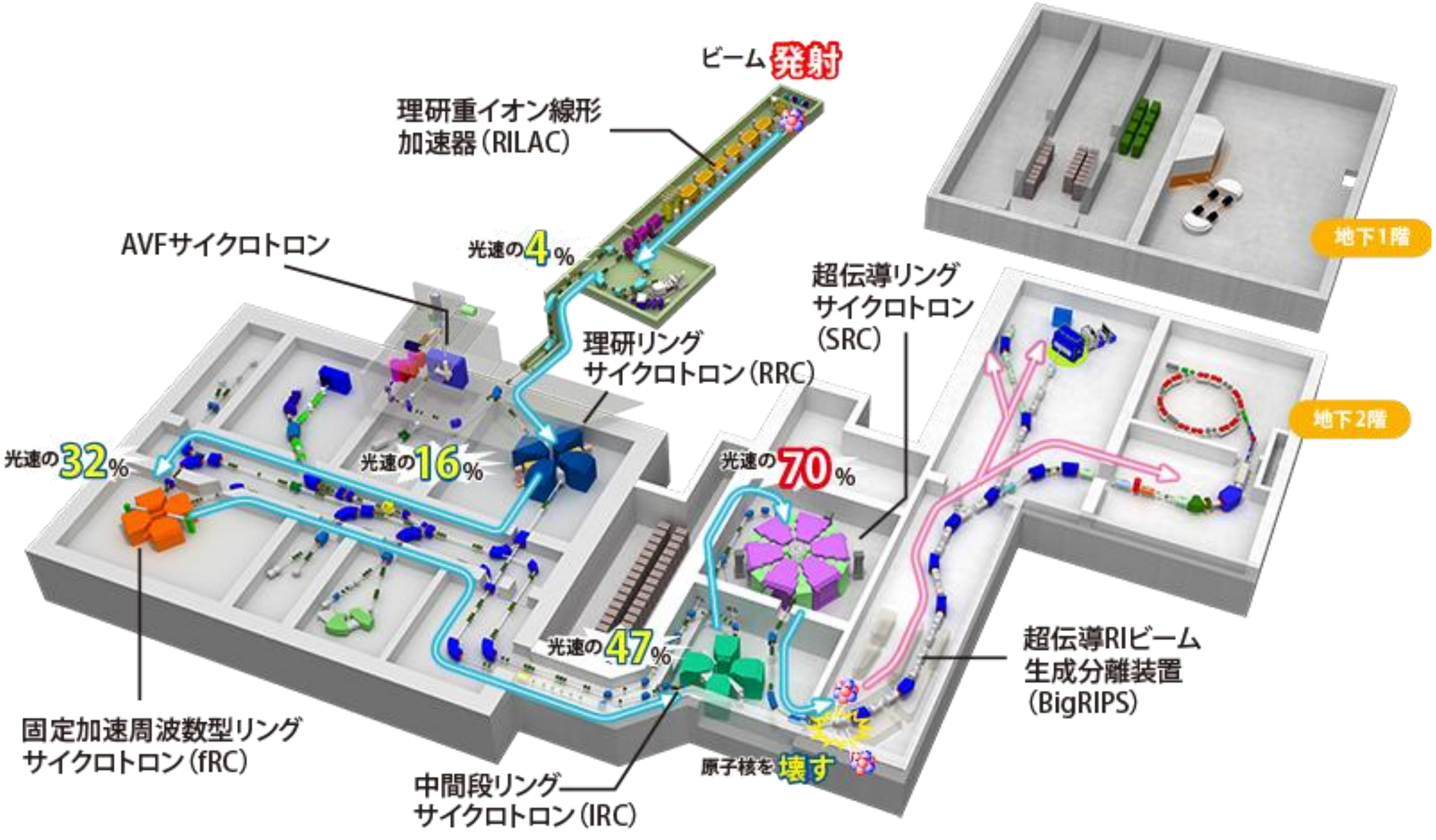
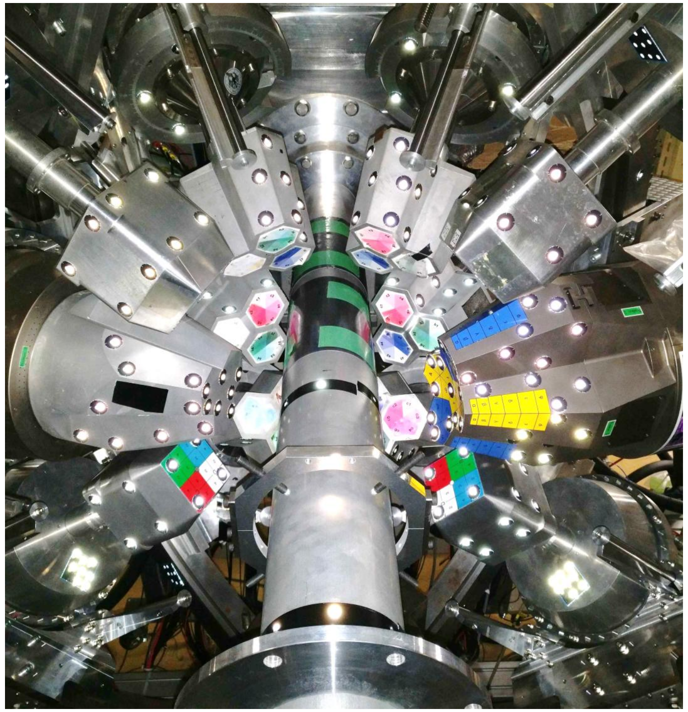
Probing shape transitions in finite nuclei with radioactive-ion beam spectroscopy

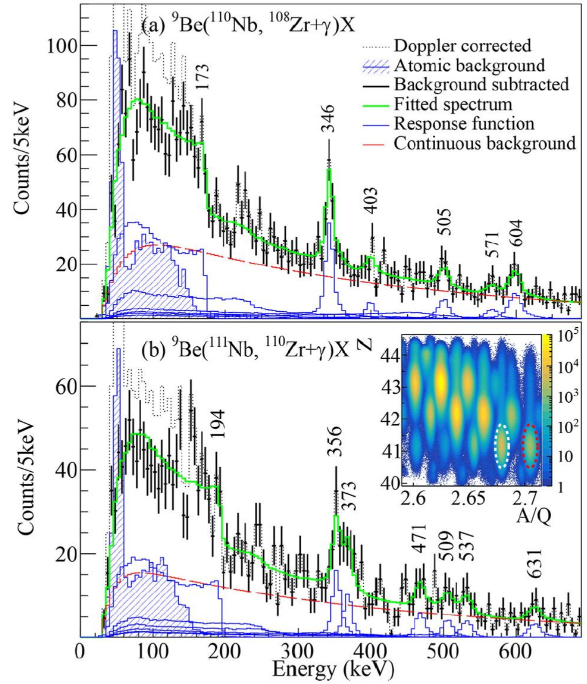
Daisuke Suzuki
Department of Physics, The University of Tokyo

Intersection of nuclear structure and high-energy nuclear collisions 2026
April 13 – 24, 2026 Yukawa Institute for Theoretical Physics, Kyoto University

Updates on in-beam gamma-ray spectroscopy using RI beams at RI Beam Factory

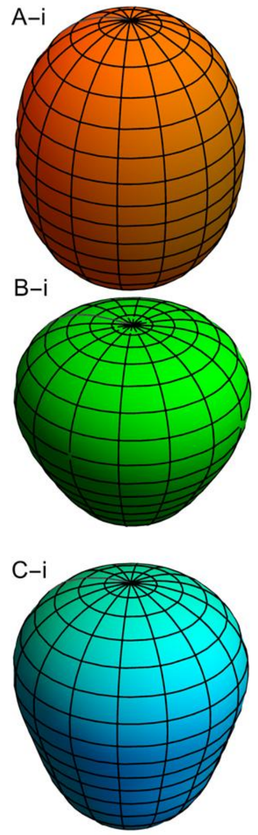






Outline

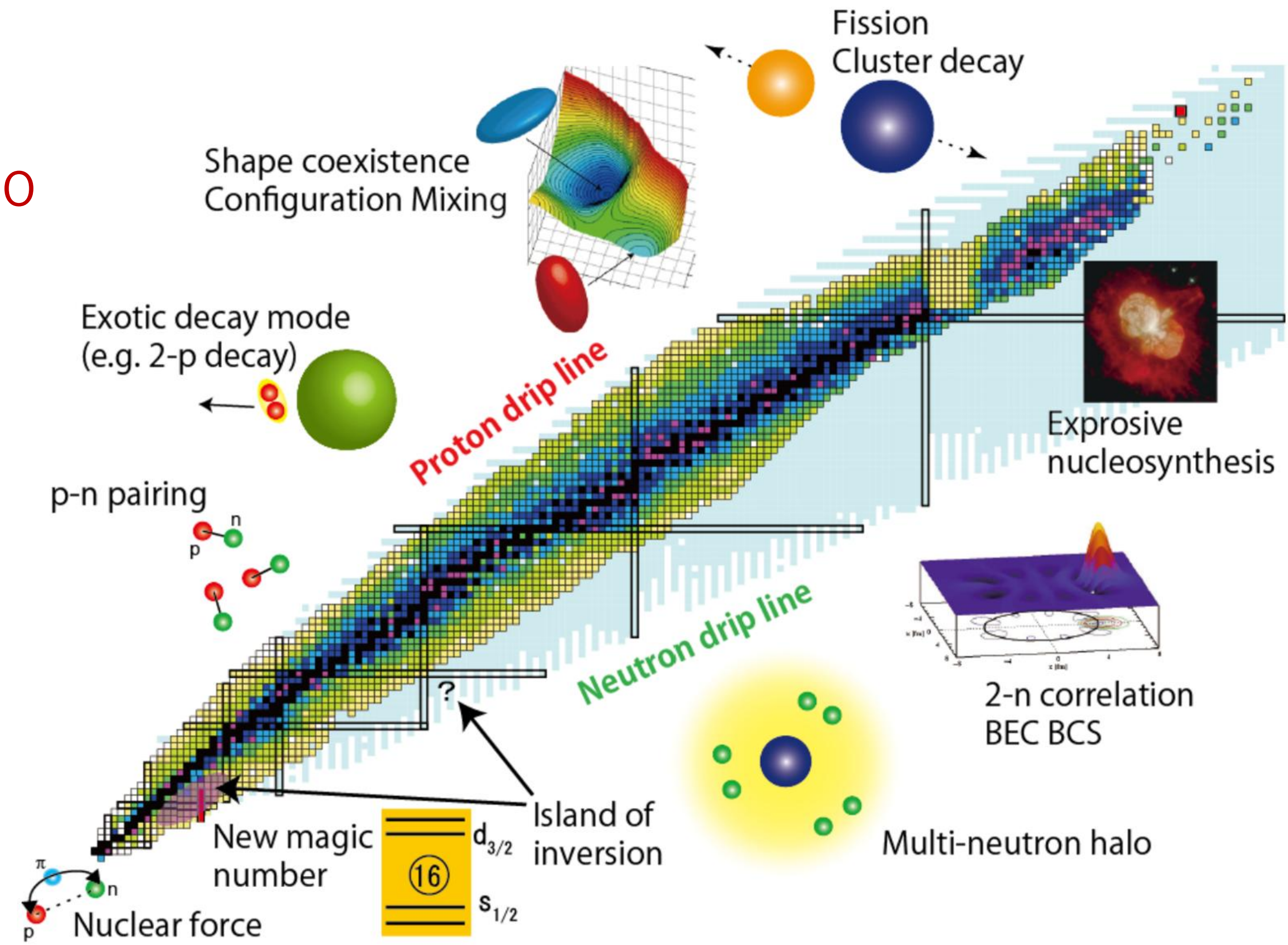
- **Introduction**
  — **Why we are interested in transitional phenomena in nuclear structure?**
- How do we approach experimentally?
- What are new experiments at RI Beam Factory?



Atomic nuclei exhibit rich structural order

Collective symmetry emerges.

- Nontrivial symmetries arise that are not explicitly built into QCD or nuclear forces
- A variety of phenomena are dynamically generated, such as:
  - Shell structure
  - BCS–BEC
  - Nuclear deformation
  - …

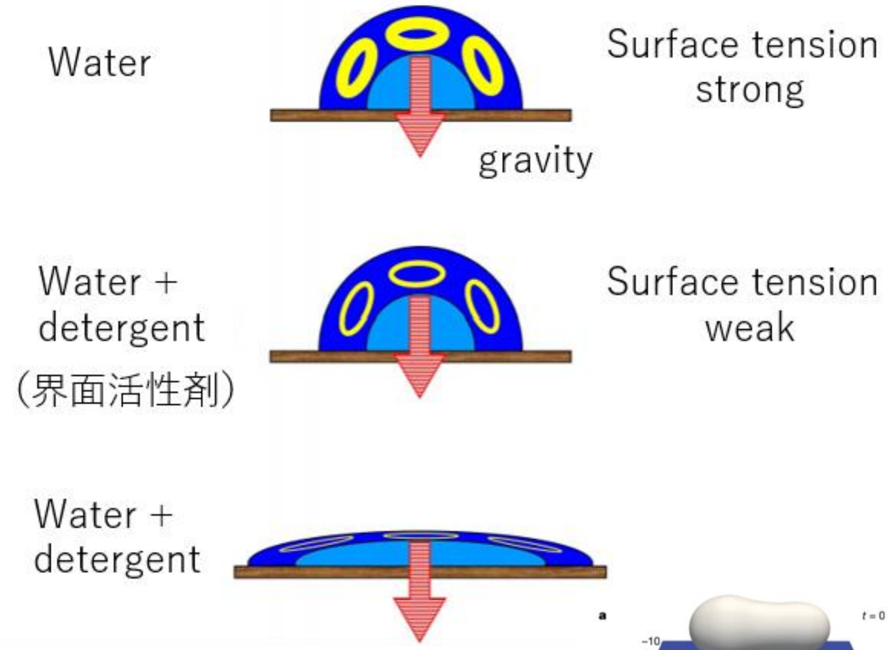


GenshikakuKenkyu Vol. 56 suppl. 3

What’s interesting about nuclear shape?

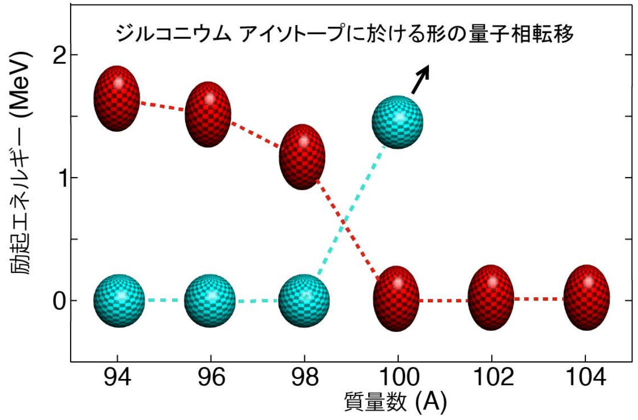
Classically counter intuitive

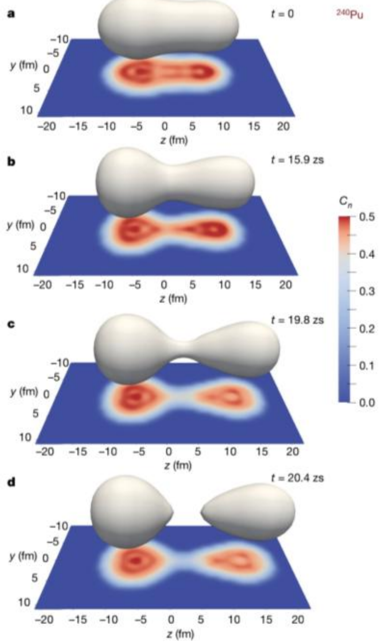
- Liquid drop favors spherical symmetry.
- Surface tension is significant in nuclei.
- — Quantum effect is essential.



Various phenomena and functions

- Coexistence, fluctuations, phase transition
- Fission
- EDM
- Nucleosynthesis
- …

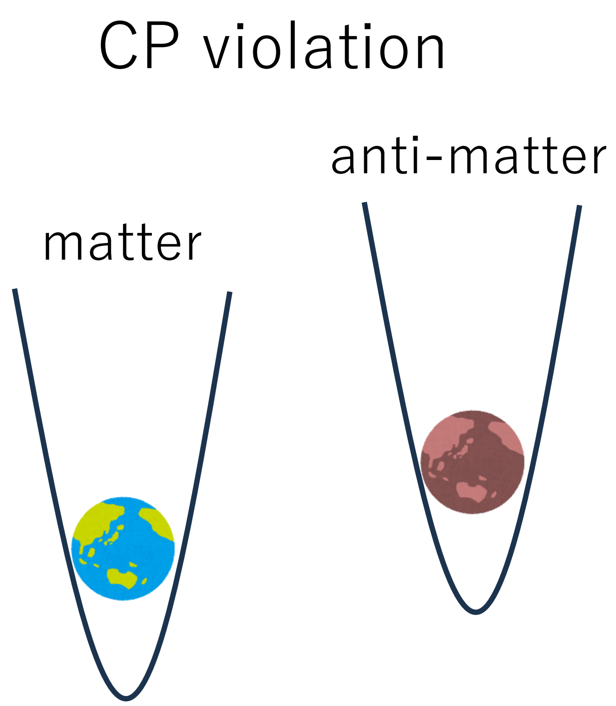




Challenge of ‘finite’ system

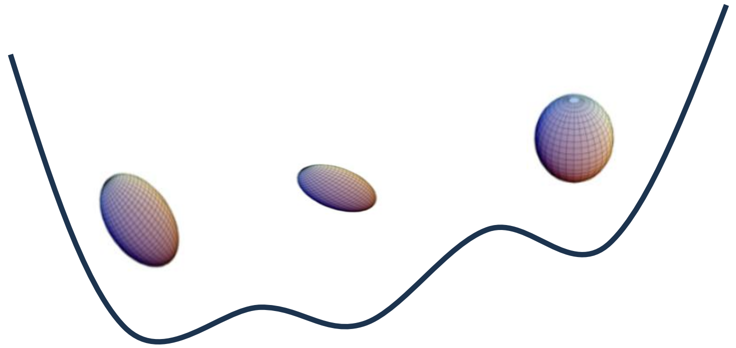
Infinite system – spontanenous breaking

- One vacuum (ground state) with specific broken symmetry is selected
- — Collective inertia is large. Fluctuations from one vacuum to the other are suppressed.
- — Stable order and sharp phase transitions



Finite nuclei ??

