Alpha clustering in dilute neutron rich matter

NuSym21 - International Symposium on Nuclear Symmetry Energy

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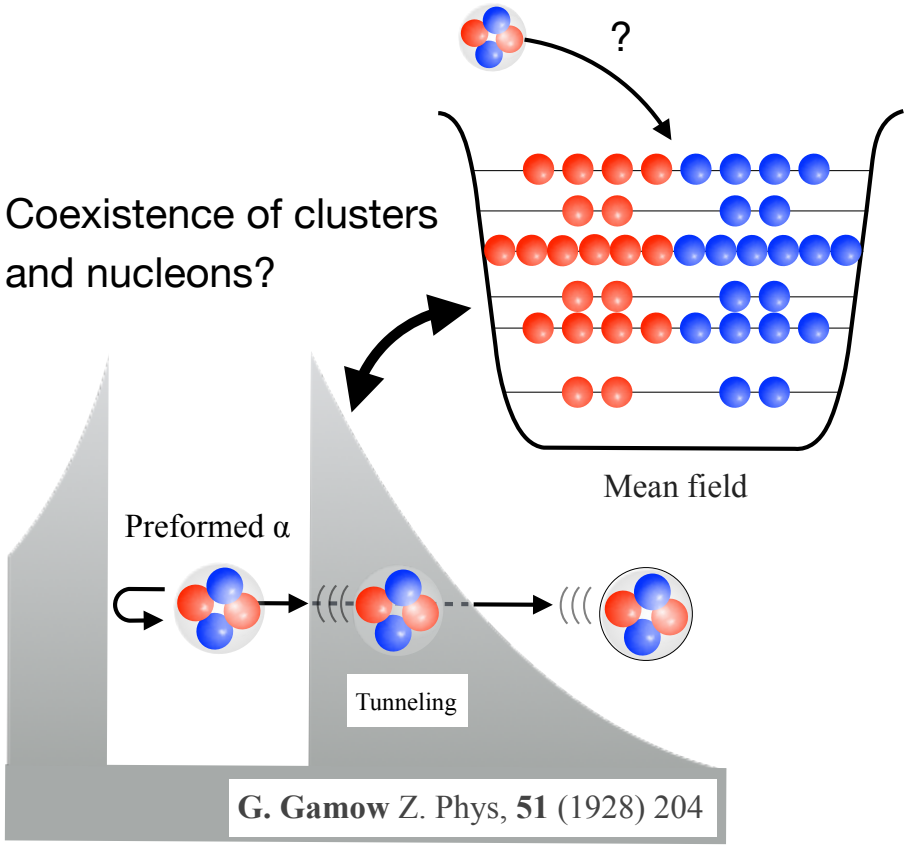
Motivation of experiment

2020 Full understanding of alpha decay? (202?)
2010 Typel gRDF (2010/2014)
RI beam Factory
2000
1990 RI beam / Neutron halo・skin(1985)
1980 Iachello・Arima IBM(1974)
1970 Ikeda diagram (1968)
1960 A.Bohr・Mottelson・Pines Super conductivity(1958)
A.Bohr・Mottelson Collective Motion(1952)
1950 Mayer・Jensen Shell model (1949)
1940 N.Bohr・ Weizsäcker Liquid drop (1935/1936)
Wheeler Cluster model (1937)
1930 Segrè Neutron
Gamow quantum tunneling (1928)
1920 Quantum physics
1910 Rutherford nuclei (1911)
Rutherford 4He nuclei (1908)
Alpha particle (1905)
1900 Curie Polonium/Radium(1898)
J.J. Thomson electron (1897)
1890 Röntgen X-ray (1895)
Becquerel Radioactivity (1896)

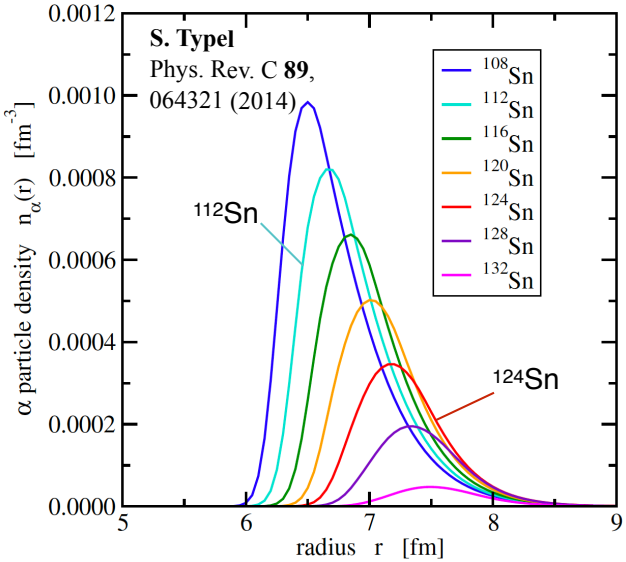
S. Typel et. al. Phys. Rev. C **81**, 015803 (2010)

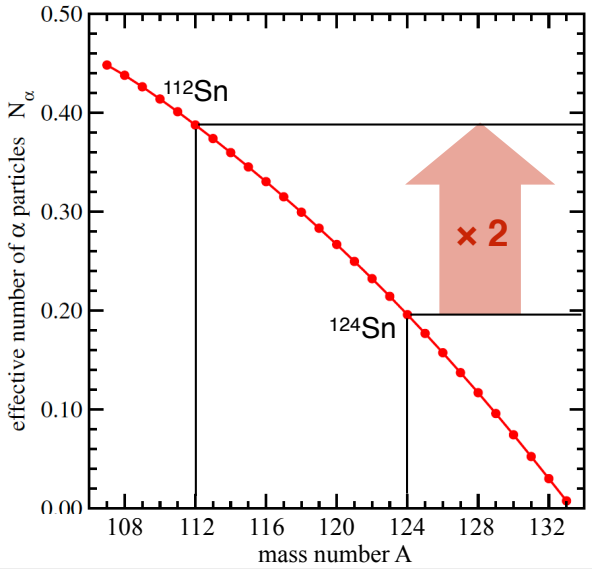
- alpha particle formation at nuclear surface.
- Study of chain Sn nuclei as reduction of alpha probability with increasing neutron excess

