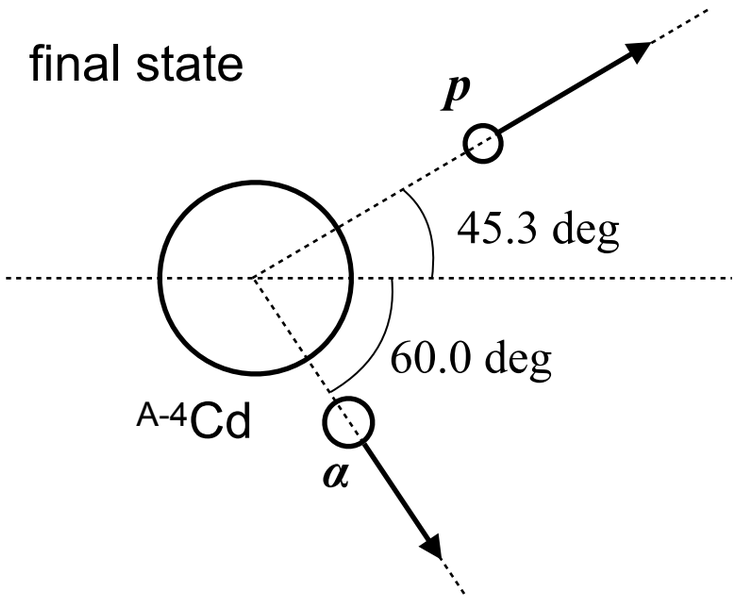


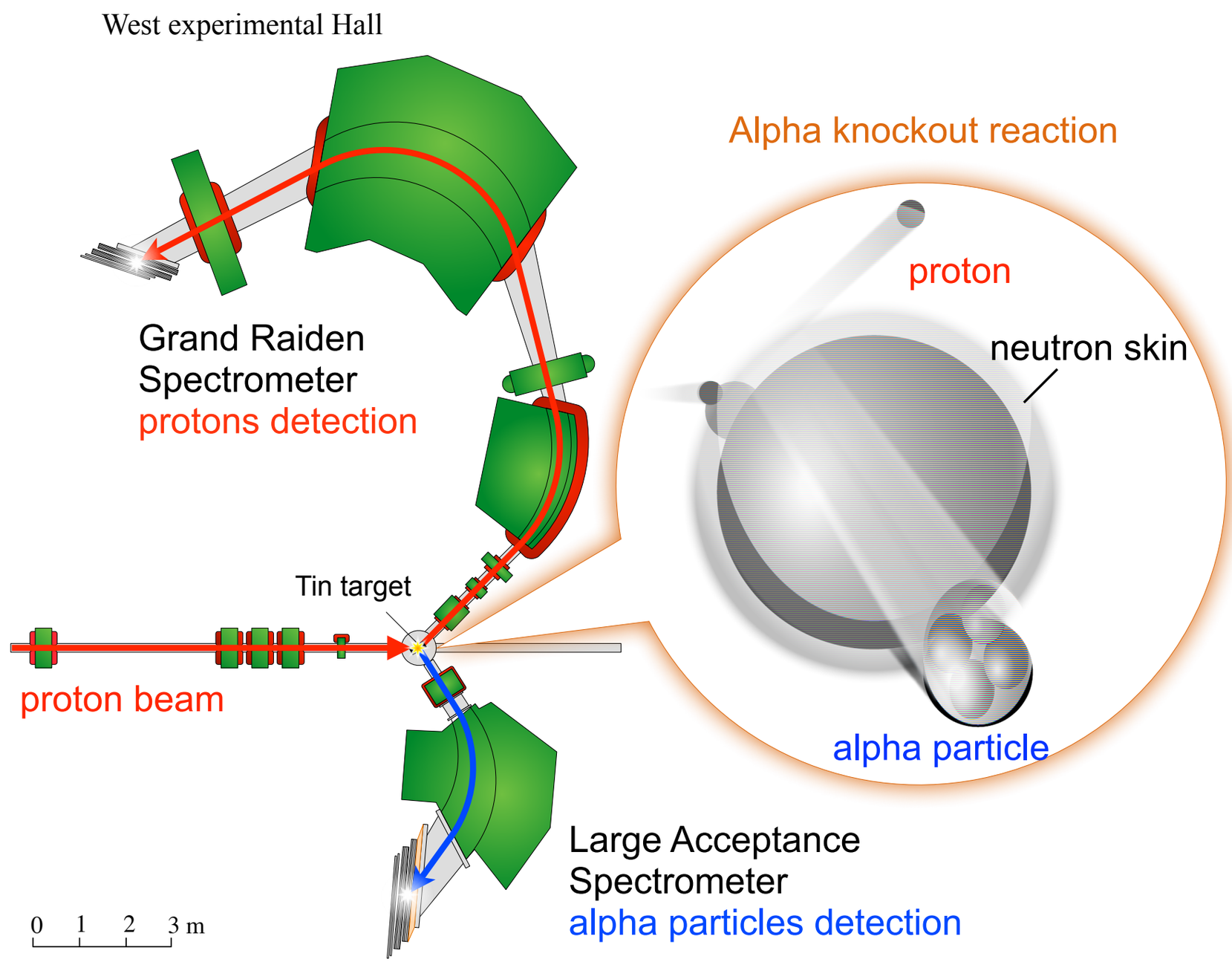
Alpha knockout reaction ^{112,116,120,124}Sn(p,pa) @ RCNP

