NEWS colloquium
2024. 11. 29

Alpha clusters in nuclear surface

Junki Tanaka
RCNP, Osaka University
RCNP Sn($p,p\alpha$) collaboration
ONOKORO collaboration

Self introduction

田中 純貴
Junki Tanaka

主な経歴

2006年3月
兵庫県立 姫路西高等学校普通科 卒業

2010年3月
岡山大学工学部 物質応用化学科 卒業

2012年3月
大阪大学大学院理学研究科 物理学専攻博士前期課程 修了

2014年4月-2016年3月
日本学術振興会 特別研究員(DC2)

2016年3月
大阪大学大学院理学研究科 物理学専攻後期課程 単位修得退学

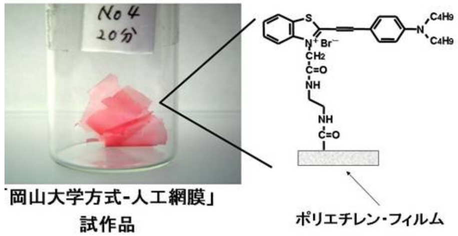
2016年4月-2017年3月
甲南大学 理工学部 平生太郎基金研究員

2016年9月
大阪大学 博士学位取得

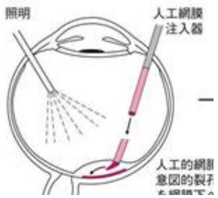
2017年4月-2019年3月
ダルムシュタット工科大学/GSI研究所 ポスドク研究員

2019年4月- 2023年8月
理化学研究所 特別研究員

2023年9月-Present
RCNP 助教 / 阪大理学研究科 助教(兼任) / 理研 客員研究員(兼任)

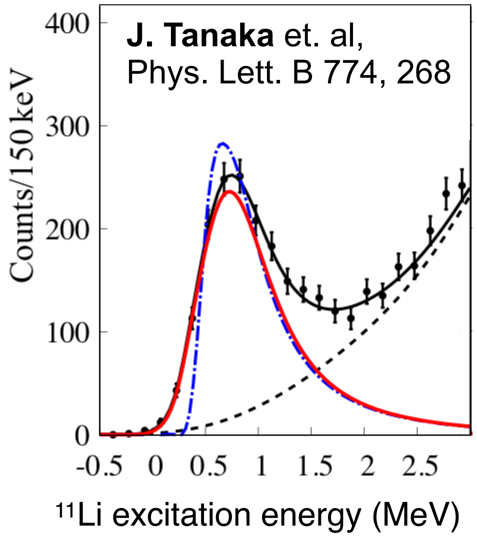


「岡山大学方式-人工網膜」試作品



The artificial retina with photosensitive dye chemically bonded to the polyethylene surface.

^{11}Li Soft dipole resonance
@ TRIUMF



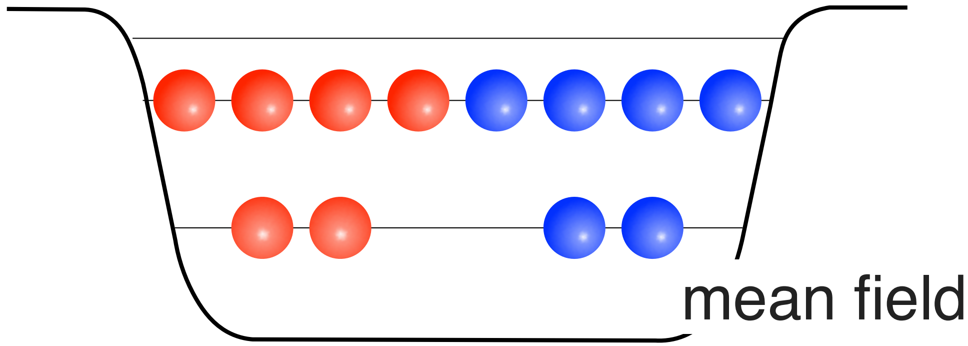
Happy to join RCNP cyclotron experiment group !

Happy to join Tamii-lab !
Tamii-lab. trip to mountain 比叡山

Correlation and Clustering

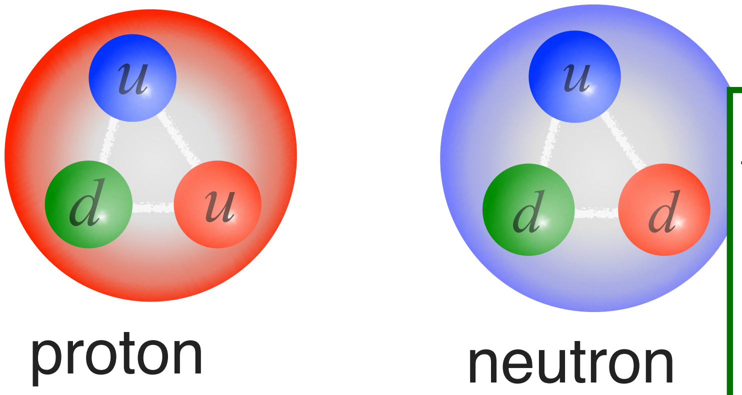
Credits: NASA, ESA, CSA, I. Labbe (Swinburne University of Technology) and R. Bezanson (University of Pittsburgh). Image processing: Alyssa Pagan (STScI)

Atomic Nuclei



The properties of the nucleus can be roughly explained by a model using a mean-field composed of all nucleons.

Quarks



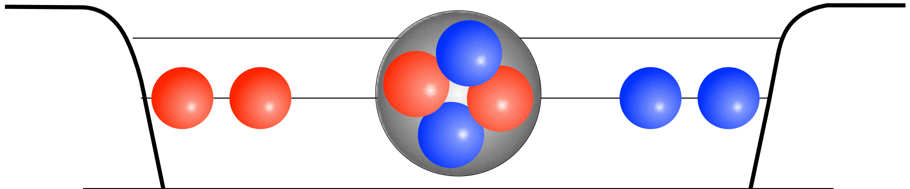
Clustering

Correlation and clustering are universal phenomenon that appears in all hierarchies of nature, from the universe to the quarks.

Clustering

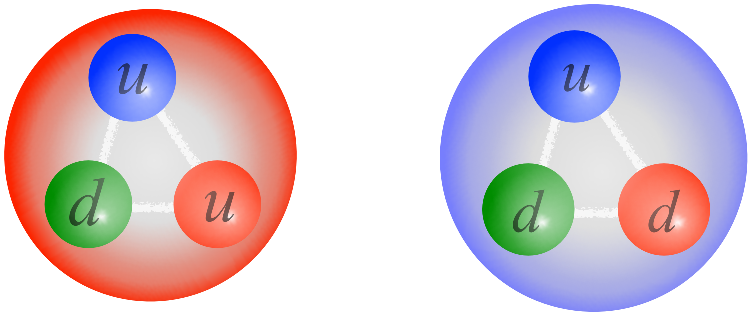
Credits: NASA, ESA, CSA, I. Labbe (Swinburne University of Technology) and R. Bezanson (University of Pittsburgh). Image processing: Alyssa Pagan (STScI)

Atomic Nuclei

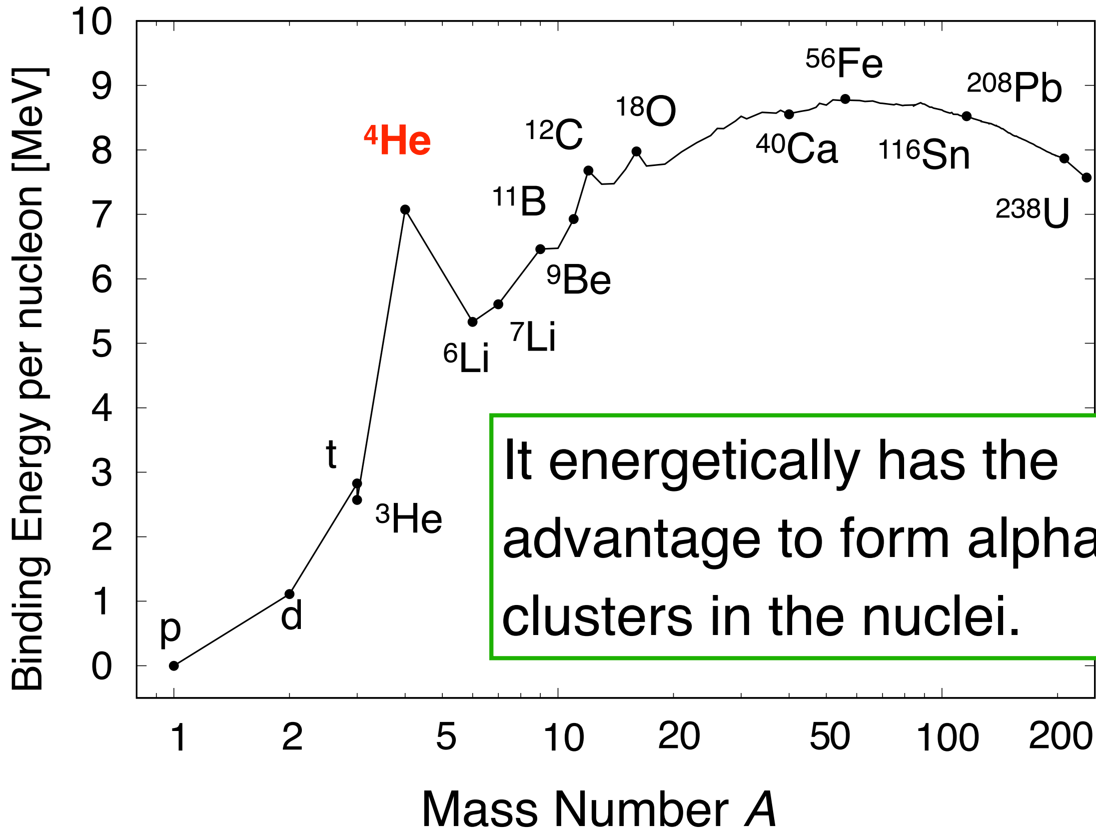


Multi-nucleons behave as if they are single particles!!

Quarks

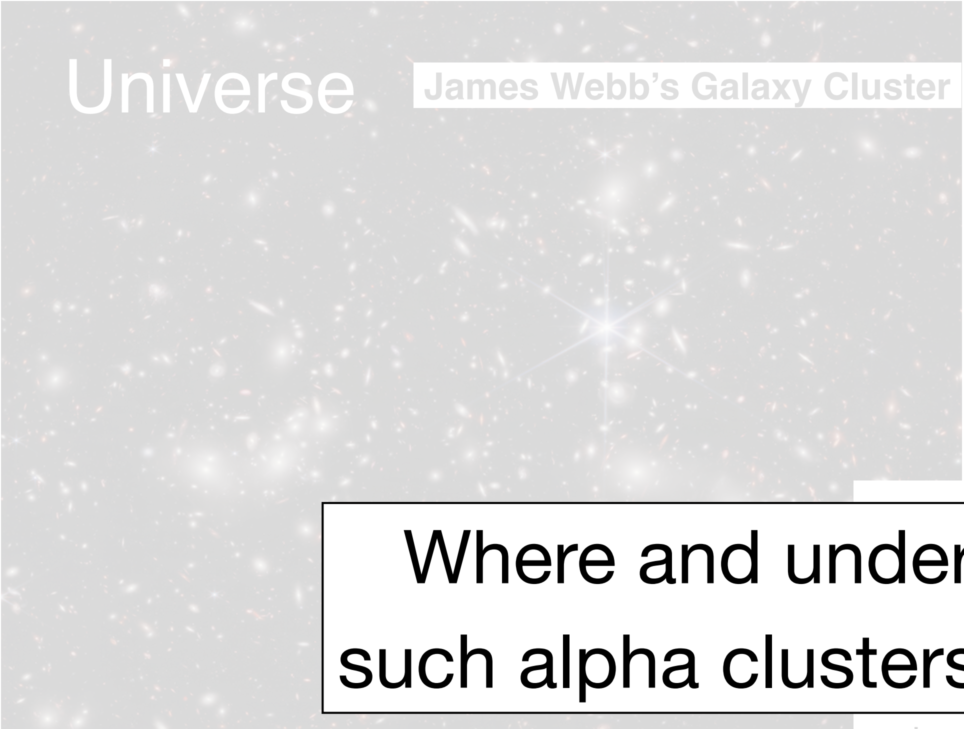


proton neutron



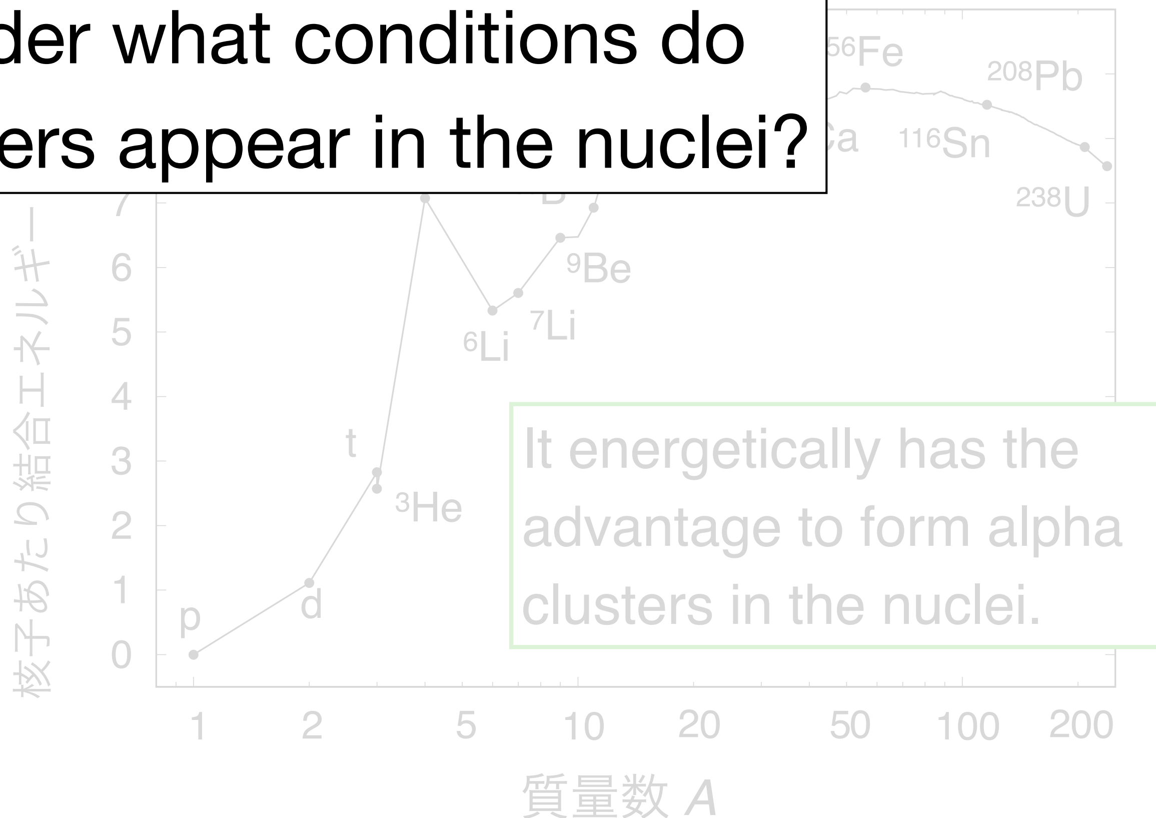
It energetically has the advantage to form alpha clusters in the nuclei.

Clustering

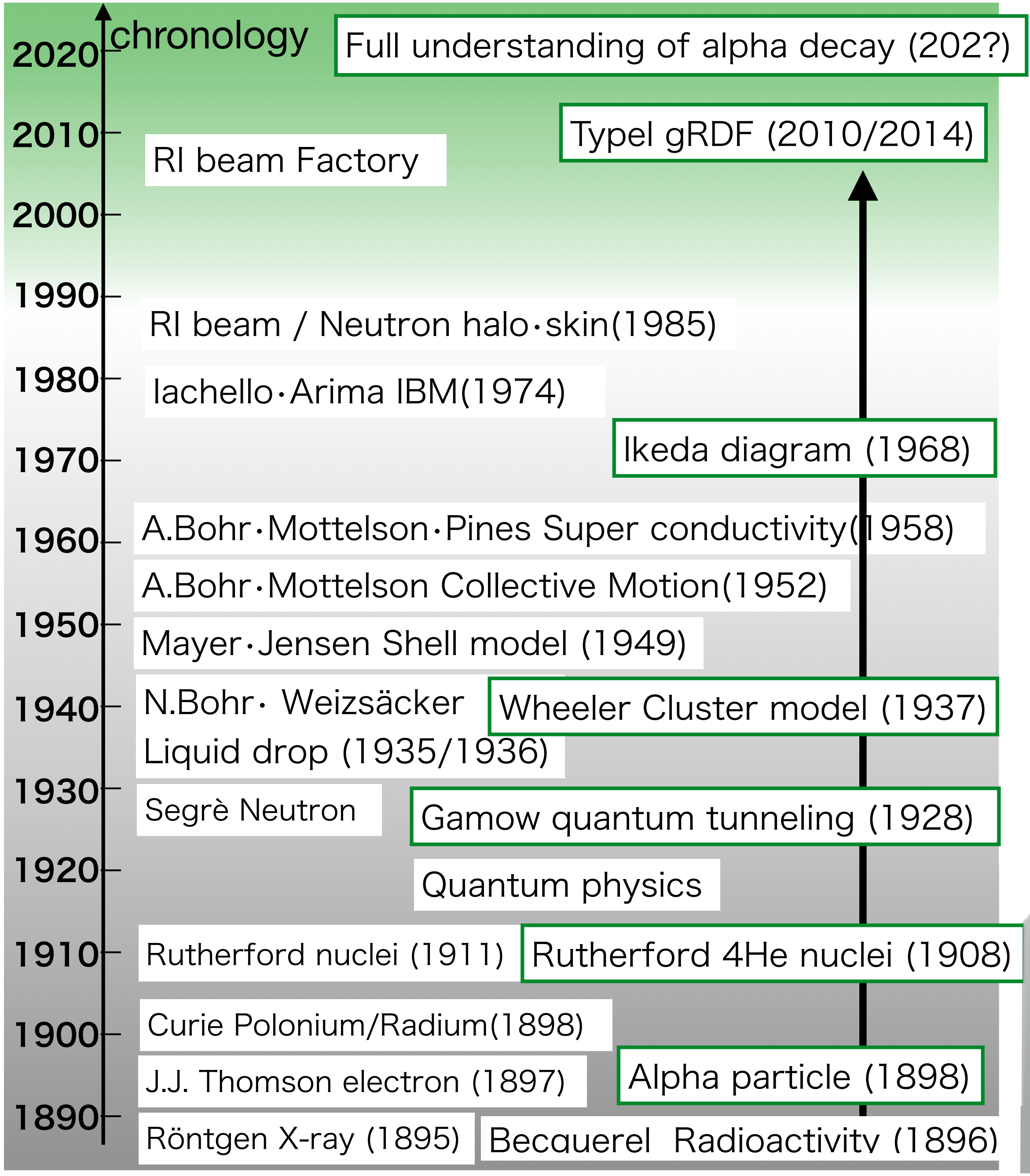


Credits: NASA, ESA, CSA, I. Labbe (Swinburne University of Technology) and R. Bezanson (University of Pittsburgh). Image processing: Alyssa Pagan (STScI)

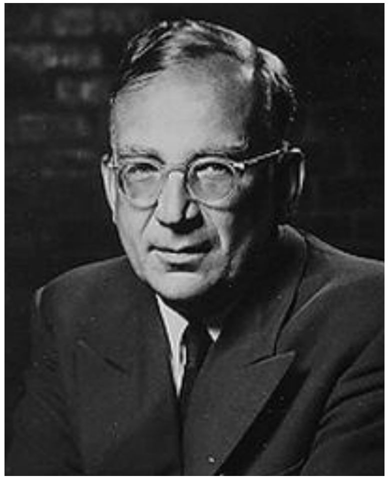
Where and under what conditions do such alpha clusters appear in the nuclei?



