Nuclear structure studies at Osaka Metropolitan University

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Osaka Metropolitan University, RIKEN

7th February 2025

OMU-NTHU Joint Meeting in Modern Advances in Physics

Department of Physics
Osaka Metropolitan University

- About 40 permanent staff members
- Three divisions
- 1) Fundamental physics division (Theory)
- 2) Astrophysics and high energy physics division (Experiment)
- 3) Condensed matter physics division (Theory and Experiment)

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Theories for particle physics, cosmology, and nuclear physics

Yoichiro Nambu (Nobel prize in physics, 2008)

- Nobel laureate in 2008 for his discovery of the mechanism of spontaneous symmetry breaking in physics systems
- Before moving to the US, he served as a professor at Osaka City University during 1949-1952 and enjoyed his life there.

Particle Theory group

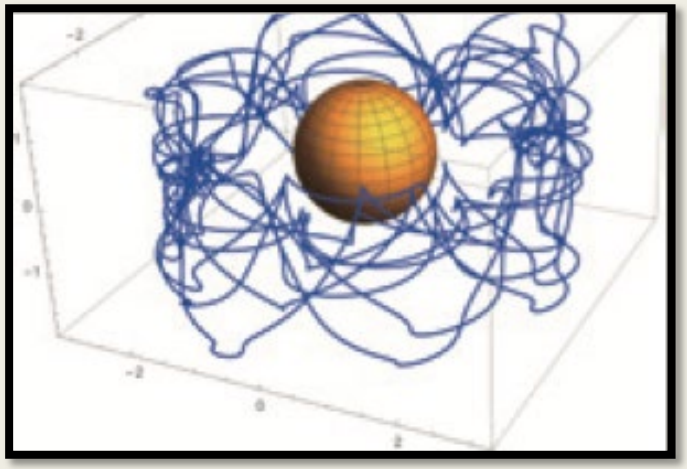
Naoyuki Haba and Nobuhito Maru

- What is the origin of mass generation?
- What is the origin of electroweak phase transition?
- Why quarks and leptons have 3 copies
- Why neutrino are much lighter than other quarks and leptons?
- Why the charge of proton is the same as minus charge of the electron?
- What is the origin of parity violation?
- Why our world is 4 dimension?

Theoretical astrophysics group

Ken-ichi Nakao and Hirotaka Yoshino

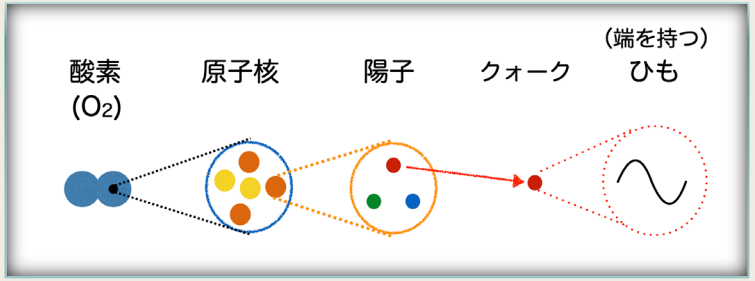
- Using general relativity, they study theoretically various physical phenomena caused by strong gravitational interactions, including the formation of spacetime singularities and the global structure of the universe and blackholes.



Mathematical physics group 1

Sanefumi Moriyama and Takahiro Nishinaka

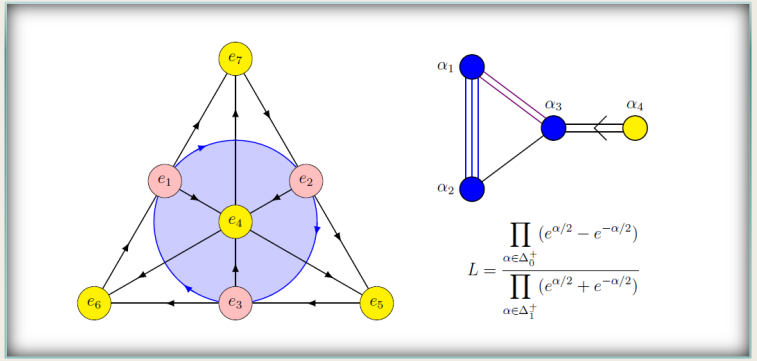
- A deep mathematical structure is hidden in field theories and string theory, fundamental laws of nature. By clarifying the structure, sometimes we understand the ultimate law of nature better and sometimes we clarify the relation between various physical theories.