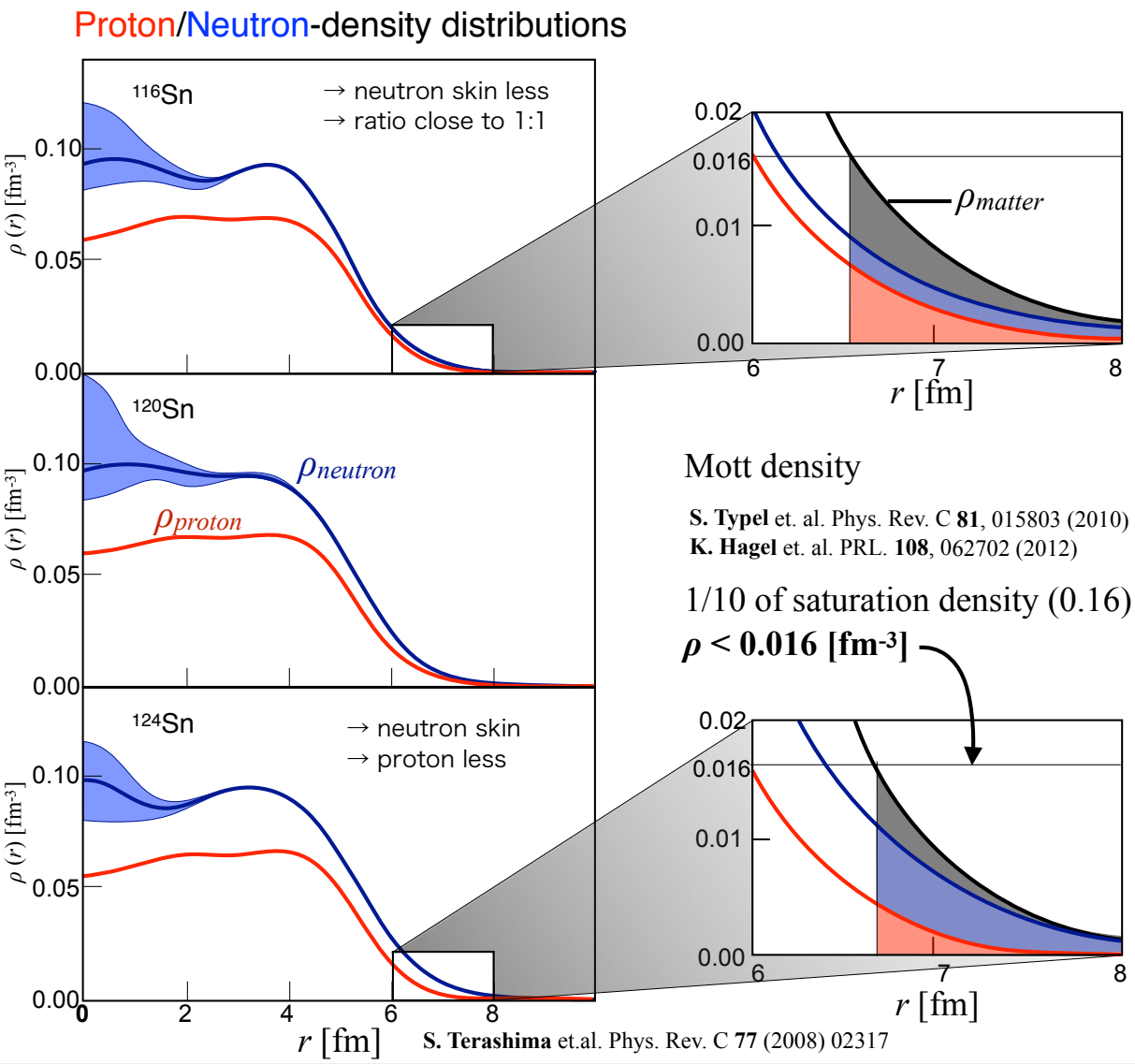
➡ This prediction motivated us to perform an experiment



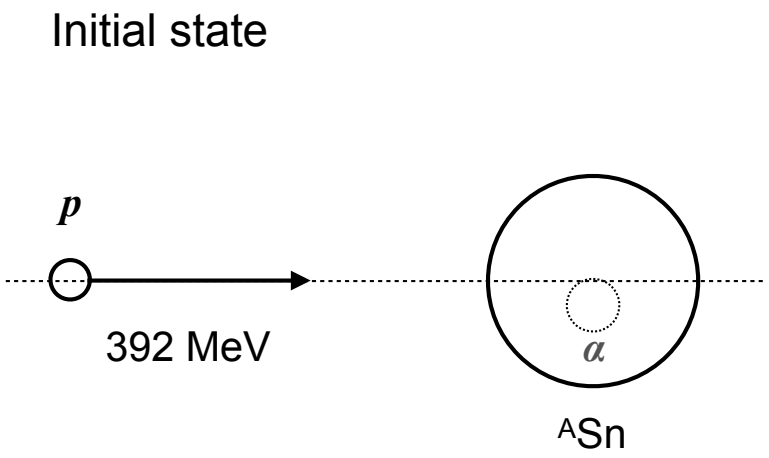
Alpha cluster formation predicted in gRDF and its relation of proton/neutron-density distributions