Alpha clusters in the ground state of heavy nuclei

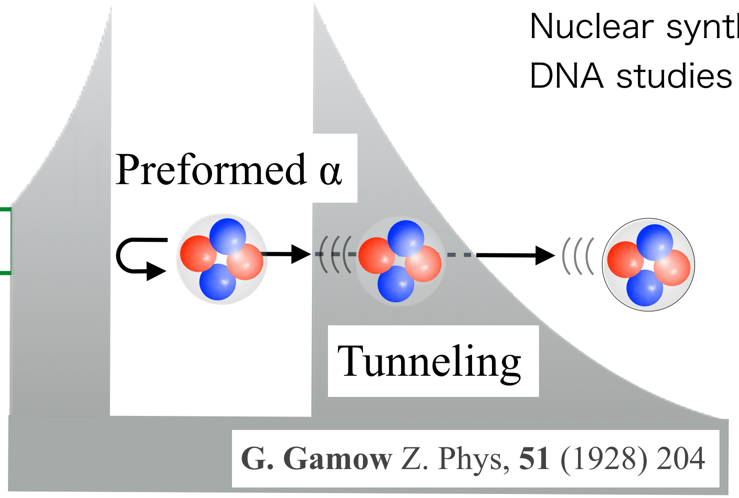


Alpha decay theory



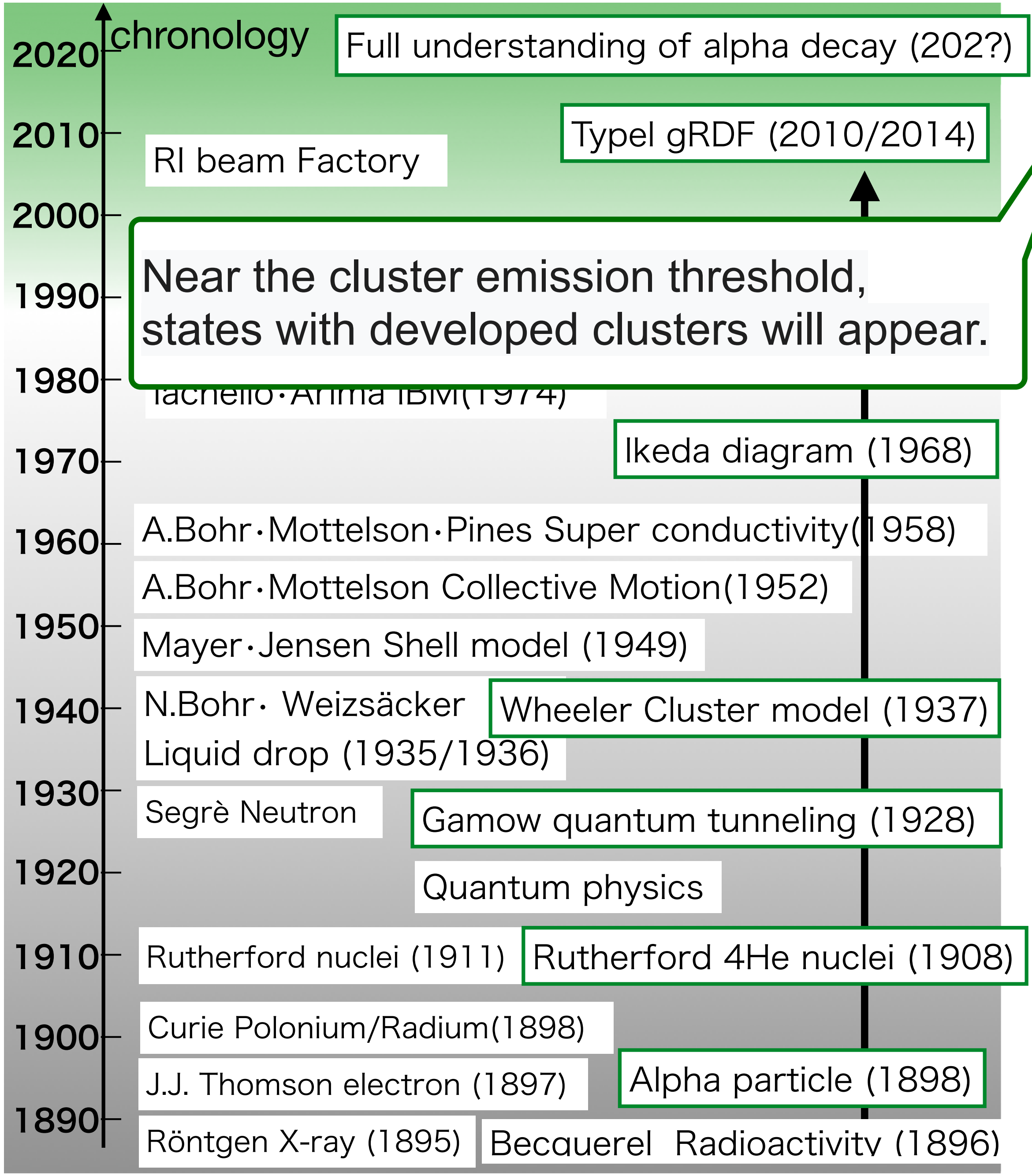
George Gamow

- Alpha decay theory
- Big Bang theory
- Cosmic MW BG
- Nuclear synthesis
- DNA studies



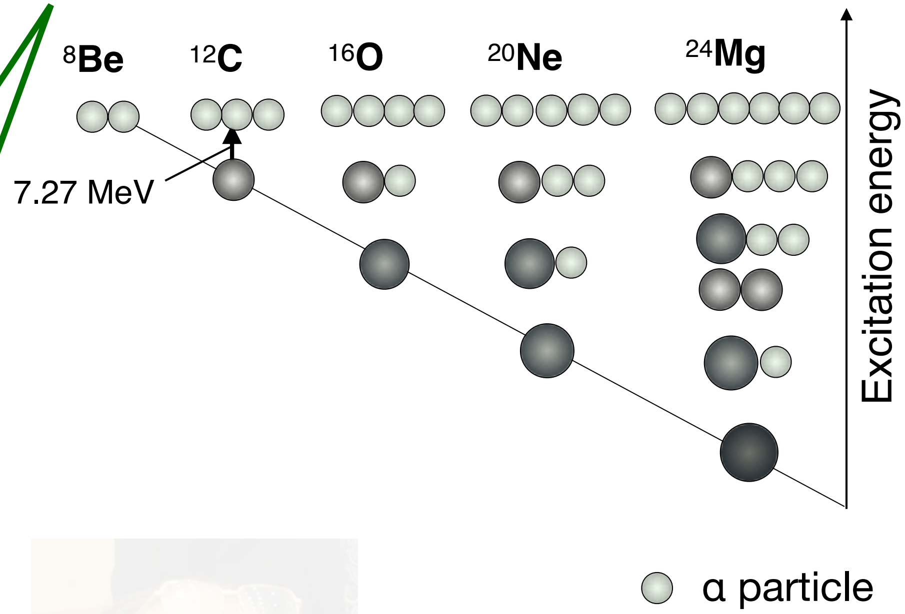
G. Gamow Z. Phys, **51** (1928) 204

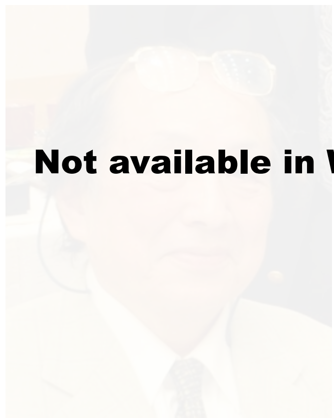
Alpha clusters in the ground state of heavy nuclei



Ikeda Diagram

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





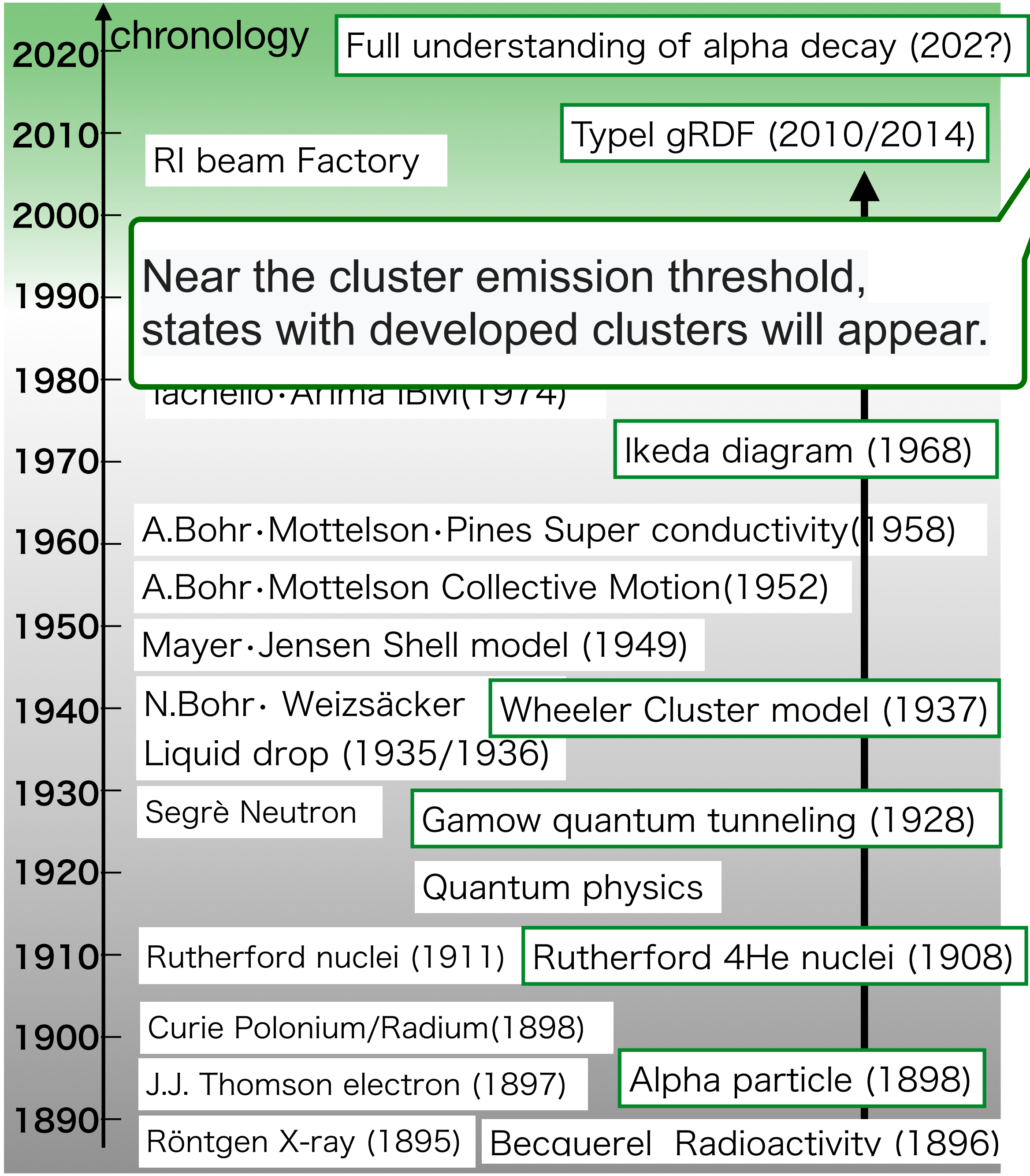
Kiyomi Ikeda

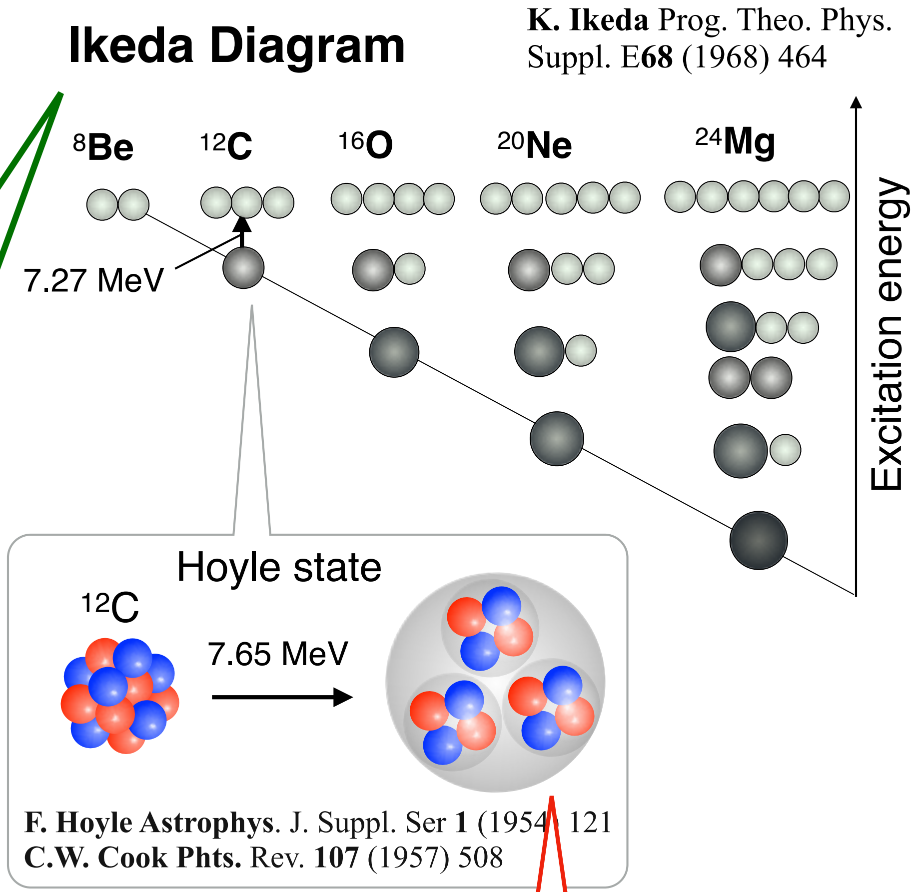
Ikeda diagram

soft dipole resonance

Ikeda sum rule

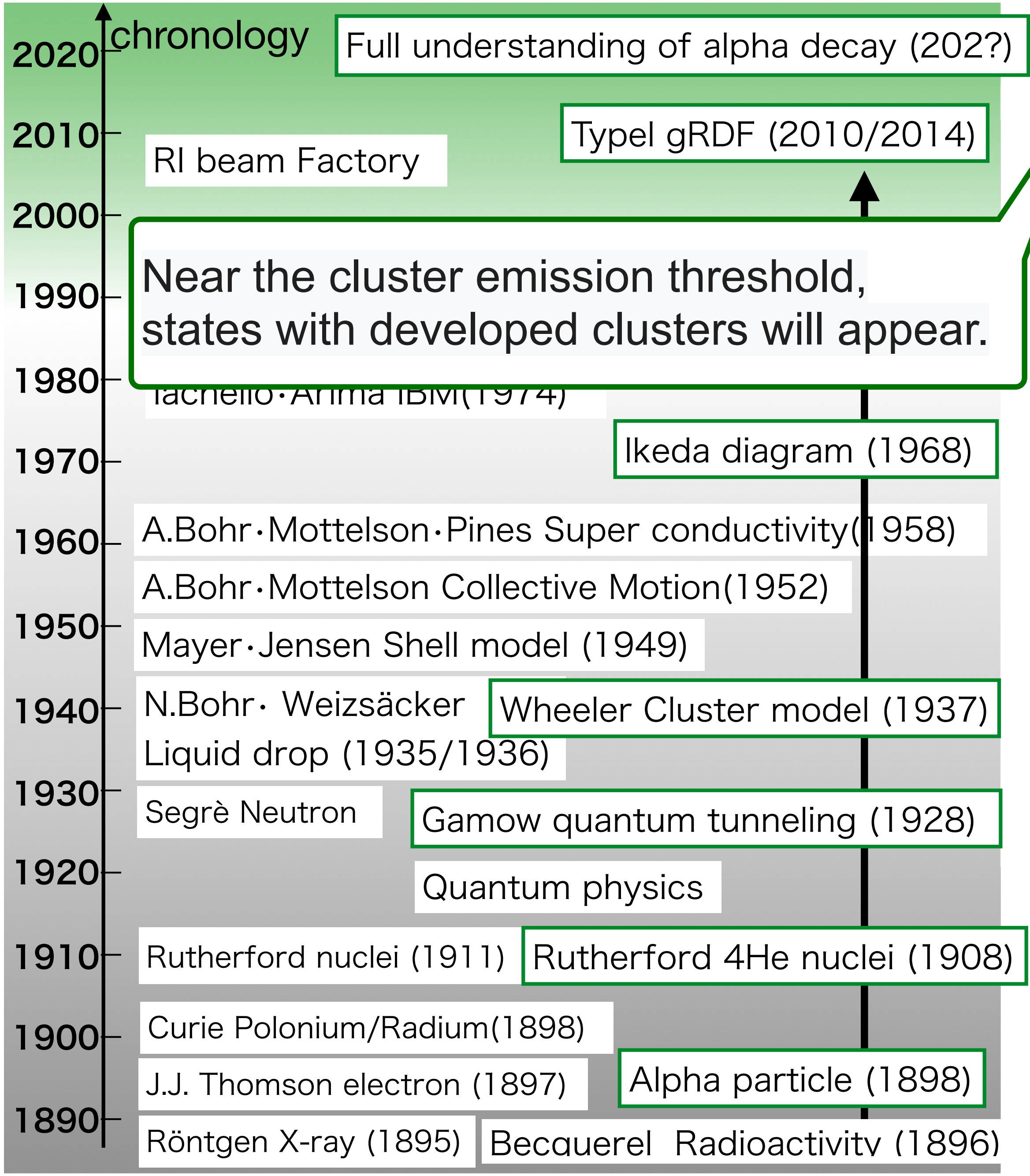
Alpha clusters in the ground state of heavy nuclei





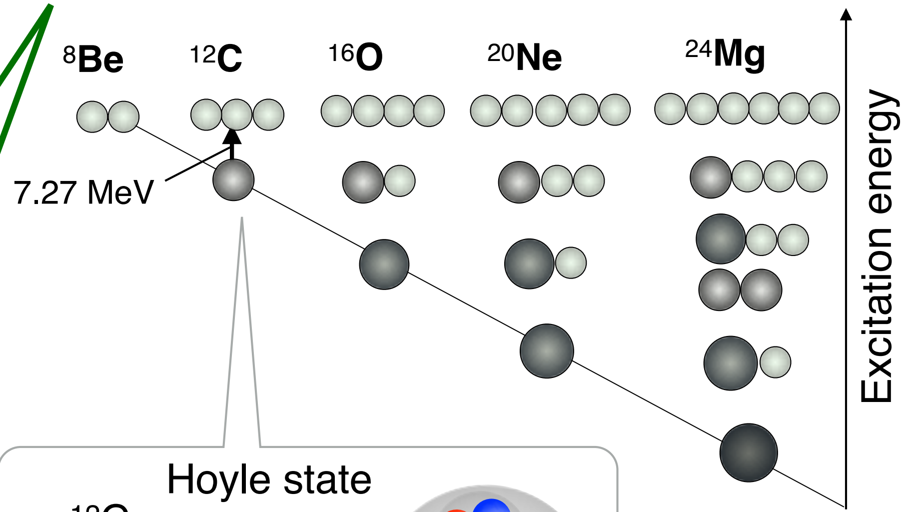
The Hoyle state plays an important role in nature, such as in the synthesis of ^{12}C in stars through the triple-alpha reaction.