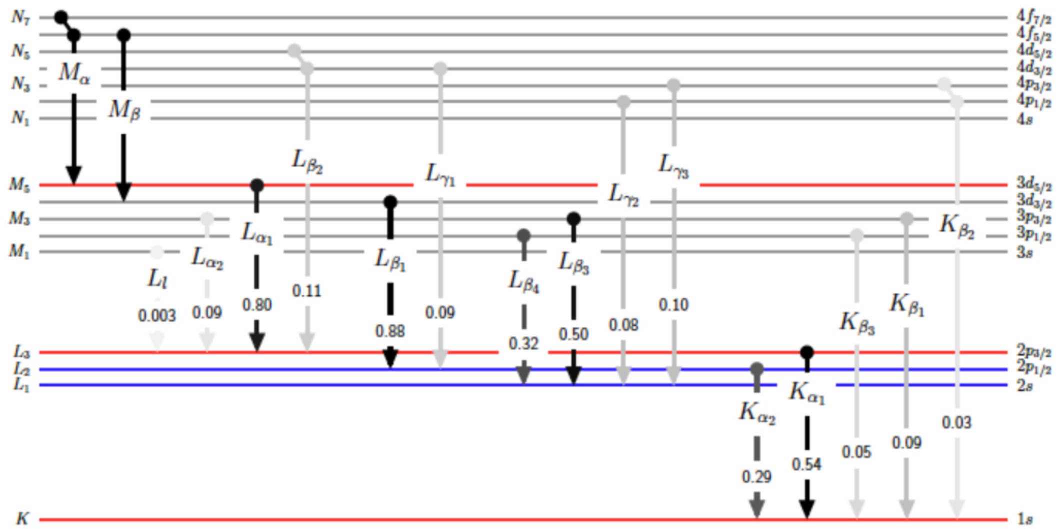
- Collective inertia is small.
- — **Broken symmetry is restored**
- — **In a classical picture, rotational motion occurs**
- — Fluctuations mix competing ground states.



Why do we believe that nuclei are deformed?

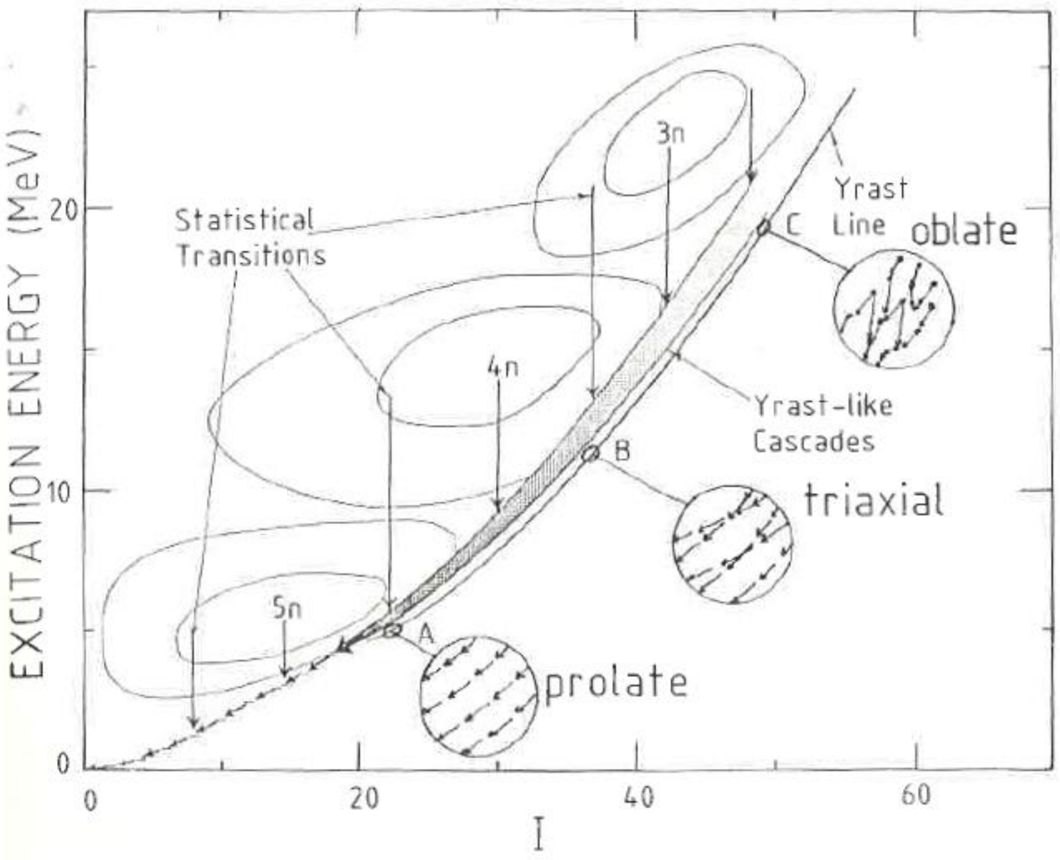
Nuclei favor E2 transitions, unlike atomic E1

Atoms: E1 dominates (single-particle transitions)



https://xraypy.github.io/XrayDB/periodictable.html

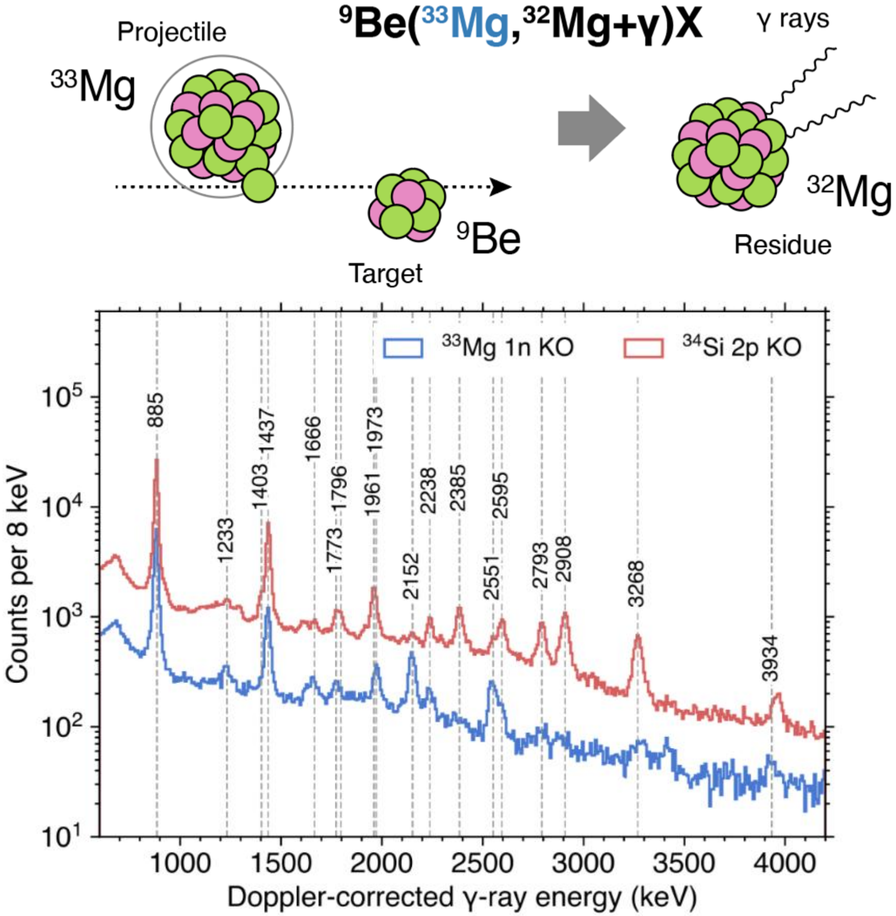
Nuclei: E2 dominates (collective transitions)



Spectroscopy is key technique

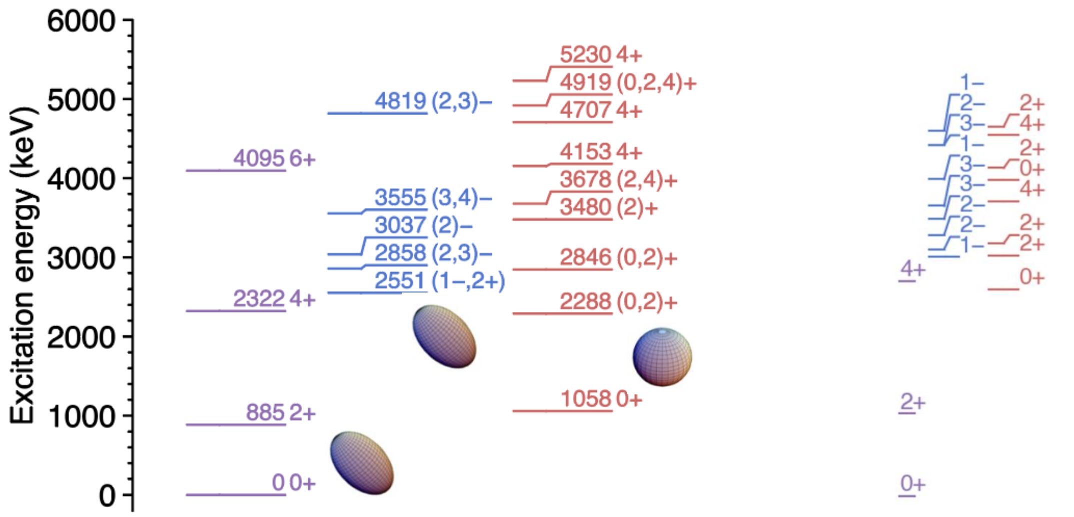
Courtesy N. Kitamura

N. Kitamura+, PRC 2020, PLB 2021, PRC 2022



Experiment

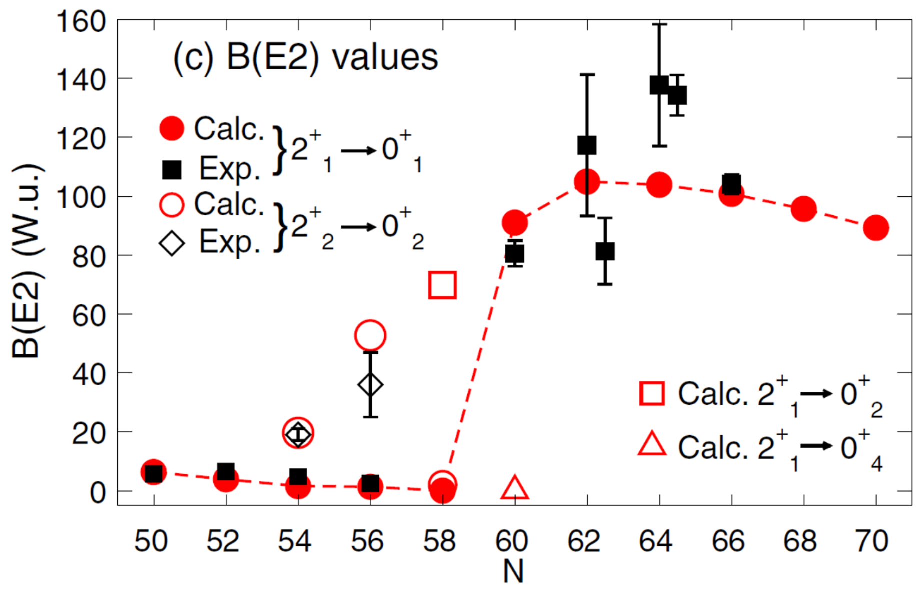
Quantum many-body calc. (nuclear shell model)

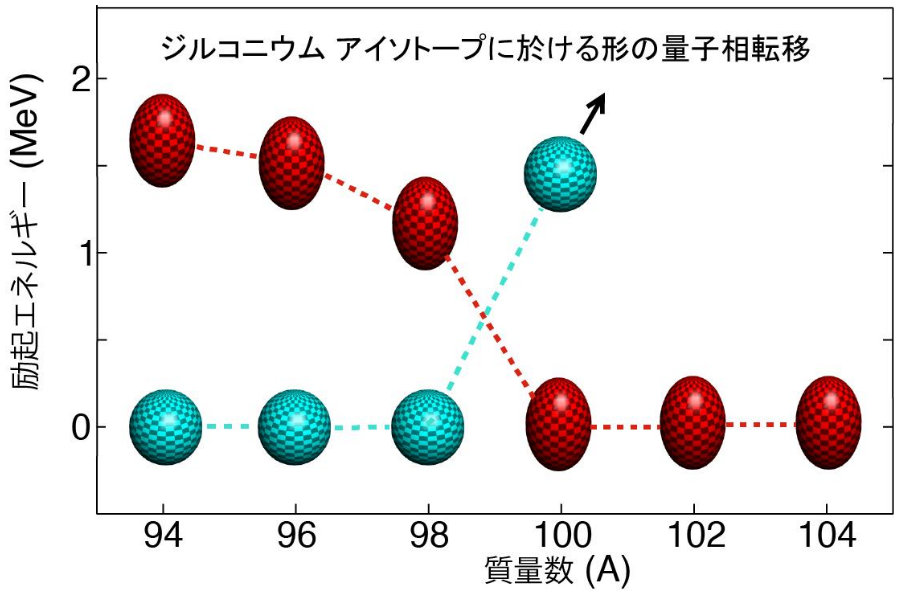


Transitional trends are key for physics

Only one state is difficult, but systematics give an insight.

B(E2) jump from ^{98}Zr to ^{100}Zr ↔ Shape transition



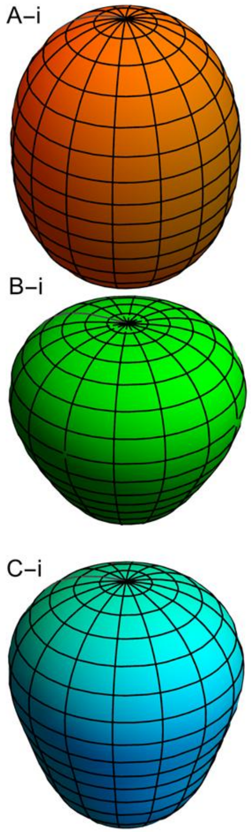


T. Togashi et al., PRL 117, 172502 (2016)

Outline

- Introduction
- **How do we approach experimentally?**

  — In-beam gamma-ray spectrscopy with RI beam
- What are new experiments at RI Beam Factory?