Mathematical physics group 2

Naruhiko Aizawa

- When we investigate physical laws of nature, we often encounter new mathematical structure unexpectedly.
  We study mysterious relations between nature and mathematics from the viewpoint of symmetries.



Nuclear theory group

Wataru Horiuchi and Naoyuki Itagaki

- Development of theoretical models for the unified understanding of the nuclear structure
- Structure and reactions of neutron-rich nuclei: exploring exotic nuclei far from the stability line
- Effects of non-central nuclear forces on the nuclear structure
- Understanding of nucleosynthesis in the universe and stars (origin of the elements)
- Neutrino-nucleus reactions in explosive astrophysical phenomena
- Exotic atoms involving muon, antikaon, etc.
- Application of nuclear physics to cancer therapy

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Come closer: Titanium-48's nuclear structure changes when observed at varying distances

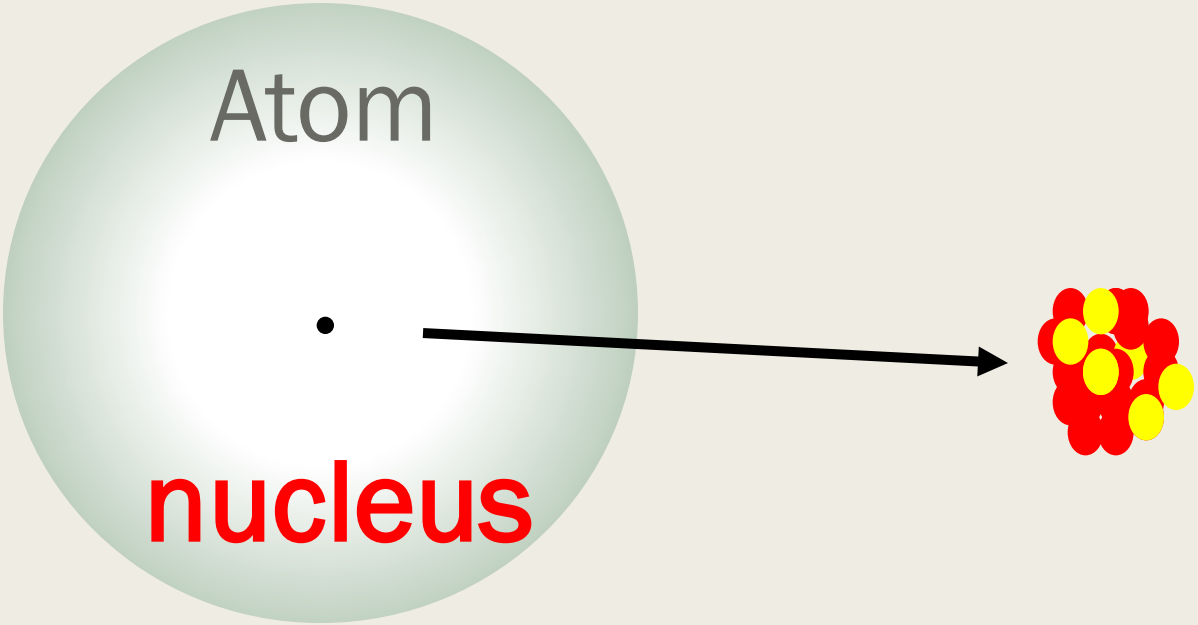
A 100-year-old physics mystery may be close to being solved as a new study reveals structural changes in titanium-48's nucleus

Date: July 19, 2024

Source: Osaka Metropolitan University

Summary: Researchers have found that titanium-48 changes from a shell model structure to an alpha-cluster structure depending on the distance from the center of the nucleus. The results upend the conventional understanding of nuclear structure and are expected to provide clues to the Gamow theory on the alpha-decay process that occurs in heavy nuclei, which has not been solved for nearly 100 years.