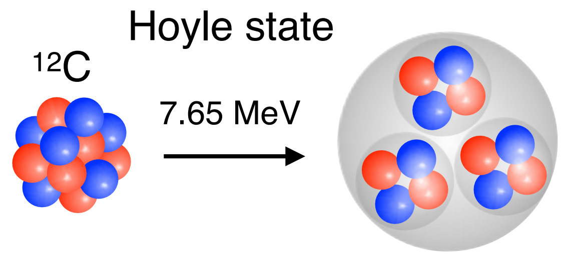
Alpha clusters in the ground state of heavy nuclei



Ikeda Diagram

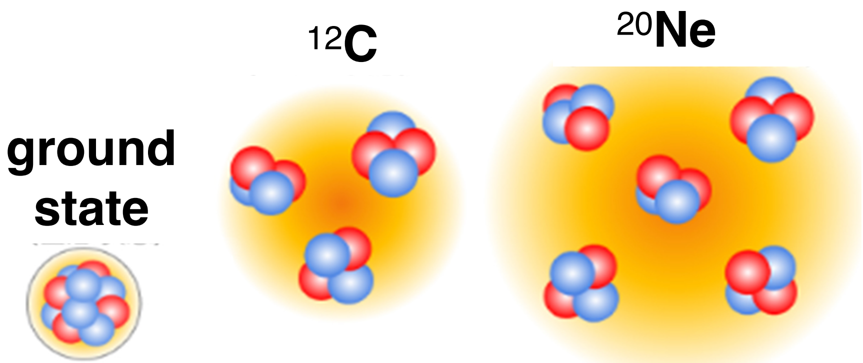
K. Ikeda Prog. Theo. Phys. Suppl. E**68** (1968) 464





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

Alpha condensate states studies



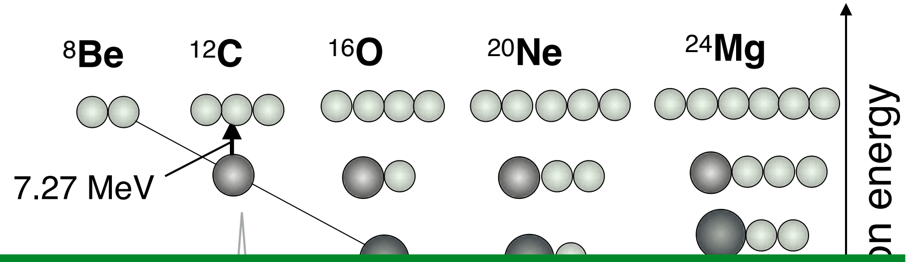
Alpha clusters in the ground state of heavy nuclei

chronology

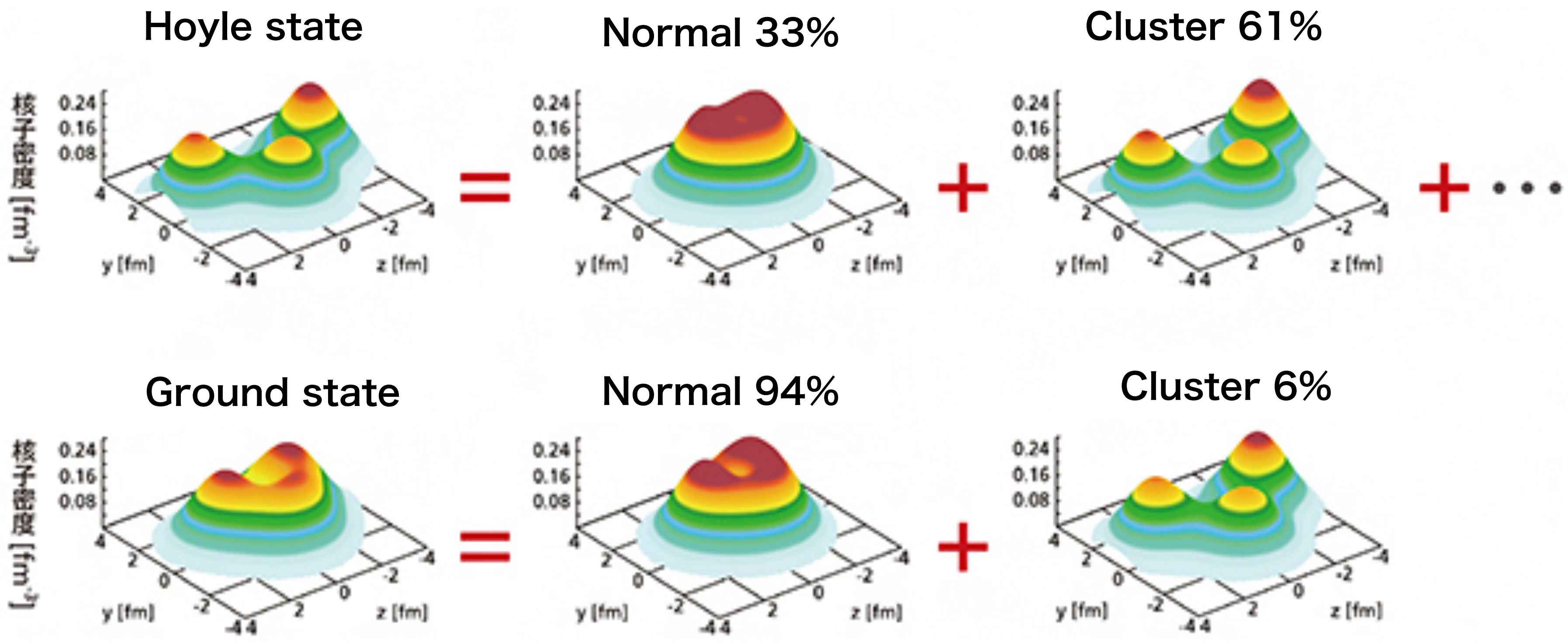
- 2020 — Full understanding of alpha decay (202?)
- 2010 — RI beam Factory; Typel gRDF (2010/2014)
- 2000
- 1990 — R
- 1980 — Ia
- 1970
- 1960 — A; A
- 1950 — M
- 1940 — N; Li
- 1930 — S
- 1920
- 1910 — R
- 1900 — C; J.
- 1890 — Röntgen X-ray (1895); Becquerel Radioactivity (1896)

Ikeda Diagram

K. Ikeda Prog. Theo. Phys. Suppl. E68 (1968) 464

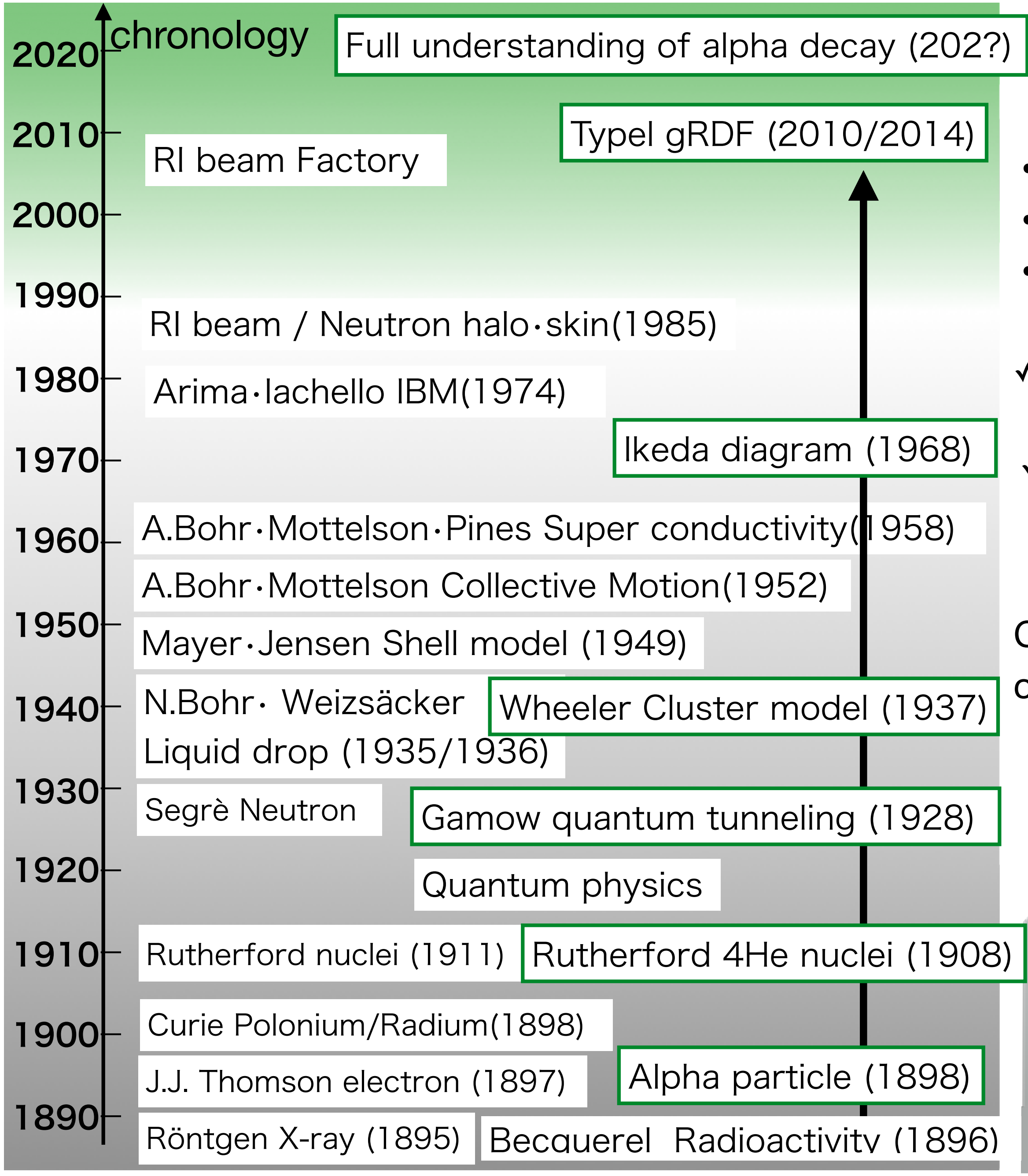


Ab initio no core shell-model calculation



T. Otsuka, T. Abe et.al. Nature Communications 10.1038/s41467-022-29582-0

Alpha clusters in the ground state of heavy nuclei



Success of theories to explain the bulk part of atomic nuclei

- Liquid drop model
- Shell model
- Collective model

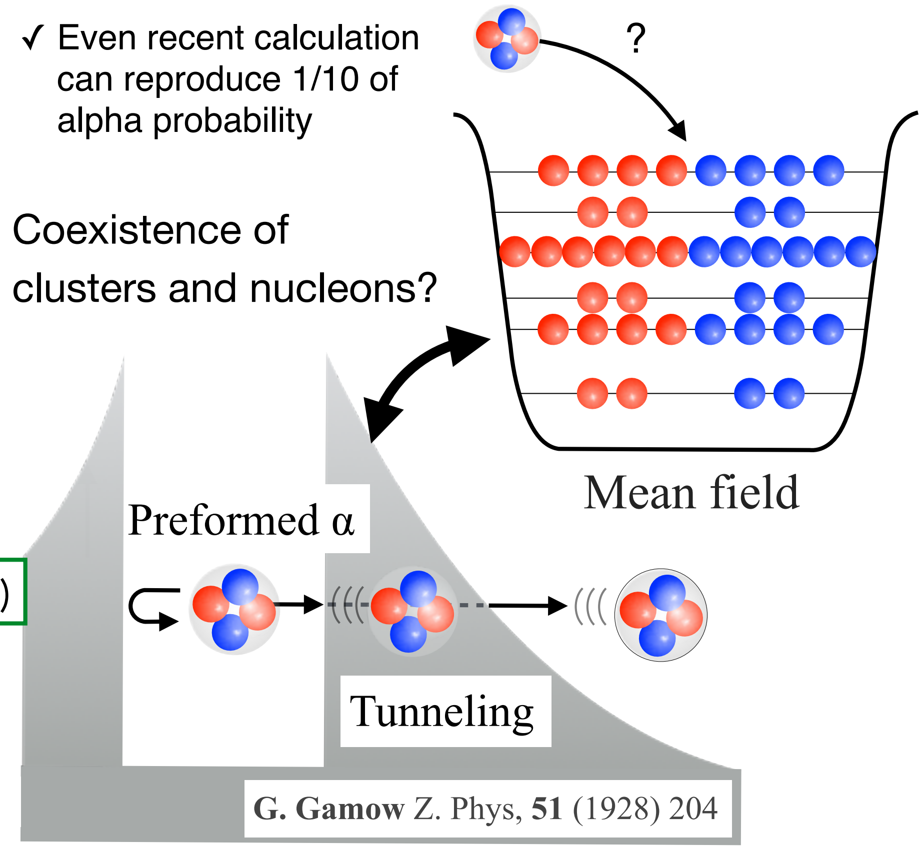
↔

- Cluster model
  → limited in light nuclei ?

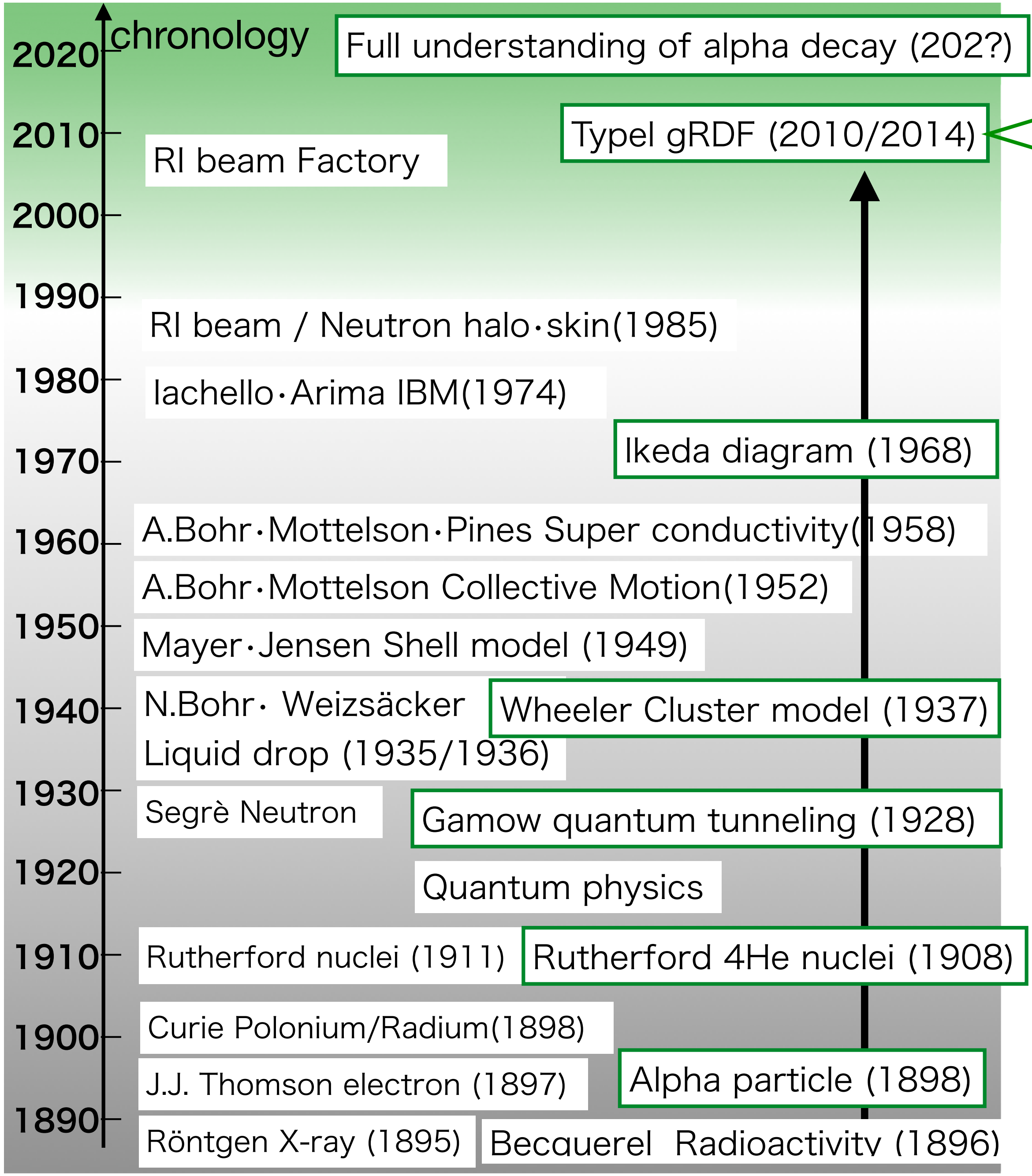
✓ Tonozuka, Arima- shell model calculation → 1/14

I. Tonozuka and A. Arima, Nucl. Phys. A 323, 45 (1979)

✓ Even recent calculation can reproduce 1/10 of alpha probability



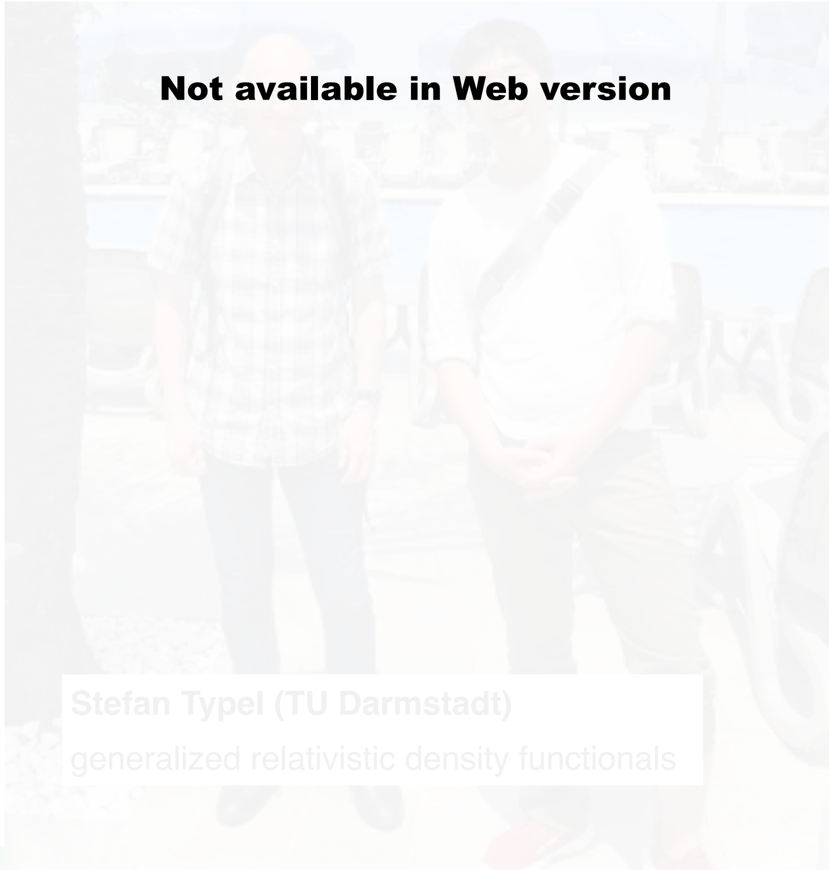
Alpha clusters in the ground state of heavy nuclei



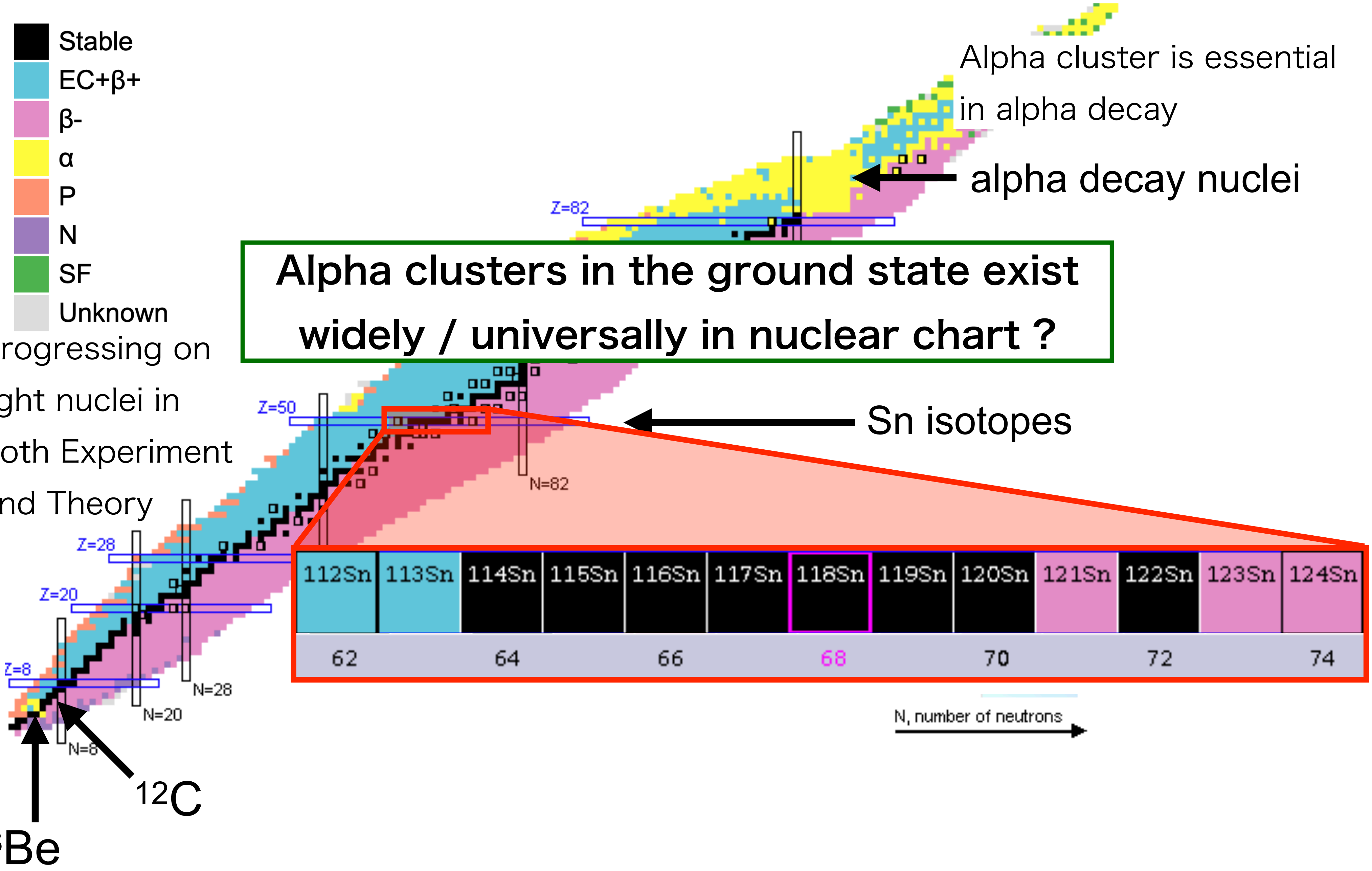
- alpha clusters develop in low-density nuclear matter.
- clustering phenomena appear on the surface of finite nuclei
- Isotopic dependence of tin isotope

→ Reduction of alpha probability with increasing neutron excess

S. Typel et. al. PRC **81**, 015803 (2010) / PRC **89**, 064321 (2014)



Alpha clusters in the ground state of heavy nuclei



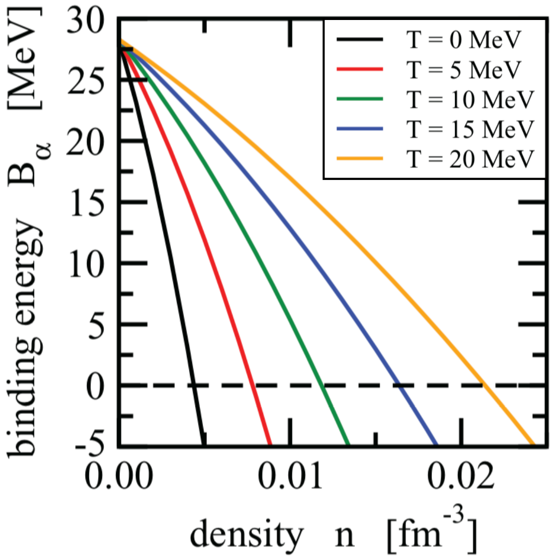
Progressing on light nuclei in both Experiment and Theory

Alpha clusters in the ground state exist widely / universally in nuclear chart ?