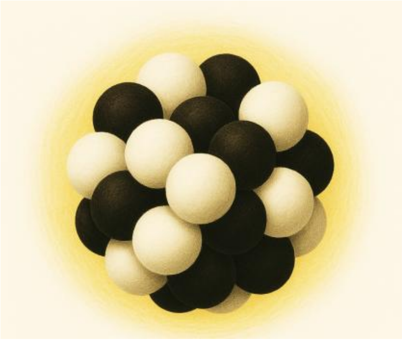
Radioactive isotope (RI) beams

One of the most important tools in modern nuclear physics

RI beams allow to control N/Z ratio

Stable isotope

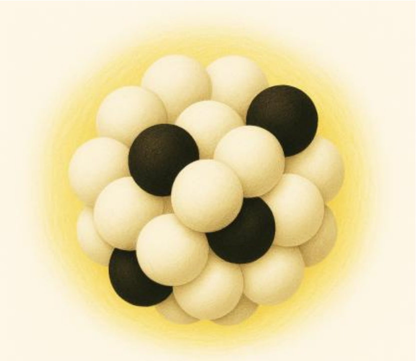
～300 isotopes



Z ～ N

Radioactive **I**sotope

～3000 isotopes



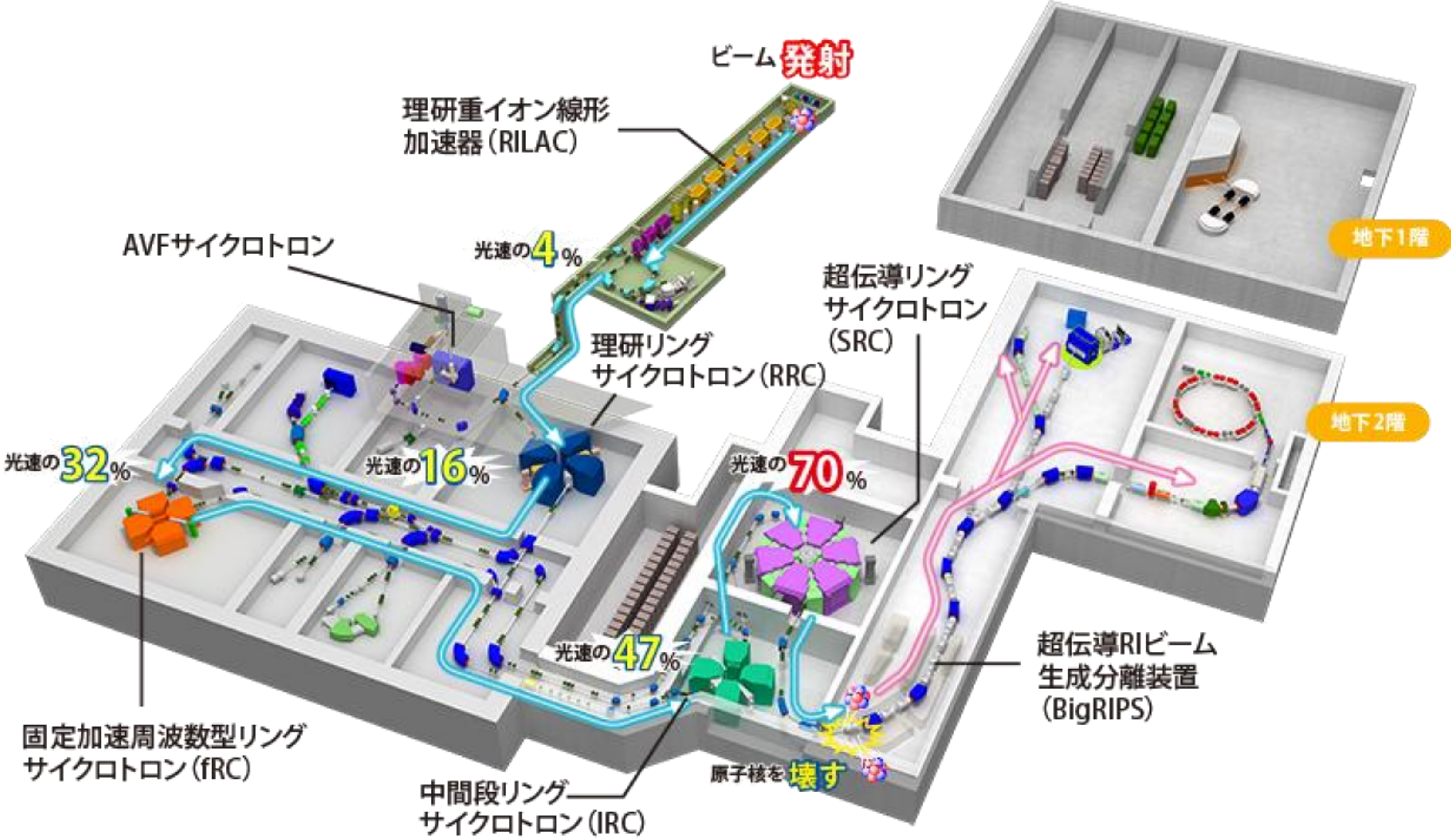
Z >> N

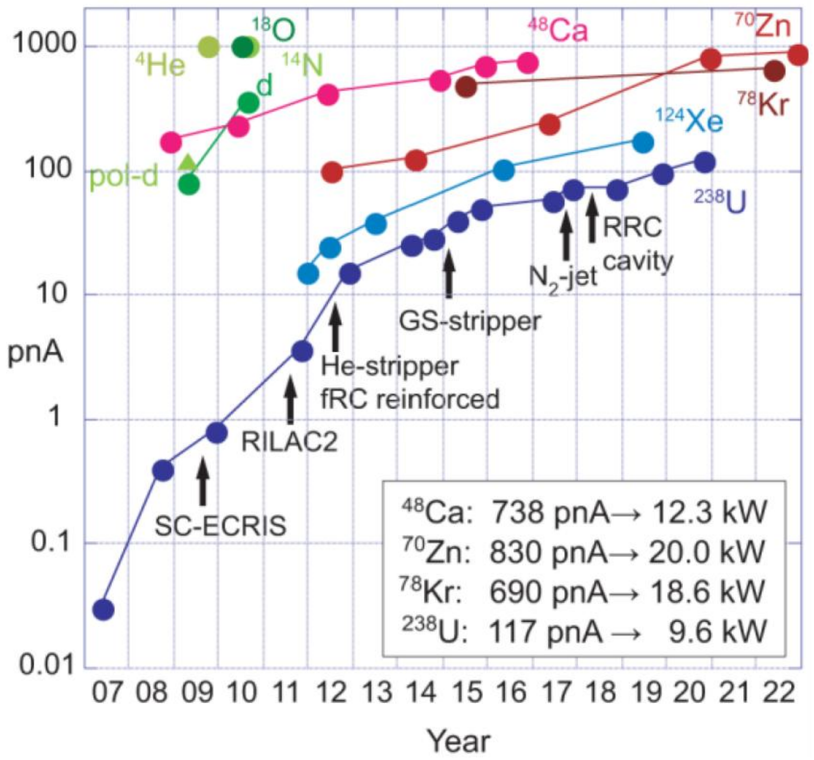
Z < < N

RI Beam Factory (RIBF)@RIKEN

Accelerator facility for **intensity frontier of short-lived RI beam**

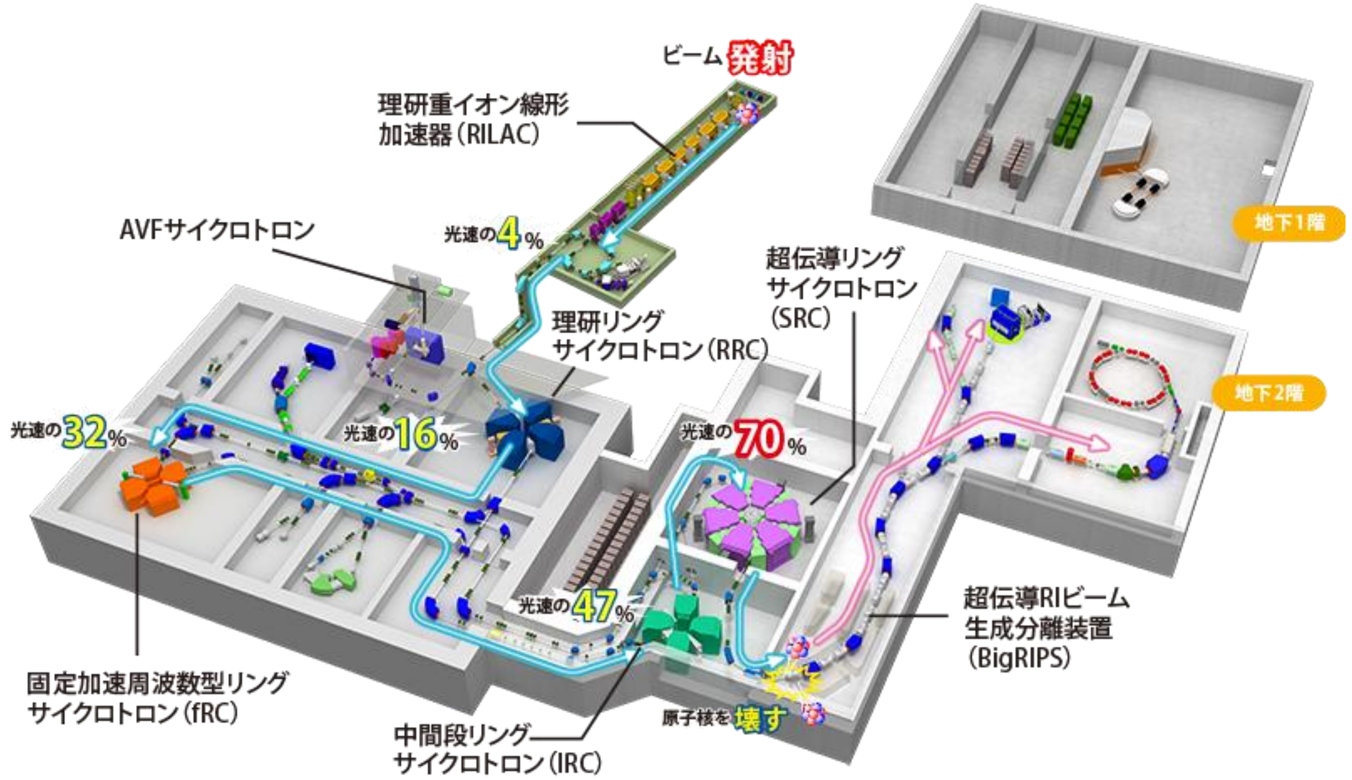
Highest intensity RI beam is provided.



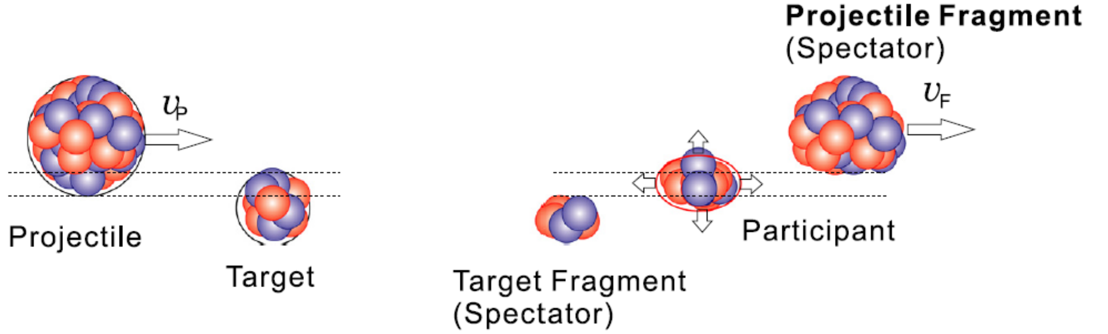


RI beam production using a 345-MeV/u heavy ion beams ($\beta \sim 0.6$)

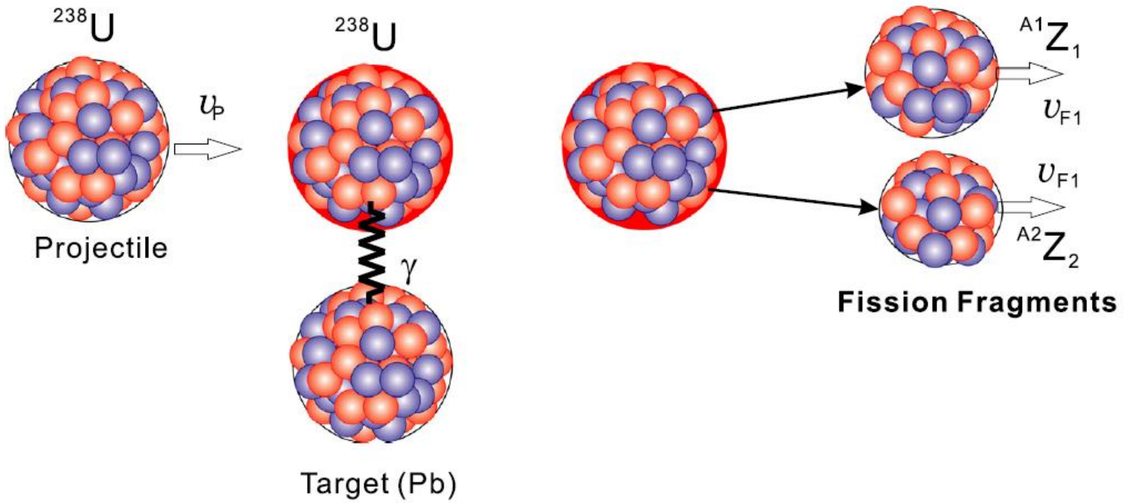
Superconducting Ring Cyclotron (**SRC**)



Projectile-fragmentation reaction

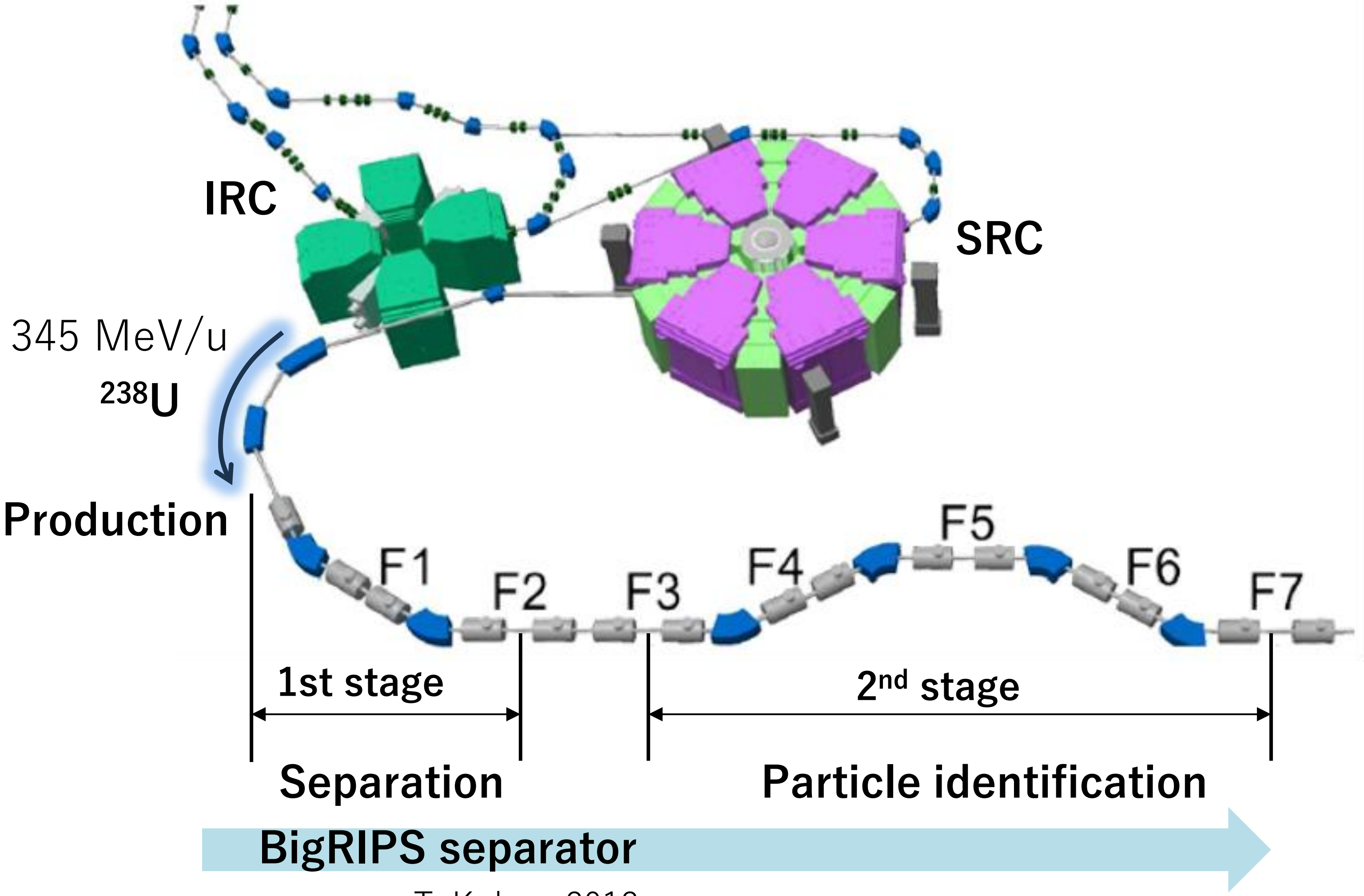


In-flight U fission



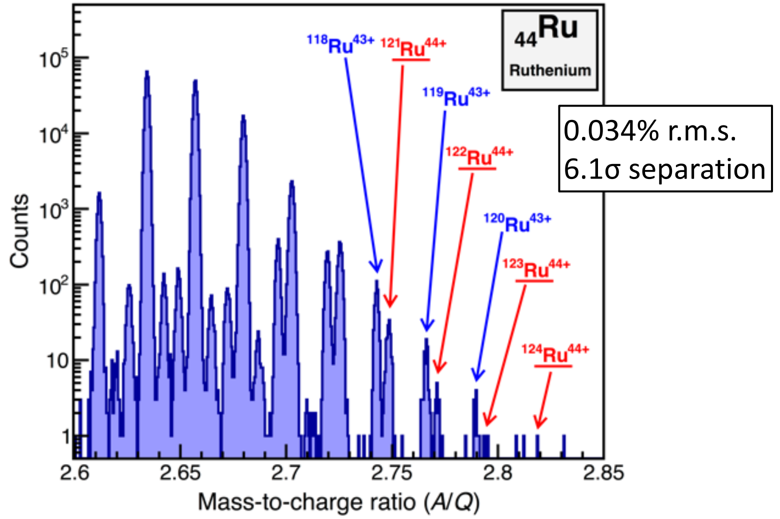
(b) In-flight fission.