Initial state



final state

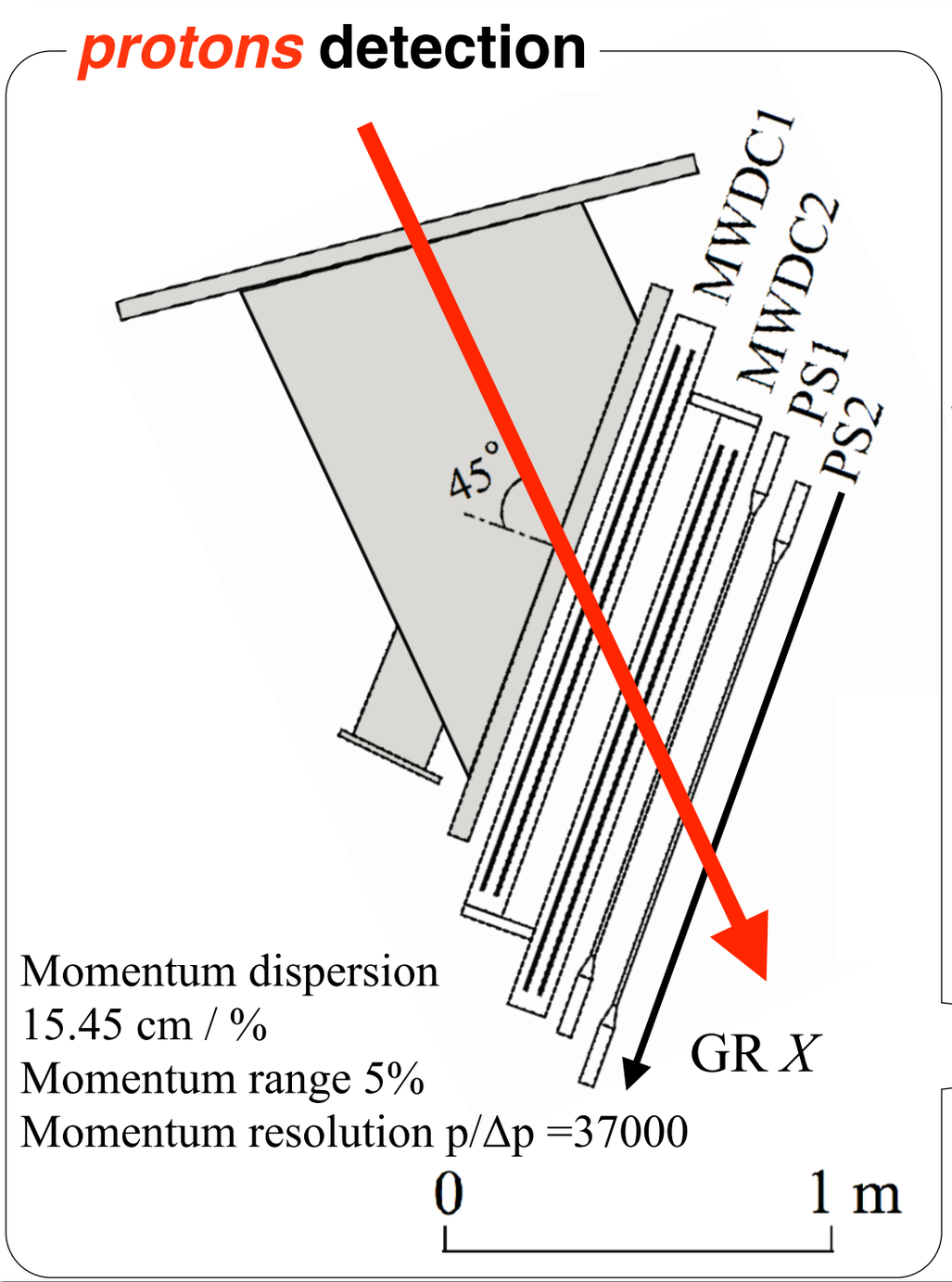


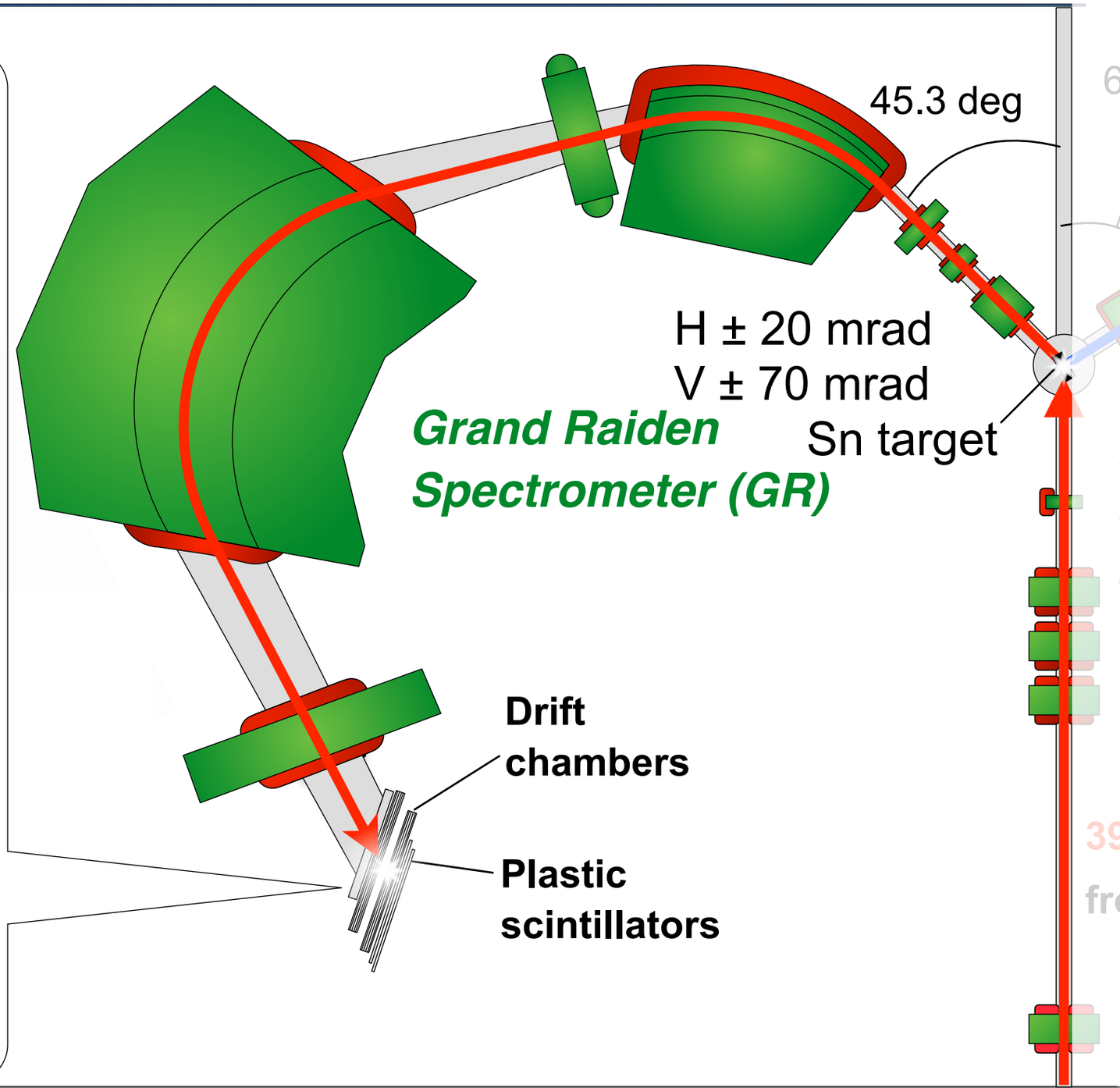


M. Fujiwara *et. al*. Nucl. Inst. Meth A **422** (1999) 484

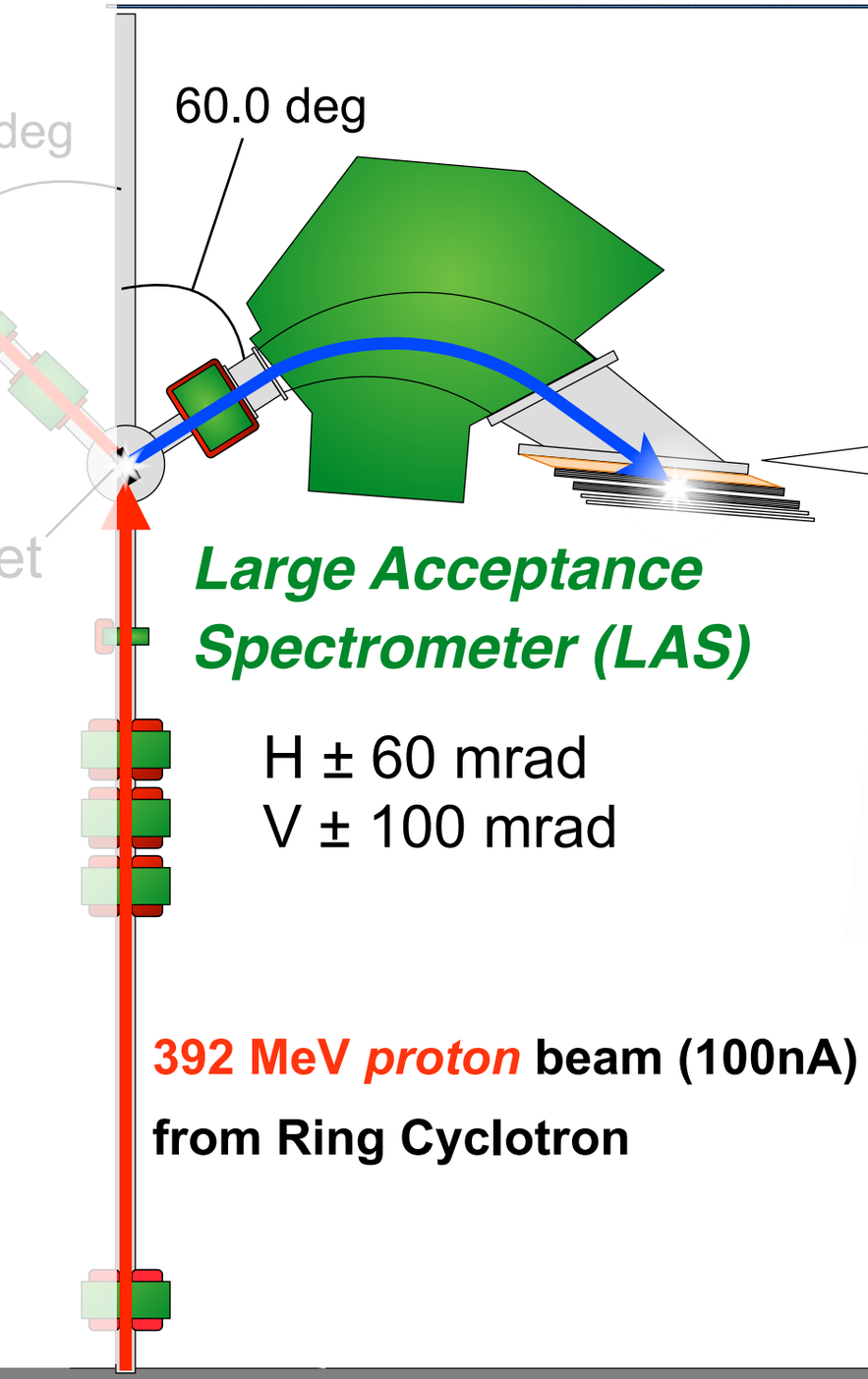
Grand Raiden Spectrometer

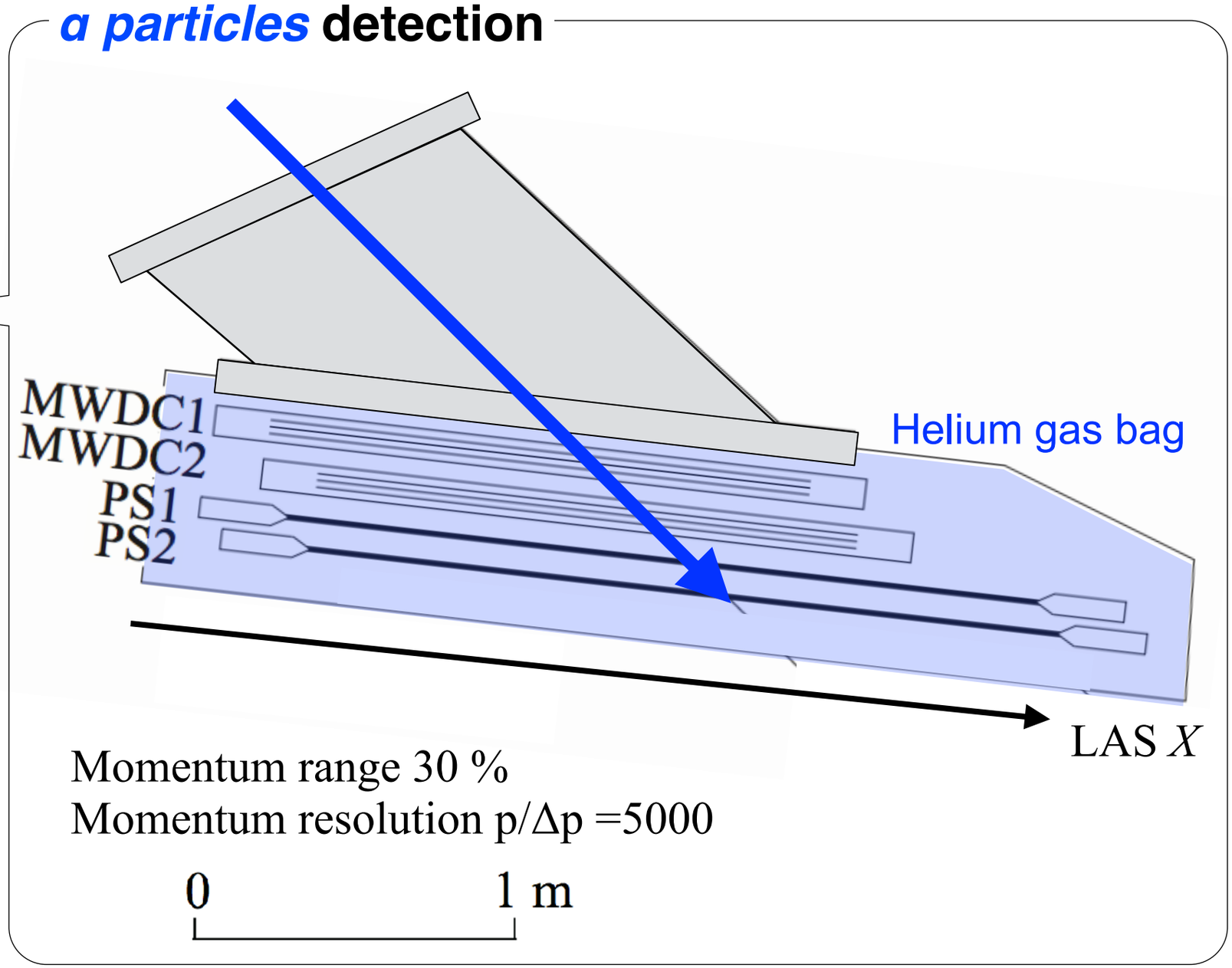
protons detection