Alpha cluster formation predicted in gRDF

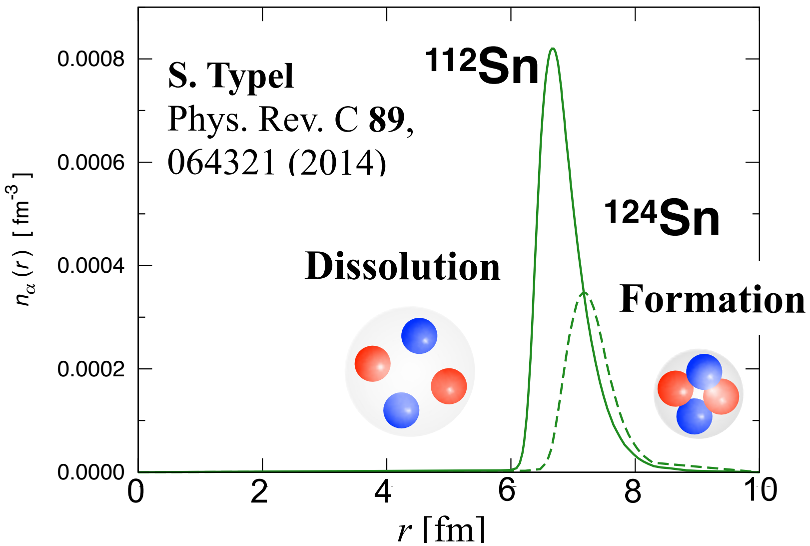
- ✓ Binding energy of alpha particles varies according to the nucleon density.
- ✓ Density is zero, it corresponds to the binding energy of a naked alpha particle
- ✓ When density is increased, the binding energy decreases, and the clusters dissolve.
- ✓ Properties of the infinite system of nuclear matter are applied to the finite nuclei.
- ✓ These degrees of freedom of alpha particles are explicitly taken into account, it determines the most energetically stable distribution of alpha particles.

Binding energy of alpha cluster changes in the nuclear matter

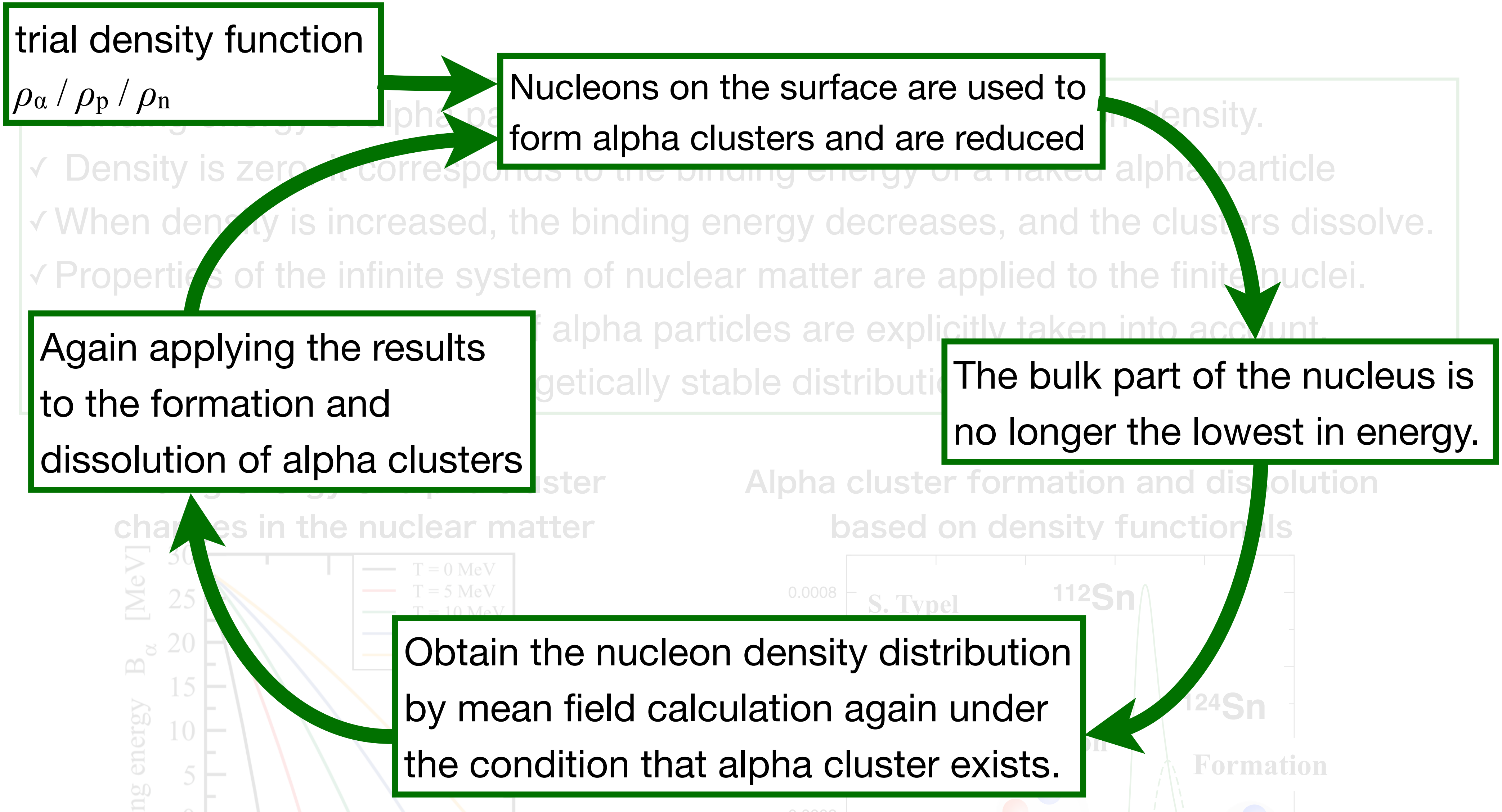


S. Typel et. al.
Phys. Rev. C **81**, 015803 (2010)

Alpha cluster formation and dissolution based on density functionals



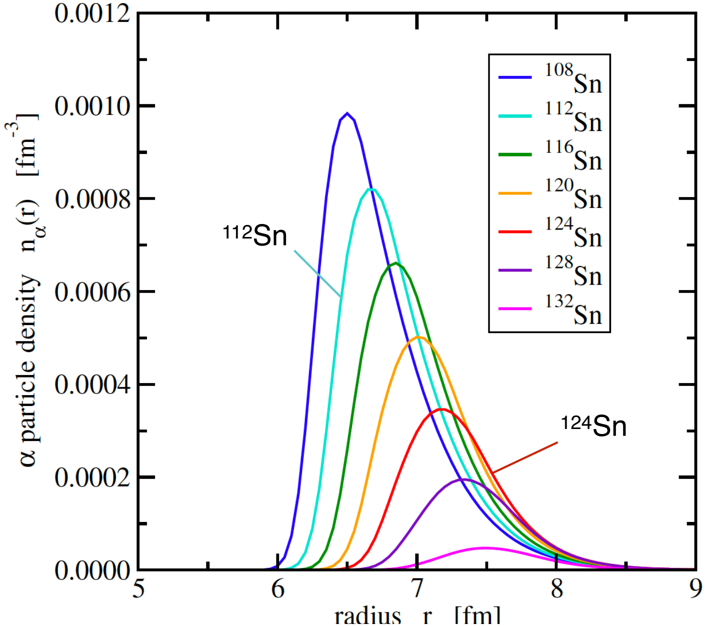
Alpha cluster formation predicted in gRDF

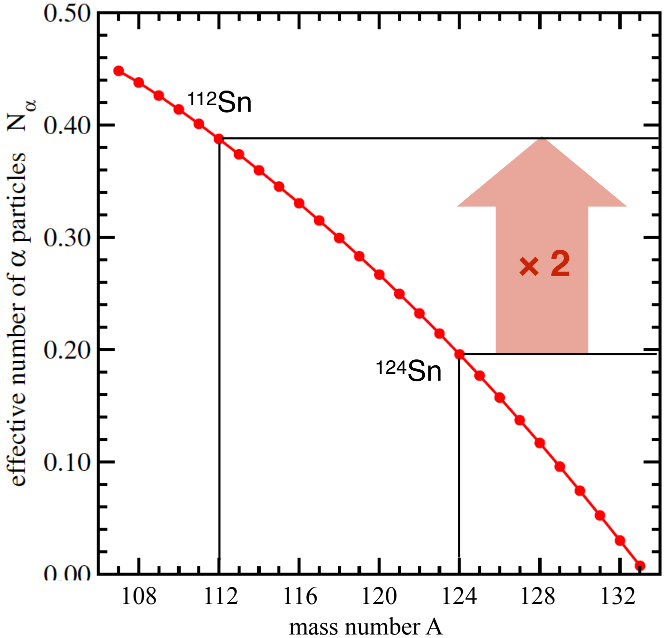


Determine the distribution of alpha clusters self-consistently with the bulk part.
→ Determine the distribution of alpha particles that will be most energetically stable for the entire atomic nuclei.

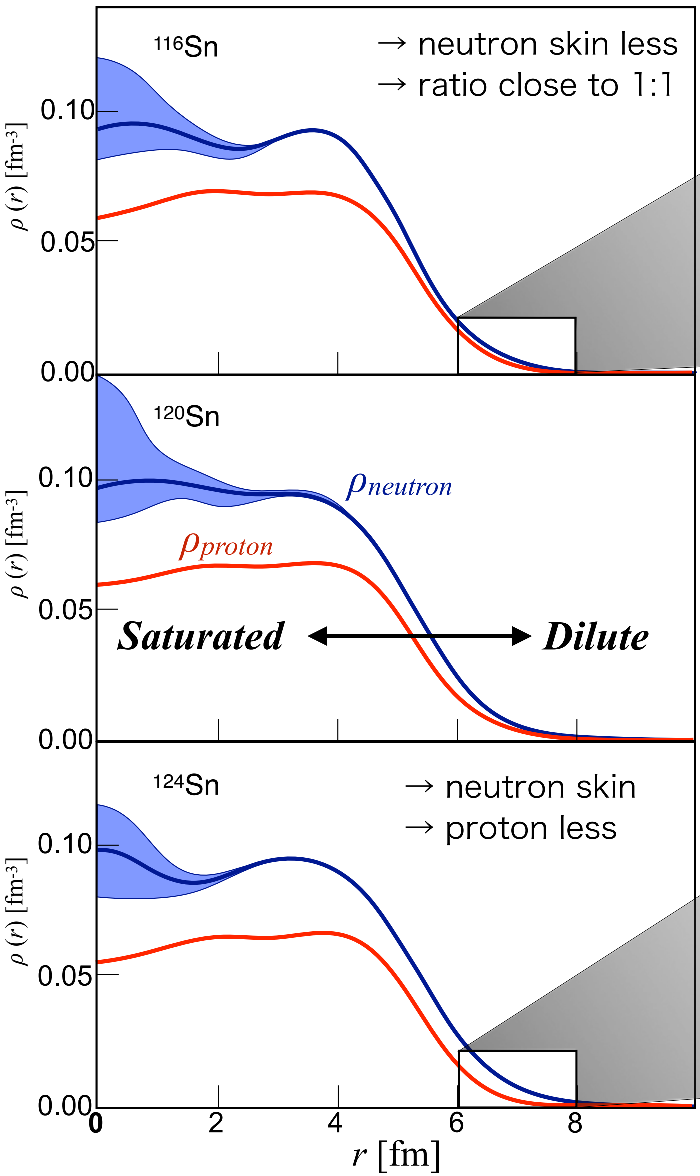
Formation and dissolution of alpha clusters

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

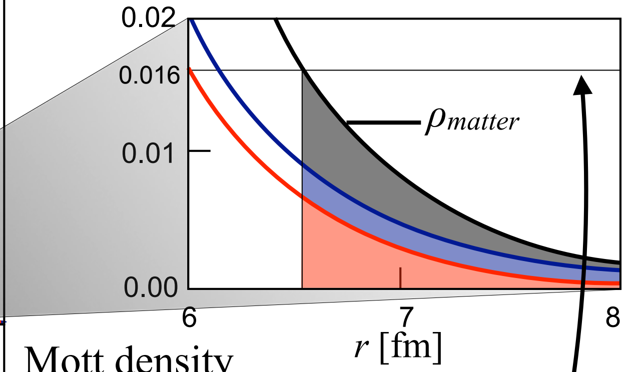




Proton/Neutron-density distributions



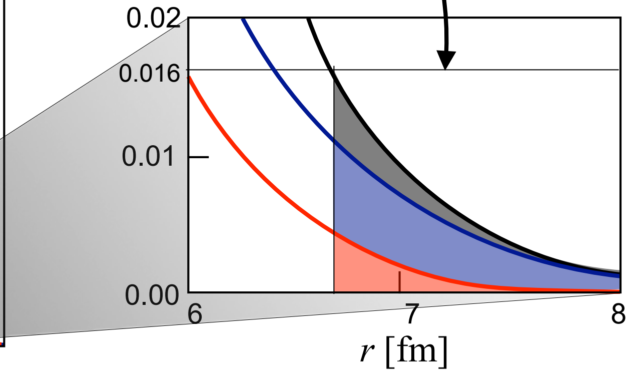
S. Terashima et.al.
Phys. Rev. C **77** (2008) 02317



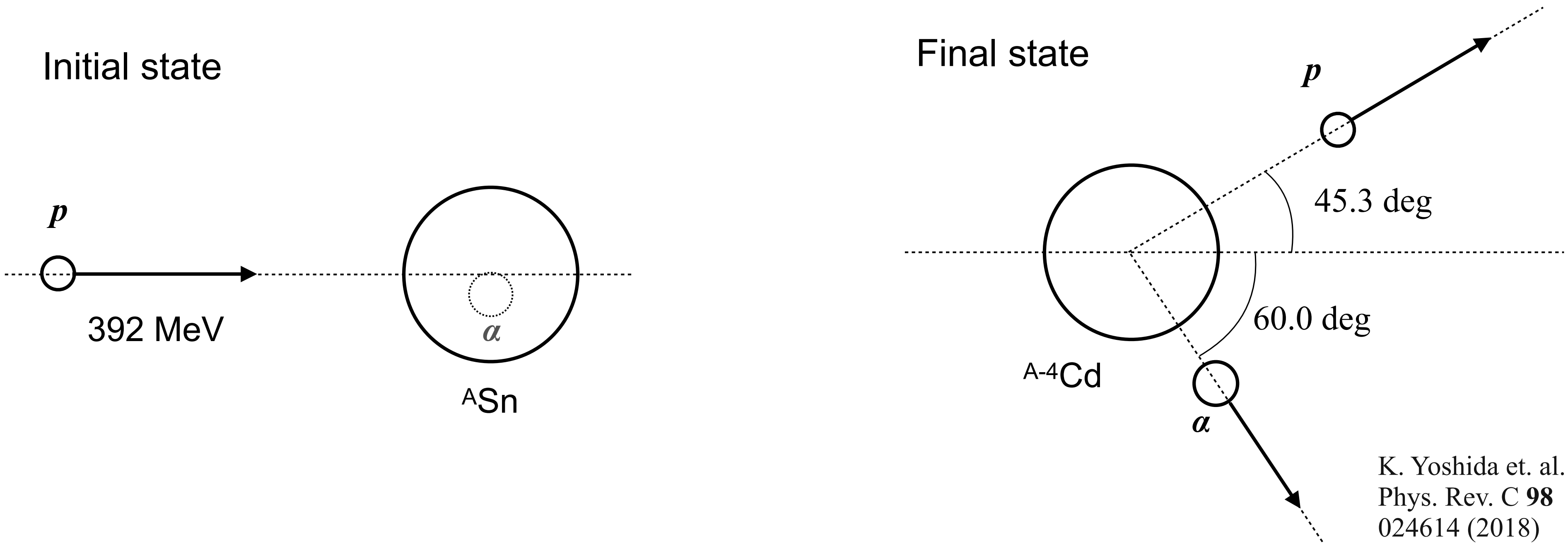
Mott density
Below 1/10 of saturation density 0.16 [fm^{-3}]

S. Typel et. al. Phys. Rev. C **81**, 015803 (2010)
K. Hagel et. al. PRL. **108**, 062702 (2012)

***ρ* < 0.016 [fm^{-3}]**



Quasi-Free Alpha knockout reaction



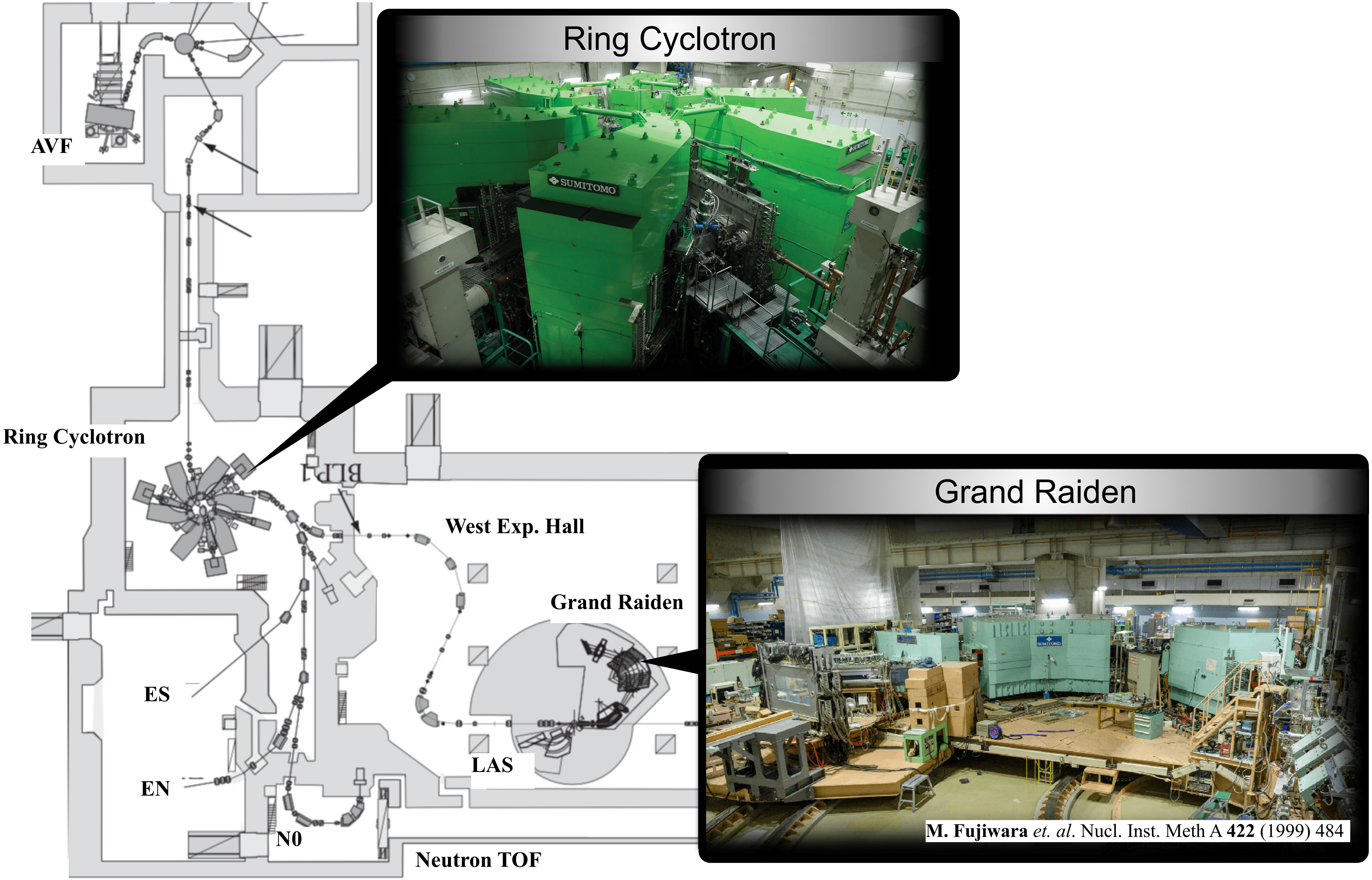
K. Yoshida et. al.
Phys. Rev. C **98**
024614 (2018)

- High-energy proton beam collides with the target nucleus.
- At the moment of the reaction, momentum is transferred.
- Alpha particles received momentum are ejected from the target.
- If the momentum transfer is large,
- the (p, pα) reaction is regarded to be p-α elastic.
- The residual nuclei are not disturbed by the reaction.