BigRIPS Superconducting RI beam Separator



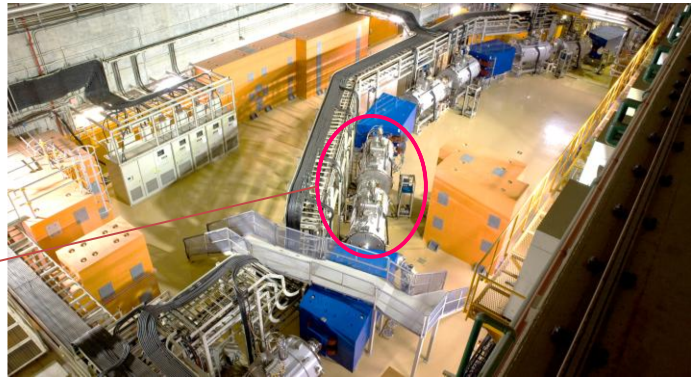
T. Kubo+ 2012

N. Fukuda+ 2013



RI beam ~250 MeV/u

Delivered to experimental halls

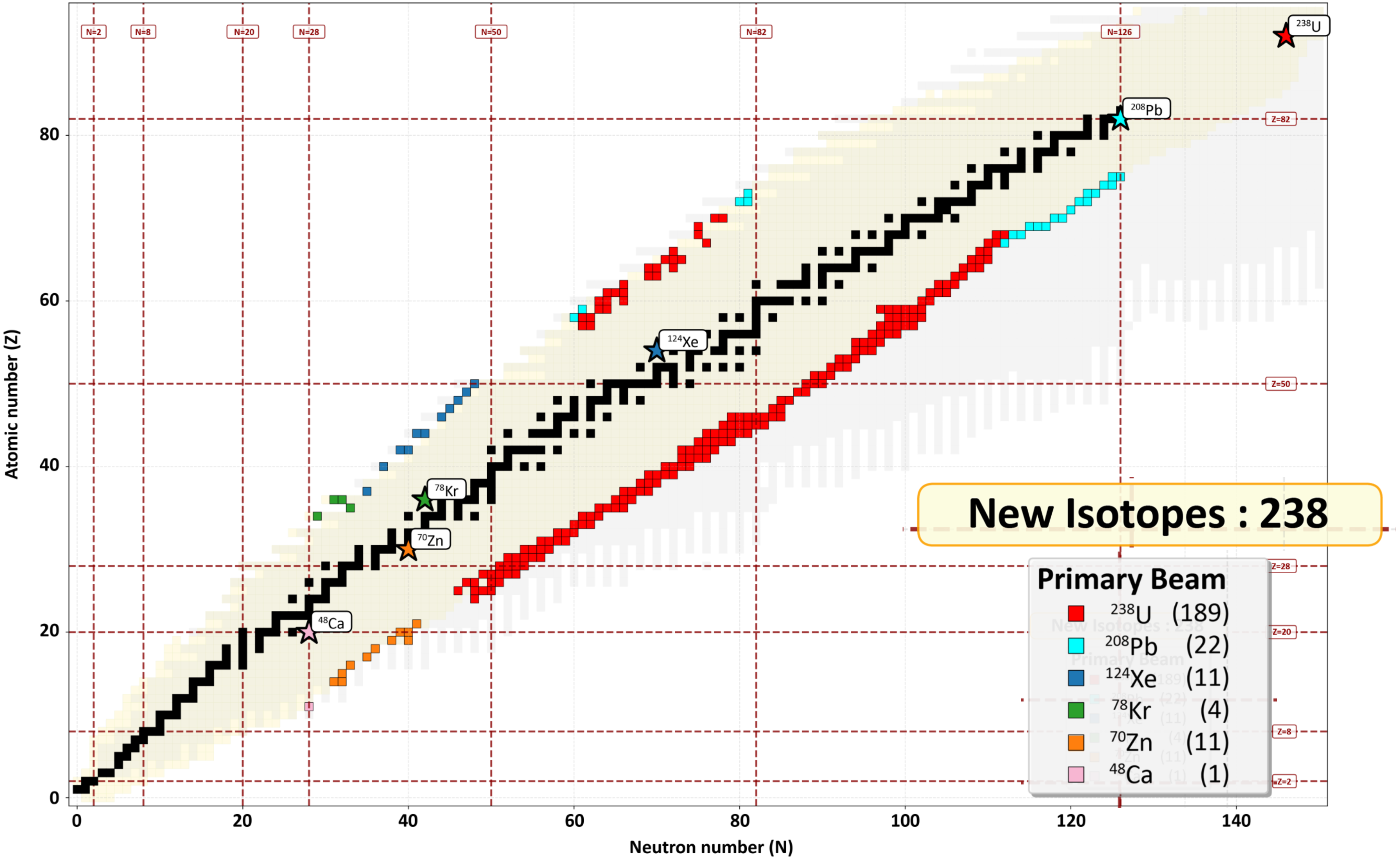


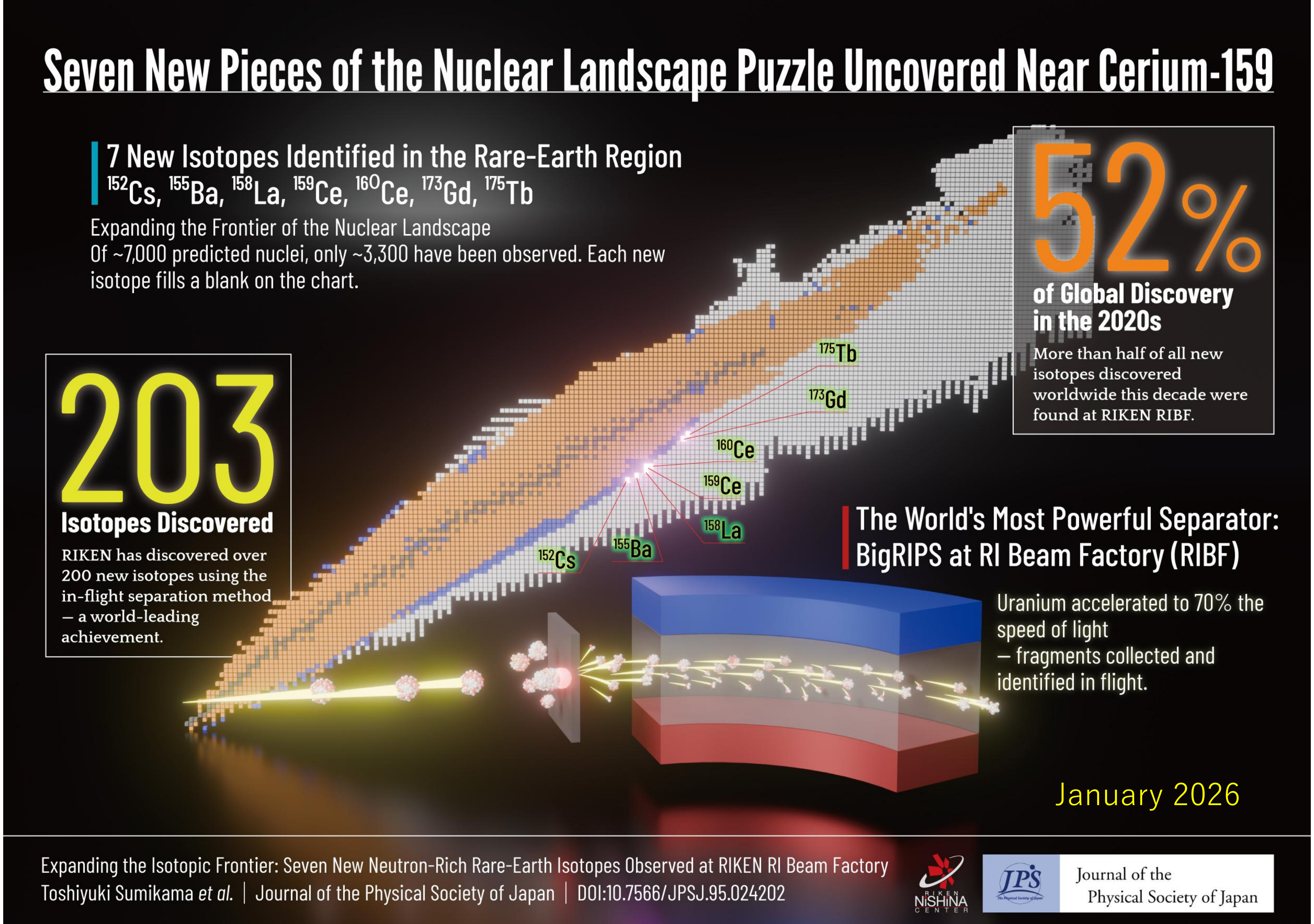
Large acceptance, high magnetic rigidity 9 Tm

momentum ± 3%, angle ± 40, 50 mrad

New Isotopes observed at RIBF (2007-2026)

Slide By Naoki Fukuda





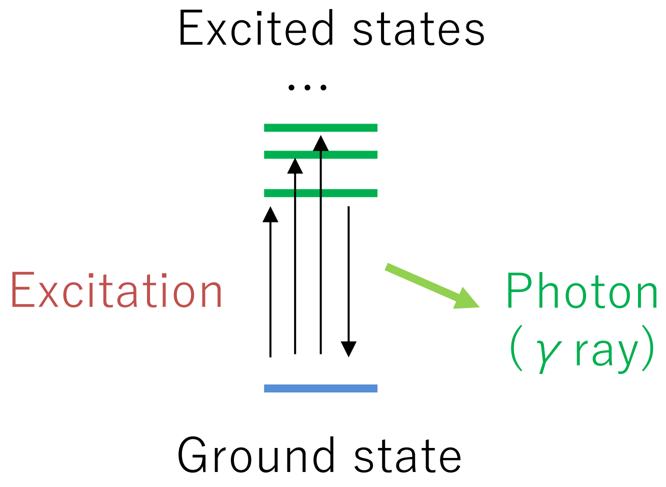
Seven New Pieces of the Nuclear Landscape Puzzle Uncovered Near Cerium-159
7 New Isotopes Identified in the Rare-Earth Region
^{152}Cs, ^{155}Ba, ^{158}La, ^{159}Ce, ^{160}Ce, ^{173}Gd, ^{175}Tb
Expanding the Frontier of the Nuclear Landscape
Of ~7,000 predicted nuclei, only ~3,300 have been observed. Each new isotope fills a blank on the chart.
203
Isotopes Discovered
RIKEN has discovered over 200 new isotopes using the in-flight separation method — a world-leading achievement.
52%
of Global Discovery in the 2020s
More than half of all new isotopes discovered worldwide this decade were found at RIKEN RIBF.
^{175}Tb
^{173}Gd
^{160}Ce
^{159}Ce
^{158}La
^{155}Ba
^{152}Cs
The World's Most Powerful Separator: BigRIPS at RI Beam Factory (RIBF)
Uranium accelerated to 70% the speed of light
— fragments collected and identified in flight.
January 2026
Expanding the Isotopic Frontier: Seven New Neutron-Rich Rare-Earth Isotopes Observed at RIKEN RI Beam Factory
Toshiyuki Sumikama *et al.* | Journal of the Physical Society of Japan | DOI:10.7566/JPSJ.95.024202
RIKEN NISHINA CENTER
JPS
Journal of the Physical Society of Japan

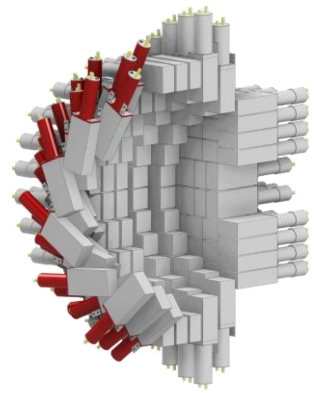
In-beam γ-ray spectroscopy with RI beams

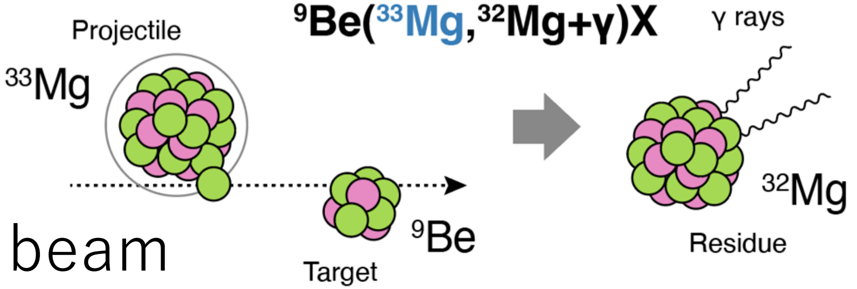
Accessing nuclear shape information through excited states

- RI beams allow to scan over N, Z.
- The ground state contains minimal accessible information.
  — Excitation collects structural information scattered over many states.
- **‘Inverse kinematics’**

  — Beam is much heavier than target







RI beam

$\beta = 0.6$

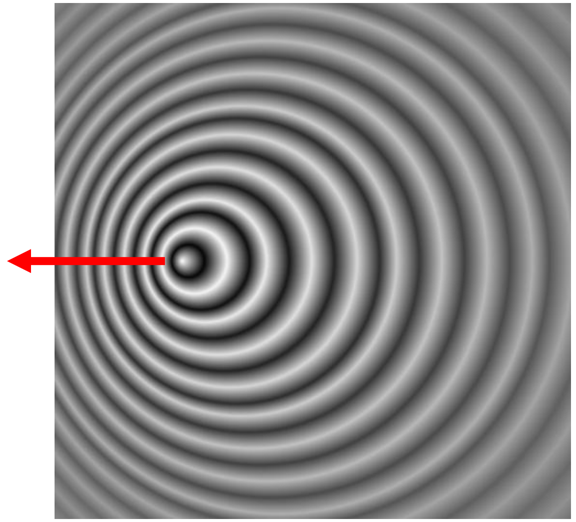
target

Doppler shift is a challenge in inverse kinematics

Photon from moving emitter shifts energy in the laboratory frame.

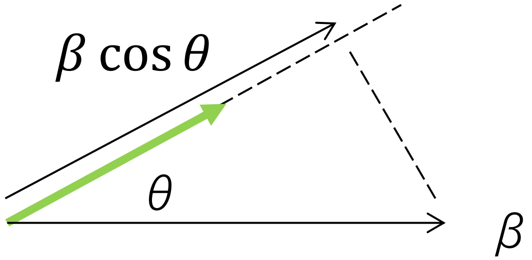
- To collect for Doppler shift, the **energy and angle information of gamma-rays** are necessary.
- Energy resolution is intrinsic property of detection medium chosen.
- The **angular resolution is often constrained by finite size of detectors**.

Waves emitted from a moving source



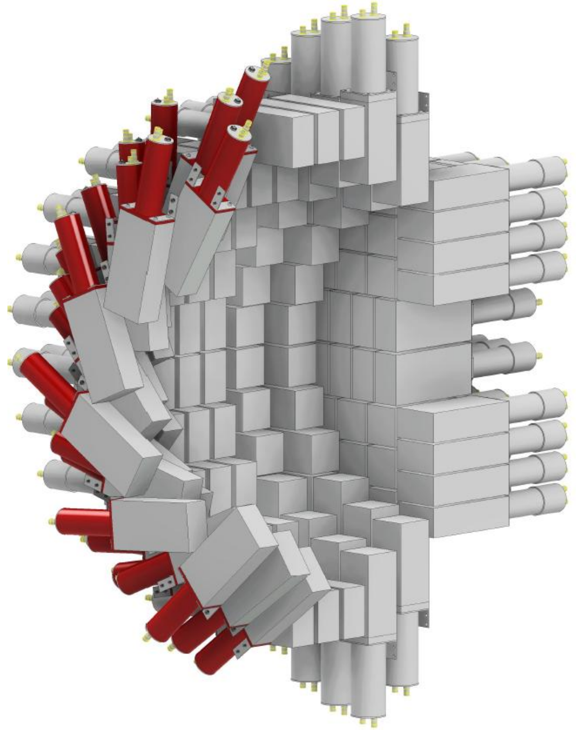
The Lorentz tranformation reads:

$$E_{\mathrm{c.m.}} = \gamma E_{\mathrm{lab}}\,(1 - \beta \cos\theta)$$



DALI2+ gamma-ray spectrometer at RIBF

Takeuchi+ NIMA 2014



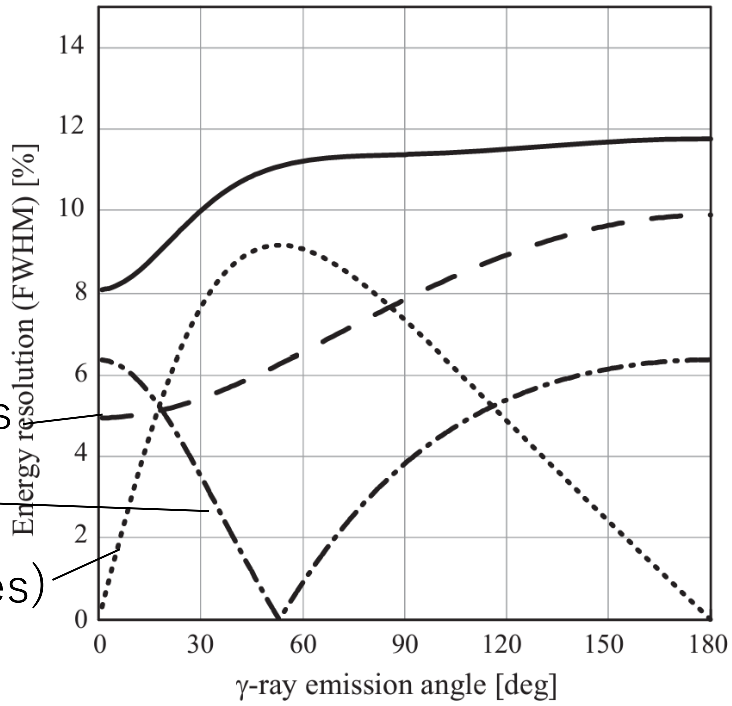
- **Multifold NaI(TI) scintillator** construction:
  160 detectors (2002) → 186 (2010) → 226 (2017)
- **High efficiency** 36 % FEP (full energy peak) efficiency*
- **Good Dopper-corrected energy resolution** 9 % (FWHM)*