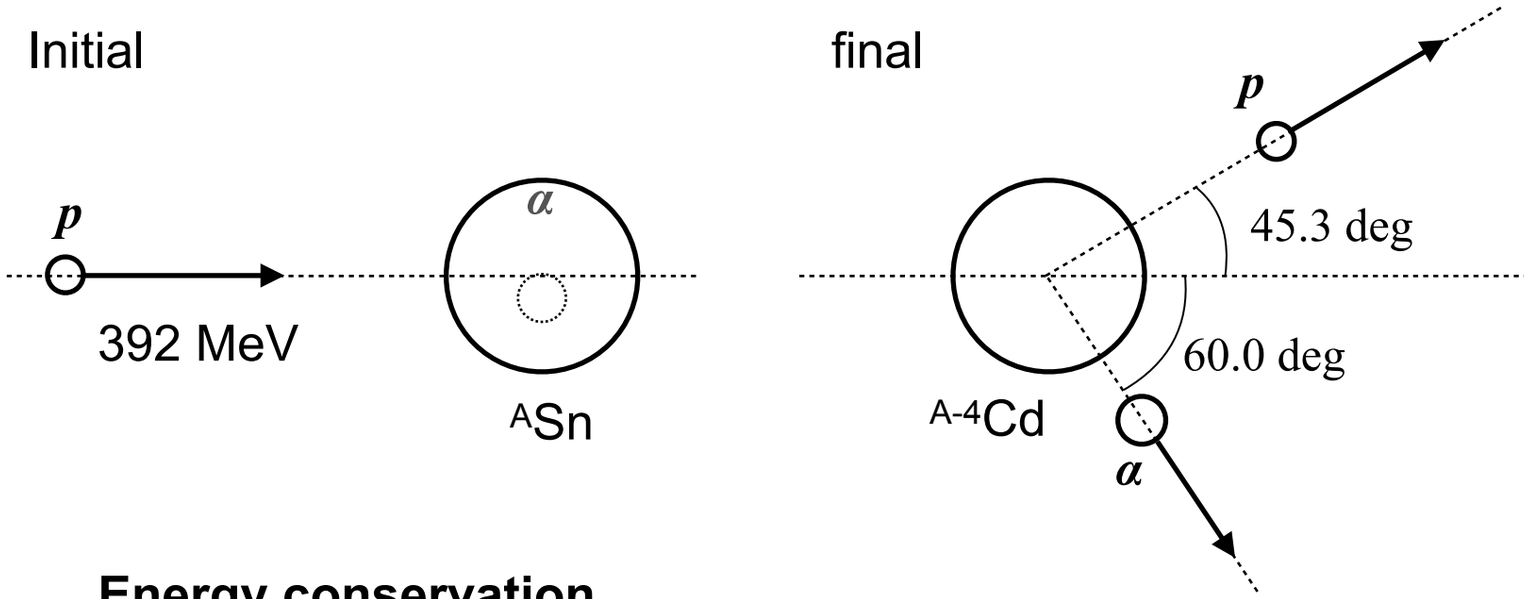


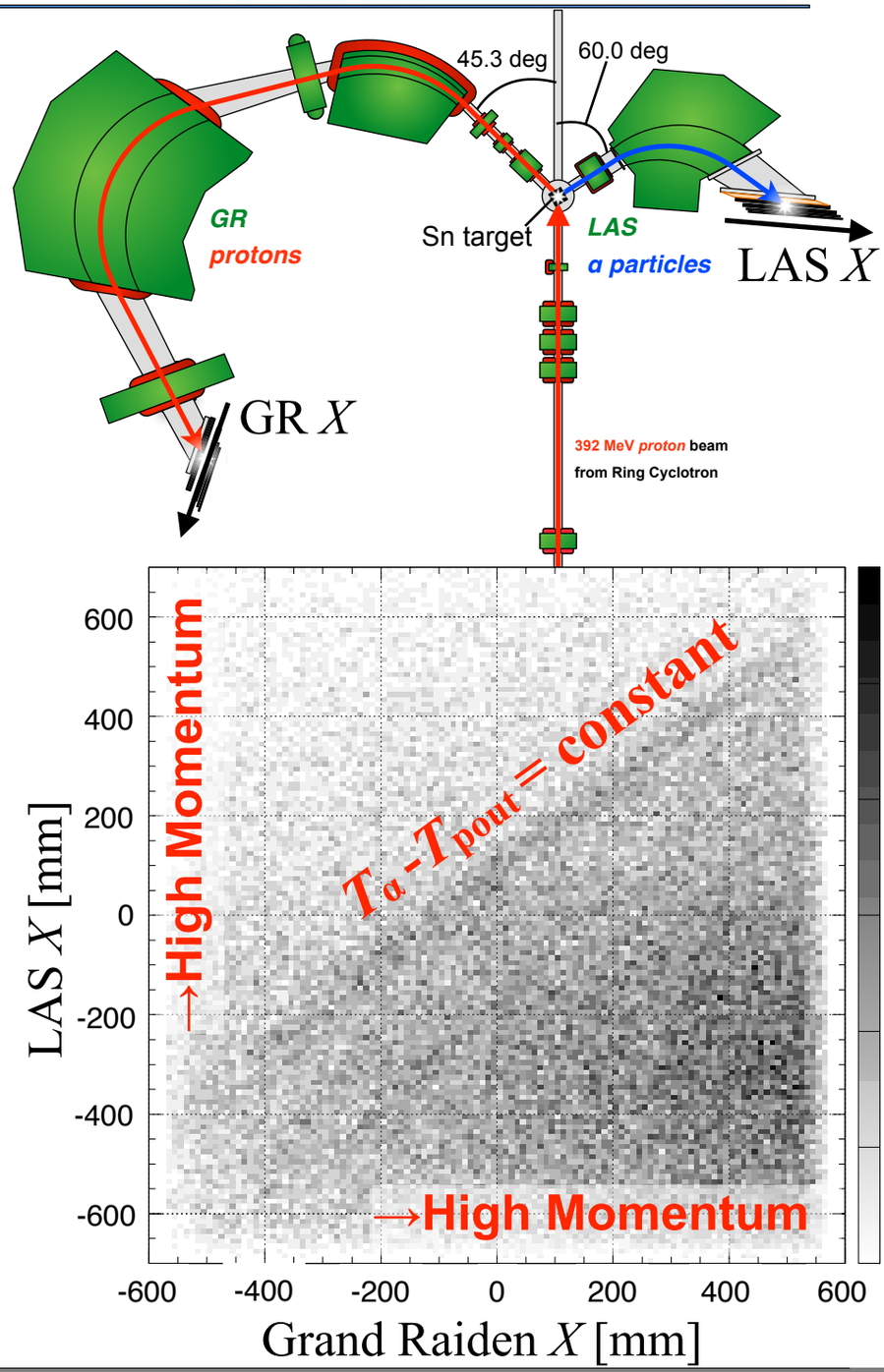
Large Acceptance Spectrometer





Setup of Sn(p,pa) and missing mass





Energy conservation

$$E_{p_{in}} + E_{Sn} = E_{p_{out}} + E_{\alpha} + E_{Cd}$$

$$m_p + T_{p_{in}} + m_{Sn} = m_p + T_{p_{out}} + m_{\alpha} + T_{\alpha} + m_{Cd} + T_{Cd}$$