Atomic nucleus



Each nucleus consists of protons and neutrons, and they interact with nuclear interaction

Nuclear structure

- Shell aspects
- Cluster aspects

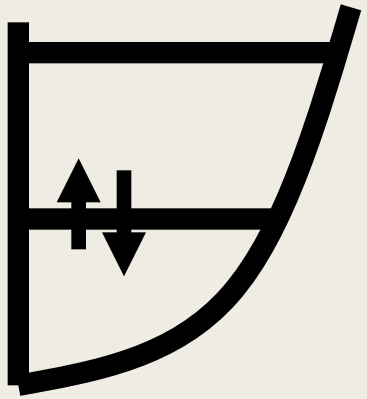
Nuclear structure

- Shell aspect:

  single particle motion of each nucleon
- Cluster aspect

Shell model

Each nucleon performs independent particle motion in a one-body potential.



`The Birth of Venus" by Sandro Botticelli

Nuclear structure

- Shell aspects:

  single particle motion of each nucleon
- Cluster aspects:

Nuclear structure

- Shell aspects:

  single particle motion of each nucleon

- Cluster aspects:

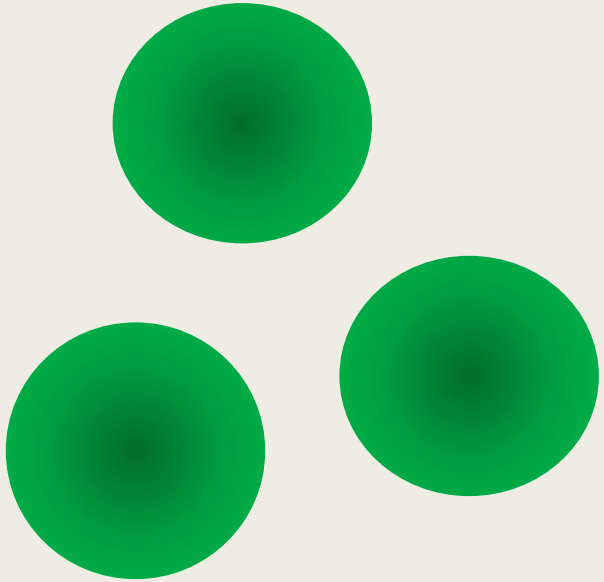
  weakly interacting states of

  strongly bound subsystem

α cluster model

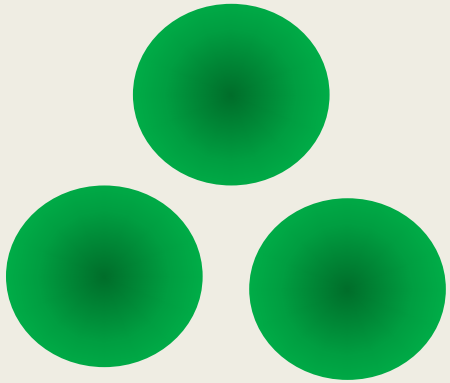
- ^{4}He is strongly bound (B.E. 28.3 MeV), which can be treated as subunits
- The relative interaction between two ^{4}He is weak (nature of π meson exchange)

``*Haystacks" by Claude Monet*

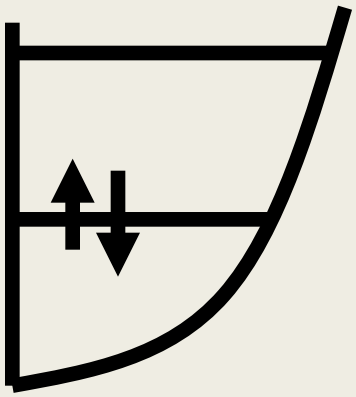


Our dream

Cluster model



Shell model



Nucleon-nucleon interaction

- Central

  $v(r)$, $v(r)(\sigma_1 \cdot \sigma_2)$,

  $v(r)(\tau_1 \cdot \tau_2)$, $v(r)(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$