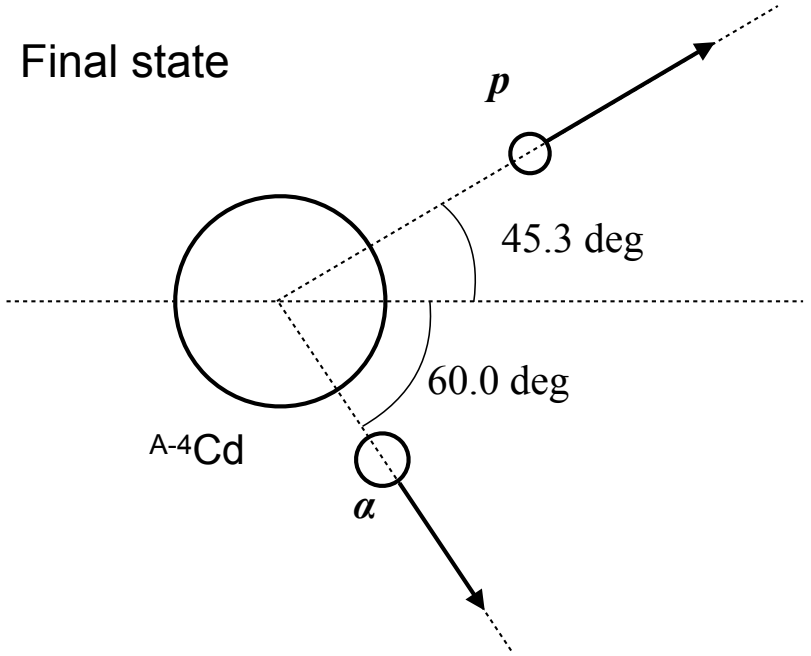






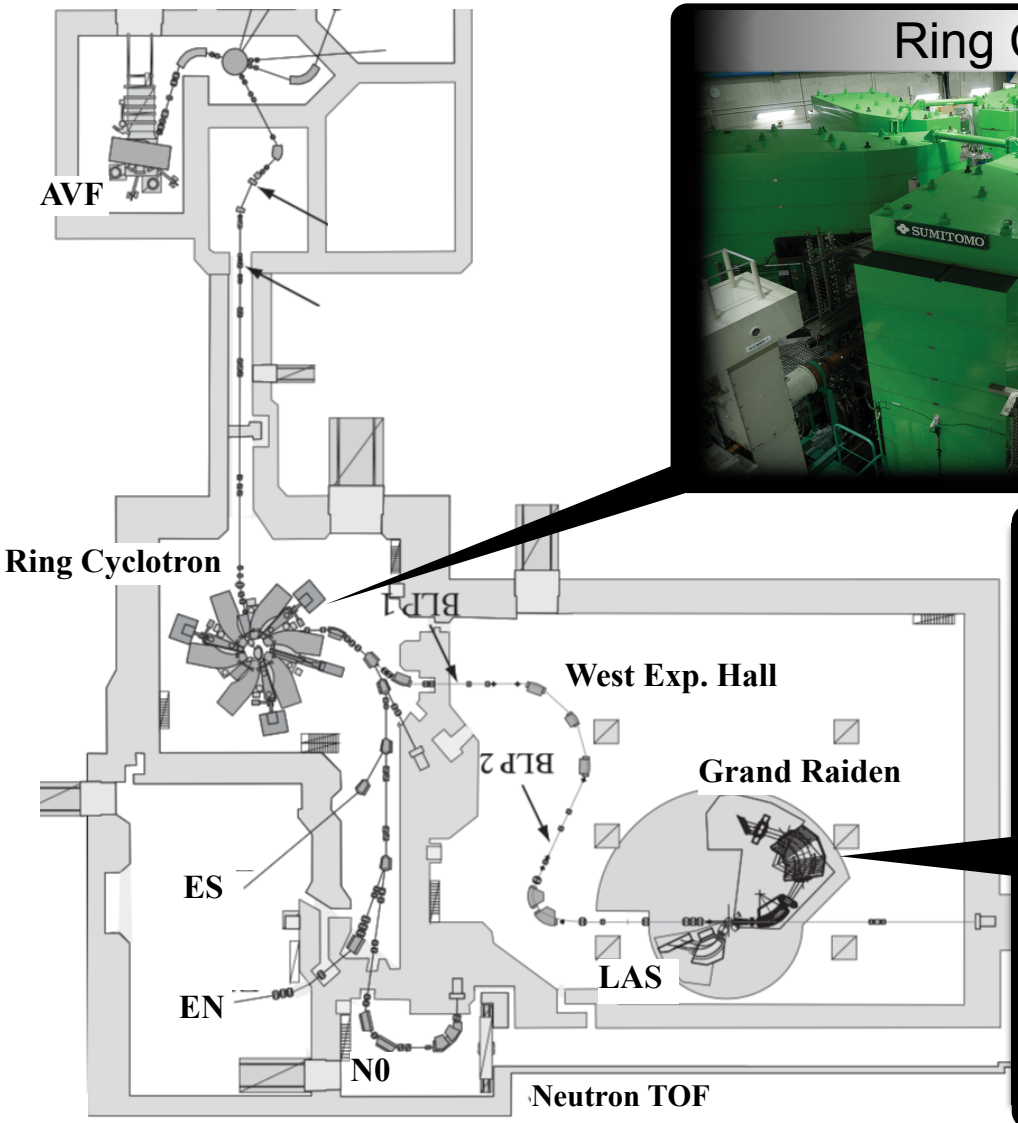
Quasi-Free Alpha knockout reaction

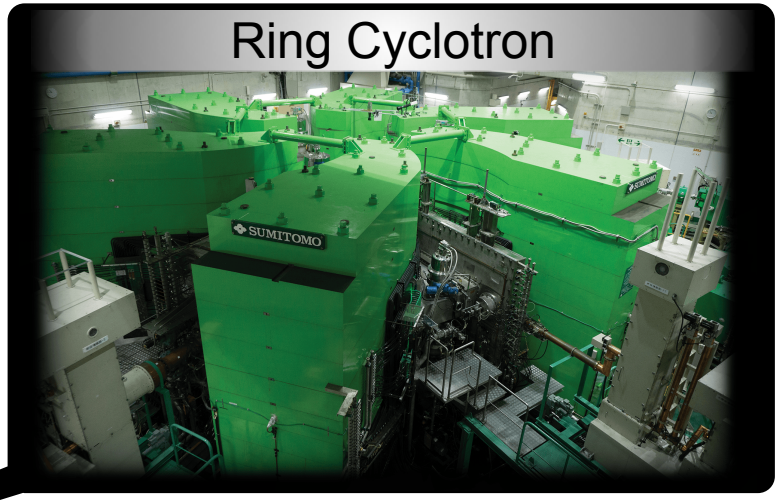


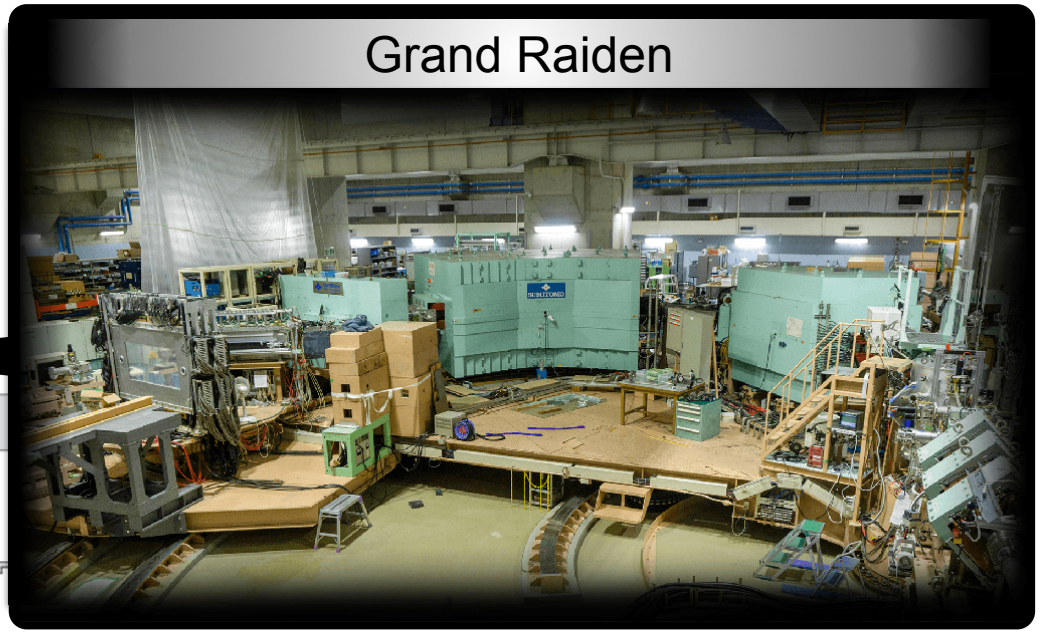


K. Yoshida et. al.
Phys. Rev. C **98** 024614 (2018)

Experiment at RCNP Osaka University

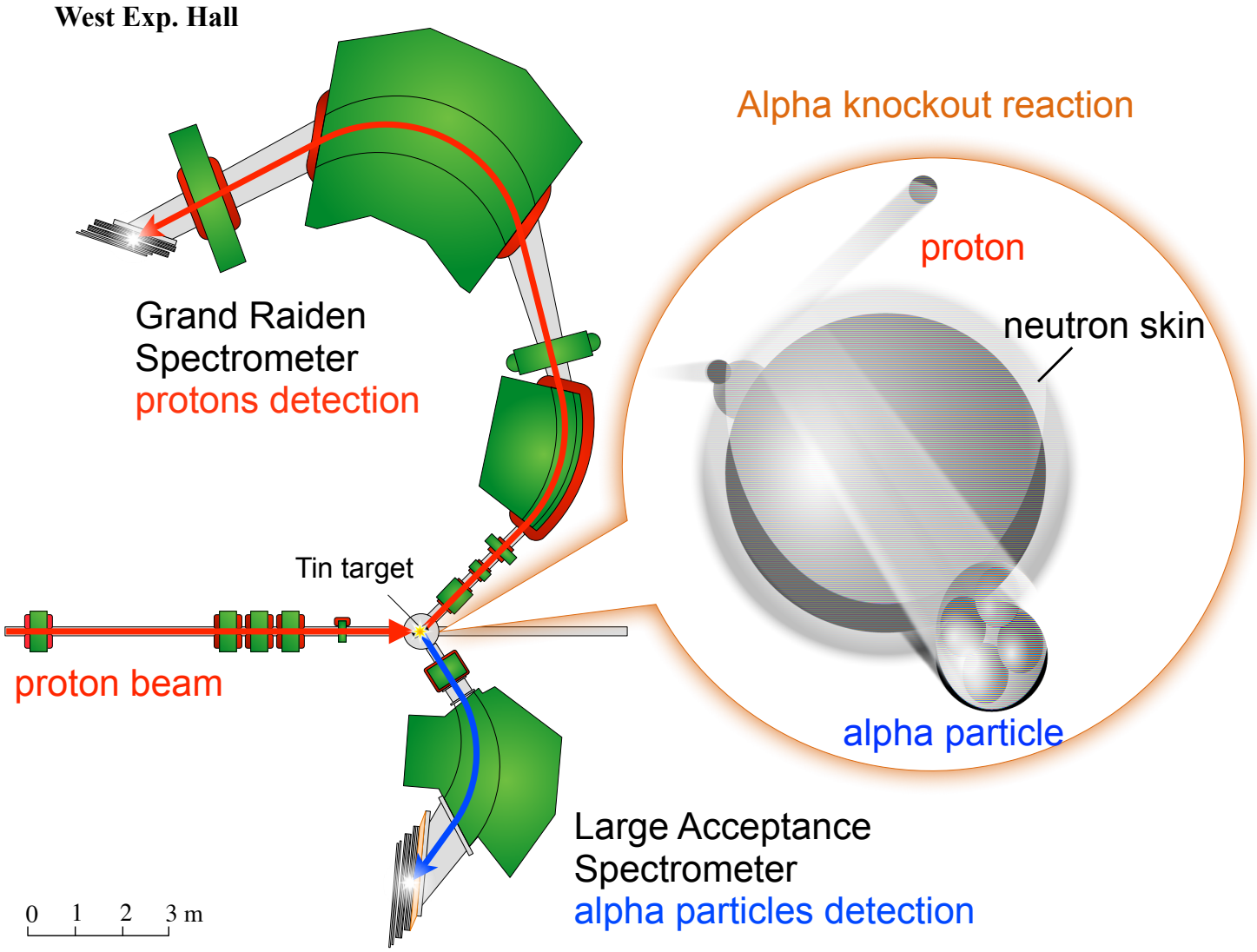