Missing Mass

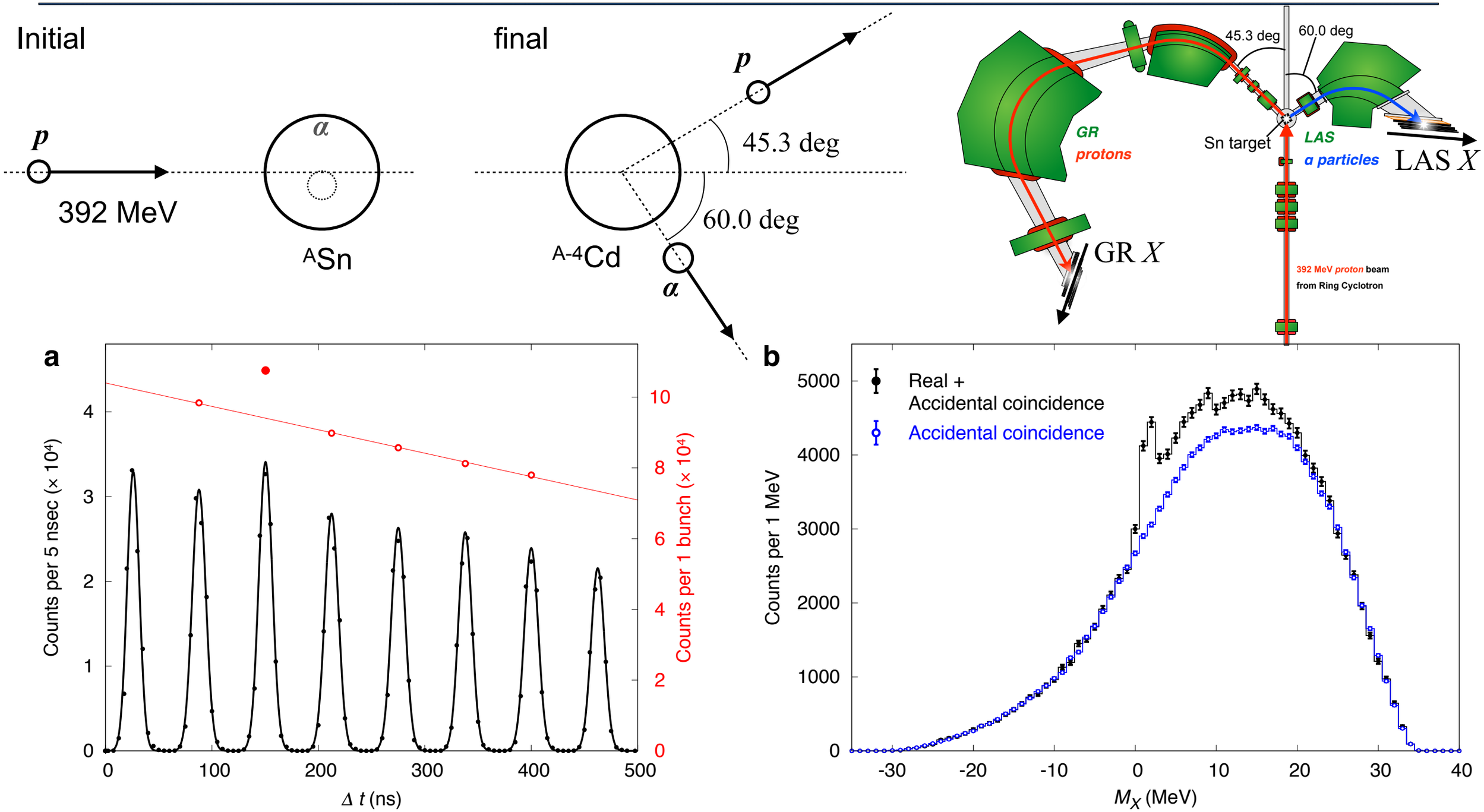
$$M_X \equiv m_{\alpha} + m_{Cd} - m_{Sn} = T_{\alpha} - T_{p_{in}} - T_{p_{out}} - T_{Cd}$$

$$= T_{\alpha} - T_{p_{in}} - T_{p_{out}} - \frac{|\vec{q}|^2}{2m_{Cd}}$$

$$\simeq T_{\alpha} - T_{p_{out}} - 392$$

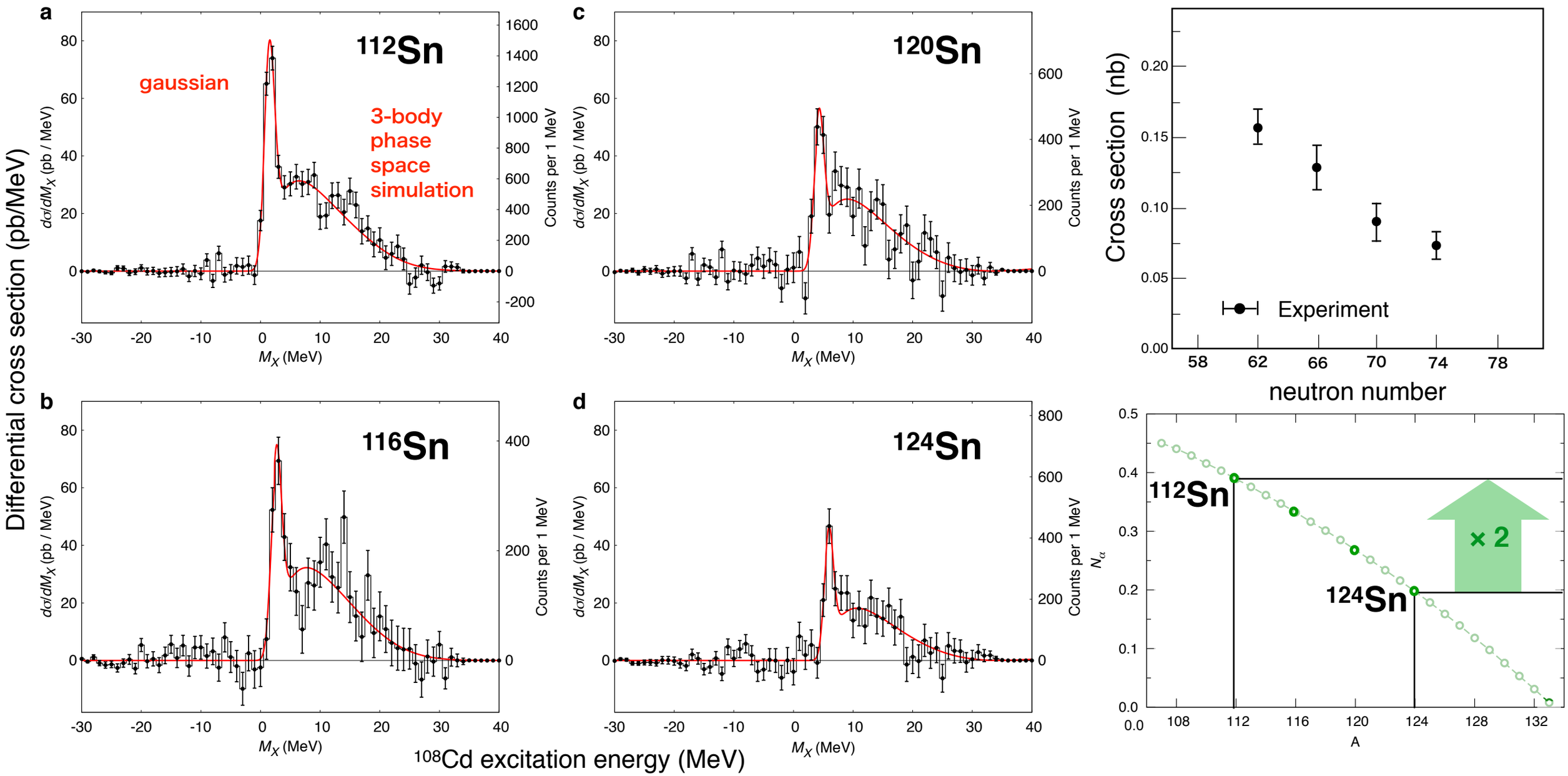
$$\frac{|\vec{q}|^2}{2m_{Cd}} \sim \frac{|50|^2}{2 \cdot 931 \cdot 108} \sim 0.012\,[MeV]$$