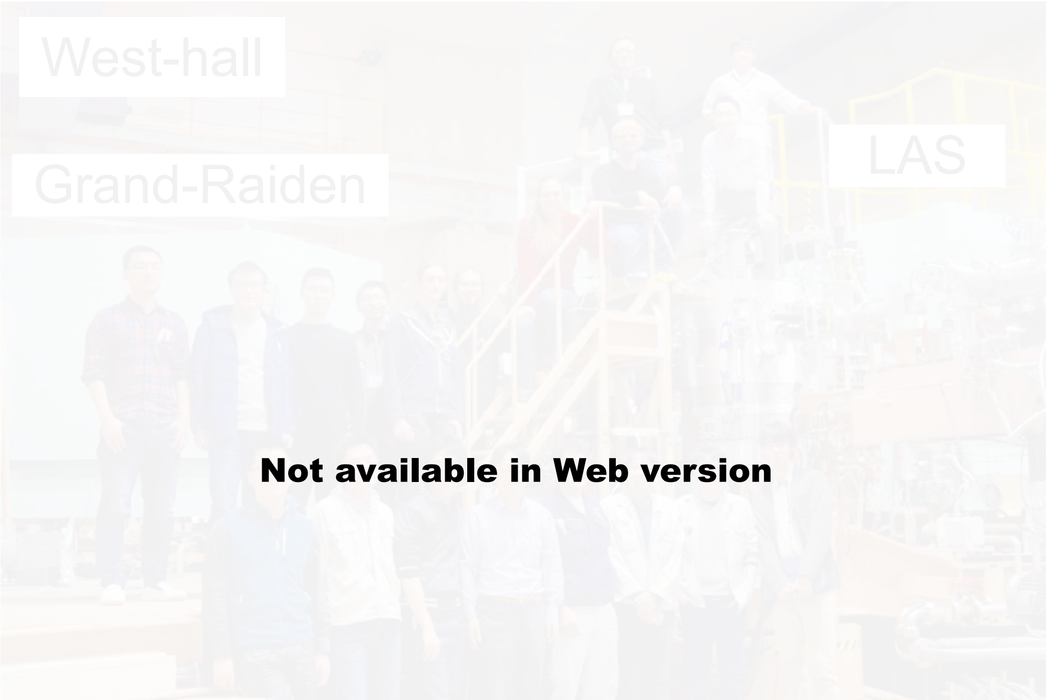
→ If this condition holds, the reaction is called "quasi-free"

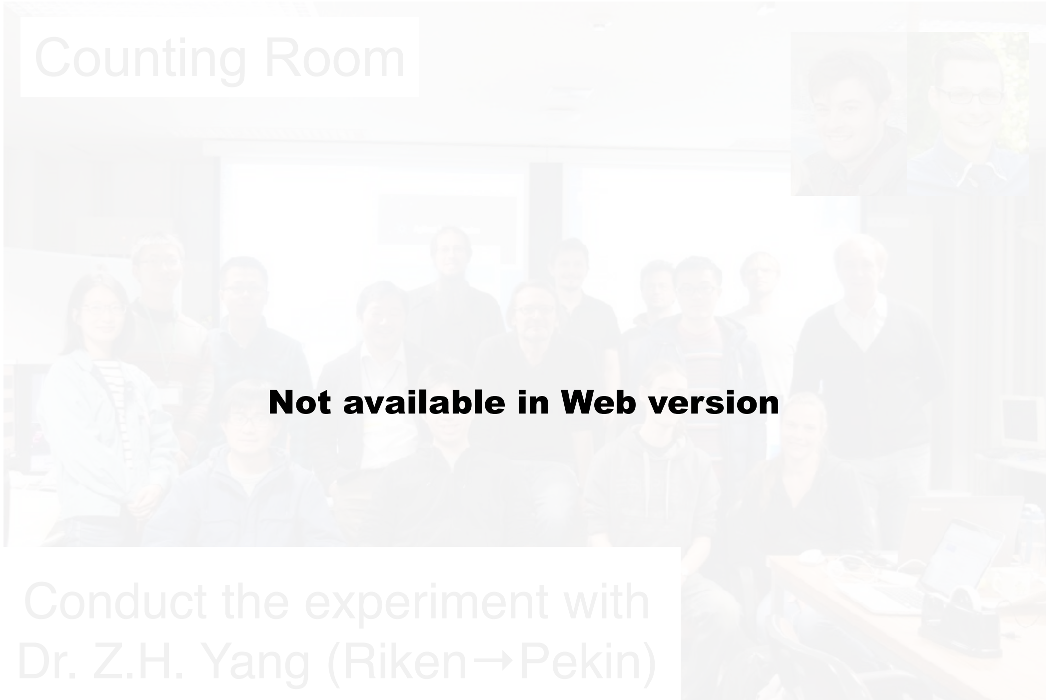
The reaction cross-section is a good measure of the probability of alphas.

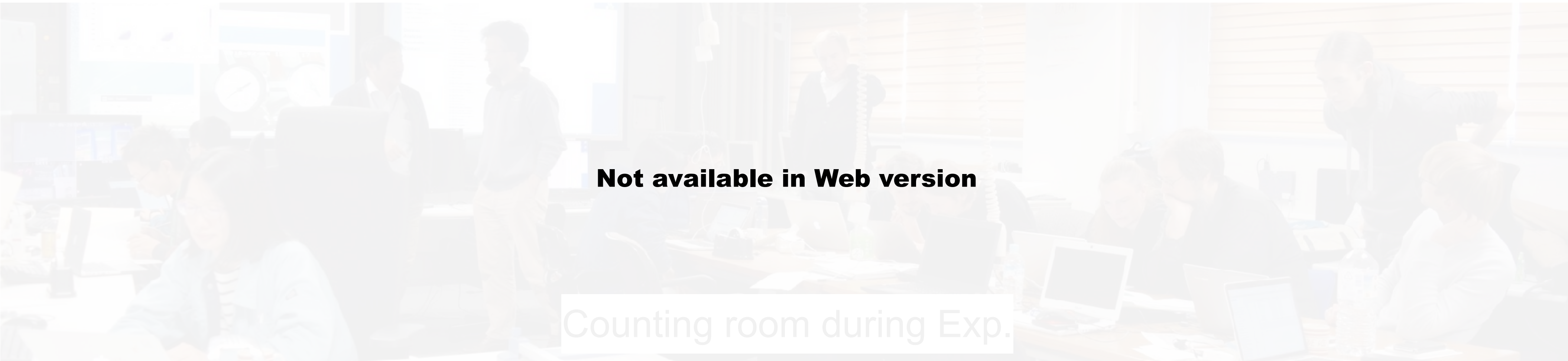
Experiment at RCNP Osaka University



Experiment at RCNP Osaka University

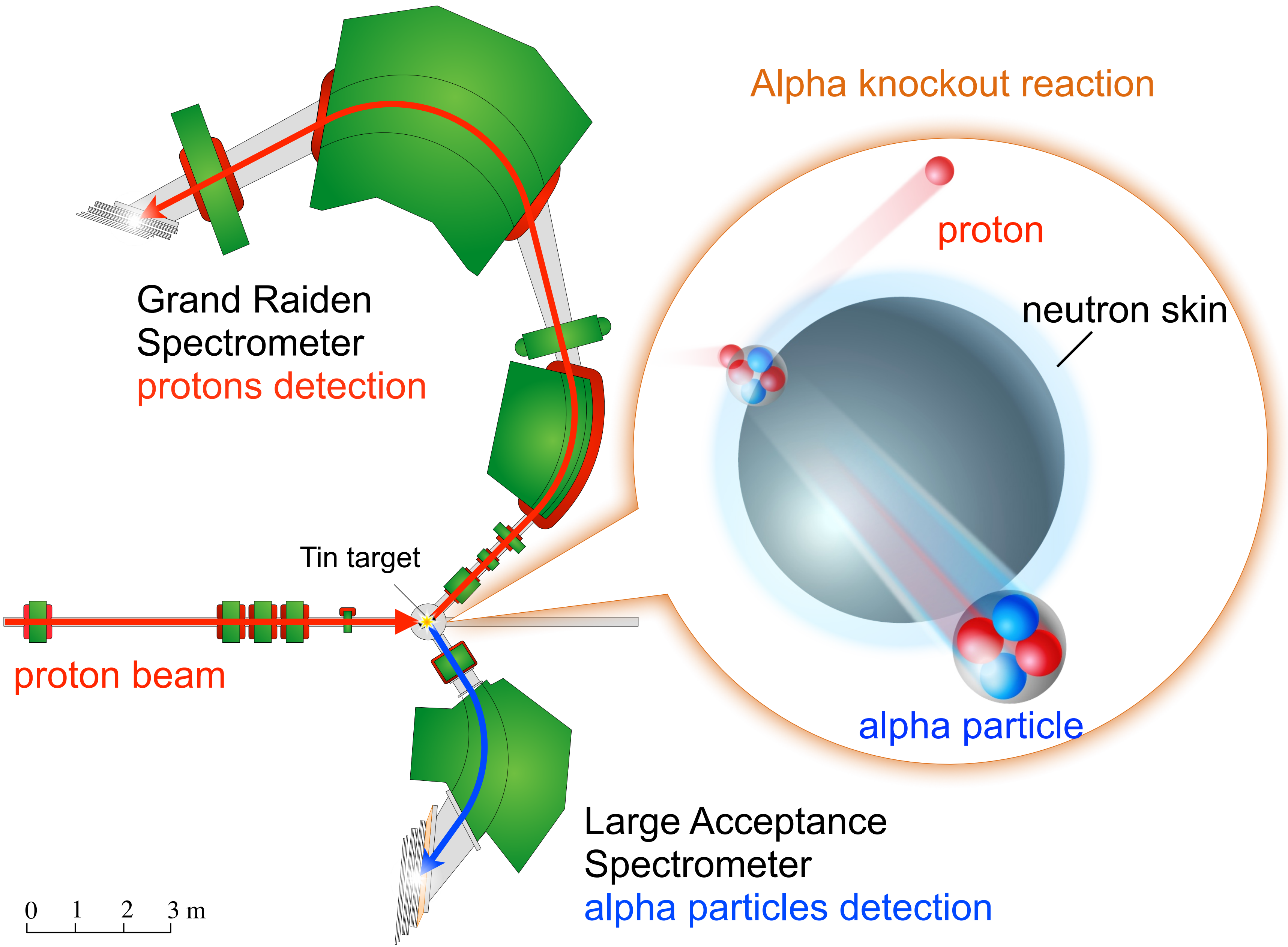






(Feb. 2018)

Alpha knockout reaction using double-arm spectrometer



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

Alpha separation energy spectrum

Energy Conservation

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

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

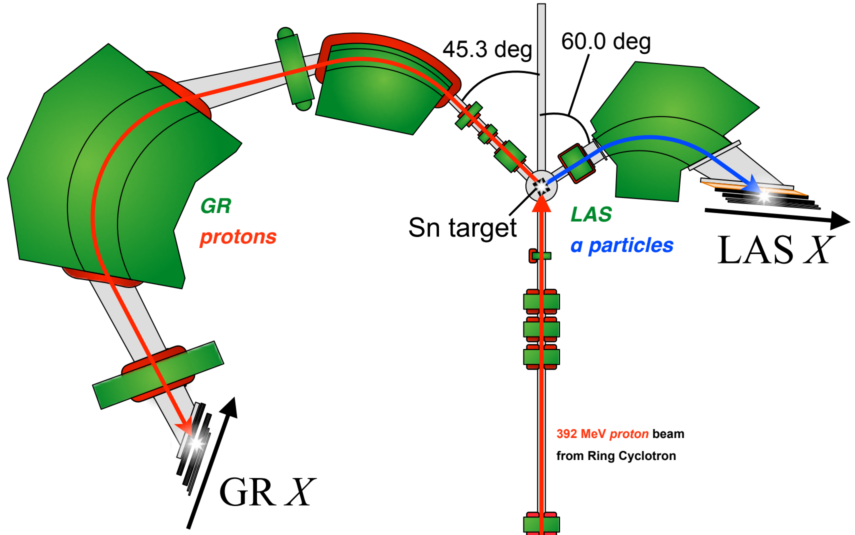
Alpha separation energy

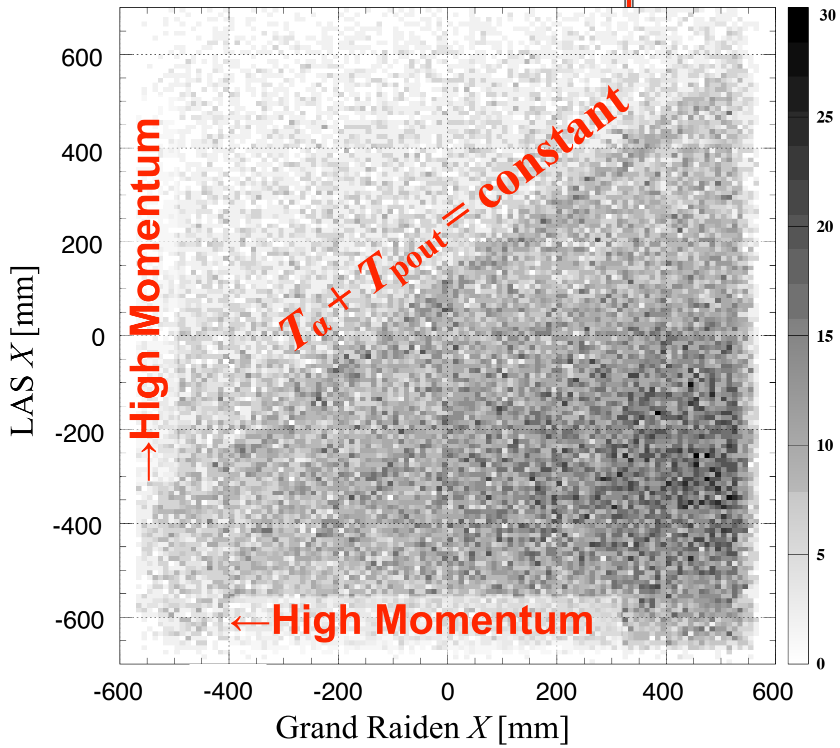
$$S_{\alpha} \equiv m_{\alpha} + m_{Cd} - m_{Sn}$$

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

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

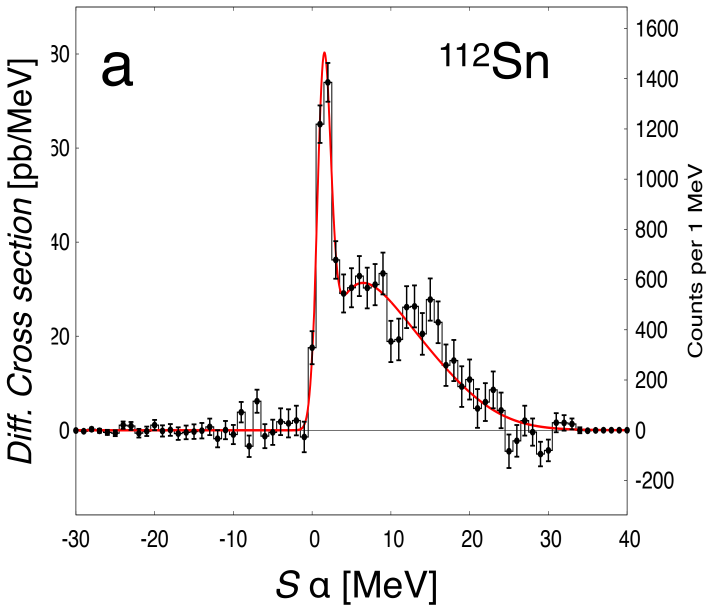
$$T_{Cd} \sim \frac{|\vec{q}\,|^2}{2m_{Cd}} \sim \frac{|50|^2}{2 \cdot 931 \cdot 108} \sim 0.01[MeV]$$

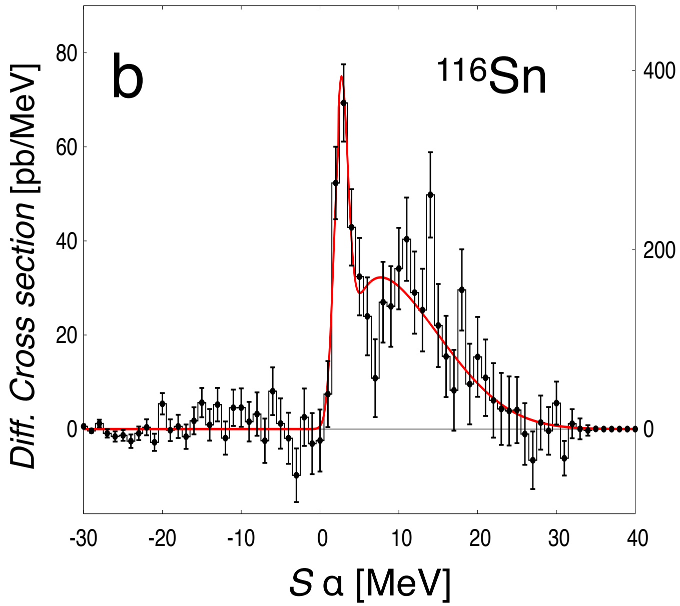


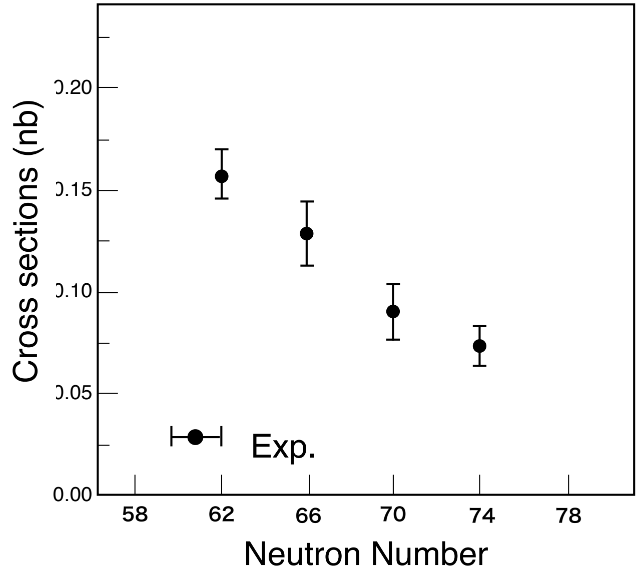


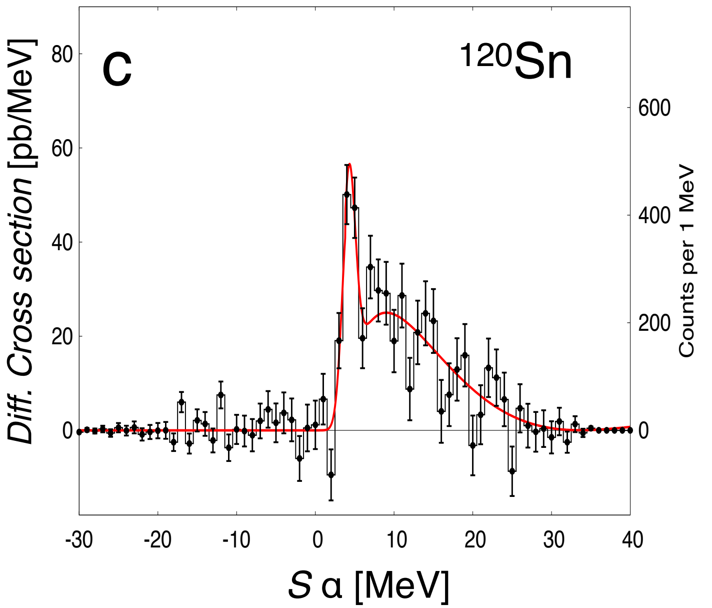
Alpha separation energy spectrum and its isotopic dependence

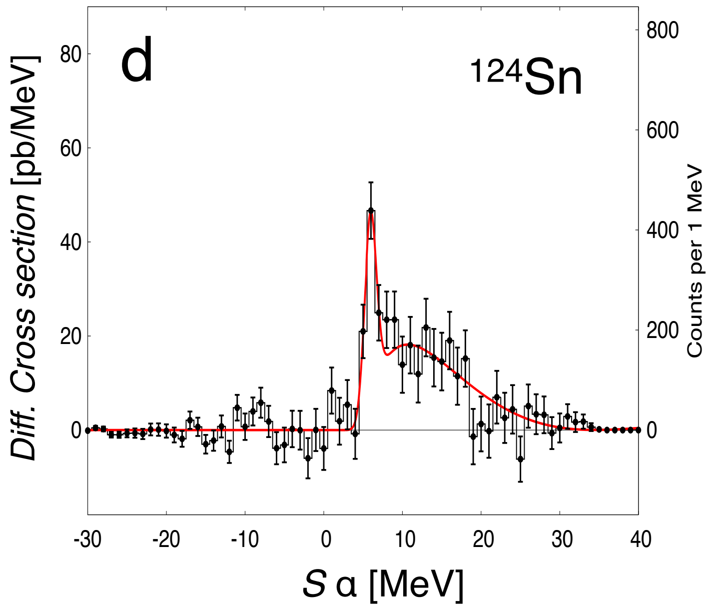
J. Tanaka, Z.H. Yang, S.Typel et al., Science 371, 260–264 (2021)