  * for 1 MeV ray at 100 MeV/nucleon

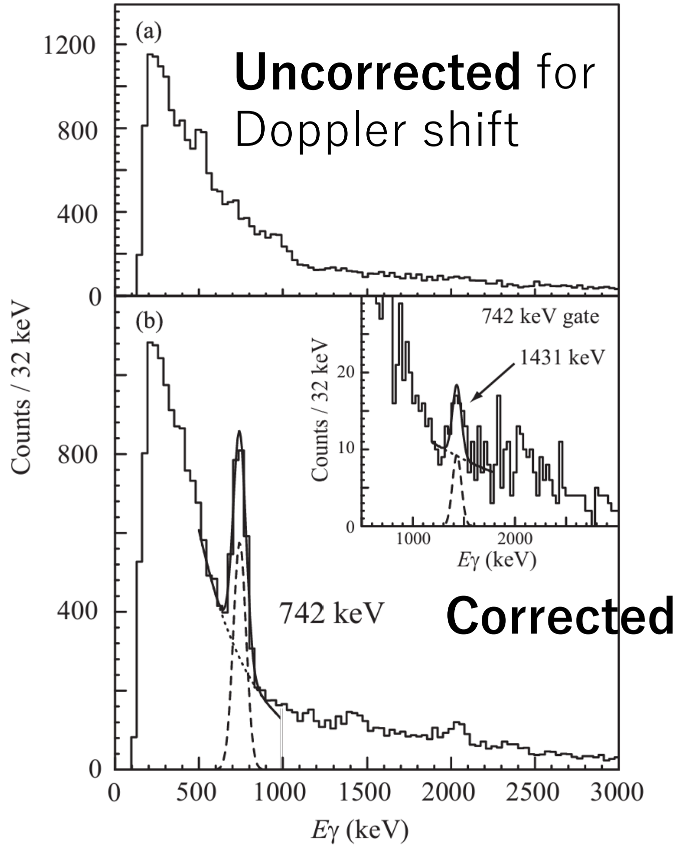
Energy resolution of the detectors

Velocity spread of emitters

Detector size (uncertainty of angles)

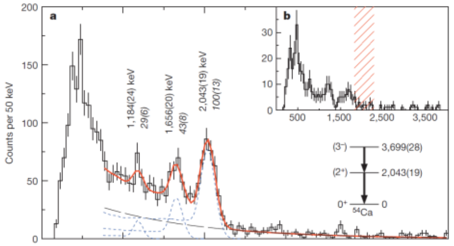


^{44}S -2p → ^{42}Si

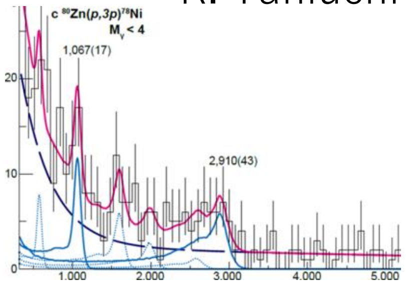


Magicity loss and emergence

D. Steppenbeck+ Nature 2013

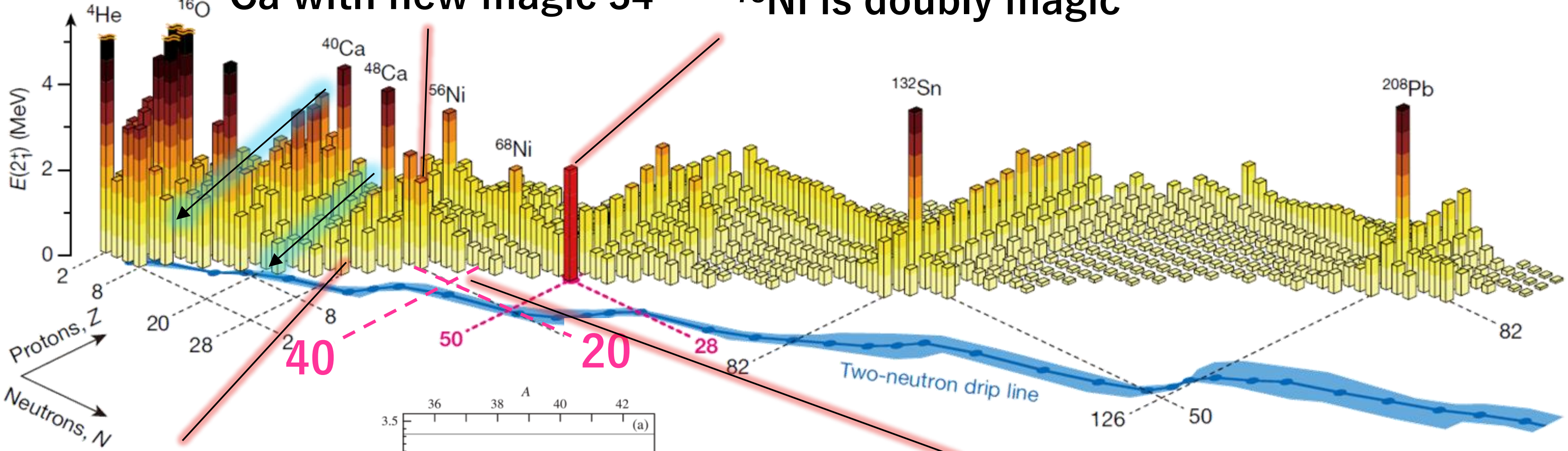


R. Taniuchi+ Nature 2019



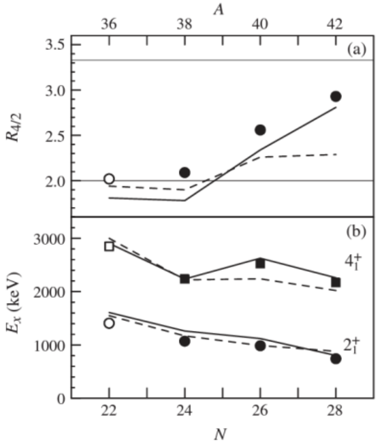
^{54}Ca with new magic 34

^{78}Ni is doubly magic



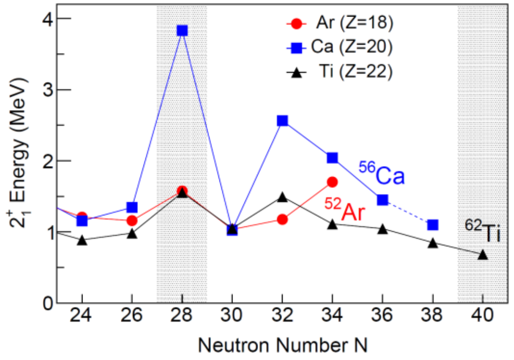
N = 28 lost in ^{42}Si

S. Takeuchi+ PRL 2012



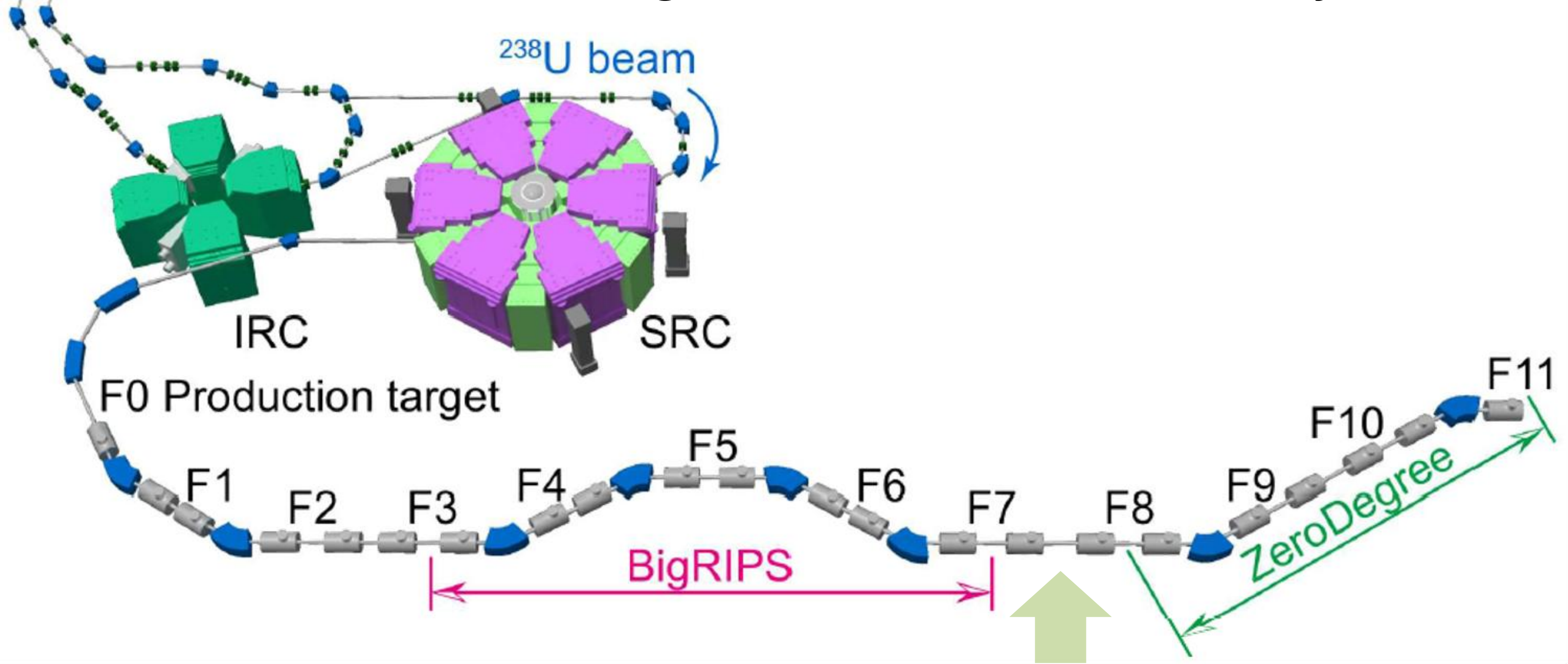
N = 40 not magic ? ^{56,58}Ca

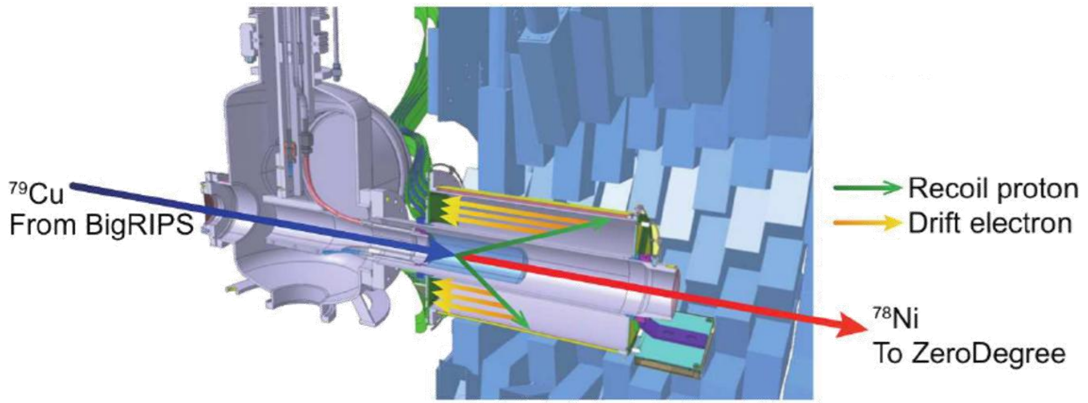
S. Chen+ PLB 2023

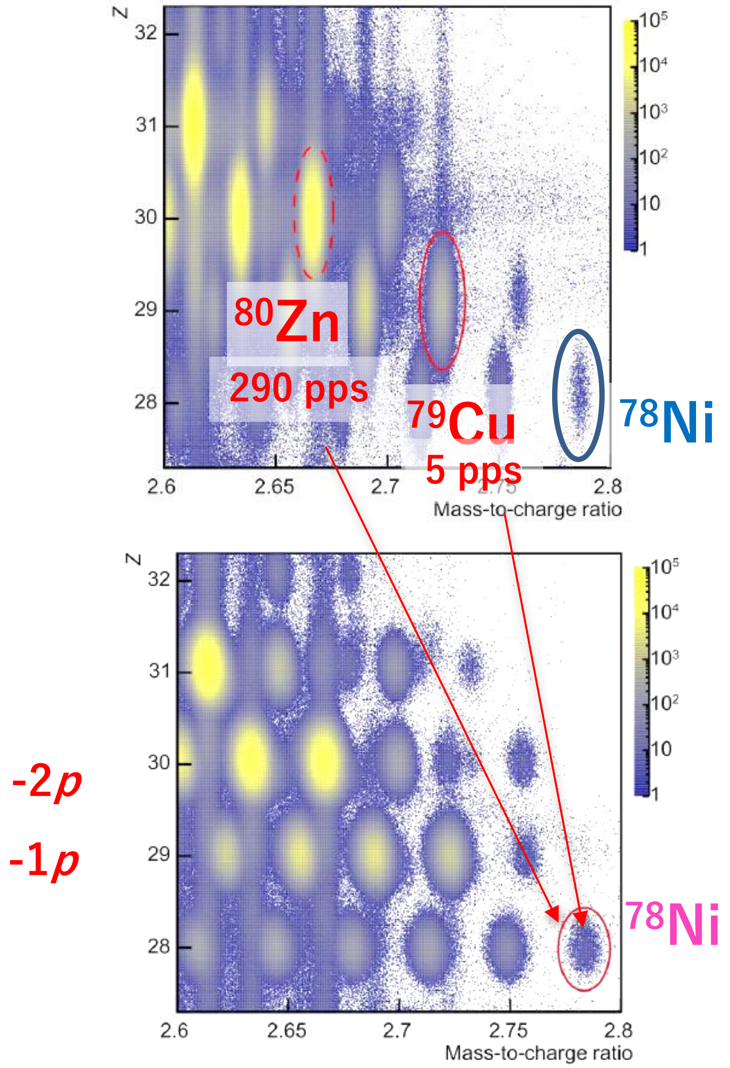


Spectroscopy of doubly-magic ^{78}Ni

^{78}Ni was populated by knockout reaction of ^{80}Zn and ^{79}Cu. The U beam intensity, 12 pnA at the time of experiment, is not **enough to secure sufficient luminosity** with conventional targets such as Be.