- Spin-orbit (rank 1 and rank 1 couple to scalar)

  $v(r)\, \mathbf{L} \cdot (\sigma_1+\sigma_2)$ Not “fine structure”

- Tensor (rank 2 and rank 2 couple to scalar)

  $v(r)\, S_{12}$, $S_{12} = 3(\boldsymbol{\sigma}_1 \bullet \mathbf{r})(\boldsymbol{\sigma}_2 \bullet \mathbf{r})/r^2 - (\boldsymbol{\sigma}_1 \bullet \boldsymbol{\sigma}_2)$

  Yukawa’s π meson

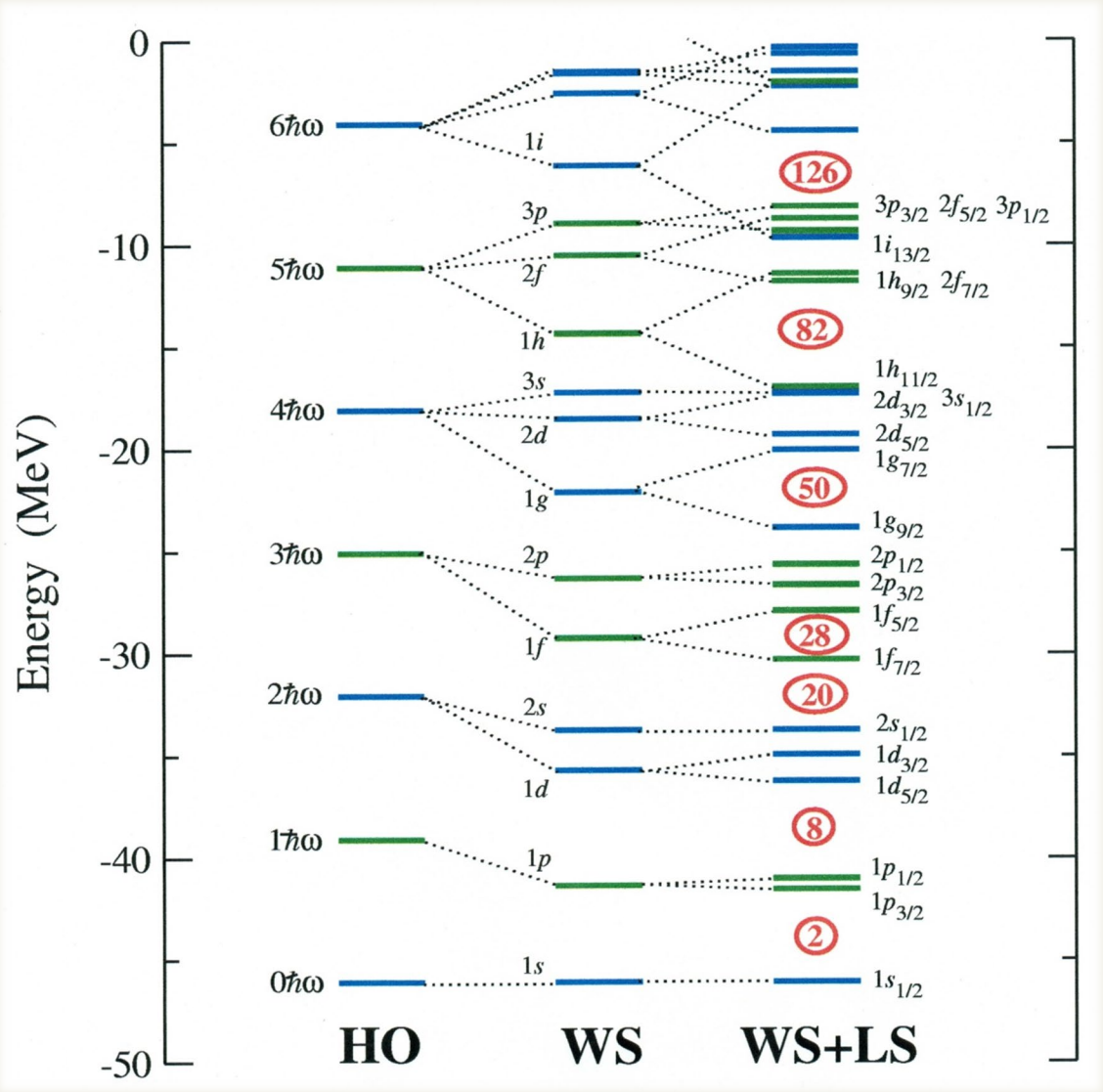
Spin-orbit interaction is a driving force, which breaks the clusters and realize the shell structure