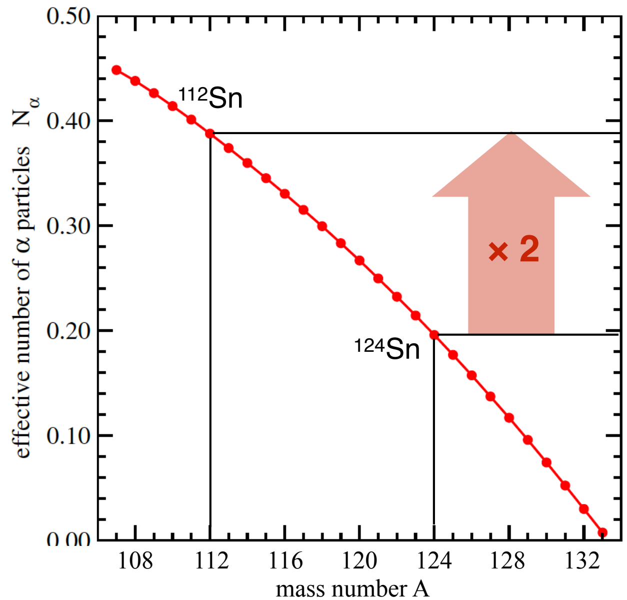












Reaction Analysis to convert predicted N_α into σ_α

Distorted wave impulse approximation

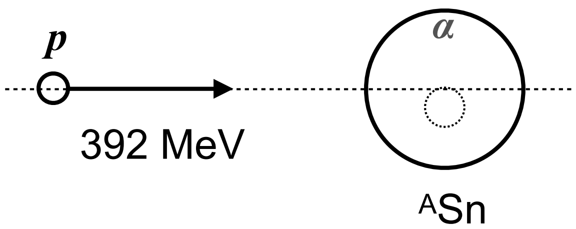
Triple Differential Cross section

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = \frac{(2\pi)^4}{\hbar v} F_{kin} |T|^2$$

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

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

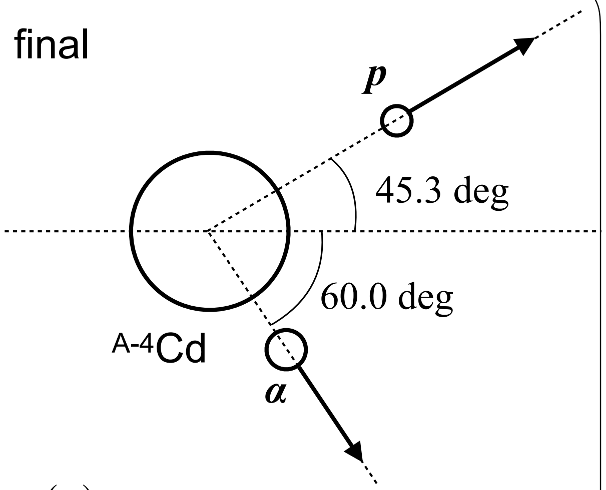
Initial



ϕ_α : α cluster w.f. from gRDF

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

final



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

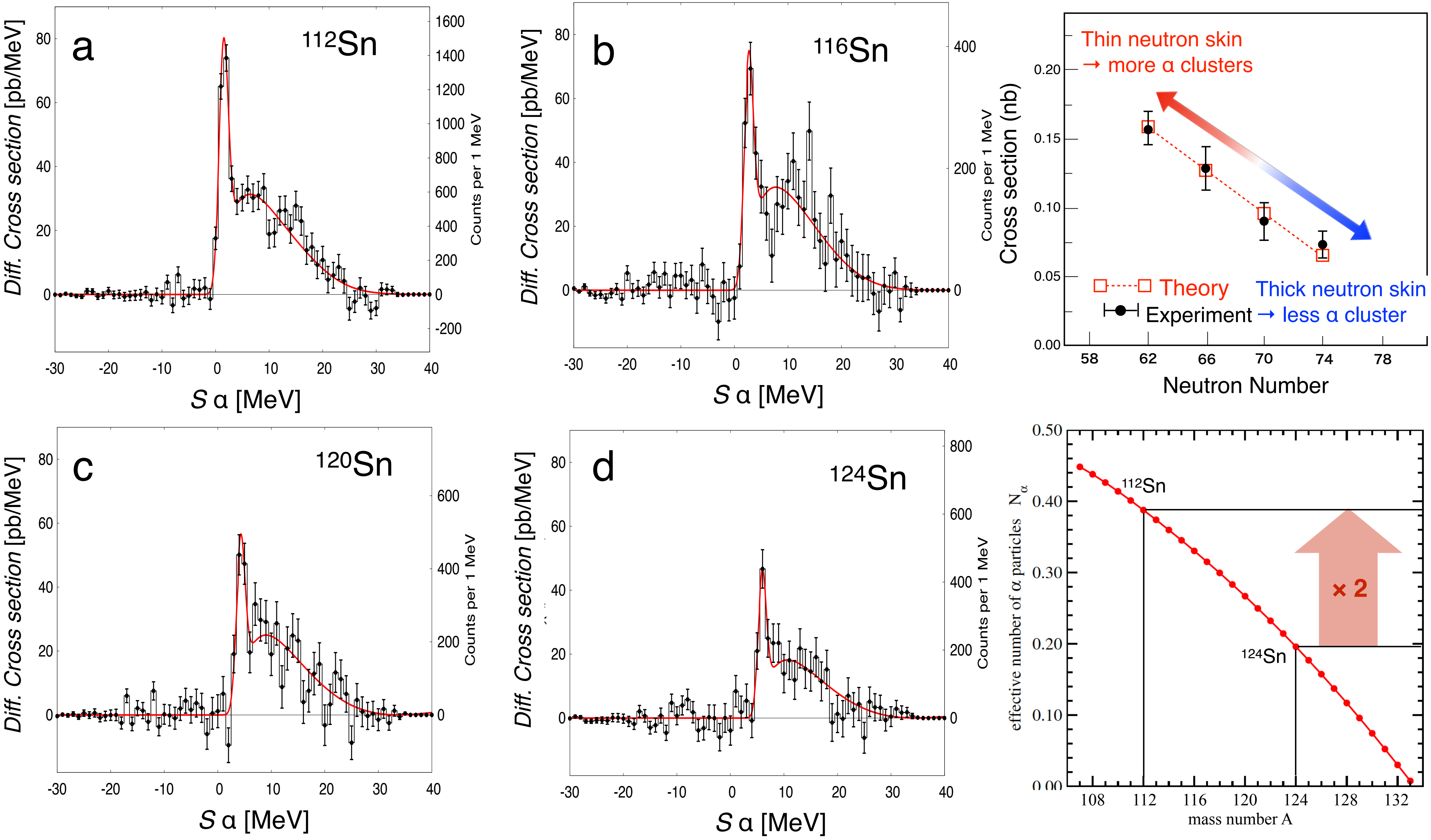
→ The depth of the imaginary part was tuned to the experimental data. Use the same reduction factor for all isotopes.

Theoretical support by S. Typel

Advice from K. Yoshida and K. Ogata

Experimental result and comparison with theory

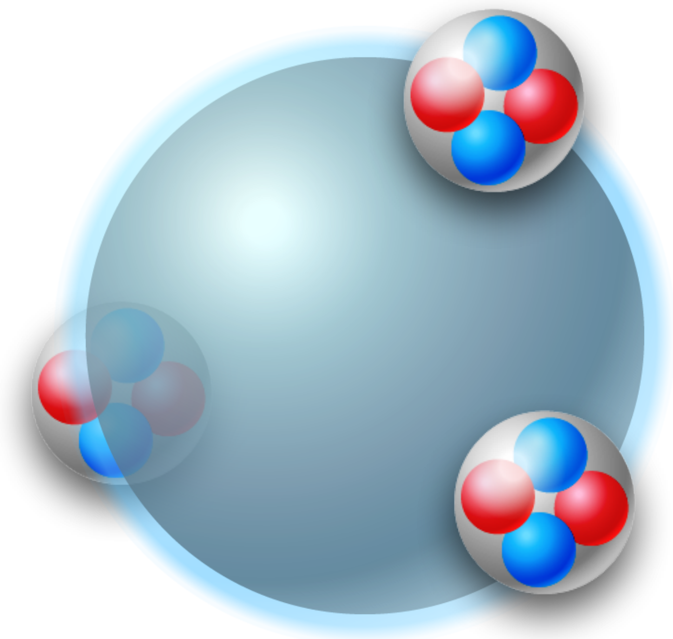
J. Tanaka, Z.H. Yang, S.Typel et al., Science 371, 260–264 (2021)



Summary of Sn(p,pα) 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.



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

The ground state of the tin nucleus is not always such one body which written in the conventional droplet model or single particle model picture, the experimental result indicated that the configurations with the alpha clusters are mixed and co-exist in certain probability by a quantum mechanical superposition. The alpha-knockout reaction selectively extracts and probes such a component.

Collaborators of Sn(p,pa) experiment

所属は研究当時

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S. Heil
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K. Ogata

宮崎大学 UNIVERSITY OF MIYAZAKI

Y. Maeda

RIKEN NISHINA CENTER

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J. Zenihiro
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K. Miki

CNS

P. Schrock

KYOTO UNIVERSITY

Y. Fujikawa

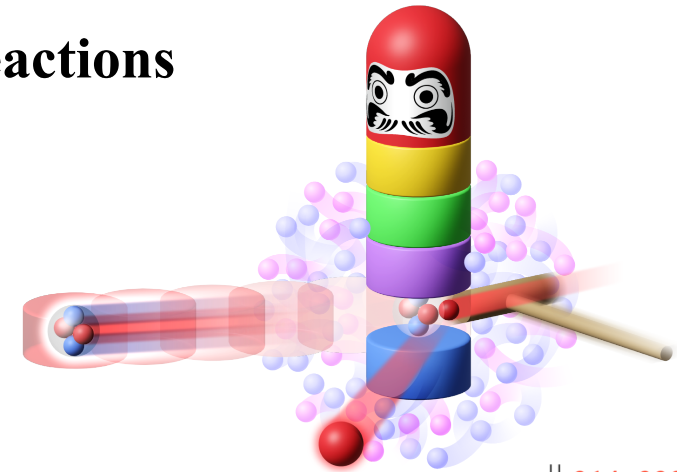
JAEA

K. Yoshida

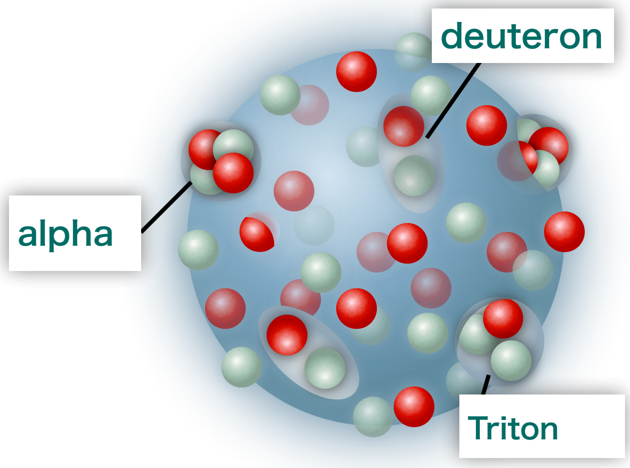
Clustering in heavy nuclei probed via knock-out reactions

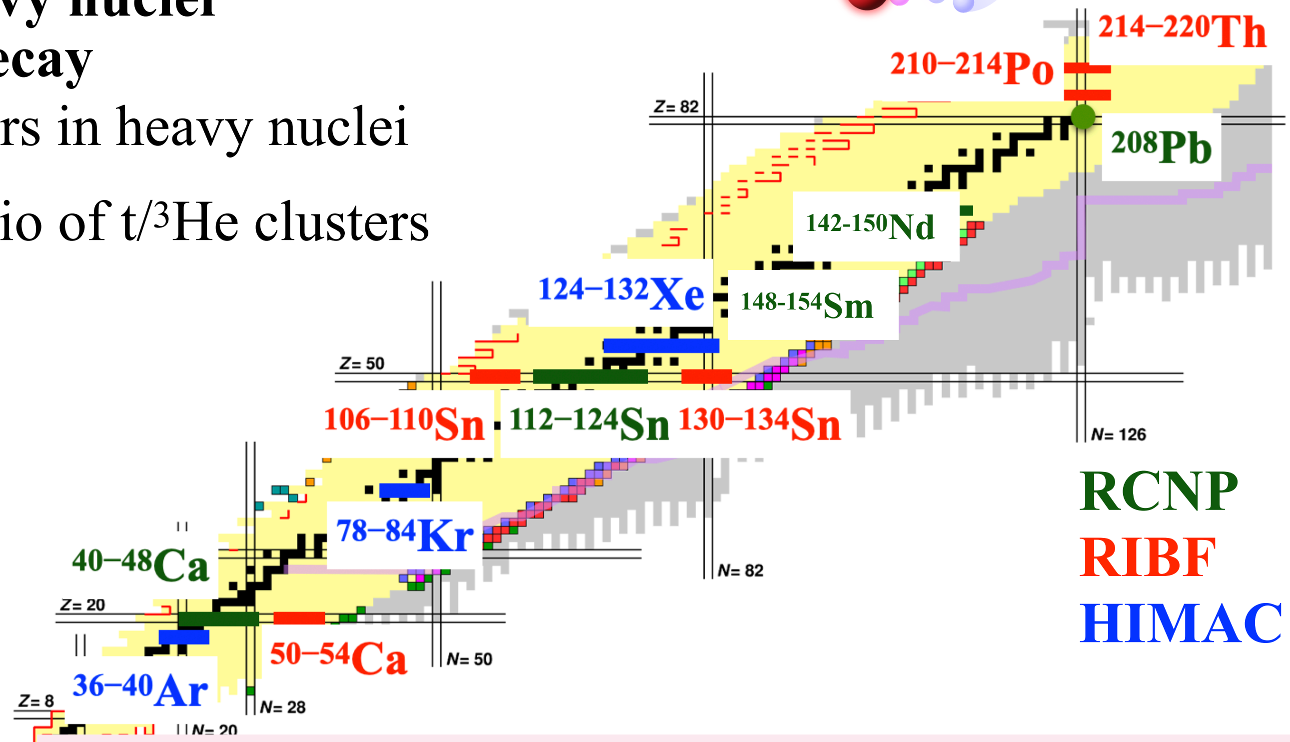
(p,pX) @ E/A = 200—300 MeV

X: d, t, ^{3}He, α



- Relative abundances of d, t, ^{3}He, α clusters and their isotope dependences
- **Surface α formation in heavy nuclei**
  → understanding of α-decay
- Discovery of deuteron clusters in heavy nuclei
- First determination of the ratio of t/^{3}He clusters

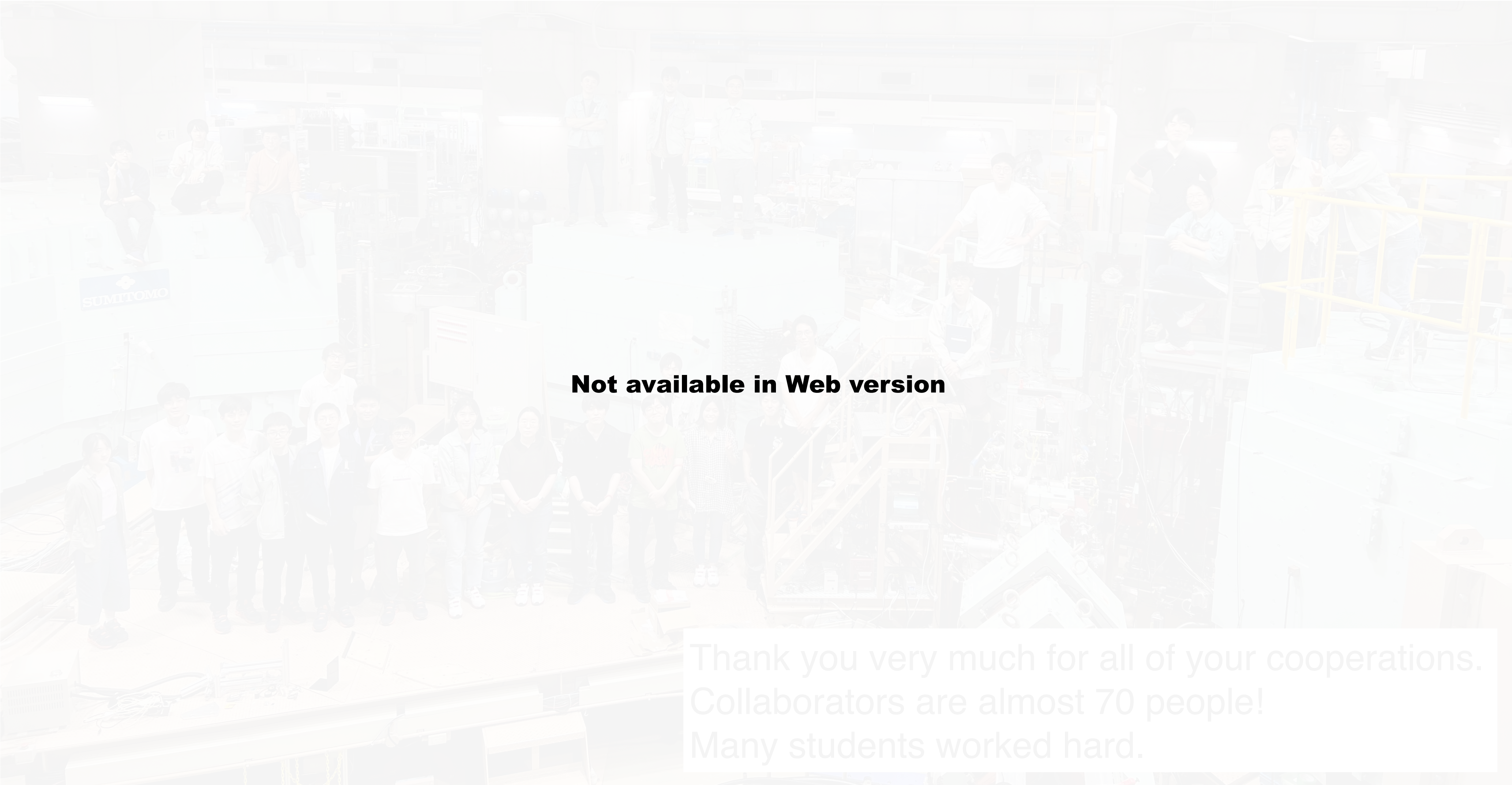




KAKENHI funded for FY2021—2025
T. Uesaka(Riken) / J. Zenihiro(Kyoto) / K. Ogata(Kyushu)

Universality of alpha clustering in atomic nuclei

$^{40/42/44/48}$Ca(p,pX)experiment@RCNP in March-May 2024



Collaboration : Kyoto Univ, RIKEN, RCNP, Kyushu Univ, Osaka Univ, Konan Univ, Miyazaki Univ, Pekin Univ, CENS IBS, IJCLab Orsay, TU Darmstadt, TU Munich, York Univ, Saitama Univ, iThemba

Today I will focus mainly on alpha knockout reactions

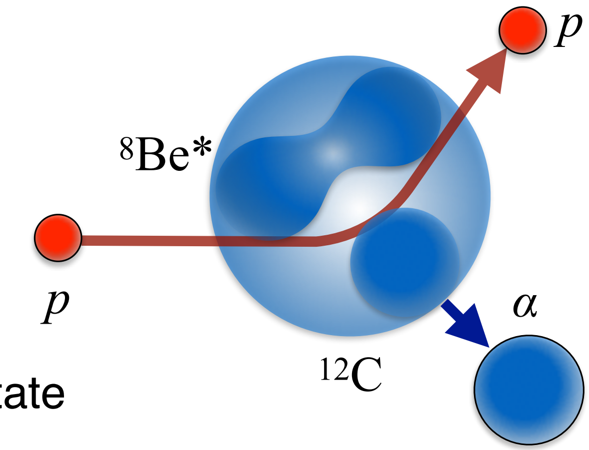
^{12}C(p,$p\alpha$)

RCNP-E545(J.T. and S. Typel): half-performed

Probing alpha clusters in the ground state of ^{12}C via alpha-knockout reactions

Motivation

- Astrophysical interest in terms of nucleosynthesis
- Hoyle state component in ^{12}C ground state
- *Ab-initio* calculations already exist.
- Residues are ^{8}Be(0+) unbound ground state and ^{8}Be(2+) excited state
- Momentum analysis may reveal spacial information of Hoyle state

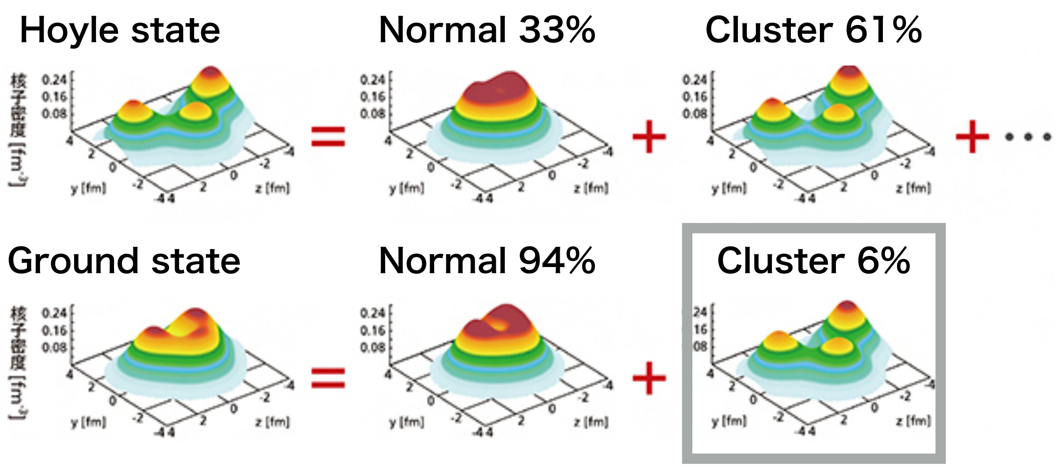


Analysis is ongoing by

Not available in Web version

Fengyi Chen (B4 Osaka Univ.) Jiawei Bian (D Pekin Univ.)