True and Accidental coincidences



Experimental Result

Missing mass spectrum of Sn(p,pa)Cd reactions

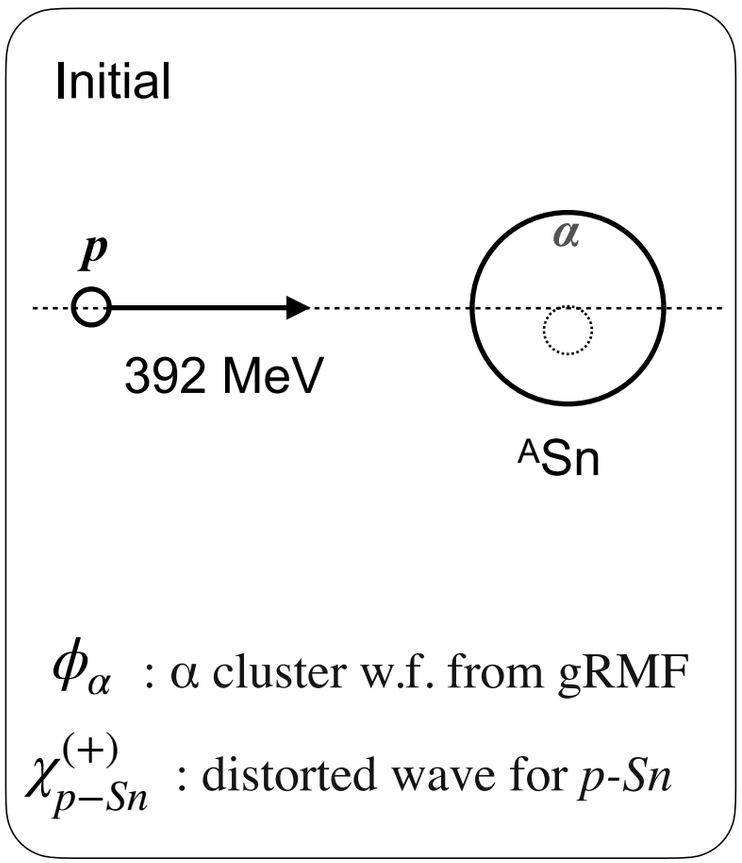


Distorted-Wave Impulse Approximation

Transition amplitude for Sn(*p*,*pα*)Cd

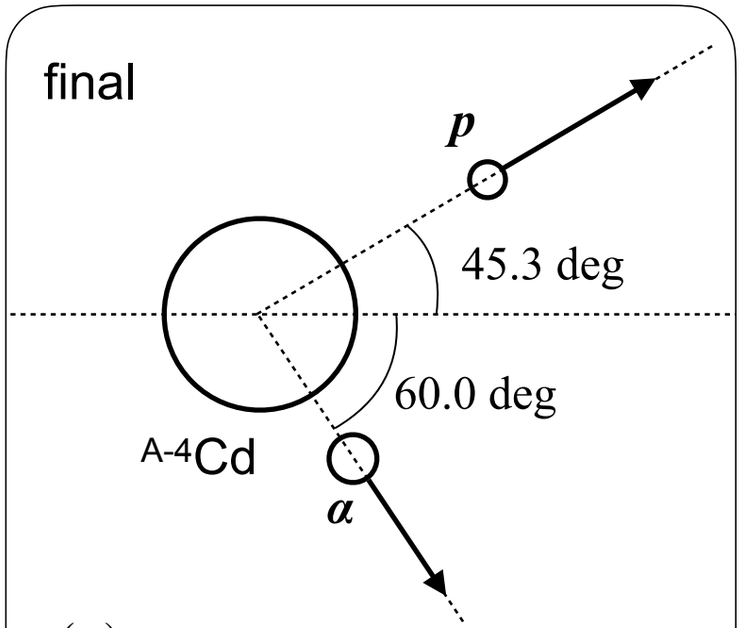
$$T = \left\langle \chi^{(-)}_{\alpha-Cd} \chi^{(-)}_{p-Cd} \left| t_{p-\alpha} \right| \phi_\alpha \chi^{(+)}_{p-Sn} \right\rangle$$

$t_{p-\alpha}$: p-α scattering matrix (Effective interaction)



ϕ_α : α cluster w.f. from gRMF

$\chi^{(+)}_{p-Sn}$: distorted wave for p-Sn



$\chi^{(-)}_{p-Cd}$: distorted wave for p-Cd

$\chi^{(-)}_{\alpha-Cd}$: distorted wave for α-Cd

1. Kinematics factor
2. p-α scattering matrix

   K. Yoshida et. al.
   Phys. Rev. C **98** 024614 (2018)
3. momentum distribution of α clusters in nuclei

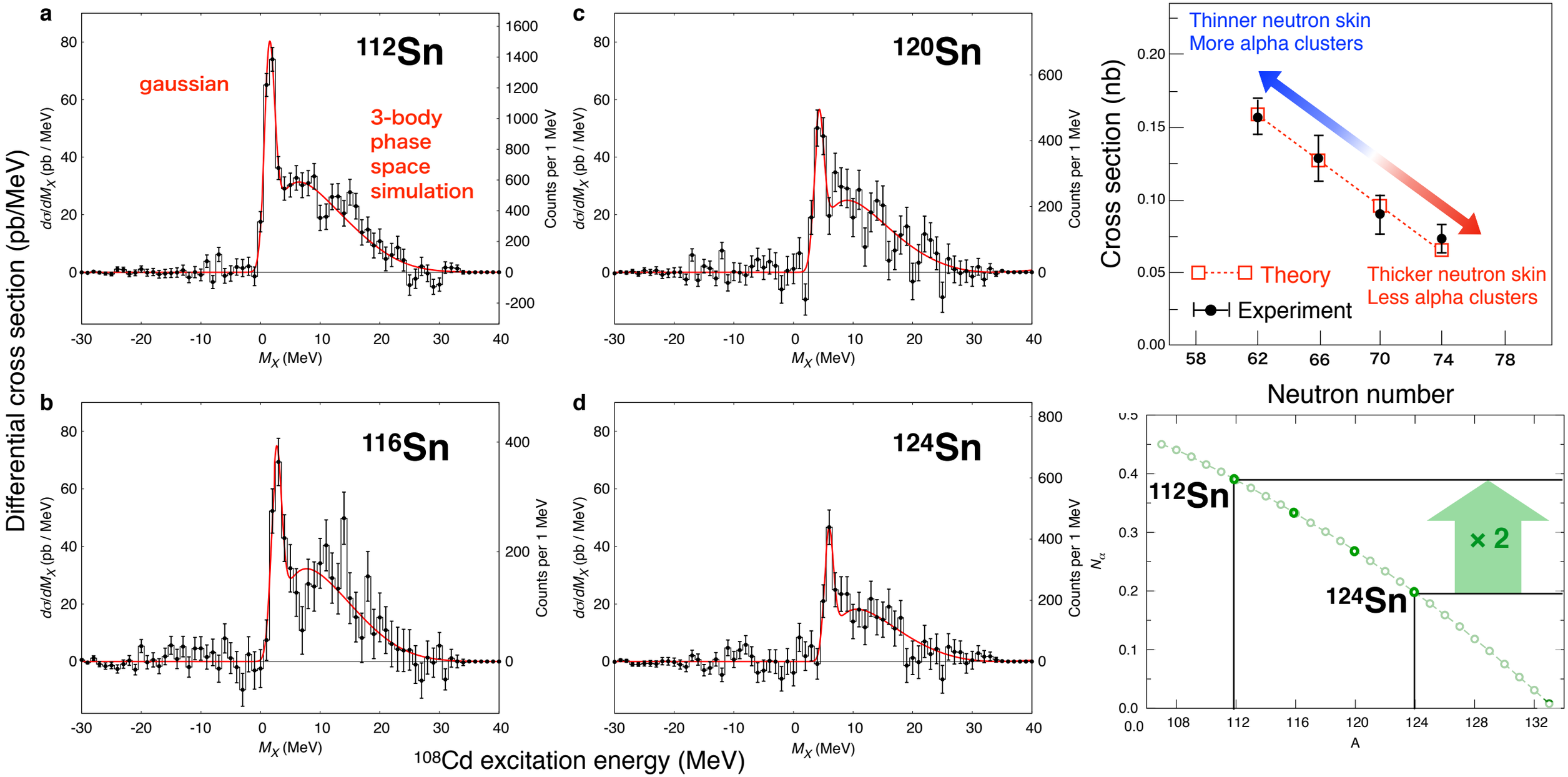
   gRMF theory by S. Typel
   Phys. Rev. C **89**, 064321 (2014)
4. absorption of proton

   Optical potential from S. Hama et. al.
   Phys. Rev. C **41** 2327 (1990)
5. absorption of alpha

   Optical potential from M. Nolte et. al.
   Phys. Rev. C **36** 1312 (1987)