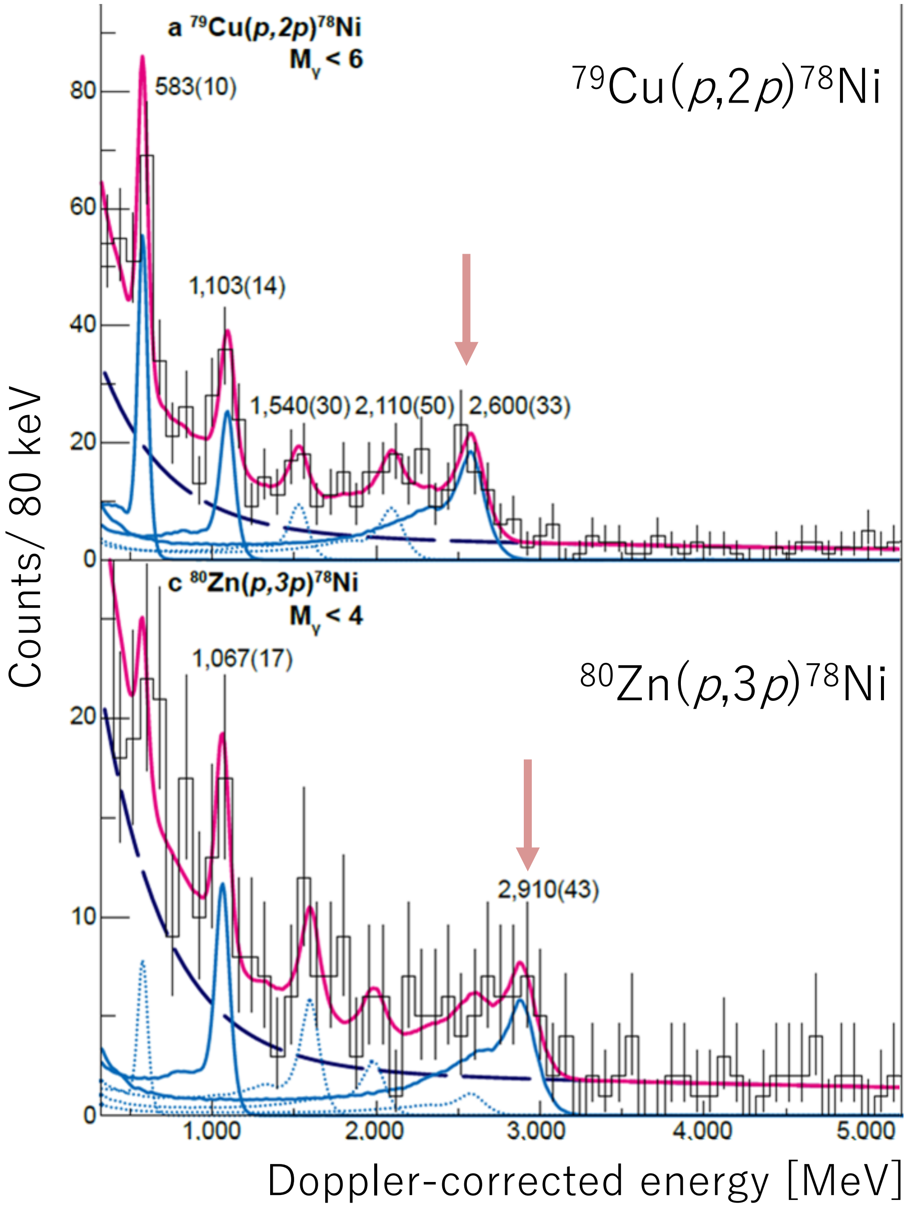




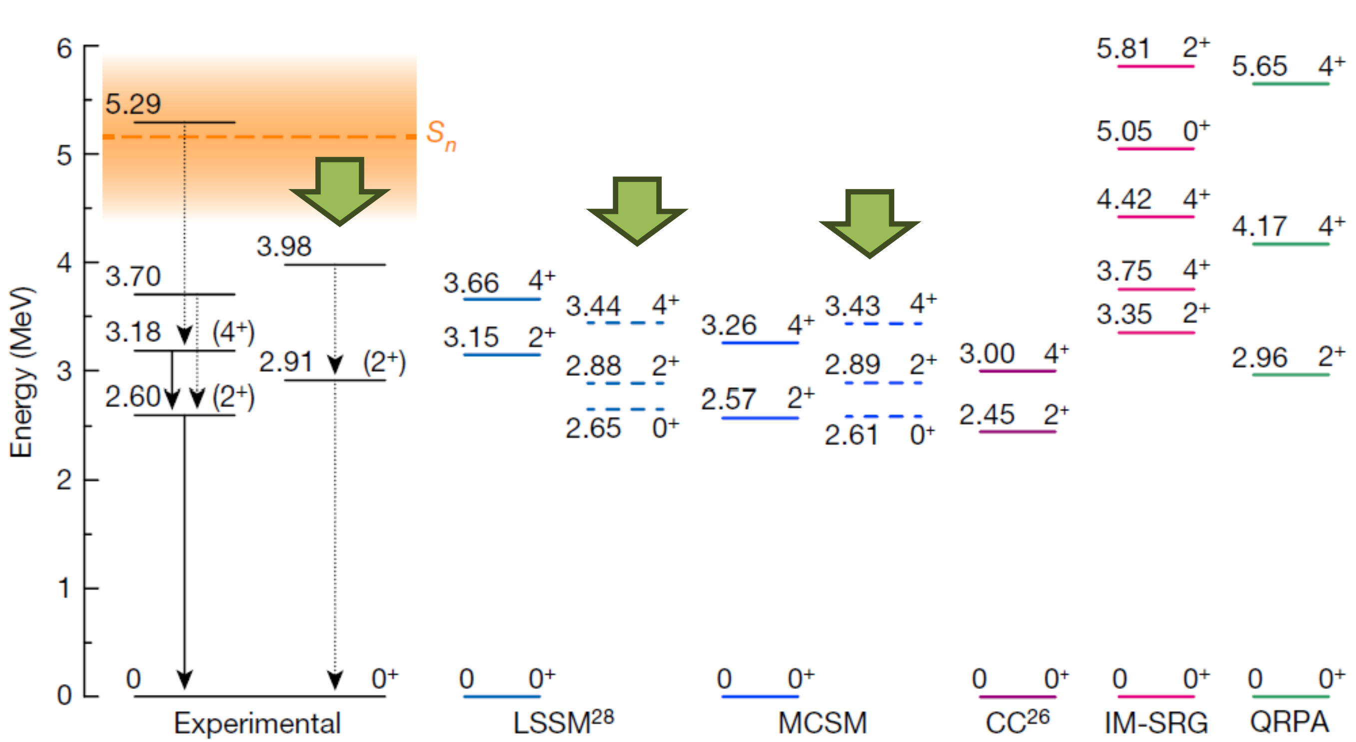


Magicity of ^{78}Ni and possible onset of deformation

R. Taniuchi+ Nature 2019

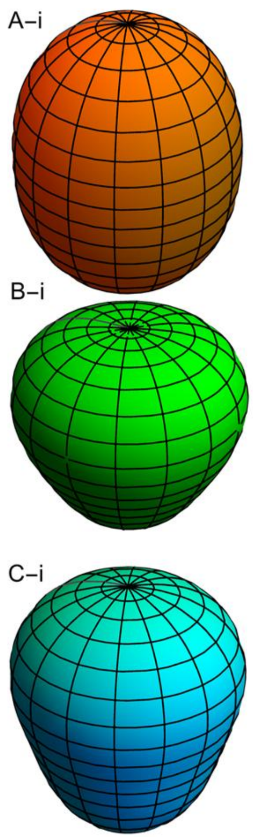


- **Magicity of ^{78}Ni was confirmed** from the high excitation energy of the newly-observed 2_1^+ state.
- Additional states are suggested, maybe corresponding to **intruder deformed states**.



Outline

- Introduction
- How do we approach experimentally?
- **What are new experiments at RIBF?**
  - — **γ softness and triaxiality**
  - — Octupole shape
  - — Shape coexistence

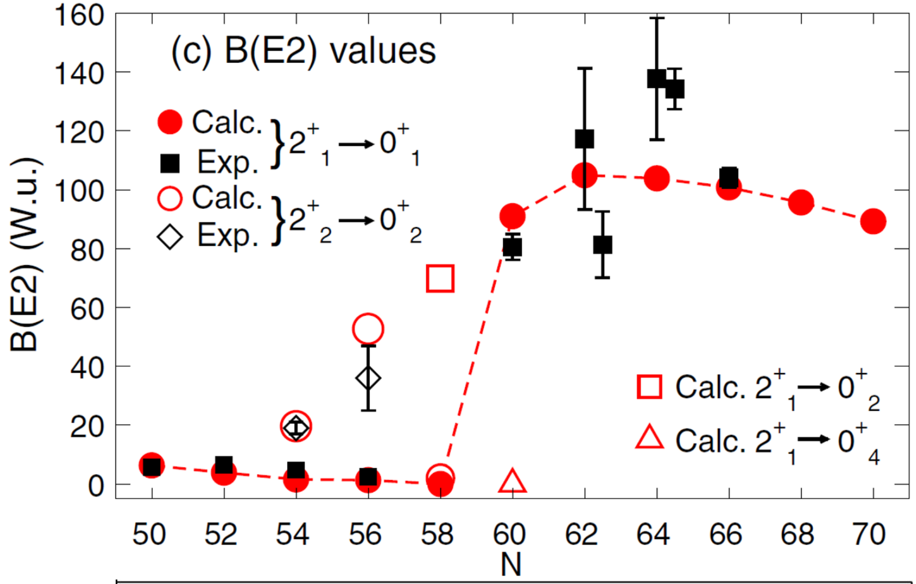


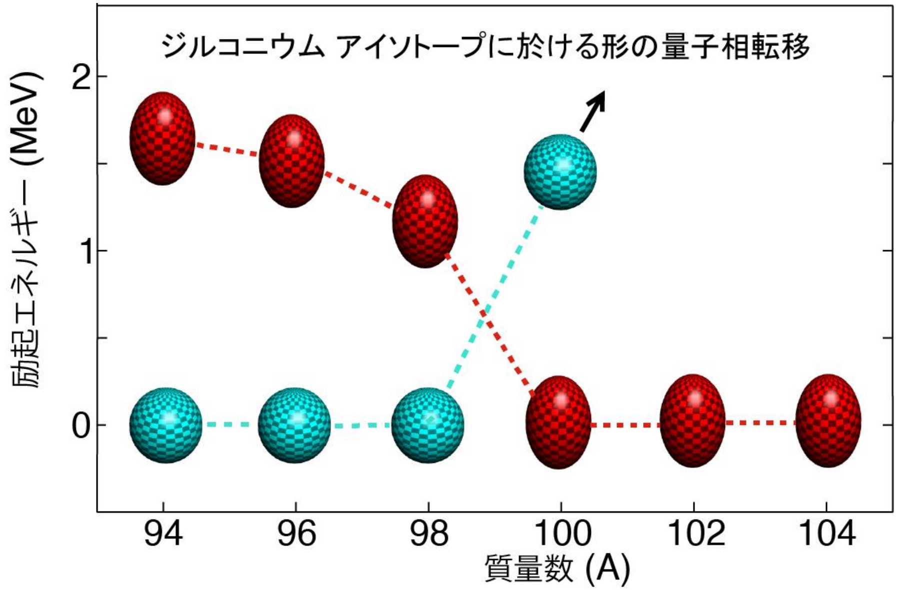
Critical shape transition in zirconium

From N = 58 to 60, a first-order–like change occurs in quadrupole shape.

- The electric quadrupole (E2) strength increases abruptly from ^{98}Zr to ^{100}Zr.
- This reflects a sudden **transition from spherical ground state to prolate ground state**

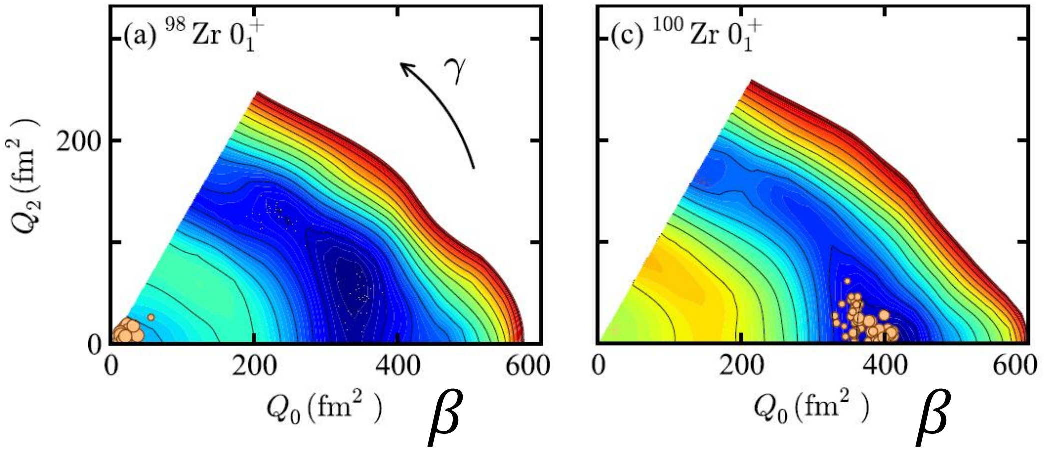
T. Togashi et al., PRL 117, 172502 (2016)

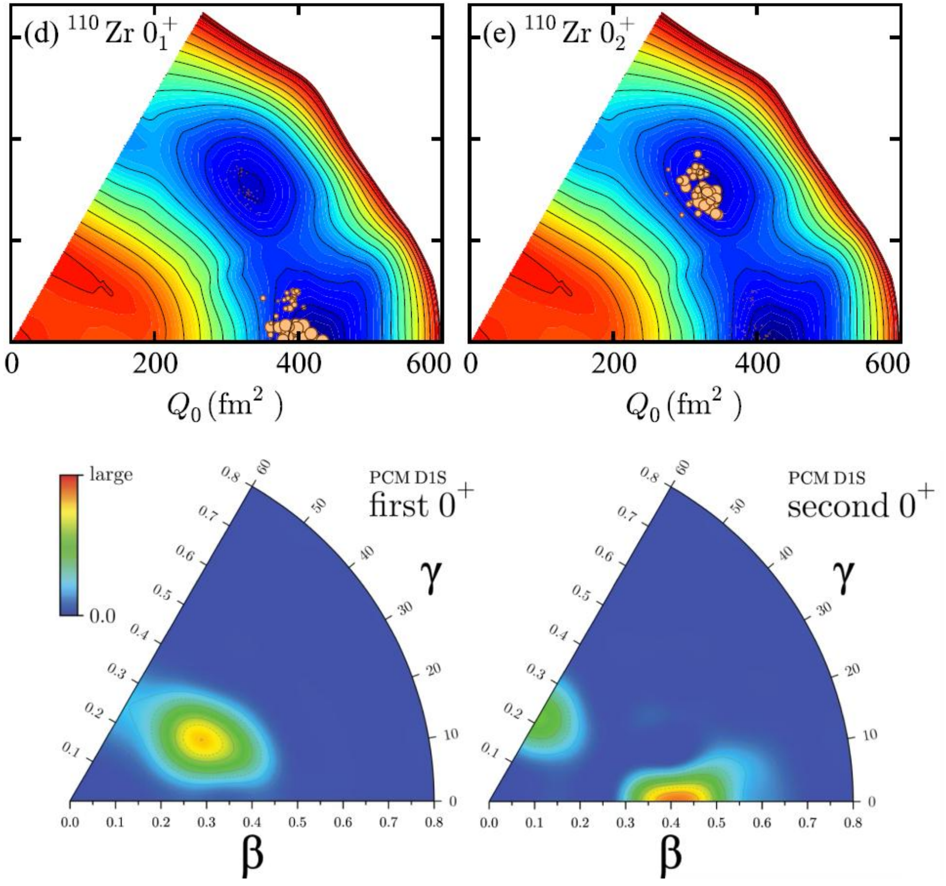




Triaxial fluctuations after Zr critical point

In ^{100}Zr, the γ degree of freedom starts strongly fluctuating.



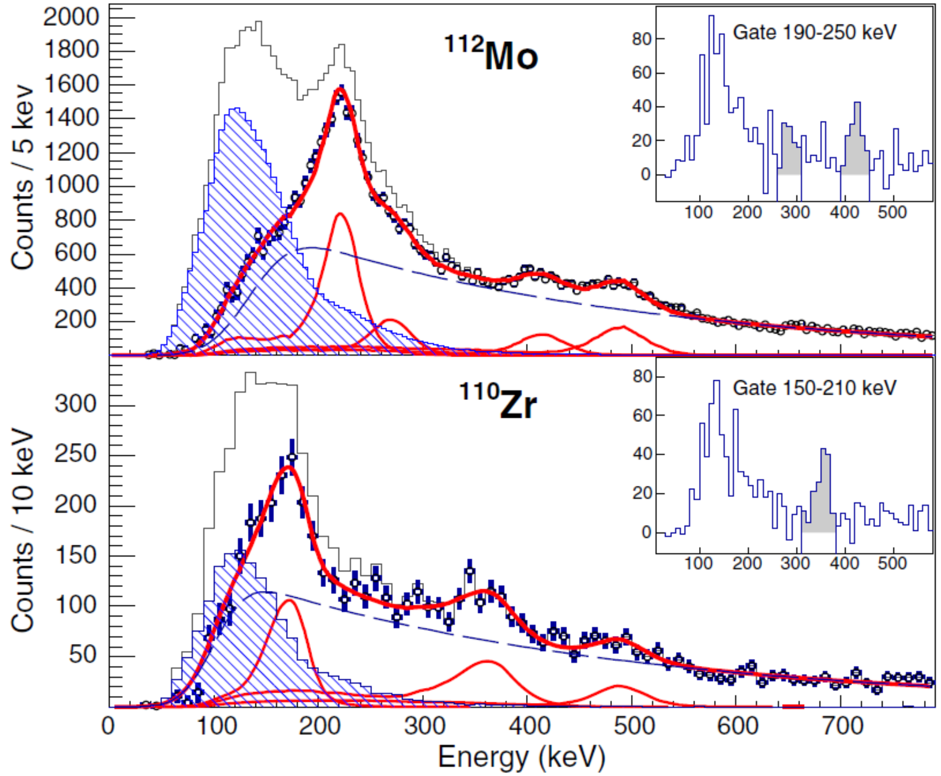


- How fluctuations evolve with neutron addition?
- Theories predict different shapes in more neutron-rich ^{110}Zr (10 neutrons addition to critical point at ^{100}Zr).

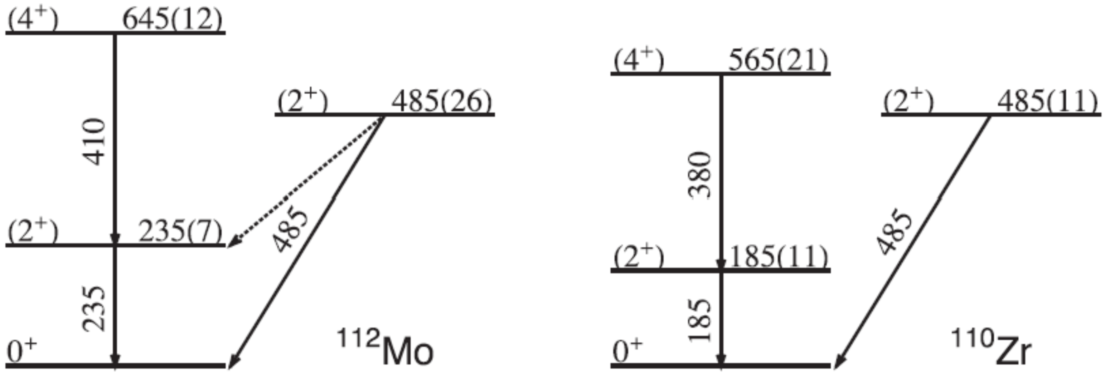
Previous study of ^{110}Zr and ^{112}Mo

Energy resolution is limited to resolve gamma-ray peaks.