Ab initio calculation



T. Otsuka, T. Abe et.al. Nature Communications 10.1038/s41467-022-29582

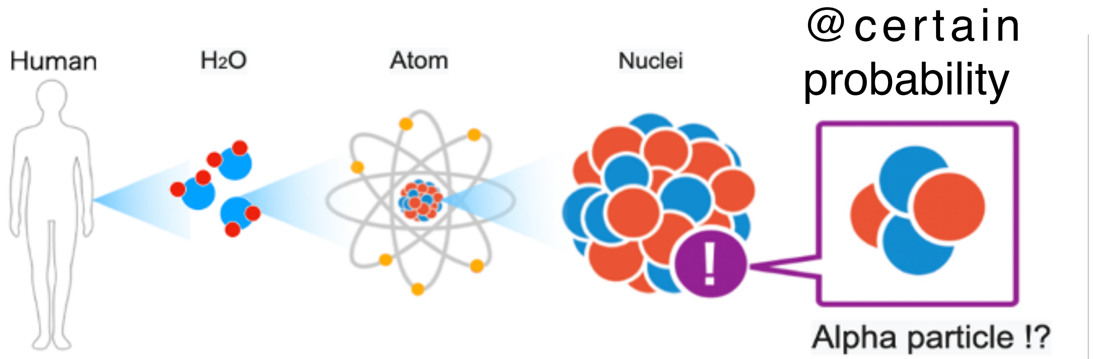
$^{16}O(p,p\alpha)$

RCNP-E545(J.T. and S. Typel): half-performed

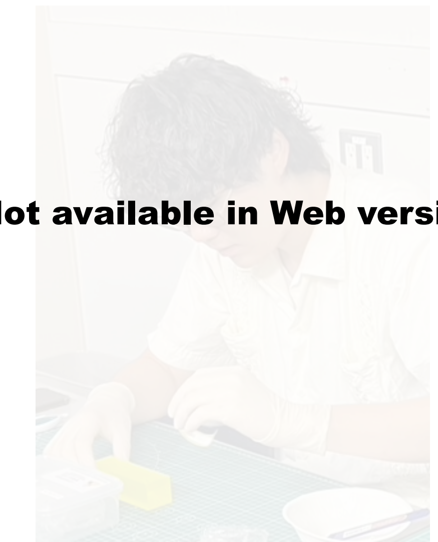
Alpha particles as building block of ^{16}O ground state probed by alpha knockout reaction

Motivation

- " Can alpha particles be the basic building blocks of atomic nuclei? "
- Conventional mean-field picture v.s. alpha cluster formation in double magic nucleus ^{16}O.
- ^{16}O is the most abundant nucleus in the human body.
  " How much alpha clusters we have in our body ? "
- Residues are $^{12}C(0^+)$ g.s.,$^{12}C(2^+)$ ex.s., and $^{12}C(0^+)$ Hoyle state.
- Momentum analysis may clarify their motion.
- Evolution of stars



Conceptual figure of alpha particles existing as building block.



Taichi Miyagawa (M1 RCNP)

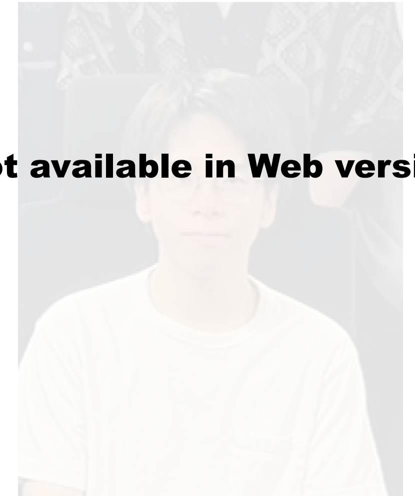
$^{40/42/44/48}$Ca(p,$p\alpha$)

RCNP-E545(J.T. and S. Typel): half-performed

Emergence of α-cluster correlations proved by α-knockout reactions in Ca isotopes

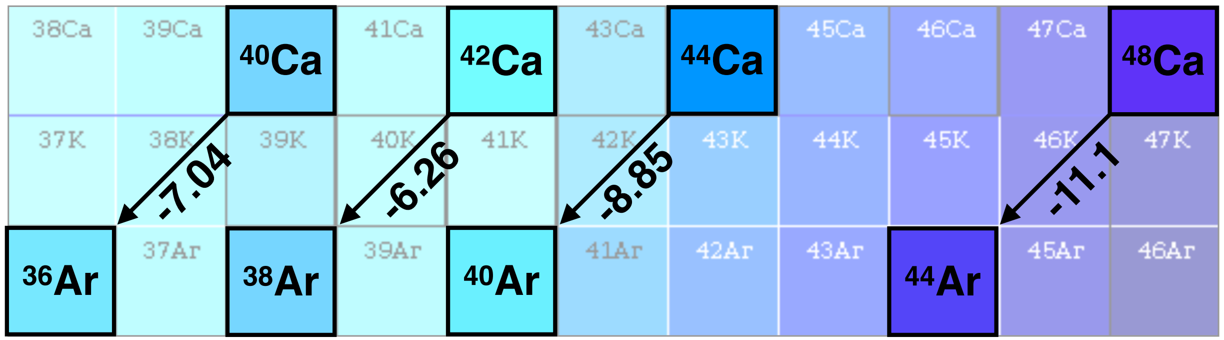
Motivation

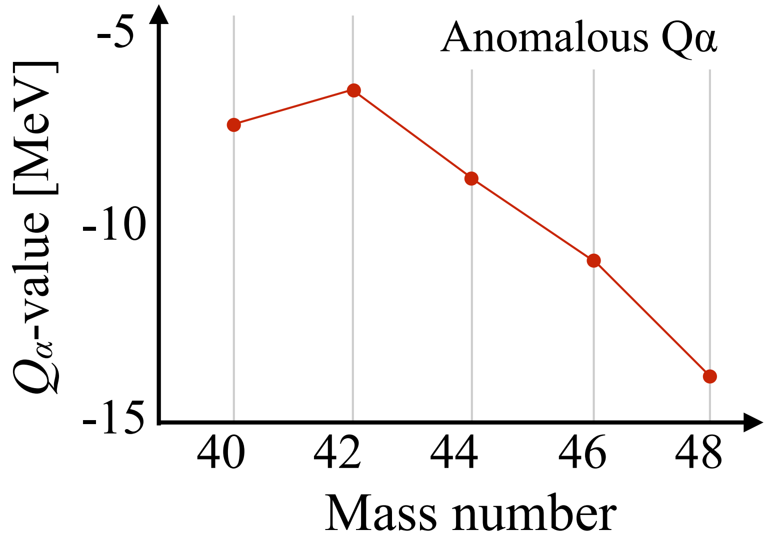
- Emergence of cluster correlations in finite many-body system
- Correlation between the α-formation probability and the Q_α value
- Anomalous isotope dependence of Q_α values in Ca isotopes
- Ca isotopic dependence of (p,pα) reaction cross-sections
- ^{40,42,44,48}Ca targets avilable
- Importance of double magic nuclei ^{40,48}Ca in nuclear matter study



Riku Matsumura (D3 Saitama Univ.)

Experimental Qa-values [MeV]





future

$^{204/206/208}$Pb(p,$p\alpha$)

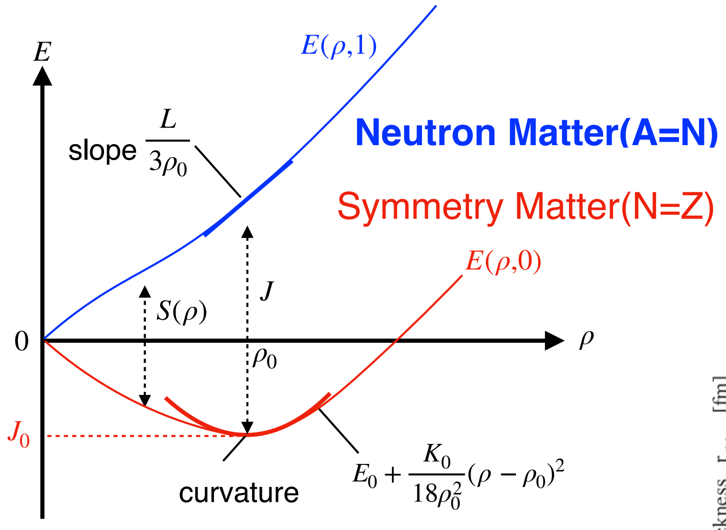
RCNP-E596(J.T. and S. Typel): Accepted Grade A

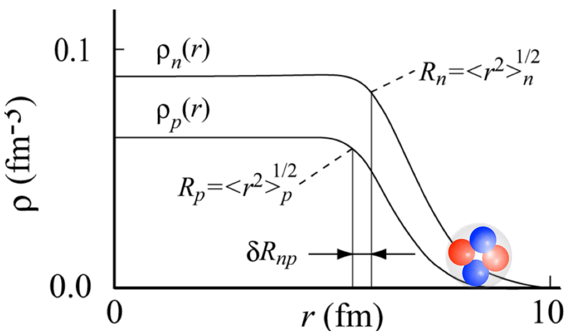
"Alpha clustering in Pb isotopes !?"

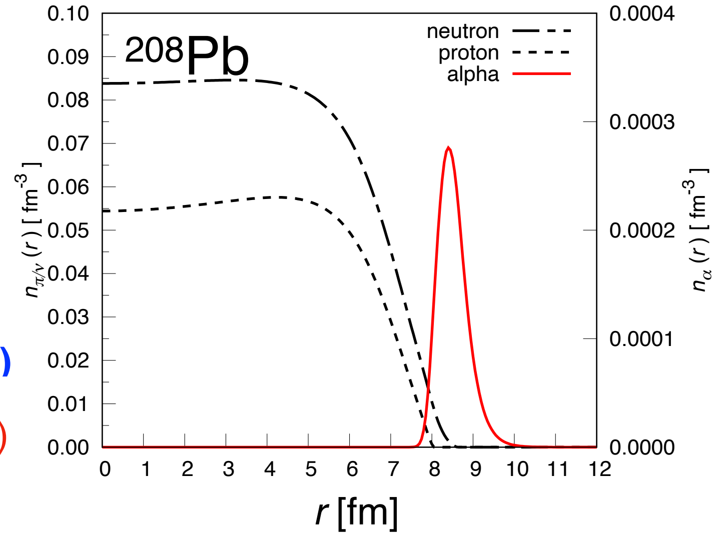
~ Approaching the relation between neutron-skin thickness and neutron-star radius/mass ~

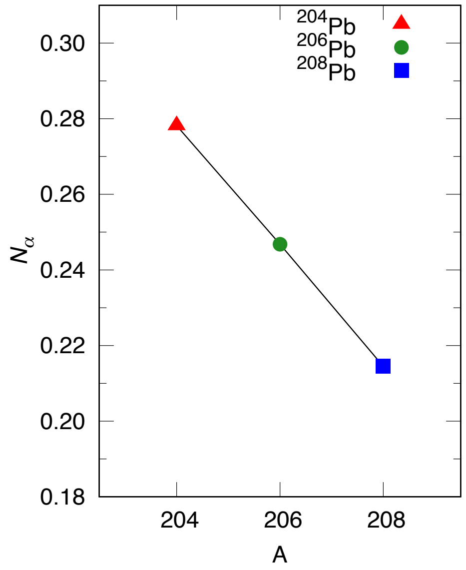
Motivation

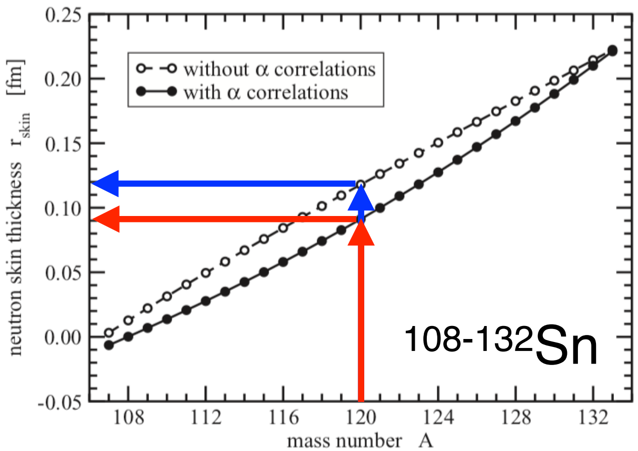
- Nuclear EOS
- Alpha cluster in ^{208}Pb
- Relation bw Δr_{np} and L



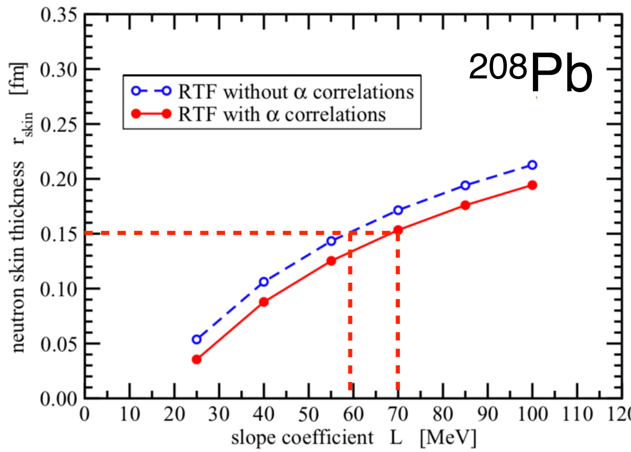








Sn isotope mass number dependence of Δr_{np}



Effect of α cluster correlation on Δr_{np} and L

Po, Th($p,p\alpha$)

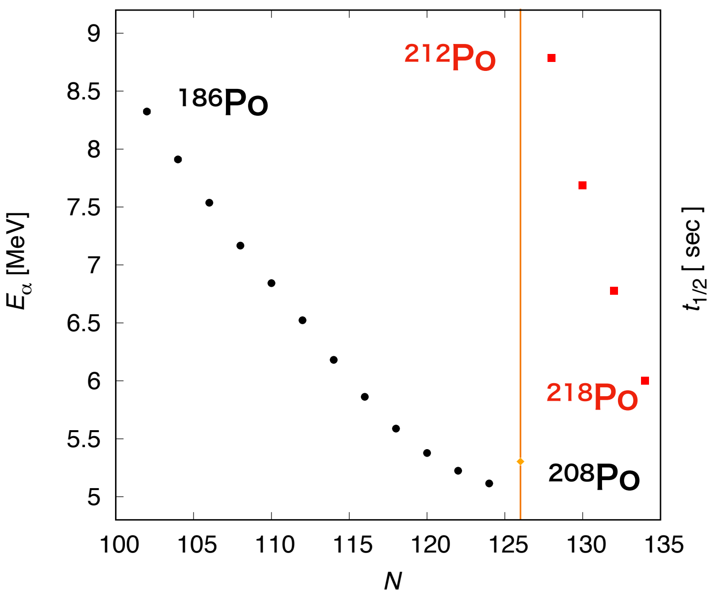
RIBF Project proposal (T. Uesaka, J. Zenihiro, Y. Kubota, and J.T.)

α-knockout reactions from α-decay nuclei

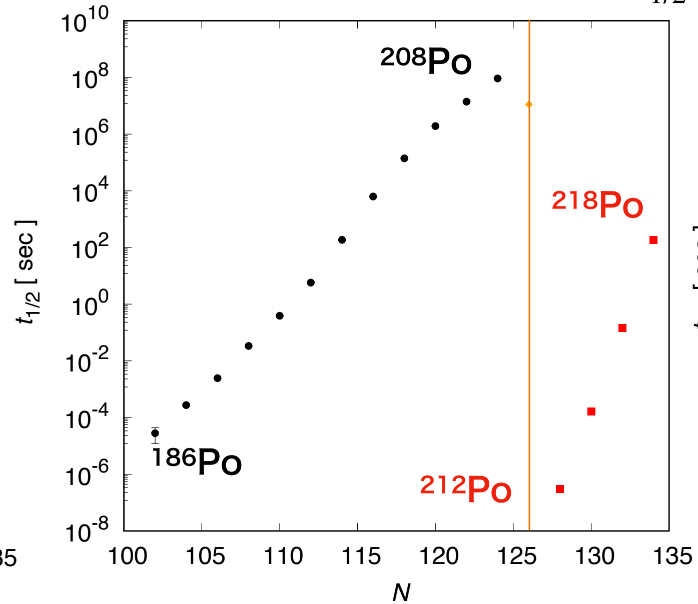
Motivation

- Clarify the relation of preformed α-particle in α-decay and surface α-cluster observed α-knockout
- Full-understanding of α-decay

Decay energy : E_α

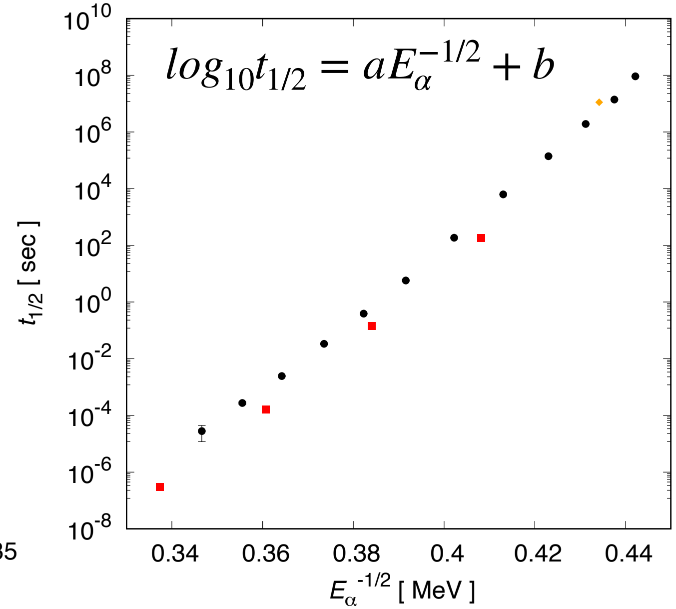


Decay width : $\Gamma_\alpha = \hbar\lambda = \frac{\hbar}{\tau} = \frac{\hbar ln2}{t_{1/2}}$



Geiger-Nuttall law :

Relation between E_α v.s. $t_{1/2}$



Characteristic change in neutron magic number 126 with a difference in **<u>lifetime of 10^{15}</u>** between ^{212}Po with an alpha decay energy of 8.8 MeV and ^{208}Po with 5.0 MeV, influenced by the double magic number of ^{208}Pb.

Quantum tunneling

$P \sim e^{-2\sqrt{\frac{2m}{\hbar^2}}\int_R^b \sqrt{V(r)-E_\alpha}dr}$ account for the 10^{15} difference in life.

Tunneling probability P from decay energy E. $\Gamma_\alpha \sim f_\alpha \nu P$

Reduced decay width

$\gamma_\alpha^2 \equiv \frac{\Gamma_\alpha}{2P} \sim \frac{1}{2} f_\alpha \nu$

f_α : α-preformation factor

ν : frequency

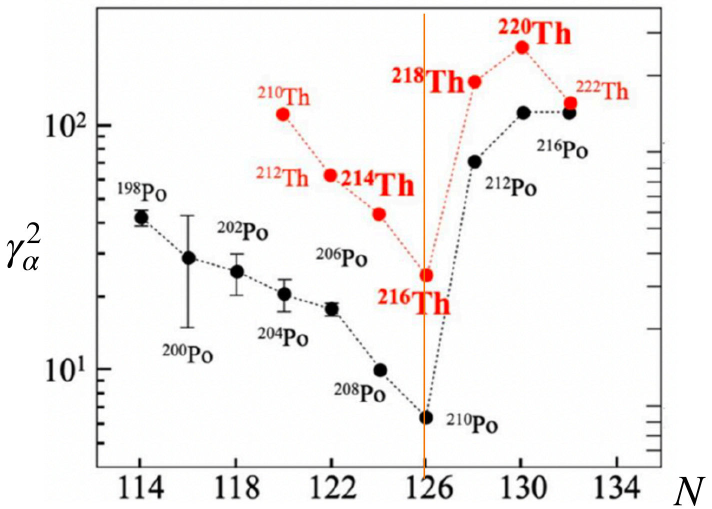
Po, Th($p,p\alpha$)

RIBF Project proposal (T. Uesaka, J. Zenihiro, Y. Kubota, and J.T.)