Experiment at RCNP Osaka University

Alpha knockout reaction ^{112,116,120,124}Sn(p,pa) and double-arm spectrometer



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

Alpha-separation energy spectrum

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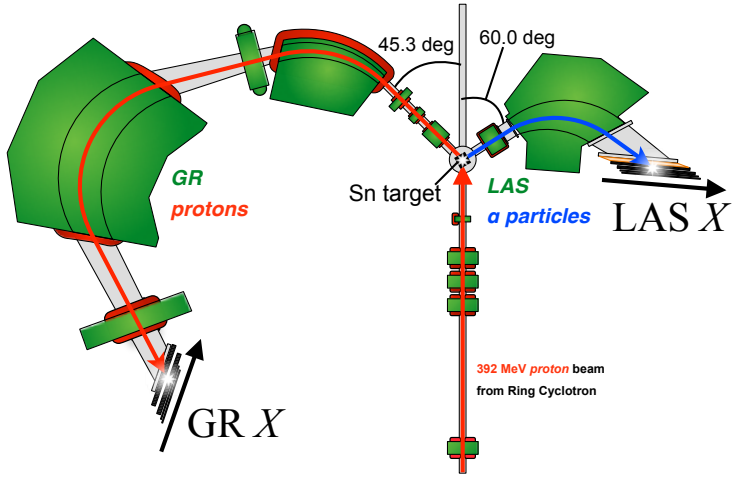
Energy Conservation