DALI2



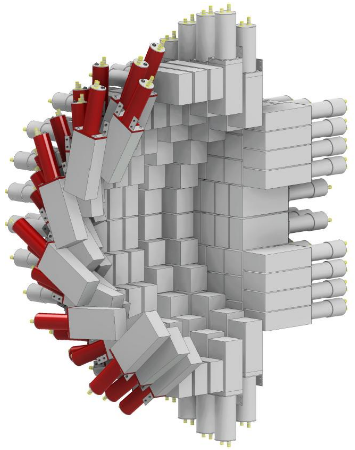
N. Paul+, PRL 2017



Higher energy resolution is critical for next step

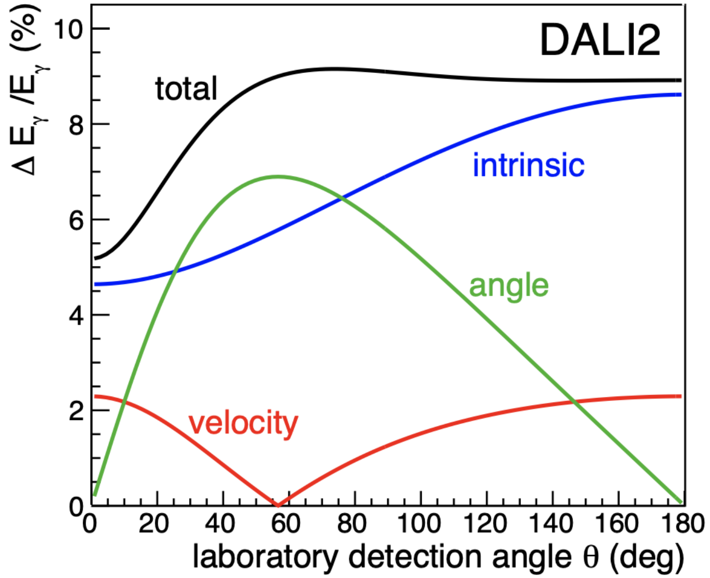
Uncertainty budget of energy resolution

NaI(Tl) array telescope DALI2



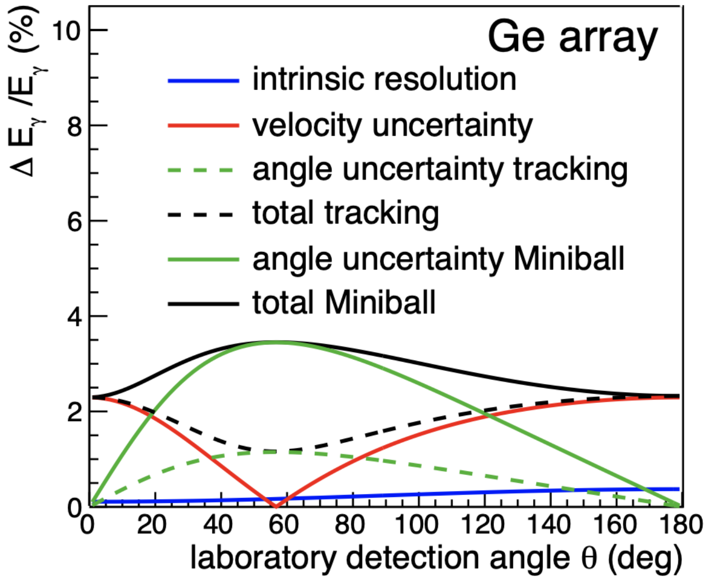
S. Takeuchi+ 2014

- About 200 NaI(Tl) detectors
- Very high detection efficiency ~25% at 1 MeV



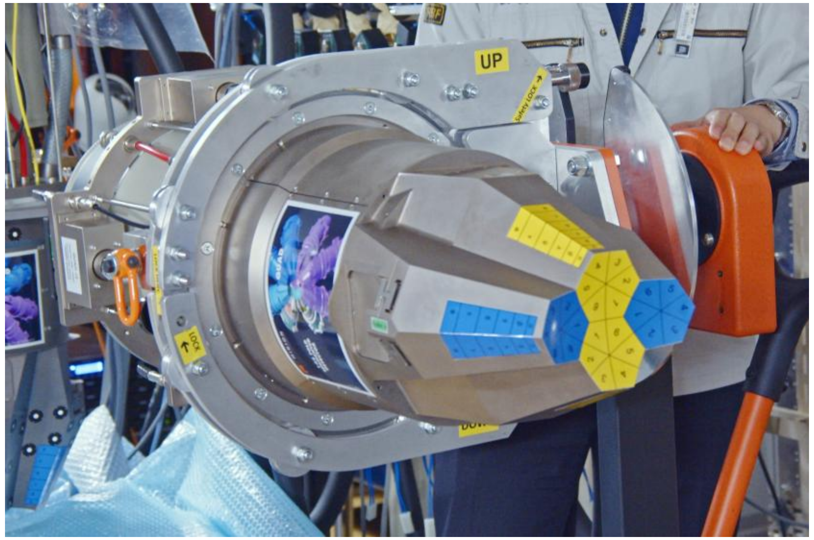
Germanium semiconductor detector

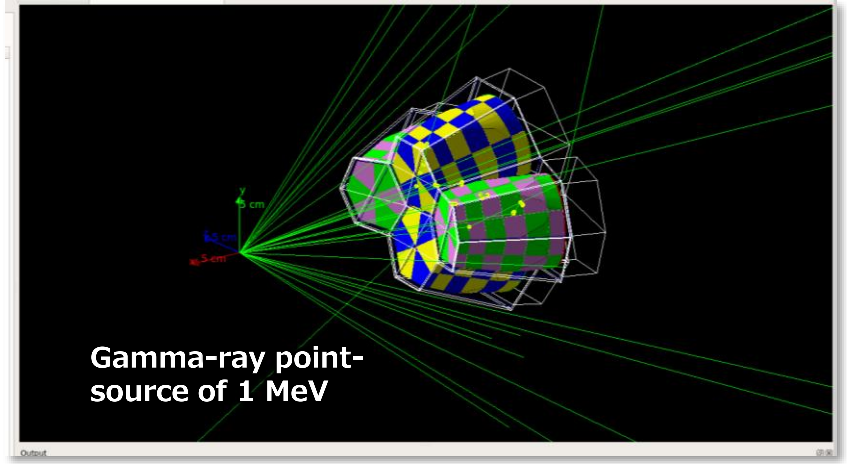
- Intrinsic energy resolution is excellent.
- **Angular uncertainty becomes the leading term.**

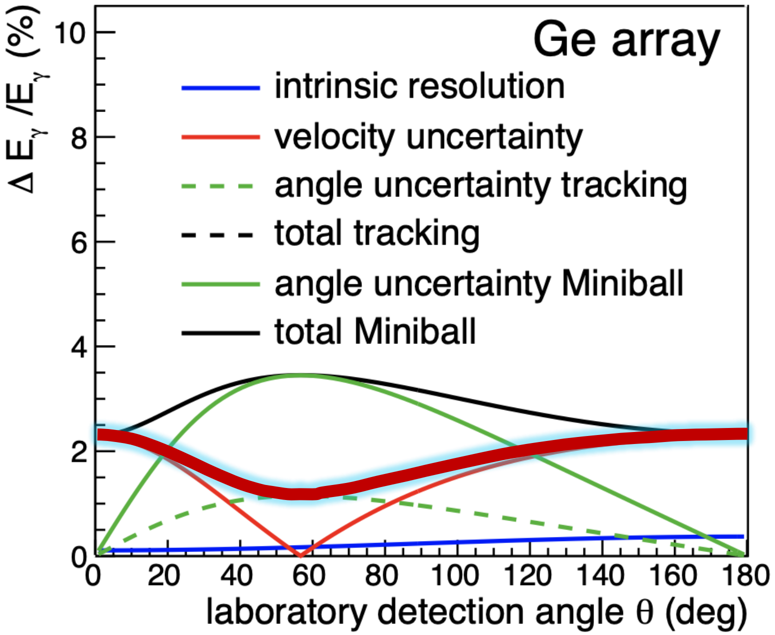


Gamma-Ray Tracking technology

Tracking Germanium detector



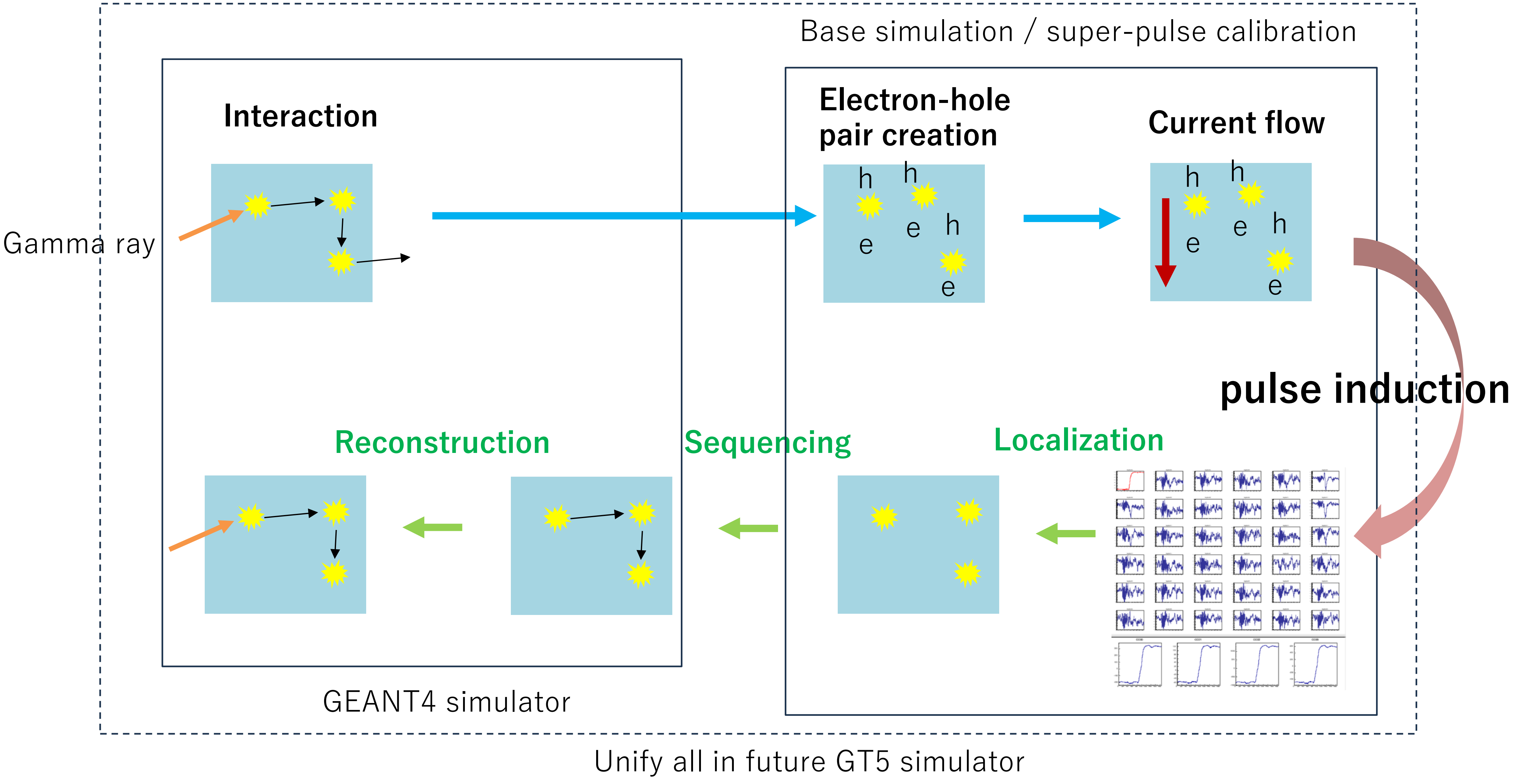




- Large size Ge crystal for detection efficiency
- **Locating interaction points inside crystal from multiple electrodes**

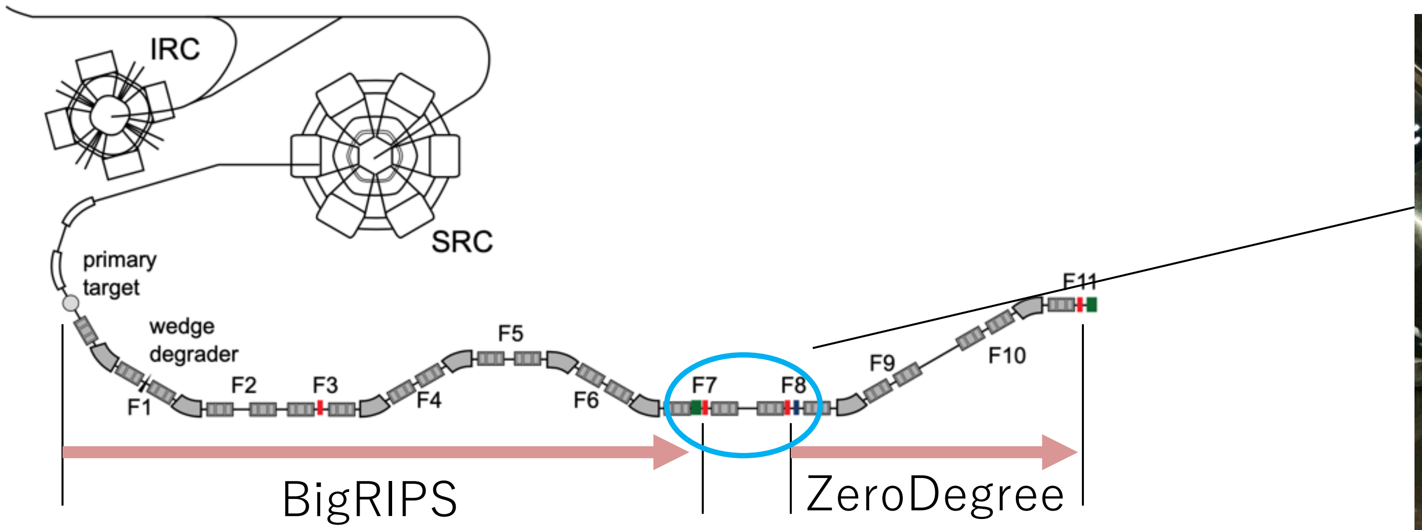
https://www.youtube.com/watch?v=wHC3wULA9IA

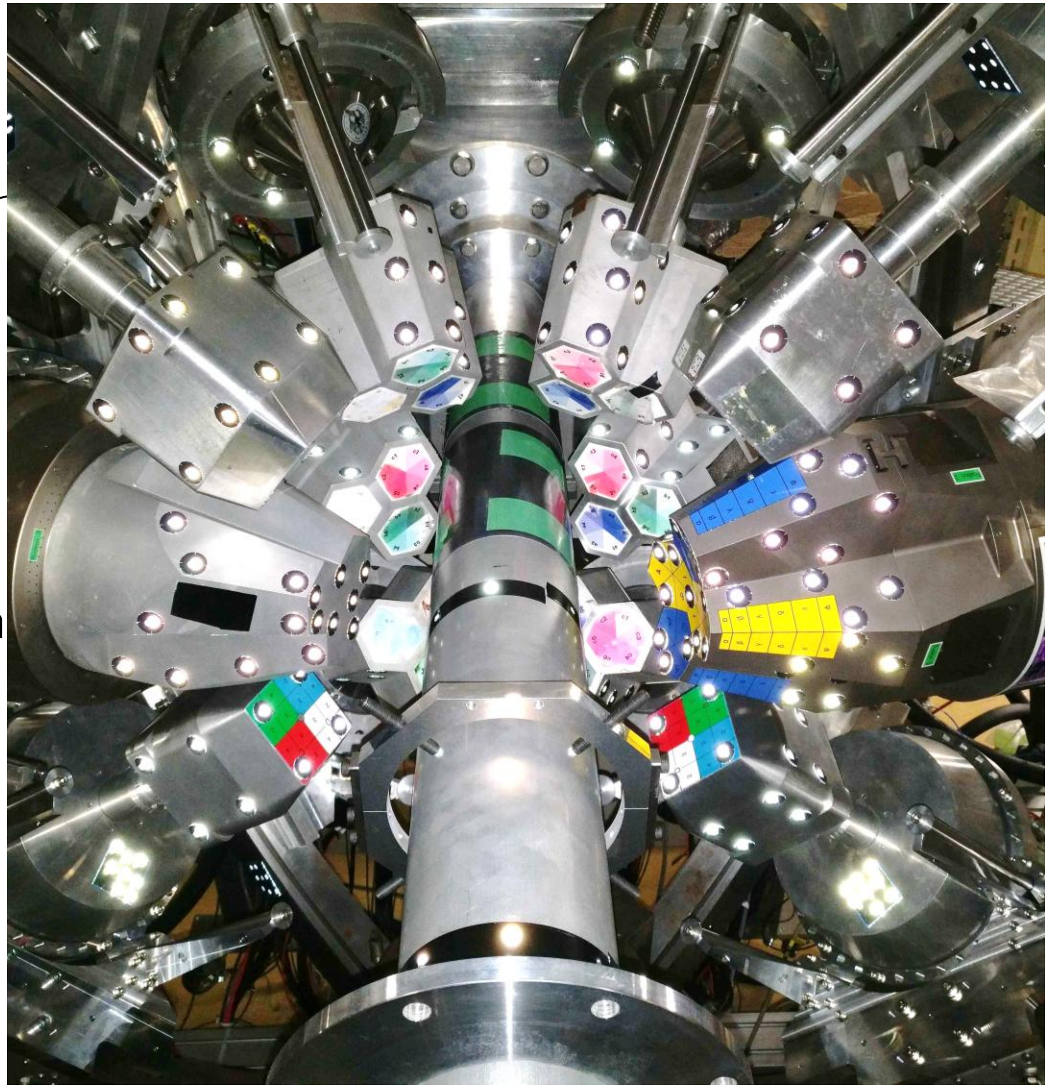
Method of gamma-ray tracking



High-resolution Cluster Array at RIBF (HiCARI) project

First use of Ge clusters for in-beam gamma-ray sepctroscopy at RIBF





HiCARI array based on large international collaboration

- 8 **Miniball triple-cluster** (6 installed, 2 backup)
- 1 **GRETINA Quad** from RCNP
- 1 **GRETINA P3** from LBNL
- 4 **Clover** detectors from IMP
- GRETINA electronics (RCNP, ANL, LBNL, U. Tokyo)
- Miniball frame from U. Köln
- In total ~3% detection efficiency @ 1 MeV