Cluster side

shell-model side

spin-orbit interaction

Single-particle orbits of shell-model

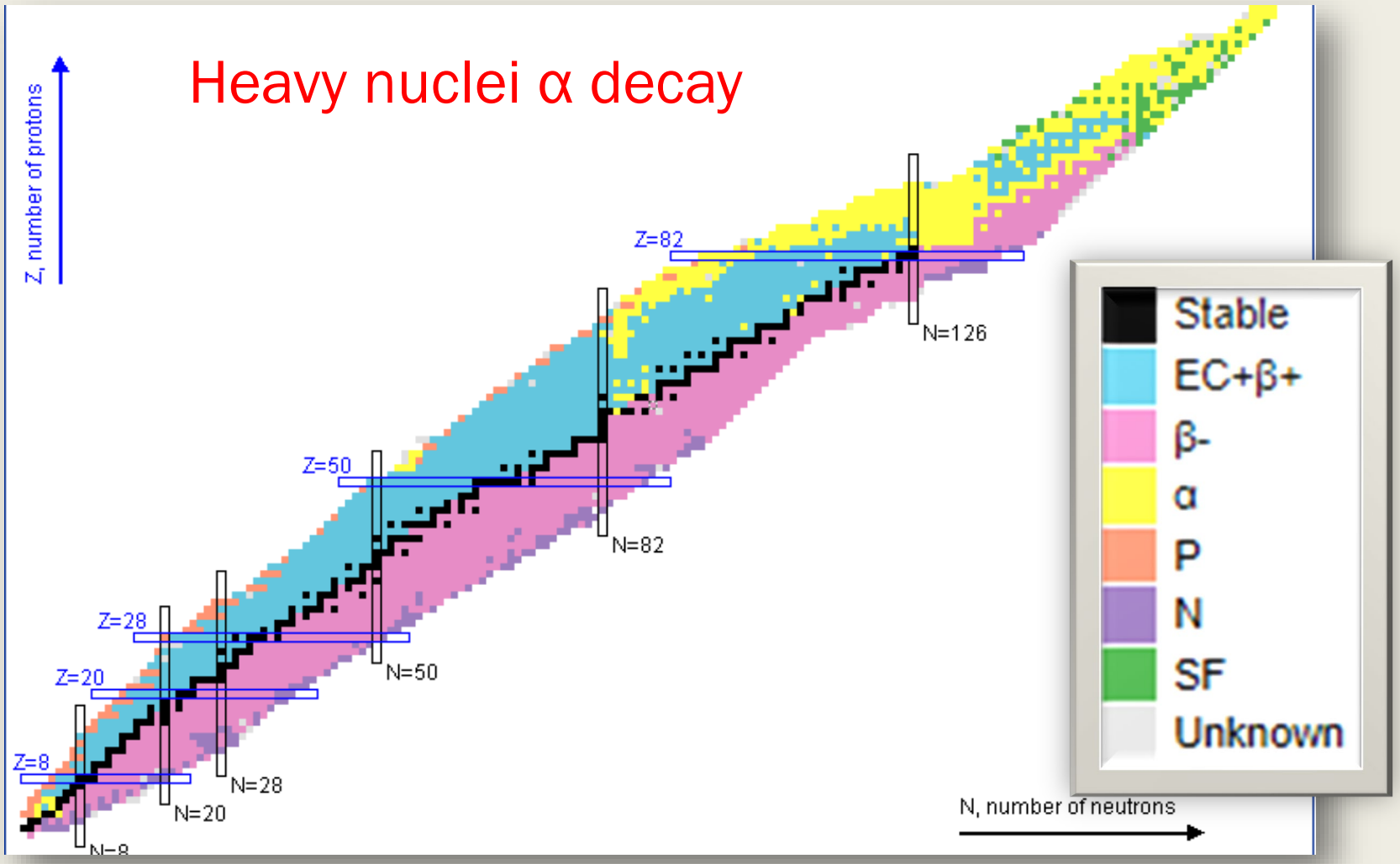


magic numbers are explained by spin-orbit effect

Decay processes of nuclei

http://ie.lbl.gov/systematics.html

protos



neutrons

Gamov's theory for α-decay – a century ago