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

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



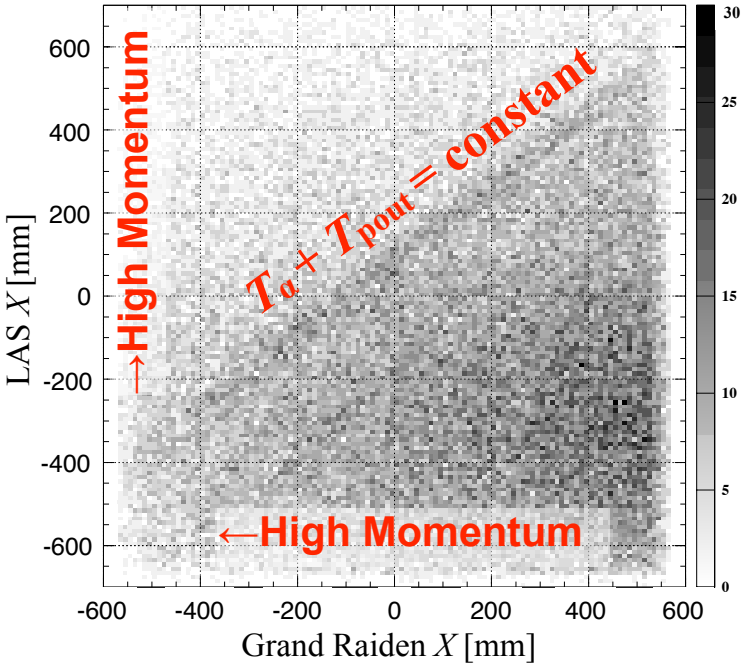
Alpha separation energy

$$S_{\alpha} \equiv m_{\alpha} + m_{Cd} - m_{Sn}$$

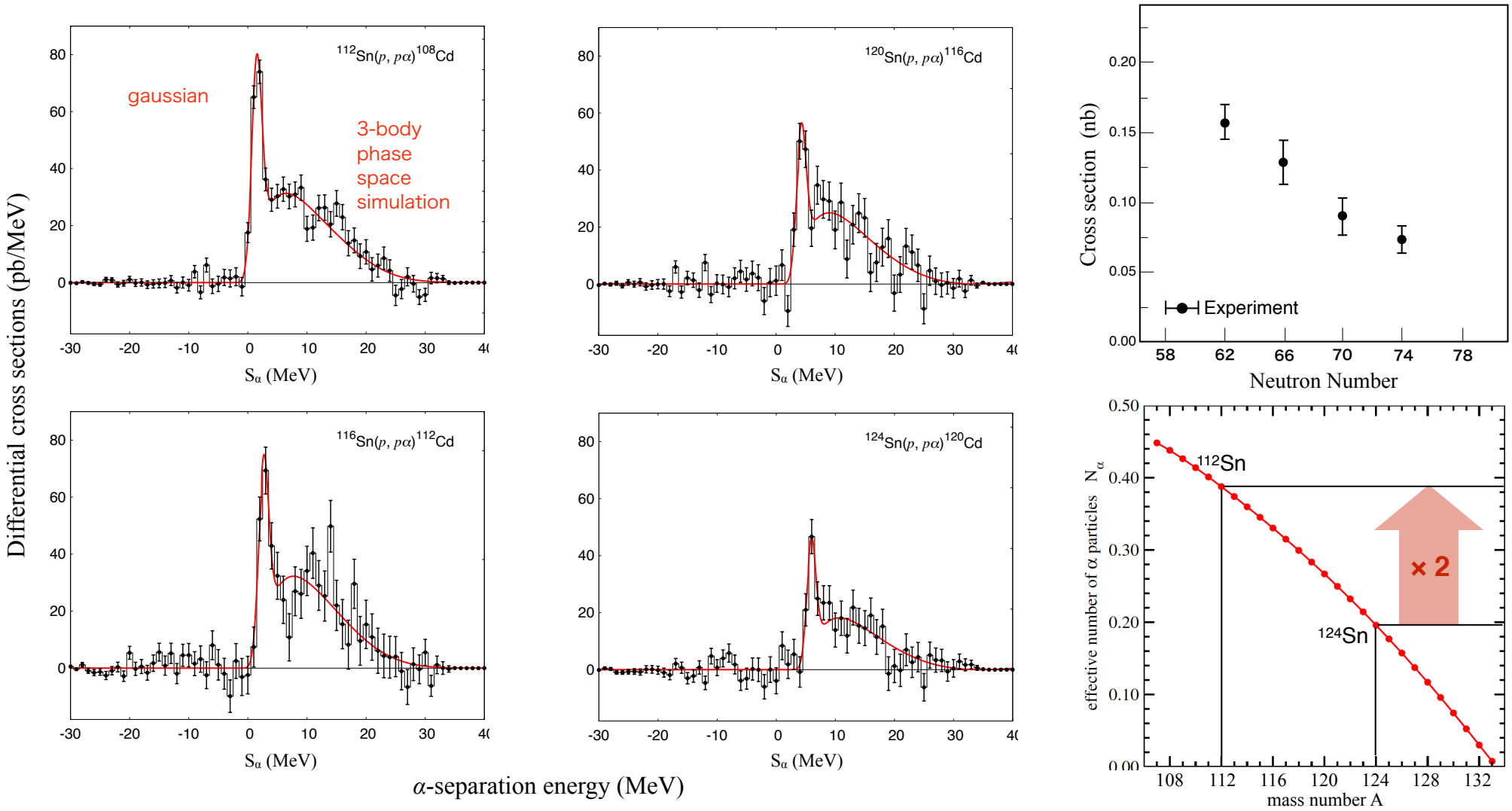
$$= T_{p_{in}} - \left(T_{p_{out}} + T_{\alpha} + \cancel{T_{Cd}}\right)$$

$$= 392 - \left(T_{p_{out}} + T_{\alpha}\right)$$

$$T_{Cd} \sim \frac{|\vec{q}|^2}{2m_{Cd}} \sim \frac{|50|^2}{2 \cdot 931 \cdot 108} \sim 0.01[MeV]$$



Alpha-separation energy spectrum and isotopic dependence of cross sections



Reaction Theories

Theoretical support by S. Typel

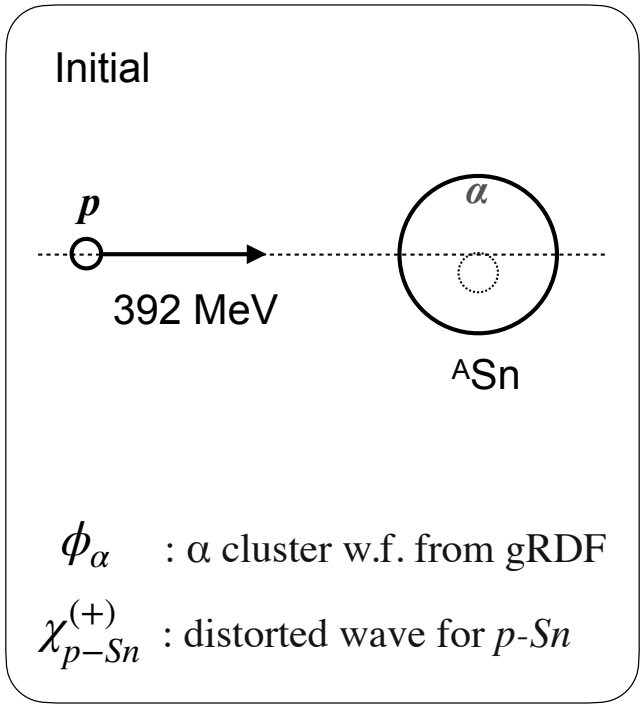
Advice from K. Yoshida and K. Ogata

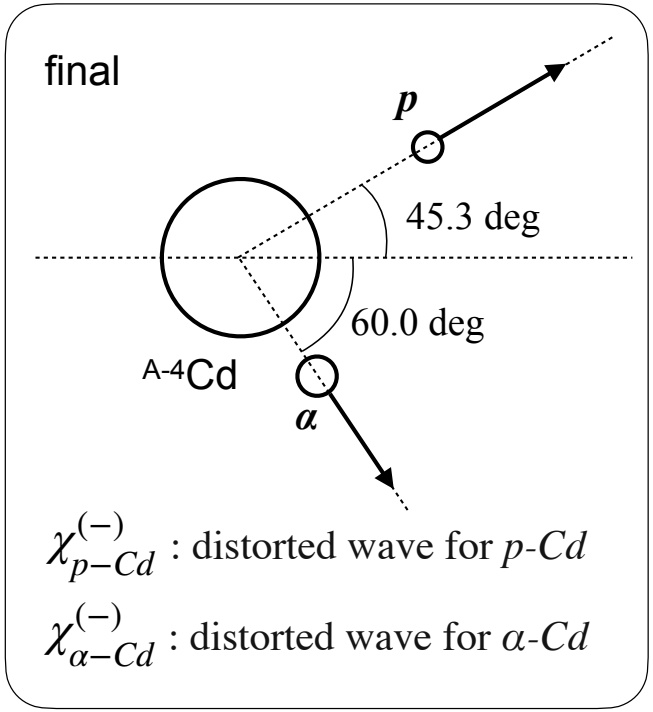
Transition amplitude for Sn(p,$p\alpha$)Cd