Reduced decay width

$$\gamma_\alpha^2 \equiv \frac{\Gamma_\alpha}{2P} \sim \frac{1}{2} f_\alpha \nu$$

f_α : α-preformation factor
ν : frequency



- 10^{15} difference in decay width.
- 10^{14} reduced by P.
- <u>**10 times difference in γ_α^2 remains.**</u>

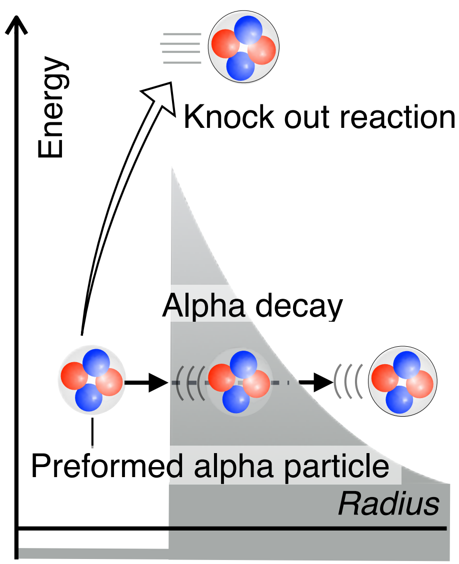
→ Is it preformation factor $f_\alpha \nu$?

→ P accurate? <u>**Shape of Coulomb barrier.**</u>

Shell model Calculation

- Absolute value comparison of γ_α^2 (^{212}Po)
- Tonozuka and A. Arima, Nucl. Phys. A 323, 45 (1979) → <u>**1/14**</u> of the experimental value.
- The importance of configurations involving higher orbitals.
- Still not fully reproduced, with discrepancies remaining within <u>**an order of magnitude**</u>. → 90% not known!

Proving preformed α particle before decay



Contrast of knockout reaction and alpha decay

- α-knockout reaction
- Higher energy than barrier
- <u>**Independent of penetrability**</u>
- good measure of α-formation
- σ(^{212}Po(p,pα))/σ(^{210}Po(p,pα))

Effect of reaction mechanism

K. Yoshida, J. Tanaka
PRC 106 (1), 014621

Preparing wave functions reproduce γ_2 values for ^{212}Po and ^{210}Po
Calculateα-knockout reaction cross sections

$$\frac{\sigma^2_{(p,p\alpha)}(^{212}\mathrm{Po})}{\sigma^2_{(p,p\alpha)}(^{210}\mathrm{Po})} \sim \frac{|RF(R)|^2(^{212}\mathrm{Po})}{|RF(R)|^2(^{210}\mathrm{Po})} \sim \frac{\gamma_\alpha^2(^{212}\mathrm{Po})}{\gamma_\alpha^2(^{210}\mathrm{Po})} \sim 10$$

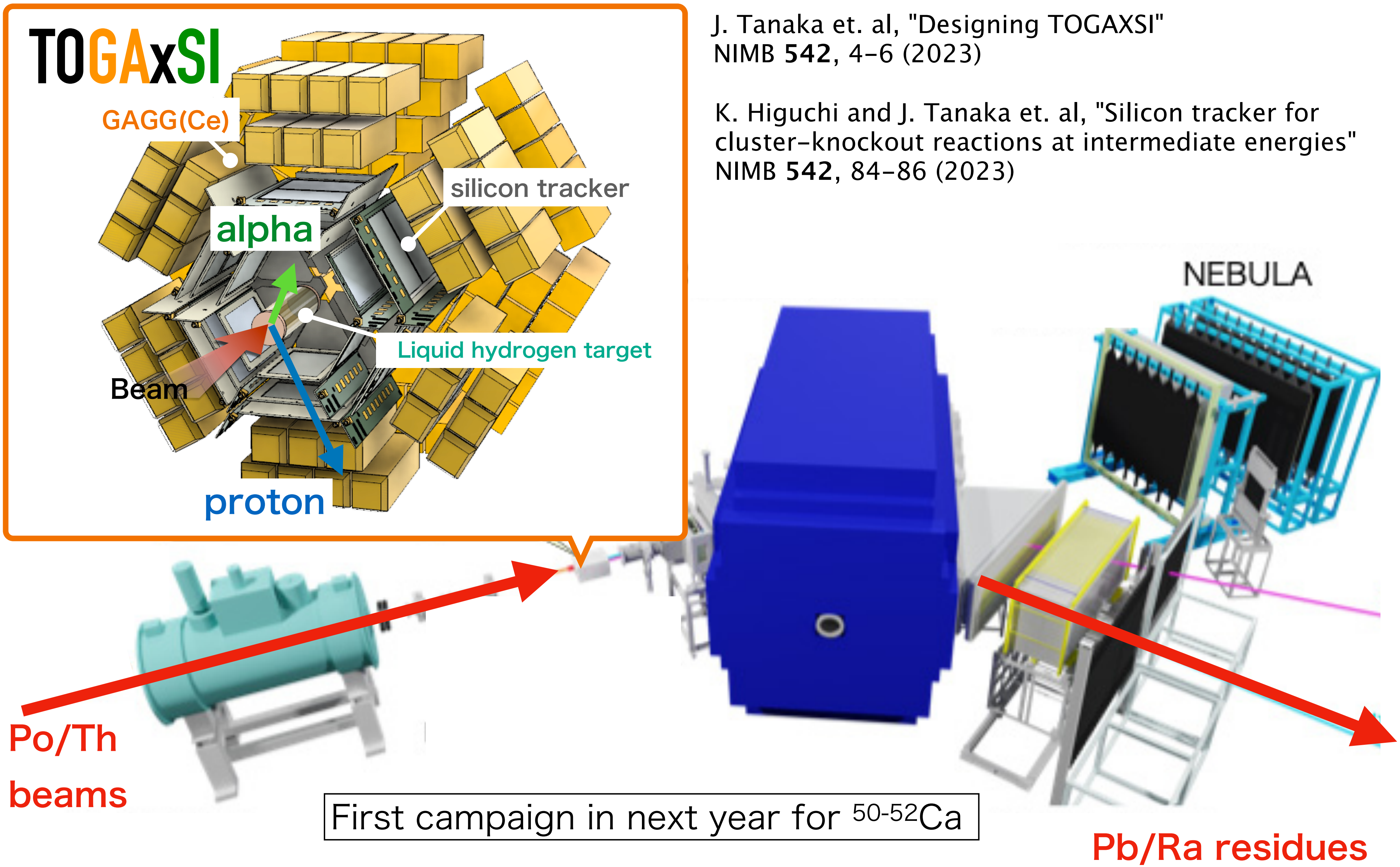
Reaction is peripheral
→ σ is almost proportional to γ_2 ($|RF|^2$ in R-matrix theory).

Po, Th($p,p\alpha$)

RIBF Project proposal (T. Uesaka, J. Zenihiro, Y. Kubota, and J.T.)

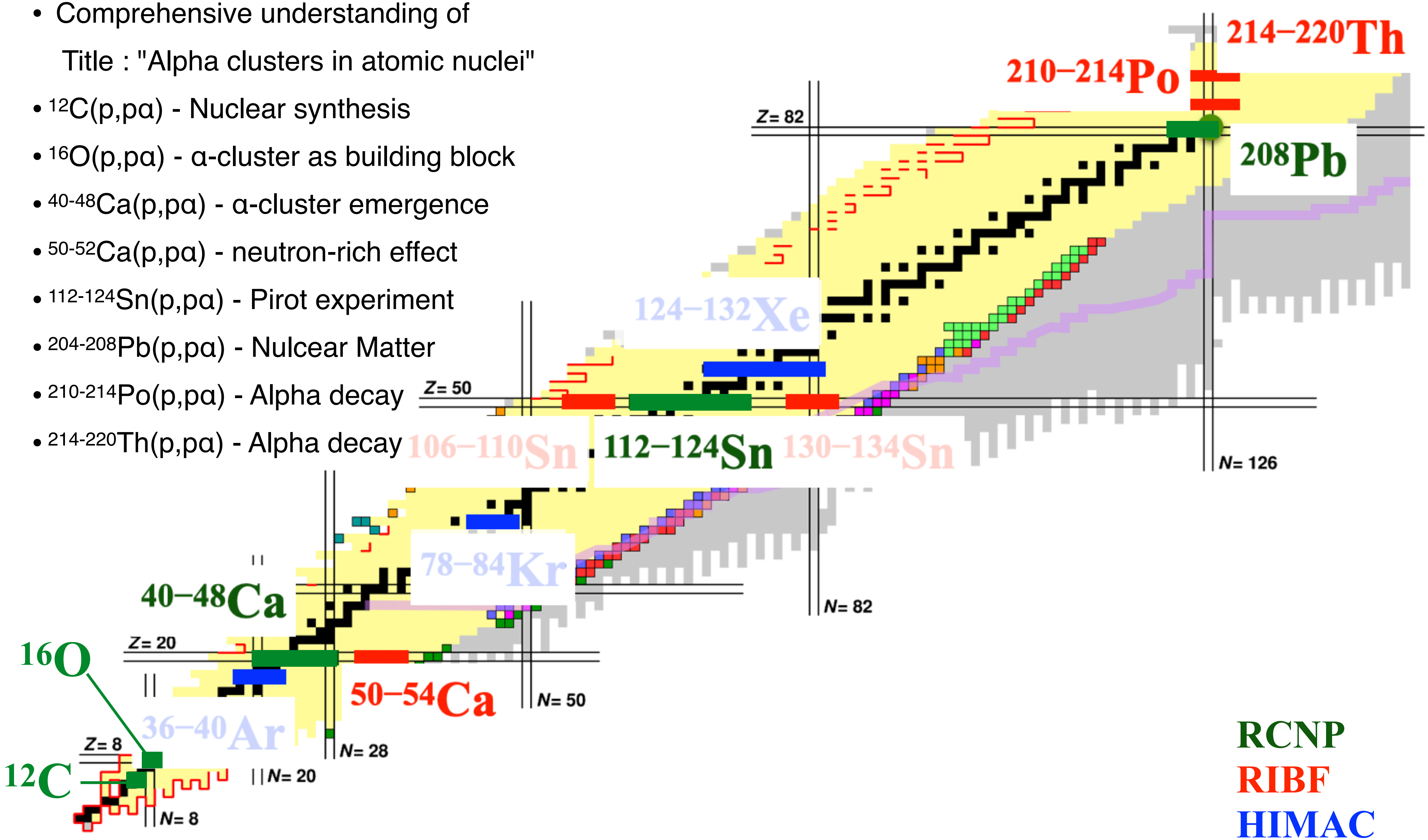
J. Tanaka et. al, "Designing TOGAXSI"
NIMB **542**, 4–6 (2023)

K. Higuchi and J. Tanaka et. al, "Silicon tracker for cluster-knockout reactions at intermediate energies"
NIMB **542**, 84–86 (2023)



Summary until near future

- Comprehensive understanding of
  Title : "Alpha clusters in atomic nuclei"
- ^{12}C(p,pα) - Nuclear synthesis
- ^{16}O(p,pα) - α-cluster as building block
- $^{40\text{-}48}$Ca(p,pα) - α-cluster emergence
- $^{50\text{-}52}$Ca(p,pα) - neutron-rich effect
- $^{112\text{-}124}$Sn(p,pα) - Pirot experiment
- $^{204\text{-}208}$Pb(p,pα) - Nulcear Matter
- $^{210\text{-}214}$Po(p,pα) - Alpha decay
- $^{214\text{-}220}$Th(p,pα) - Alpha decay

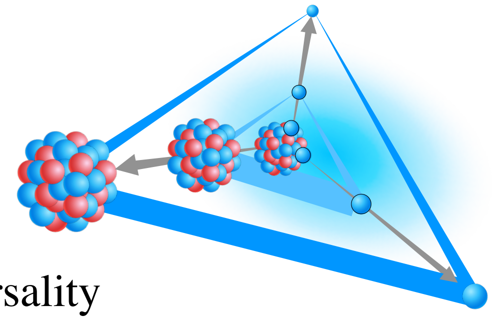


More future

Of course, I continue alpha knock out reactions, but here I introduce others

Nuclear Giants

Motivation



- Explore the largest nuclear system (exclude gravity-bound neutron stars)
- Scale-conversion symmetry and its universality
- Unified understanding of neutron halo and Efimov states
- Large scattering length and large neutron-capture cross sections

RCNP Core-Net

Exploring Nuclear Giants: Structure and Reactions of Extremely Large Nuclei

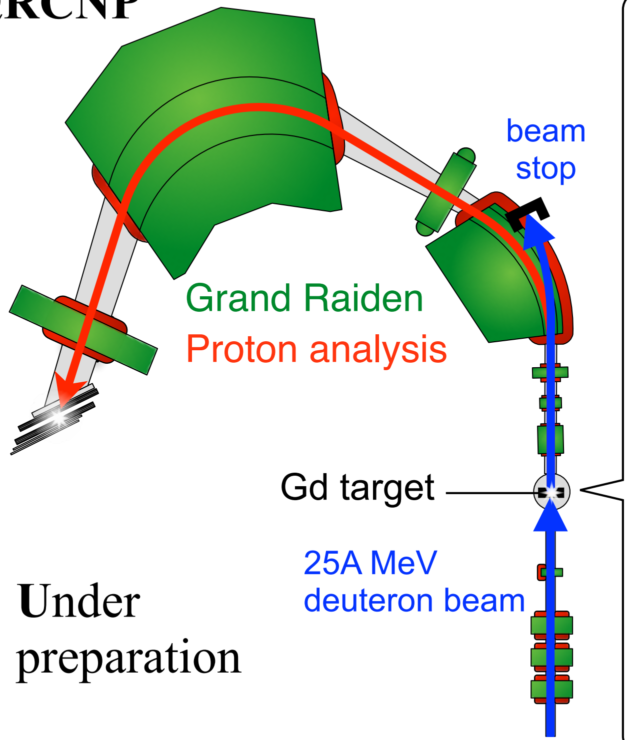
S. Endo (UEC)

T. Fukui (Kyushu)

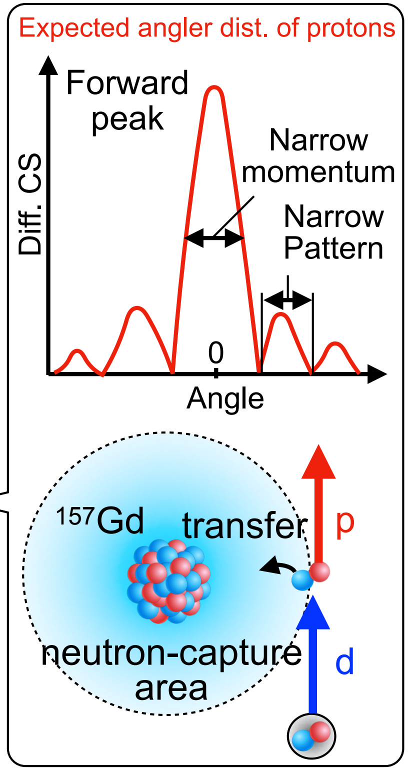
S Endo, J Tanaka, Efimov state in excited nuclear halos arXiv preprint arXiv:2309.04131

Tamii-lab honer seminar for undergraduate students

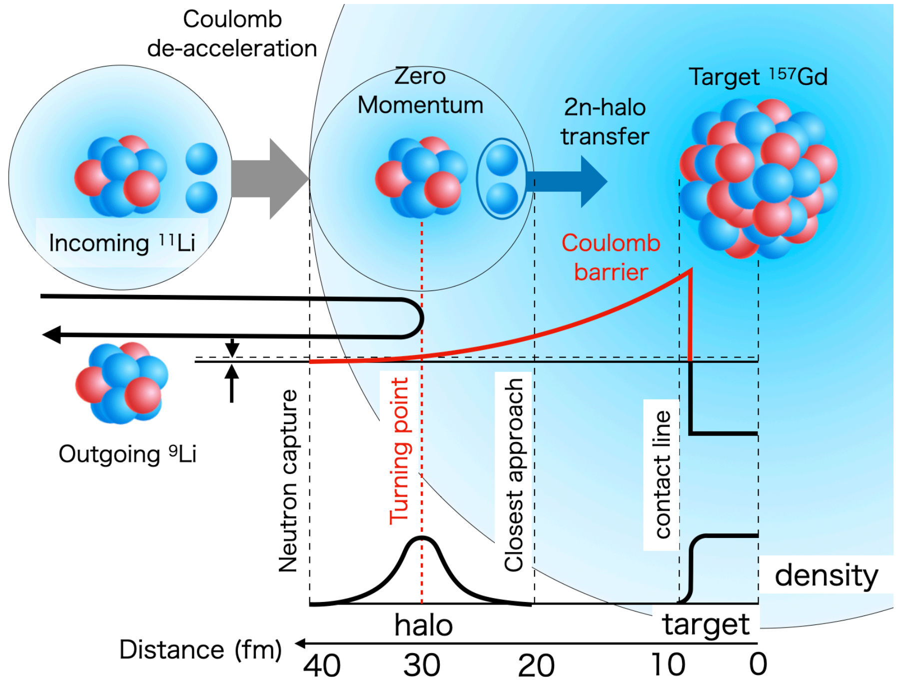
@RCNP



Under preparation



@ISOL facility



Dreaming more future

As a RCNP staff, I should, or I am happy to think of RCNP-experiment future!

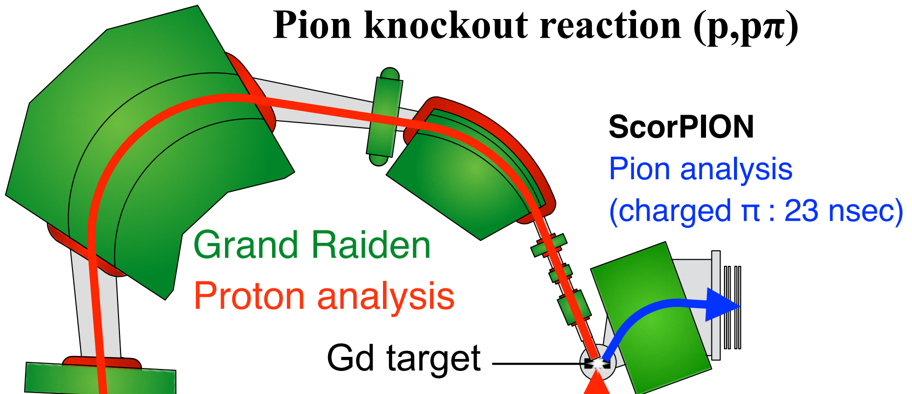
PIONeer KEIKAKU ~ Dream ~

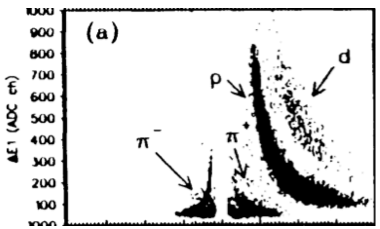
Motivation

- Importance of Pions in atomic nuclei
  "Why nuclear matter saturate?" - tensor force (Bethe)
  "Why atomic nucleus no-collapse?" - repulsive core
  "Why stable? / unstable?" - binding energy
  "What is three nucleon forces" - Δ(n-π resonance)
  "Why alpha cluster formed?" - binding energy of alpha
- Last few decades, understanding of tensor force progress
- Still there are challenges in theory
- Delving into **essence of atomic nuclei** at RCNP.
- Generate many groundbreaking studies.

<u>All the complexity = The nature of the nucleus comes from pions!</u>

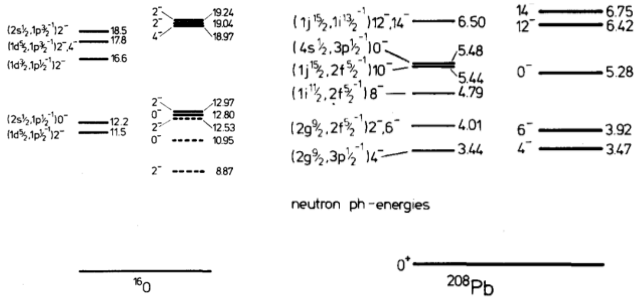
Pion knockout reaction (p,pπ)





1st-stage proton-400MeV

- Pion production threshold 280 MeV
- unnatural parity, pionic mode spectroscopy
- isotope dependence
- **High resolution** missing mass spectroscopy

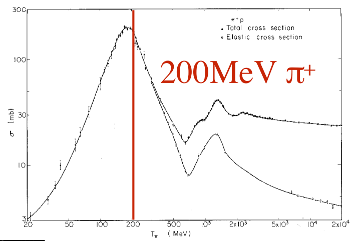


Pion cloud knockout from proton

- p-wave scattering

(Discussion@iThems : T. Hatsuta, A. Hosaka, K. Yoshida, and J.T.)

Higher energy proton-2 GeV



- p-π+ scattering
- 2 GeV proton
- high momentum

Let's knockout π !

- Grow-up project
- Yield estimation
- Write white paper

Discussing with

H. Toki (RCNP)

Thank you so much!

From the bottom of my heart, I hope many of you could provide the suggestion for the future !

Thank you !!