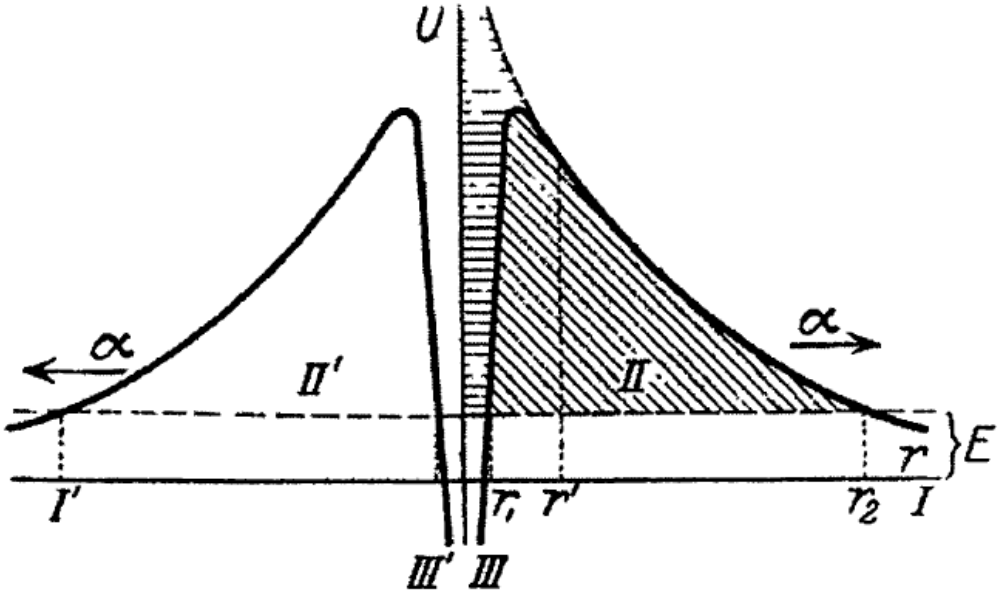


Figure 2. Gamow's nuclear-potential well, with the potential energy *U* plotted against the distance *r* from the center of the nucleus and assuming that the α particles have energy *E*. *Source*: G. Gamow, "Zur Quantentheorie des Atomkernes," *Zeit. f. Phys.*, ***51*** (1928), 210.