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

$t_{p-\alpha}$: free p-α scattering matrix

χ : distorted waves





1. Reaction Kinematics
2. p-α scattering matrix

   K. Yoshida et. al.
   Phys. Rev. C **98** 024614 (2018)

3. momentum of α in nuclei

   gRDF theory by S. Typel
   Phys. Rev. C **89**, 064321 (2014)

4. absorption of protons

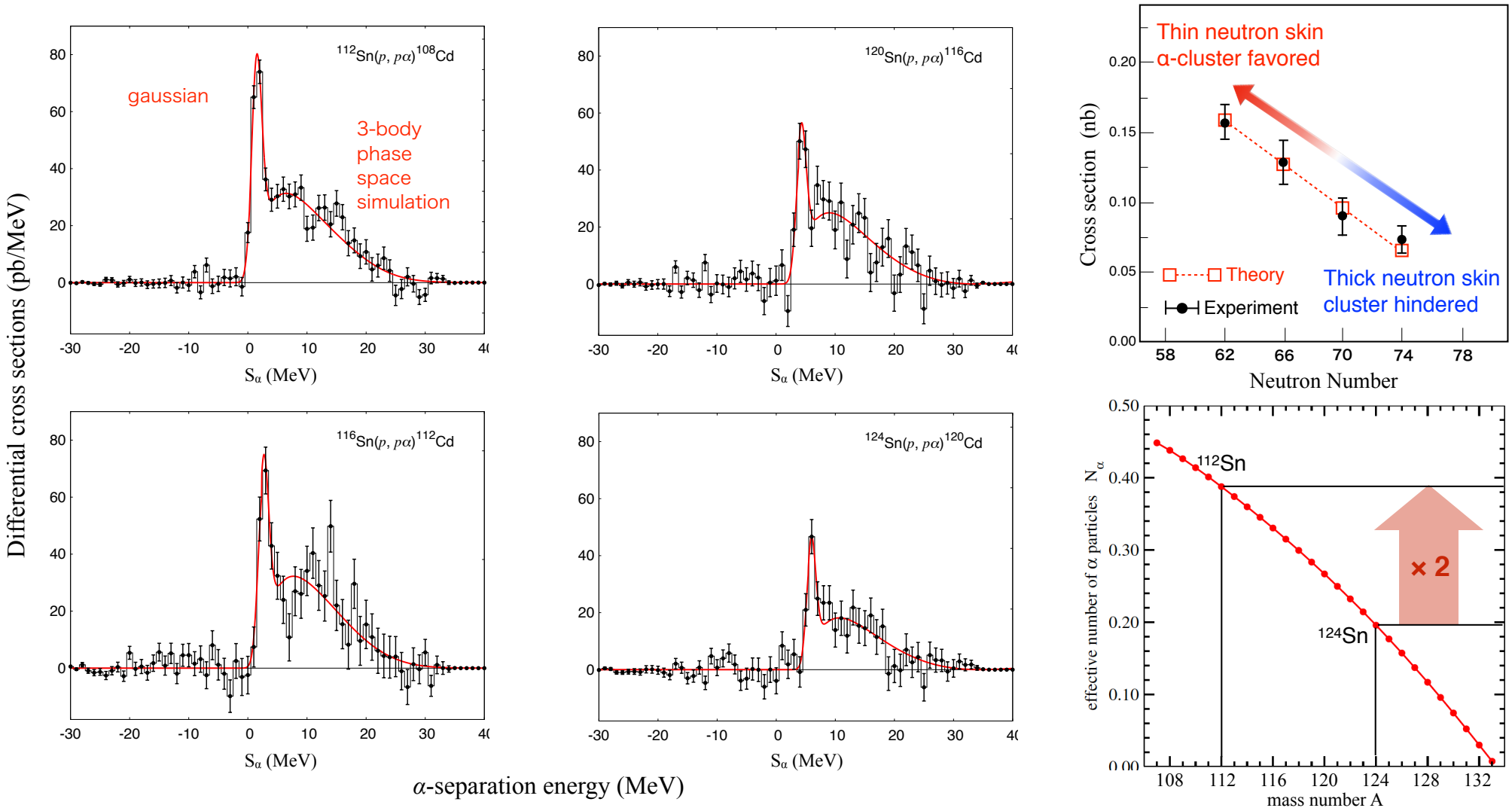
   Optical potential from S. Hama
   et. al. Phys. Rev. C **41** 2327 (1990)

5. absorption of alpha

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

→ The depth of the imaginary part was tuned to the experimental data. Use the same reduction factor for all isotopes.

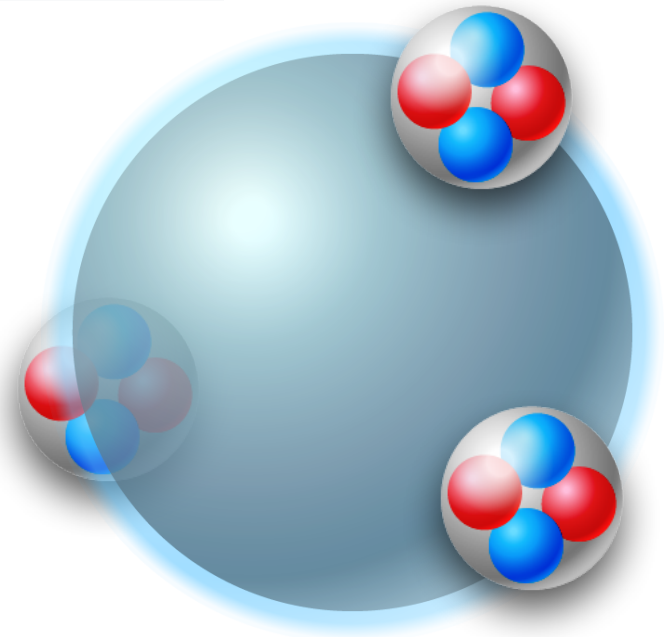
Experimental result and comparison with theory



Summary of the experiment

1. The existence of alpha clusters in the ground state of heavy nuclei (Sn) was clarified by measuring the cross section of the alpha knockout reaction.

2. The isotope dependence of the reaction cross section is consistent with the theoretical prediction, and what we observed is likely to be alpha clusters localized on the nuclear surface.