Experimental Result and Comparison to Prediction

Missing mass spectrum of Sn(p,pa)Cd reactions



Publication

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

REPORT

NUCLEAR PHYSICS

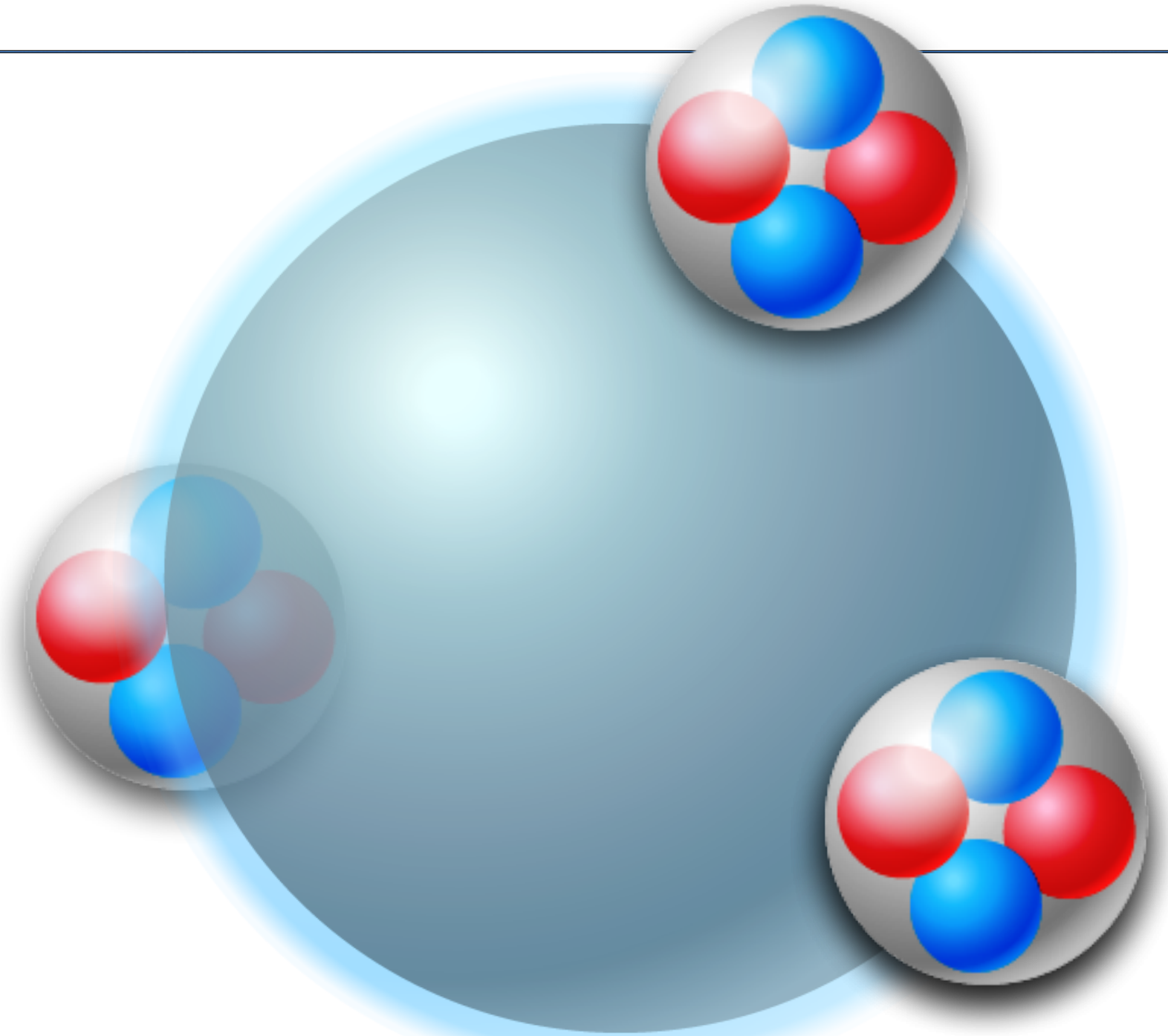
Formation of α clusters in dilute neutron-rich matter

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]

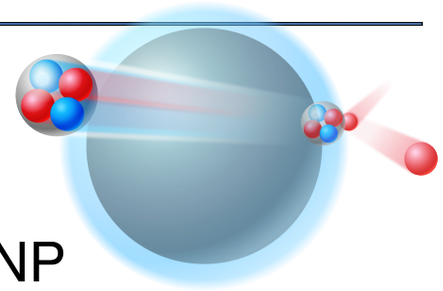
The surface of neutron-rich heavy nuclei, with a neutron skin created by excess neutrons, provides an important terrestrial model system to study dilute neutron-rich matter. By using quasi-free α cluster–knockout reactions, we obtained direct experimental evidence for the formation of α clusters at the 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.

Correlations and clustering are universal phenomena in composite systems for all scales of the material world, which range from the largest structures in the Universe to minute hadronic systems made of quarks. The atomic nucleus is a many-body quantum system that consists of nucleons, namely protons and neutrons. It can be described in the first approximation as nucleons moving independently in an attractive mean field generated by all nucleons. Their fermionic nature leads to the development of a shell structure with well-defined single-particle levels understanding the properties of atomic nuclei, nuclear matter, and giant objects in the Universe such as neutron stars (*4*). In nuclear matter, nucleons form light nuclear clusters that comprise deuterons (^{2}H), tritons (^{3}H), helions (^{3}He), and α particles (^{4}He) at densities sufficiently below the saturation density of nuclei (*5*). Deuteron-like clusters can also be found as short-range correlated pairs at higher densities (*6*–*8*). The α particle, as a compact four-nucleon correlation, plays a particular role because its strong binding is beneficial for the cluster formation.

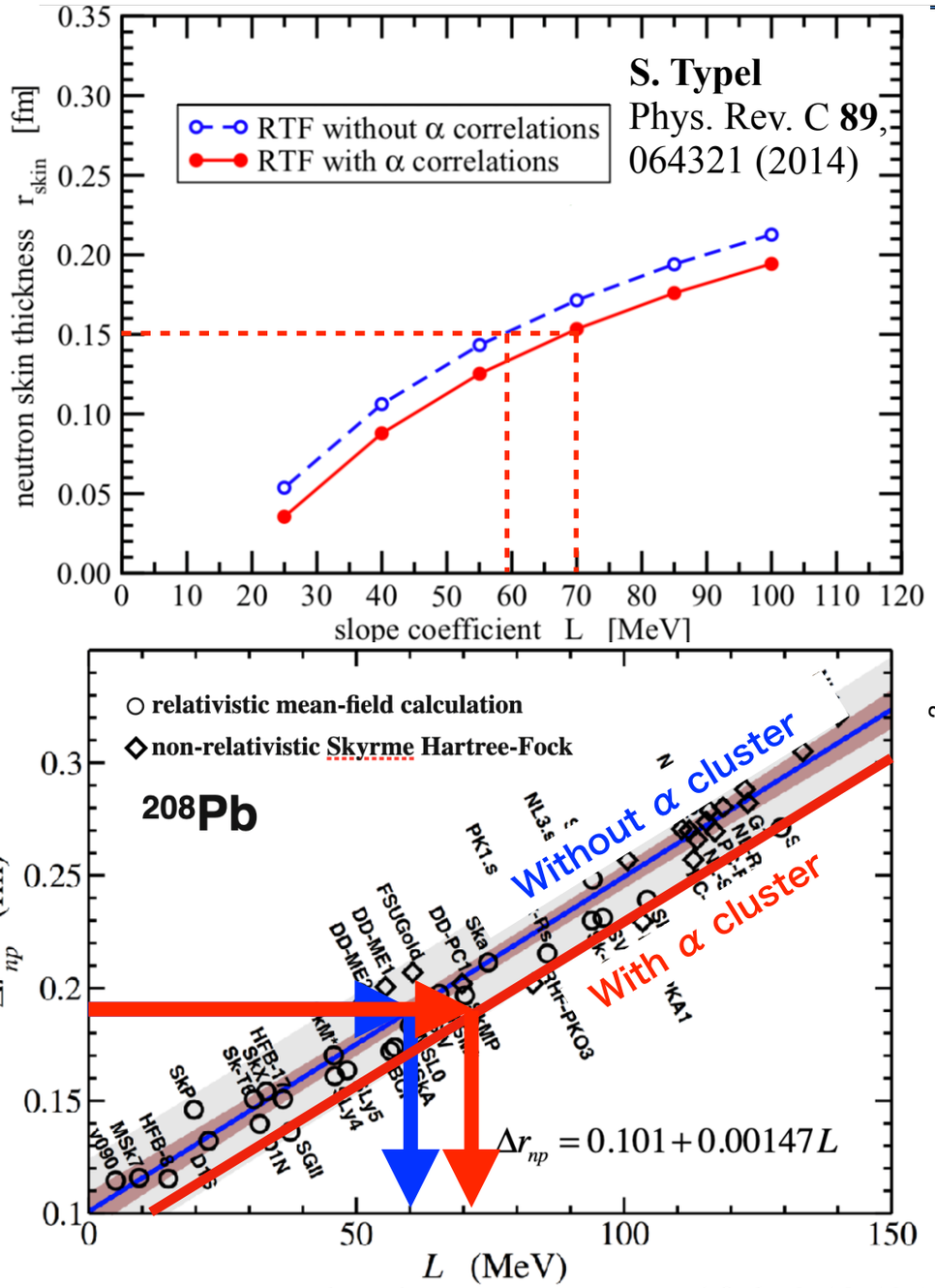
Picture of the ground state of heavy nuclei is like this?