Estimation of barrier penetration probability

Basic question

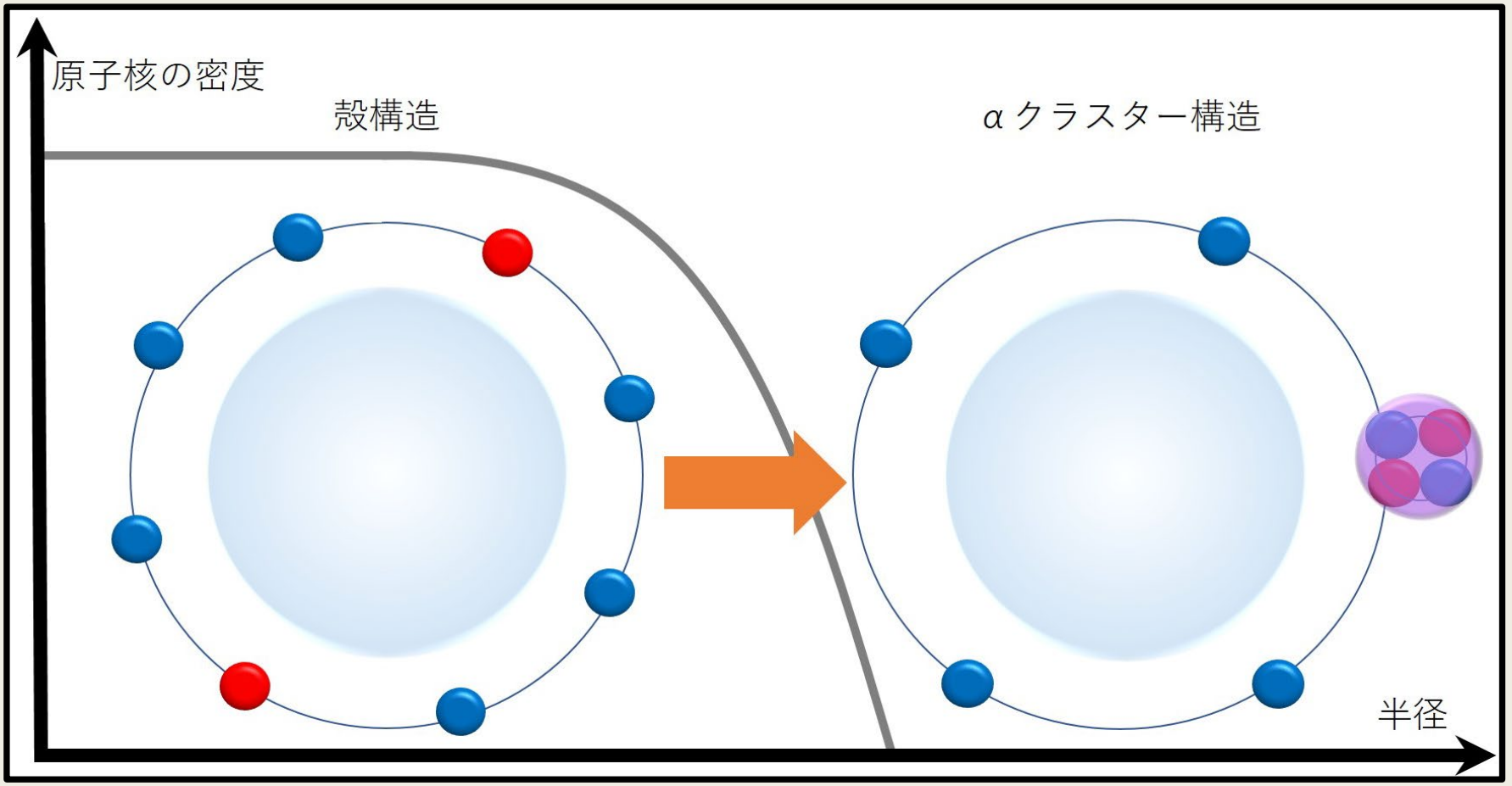
- Alpha cluster should exist in heavy nuclei since they alpha decay.
- However, shell picture becomes dominant with increasing mass number.
- How can we explain these contradicting two statements?

We developed a method, antisymmetirized quasi cluster model (AQCM), which provides shell- and cluster-model wave functions on the same footing
(we can transform cluster to shell)

We can calculate the proton (alpha) elastic scattering on these model wave functions based on the Glaubar-model.

By comparing with the experimental data, we can clarify which model is relevant as a function of the distance from the center.