Publication

REPORT

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

NUCLEAR PHYSICS

Formation of α clusters in dilute neutron-rich matter

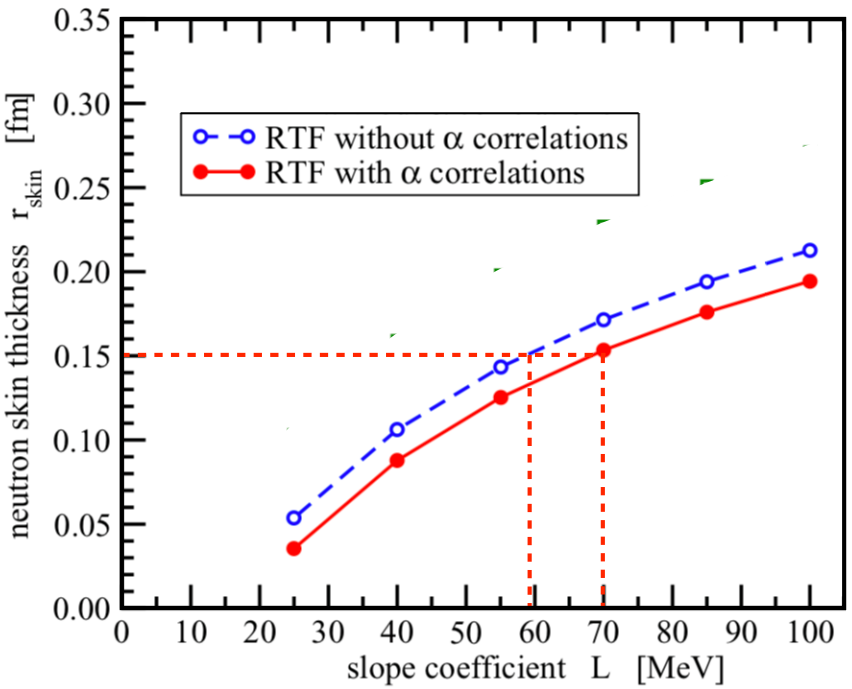
Junki Tanaka[1,2,3]*, Zaihong Yang[3,4]*, Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], 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.

- Relation of nuclear EOS
- Origin of α particles in α decay

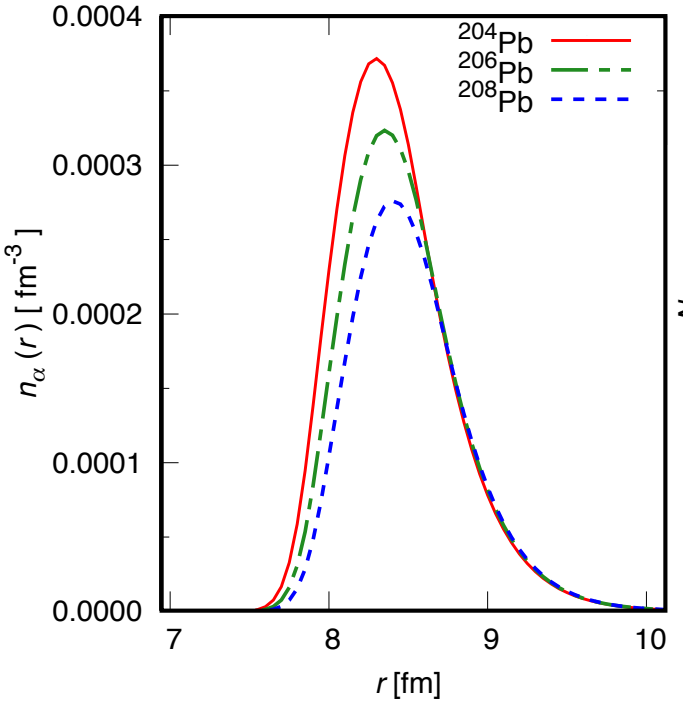
With or Without alpha clusters affects the relation between neutron-skin thickness and slope parameter