Future Plan toward nuclear EOS



Pb(*p,pα*) : suspended Ca(*p,pα*) : accepted@ RCNP

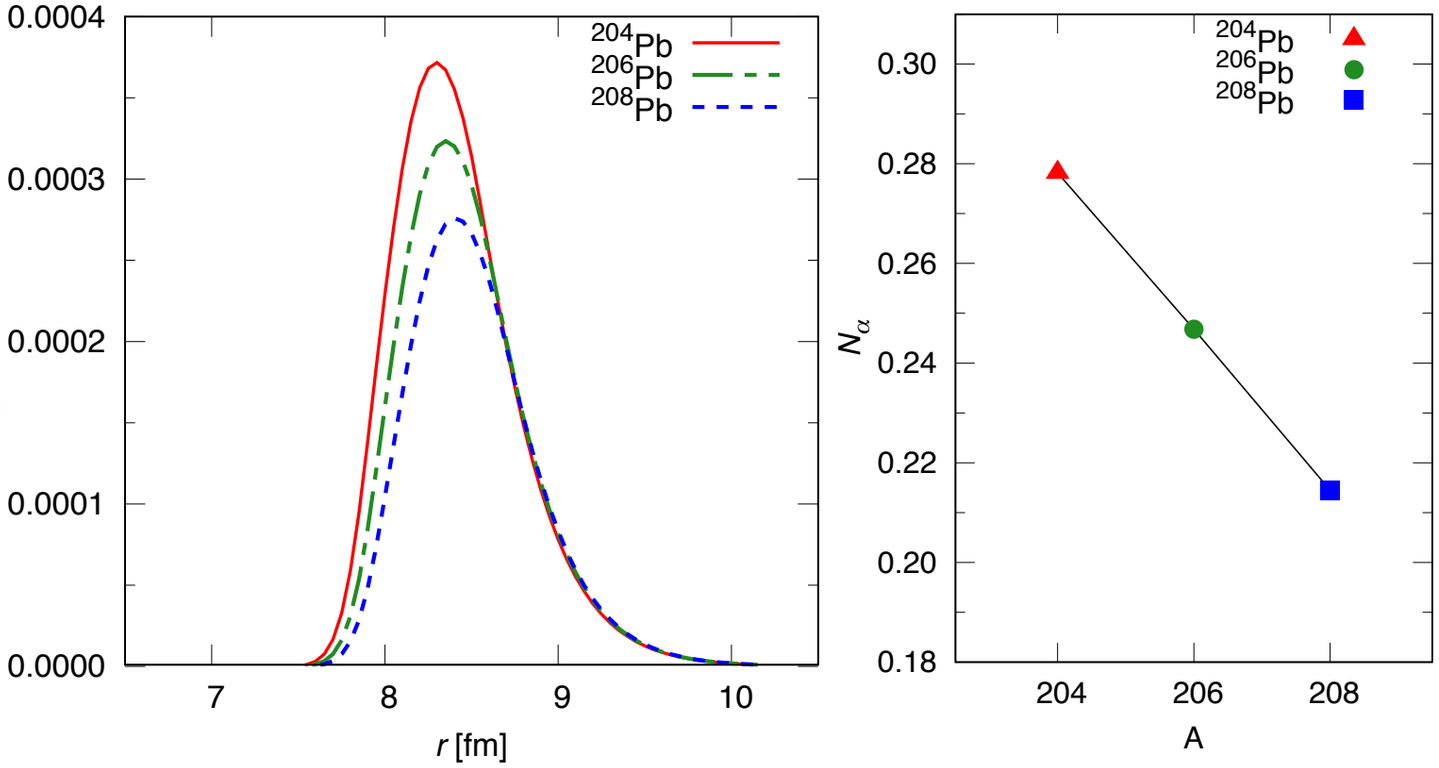


X. Roco-Maza *et al.*, Phys. Rev. Lett. **106**, 252501 (2011)

Neutron-skin thickness Δr_{np}

↓ ↑

α cluster formation



Preliminary for PAC presentation

Your contributions are always welcome !