Coexistence of two pictures for the nuclear structure



M. Okada, W. Horiuchi, and N. Itagaki, Phys. Rev. C.**109** 054324 (2024)

Microscopic understanding of the alpha decay

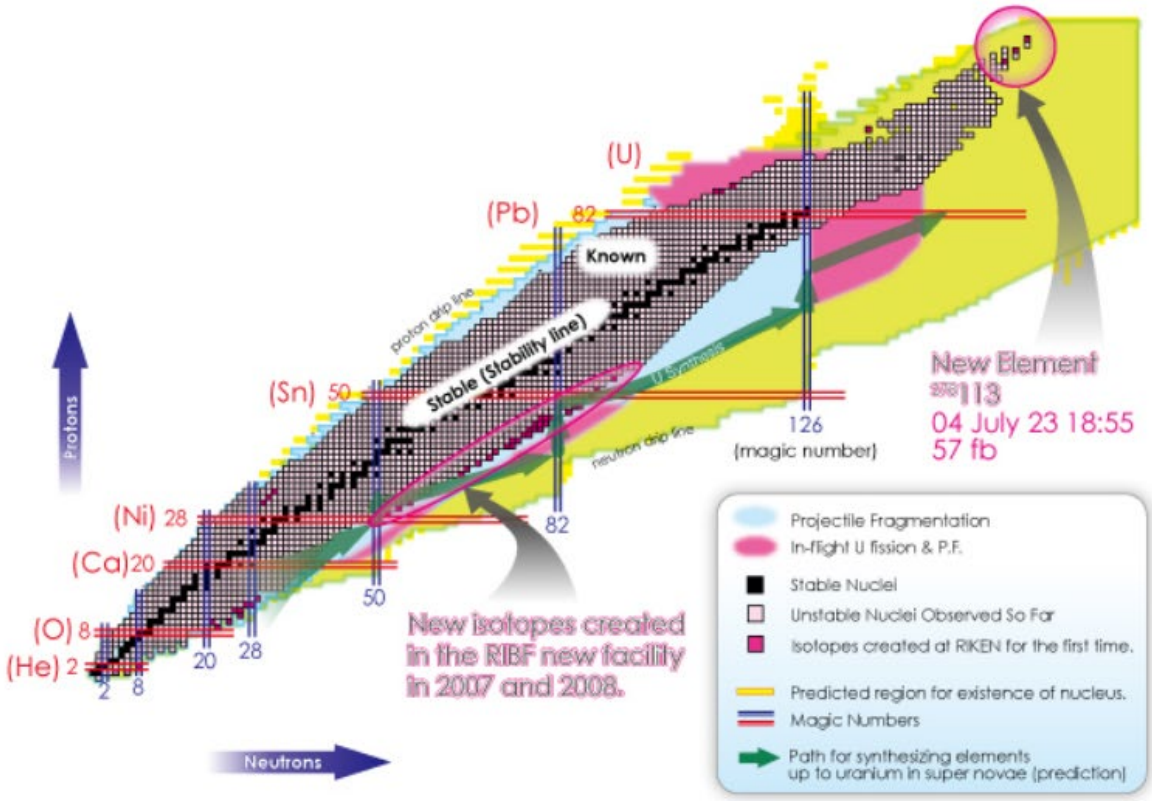
- In Gamow's era, alpha particle was considered as one of basic constituents of the nucleus and he calculated the penetration probability from the surface.
- Whether alpha particle really exist around the surface can be discussed in connection with the competition with the shell structure.

Number of new neutron-rich nuclei observed at RIKEN, Japan

The universe is made up of protons and neutrons — What is a table of nuclides?

How many kinds of nuclei exist in the universe?

Is it 100 or 1000? In fact, it is believed that there are about 10,000 types of nuclei, which are depicted in the following figure.



Each small cell represents a nucleus (the cell boundary is omitted for yellow, pink, and light blue areas).

Nuclear Physics Research | RIKEN Nishina Center

Summary

- There is ``fundamental physics division" at Osaka Metropolitan University and 9 stuff members are studying particle physics, cosmology, and nuclear physics.
- Nuclear structure shows different aspects such as shell and cluster, and we are making an effort to combine them.
- We are looking forward to discussing more and promoting possible collaborations.

13 April – 13 October 2025