S. Typel Phys. Rev. C **89**, 064321 (2014)

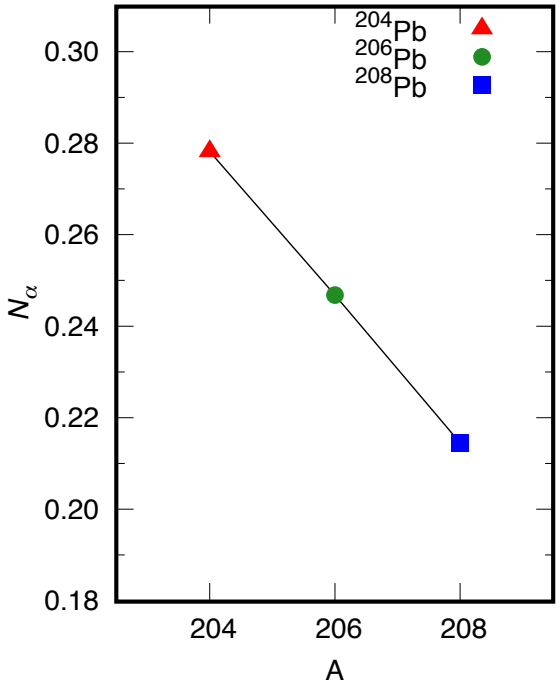


Relation between neutron-skin thickness and slope parameter

Pb(*p,pa*) proposal @ RCNP J.Tanaka/S.Typel

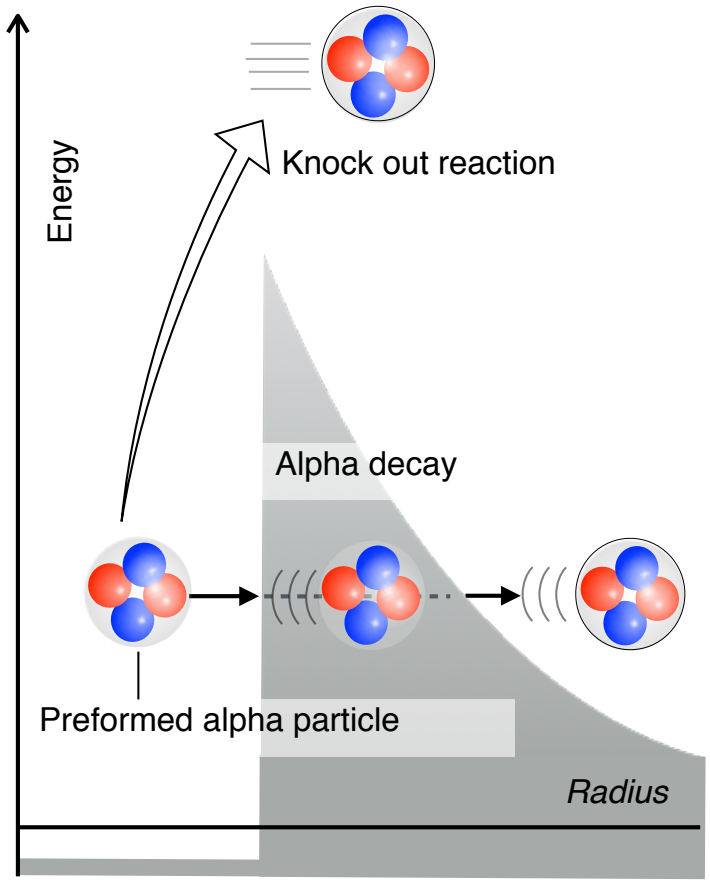


Alpha density distribution n_α in $^{204/206/208}$Pb

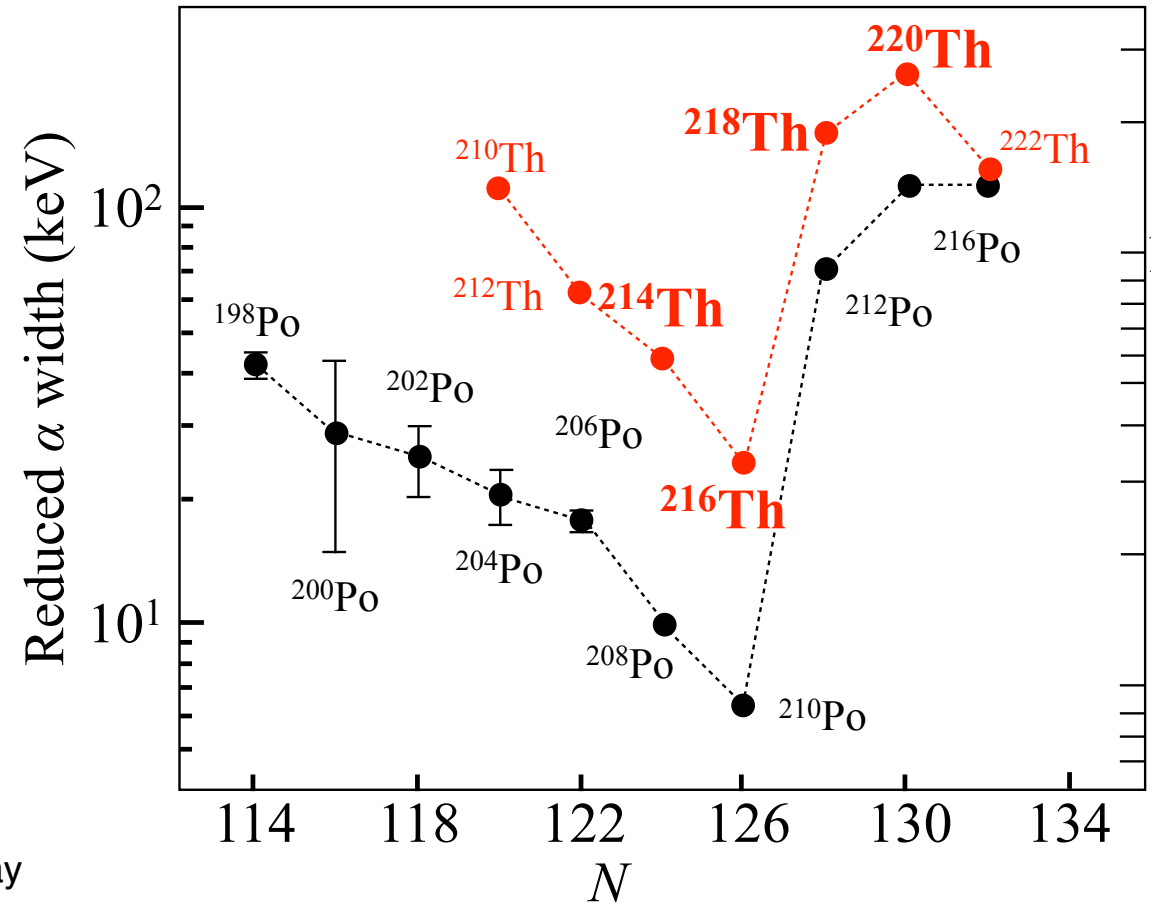


mass number dependence of N_α

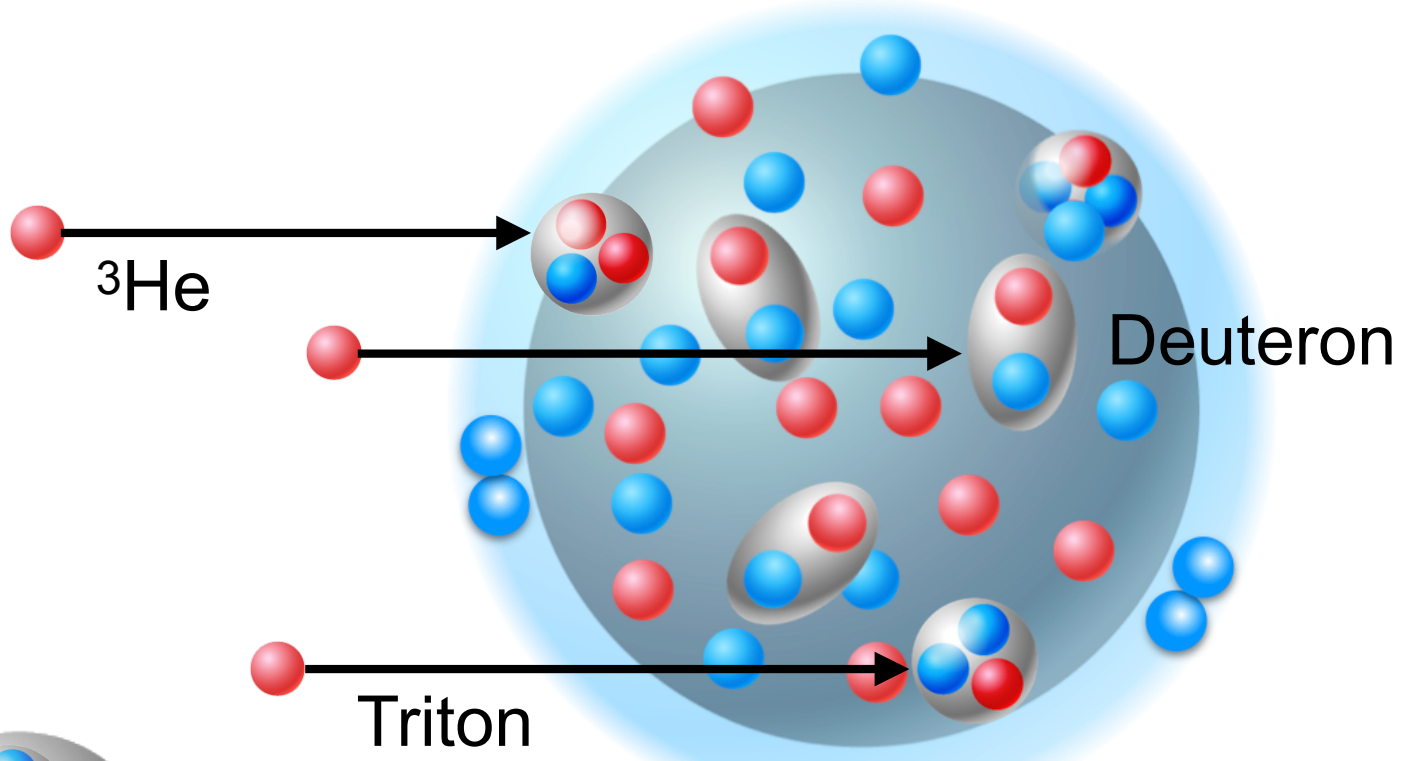
Knocking out alpha clusters from alpha decaying isotopes

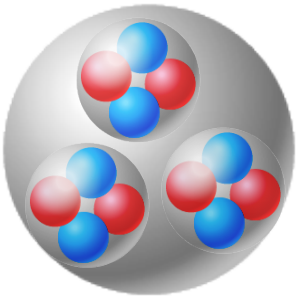


Contrast of knockout reaction and alpha decay



New picture of atomic nuclei





Thank you very much for your listening!