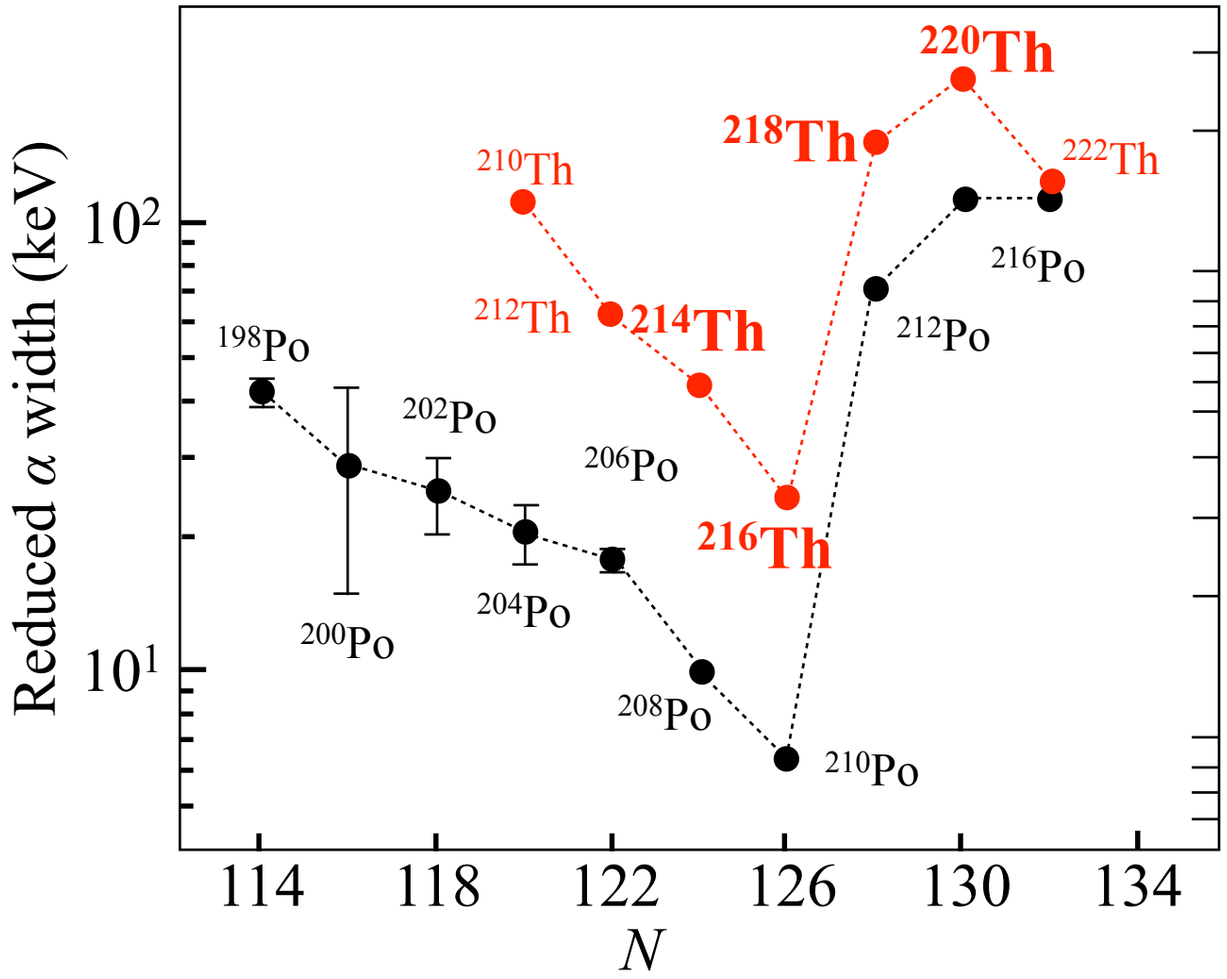
Future Plan toward alpha decay

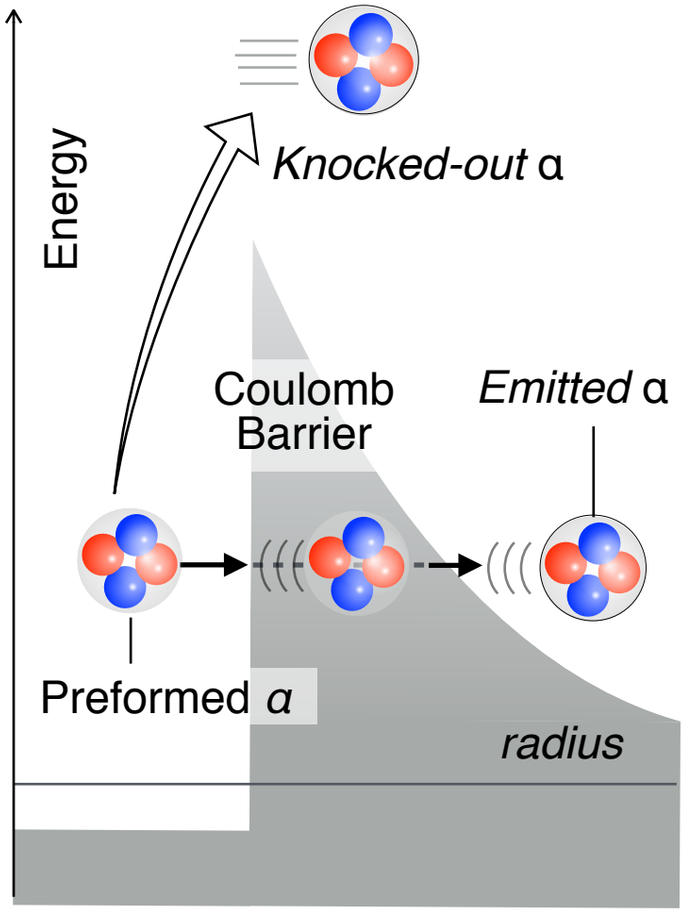
RIBF : Th(p,pa) accepted B

Let's knockout preformed alpha particles in alpha decay nuclei !

We can study surface α / α-decay with **completely different kinematics** - QFS (*p,pα*)

John O. Rasmussen , PR**115** (1959) 1675 A.N. Andreyev et.al., PRL. **110** (2013) 242502



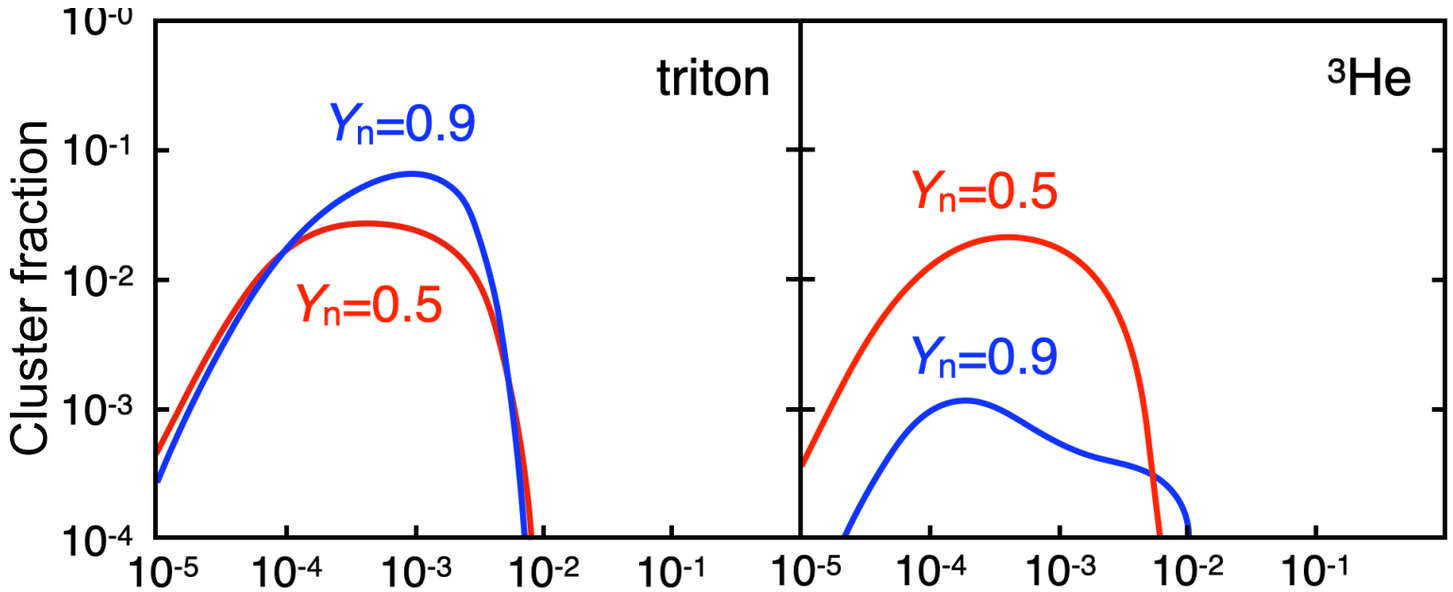


Your contributions are always welcome !

Future Plan toward other clusters

Xe(*p,pt*) and Xe(*p,p*^{3}He) @ HIMAC accepted

- Triton and ^{3}He clusters knock out reaction



Observable

Ratio between

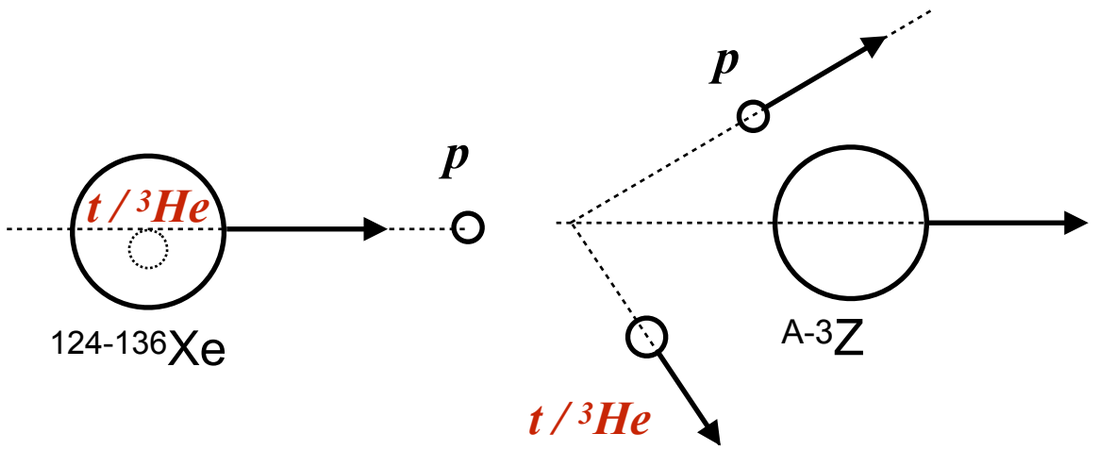
triton knockout cross section and

^{3}He knockout cross section

$$\frac{\sigma(Xe(p,pt))}{\sigma(Xe(p,p^3He))}$$

Initial state

Final state

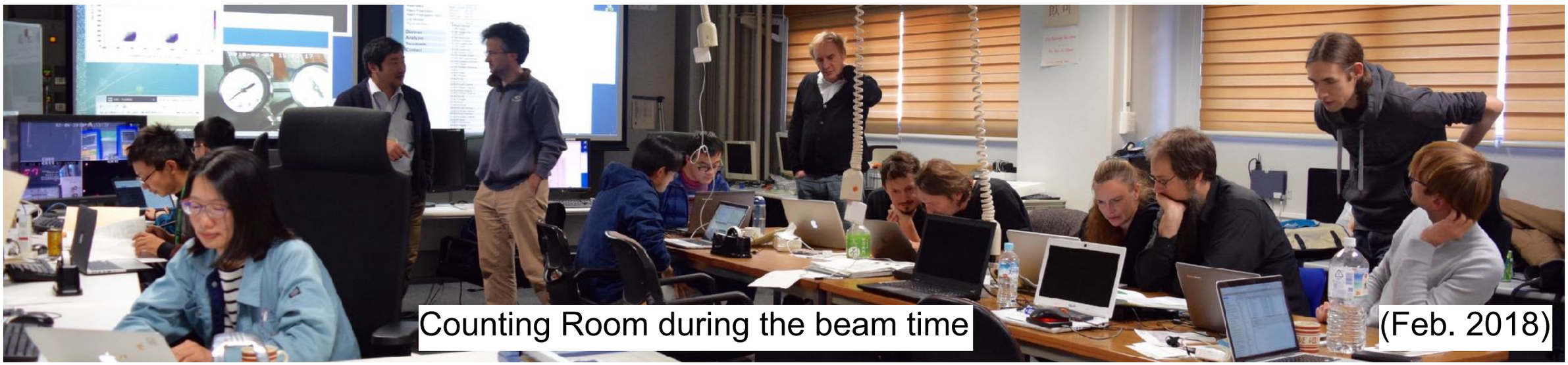


Ratio increase by increasing neutron fraction ?
Pilot experiment to examine triton and ^{3}He clusters

Same kinematics for ^{3}H and ^{3}He
→ Simultaneous measurement of two different channel with the same experimental condition.

Your contributions are always welcome !

Sn(p,pα) 2018 collaboration



Sn(p,pα) 2018 collaboration

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JAEA

K. Yoshida

I hope we can continue our great collaboration.

Your new contributions / suggestions are always welcome.

Thank you