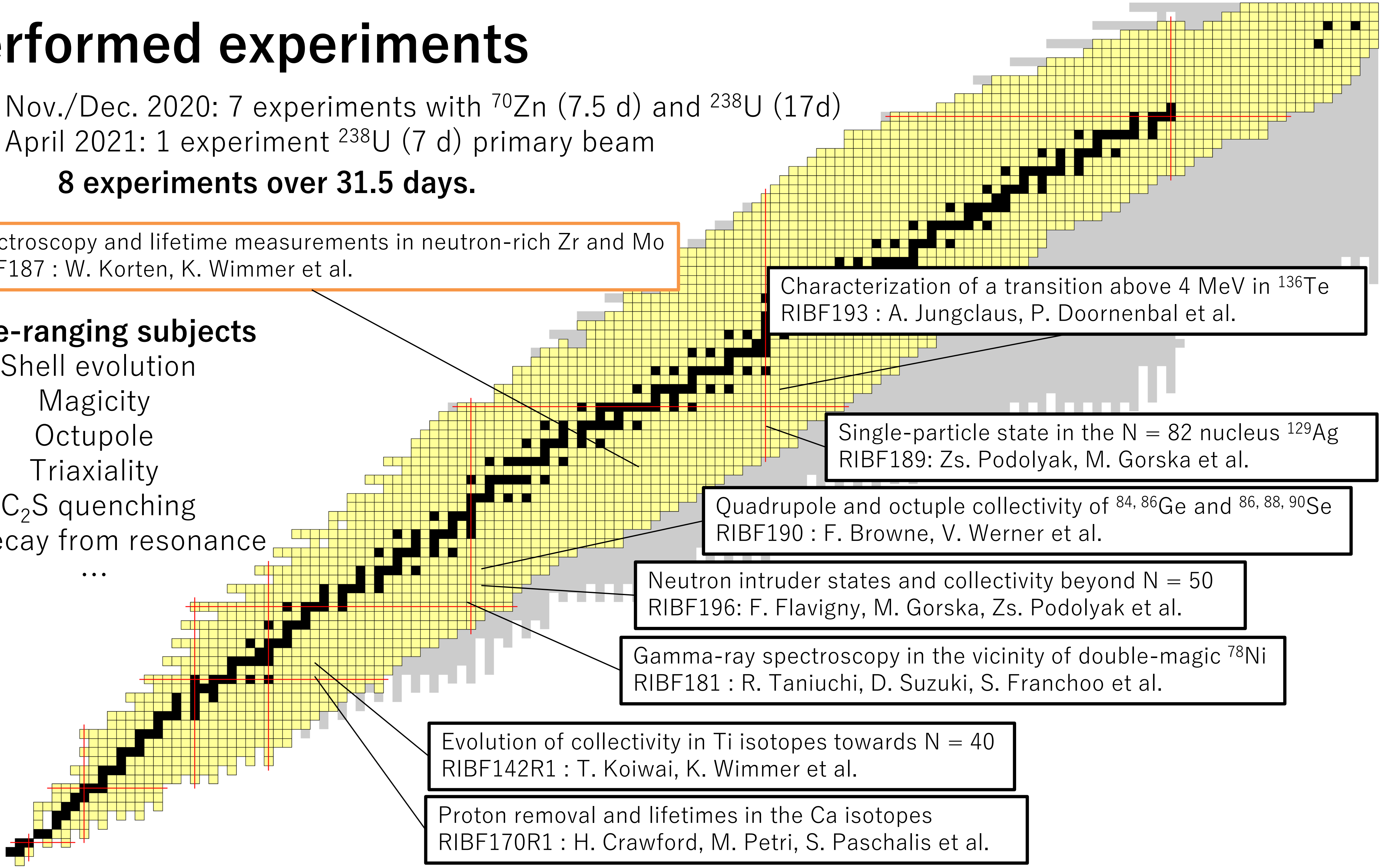
Performed experiments

- Nov./Dec. 2020: 7 experiments with ^{70}Zn (7.5 d) and ^{238}U (17d)
- April 2021: 1 experiment ^{238}U (7 d) primary beam

8 experiments over 31.5 days.

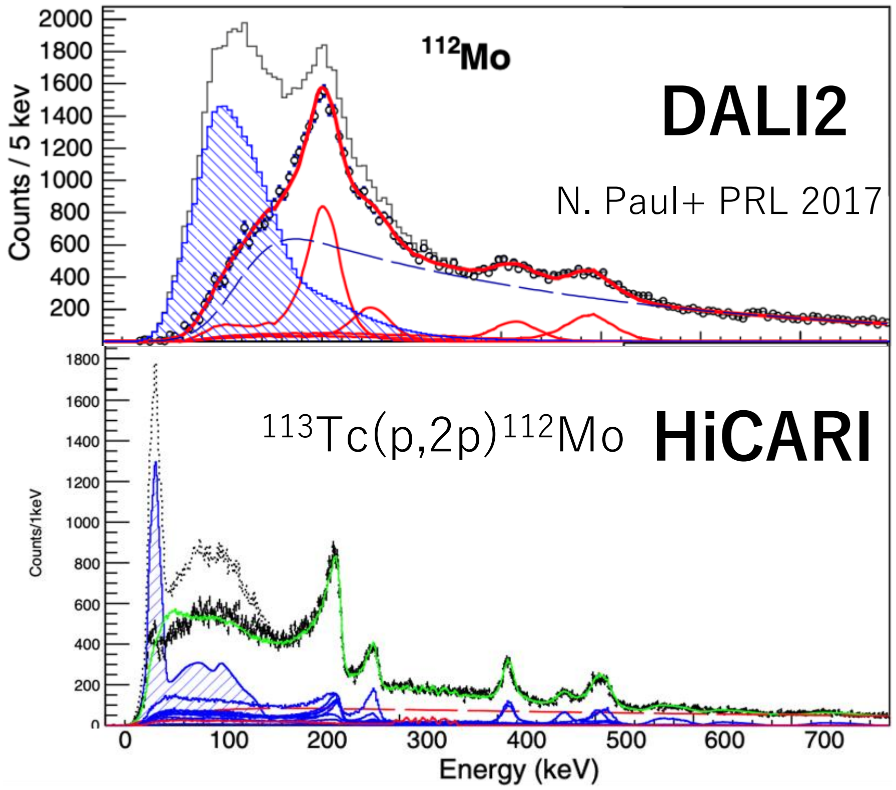
Wide-ranging subjects

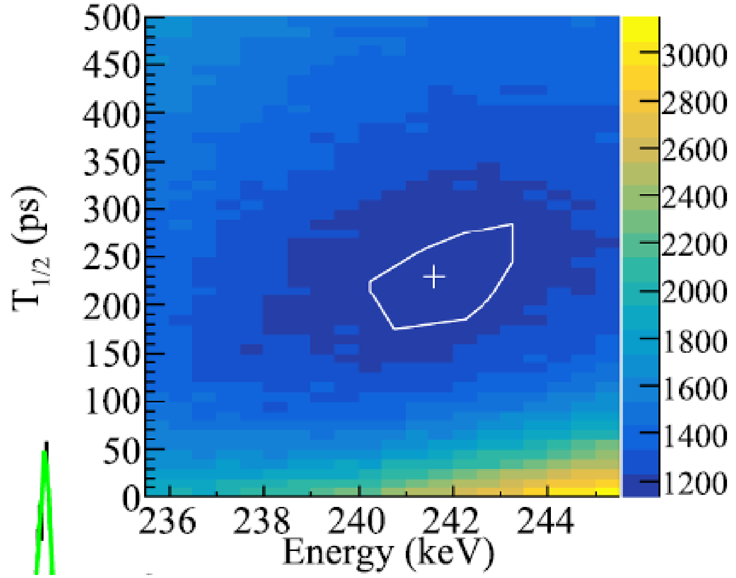
Shell evolution
Magicity
Octupole
Triaxiality
C_2S quenching
γ-decay from resonance
…



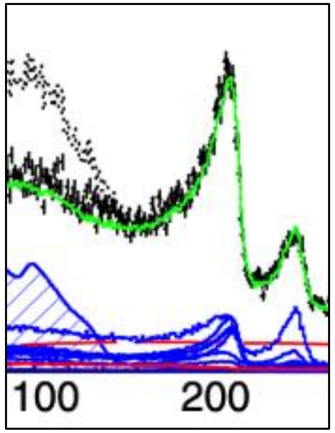
Spectroscopy of ^{108,110}Zr and ^{110,112}Mo

- Neutron-rich ^{108,110}Zr and ^{110,112}Mo nuclei were studied by HiCARI telescope.
- Lifetime is determined from the line shape of the gamma-ray peak.



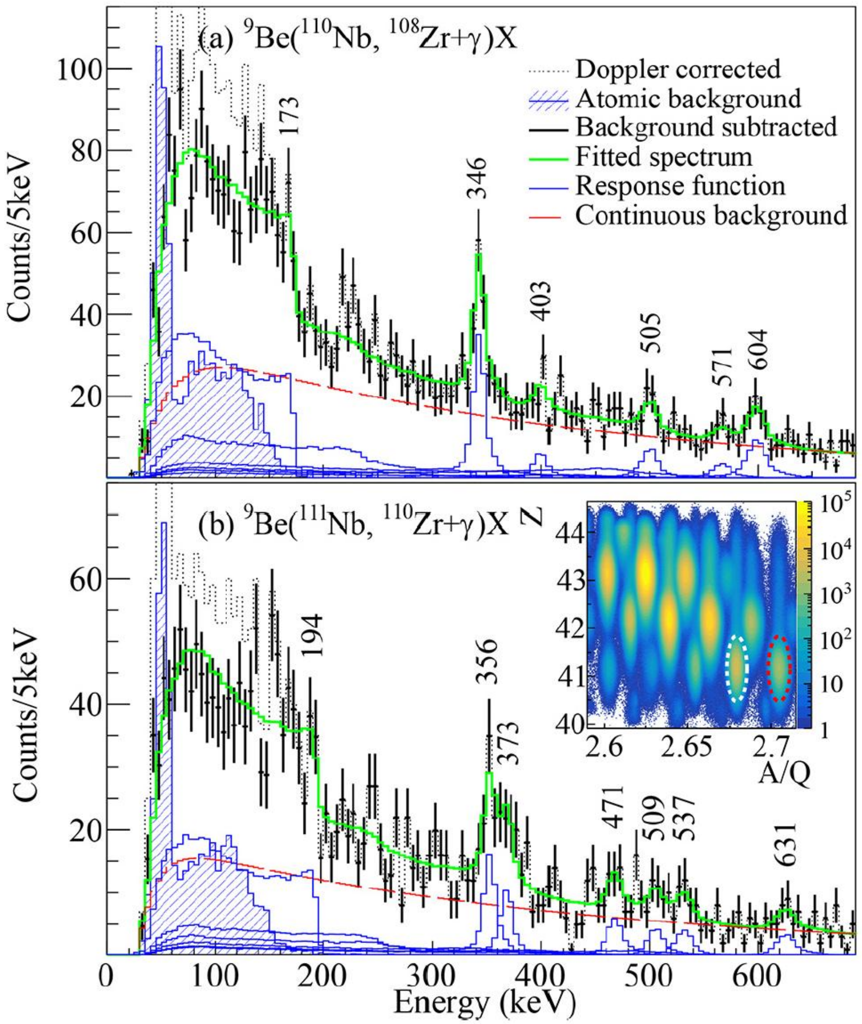


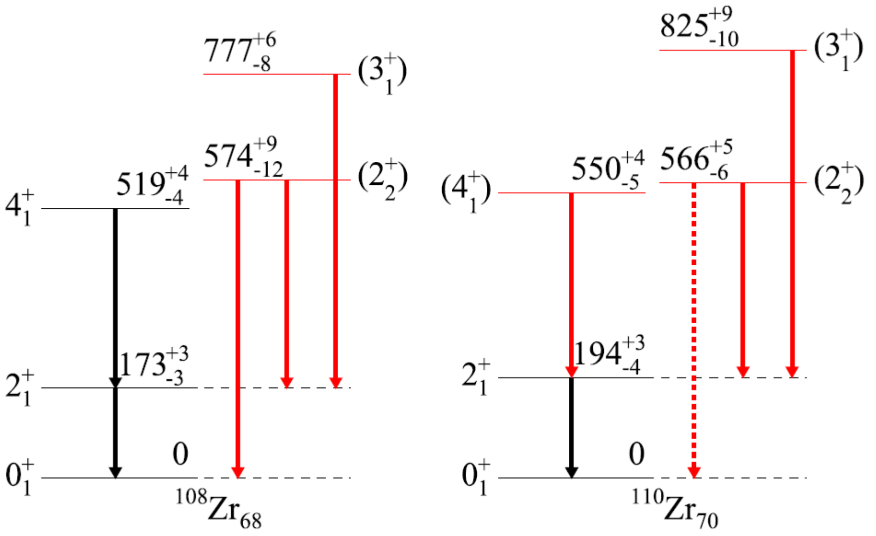
Lifetime for gamma-decay

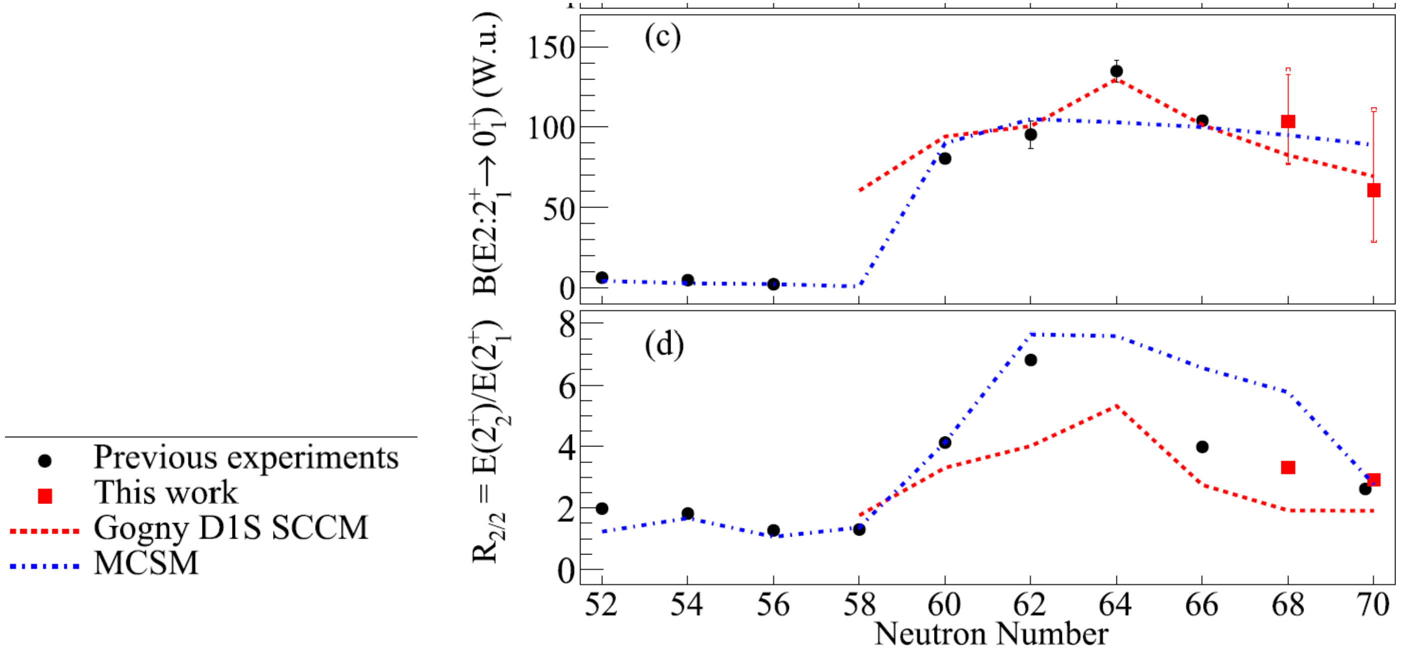


Triaxial shape in Zr isotopes

Measurement of E2 transition strengths clarified the development after the critical point at N = 60.



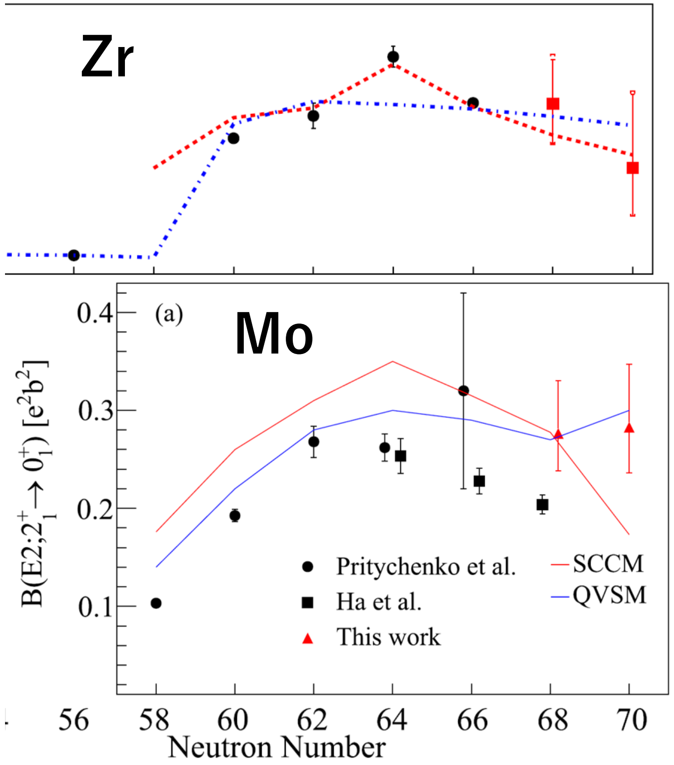


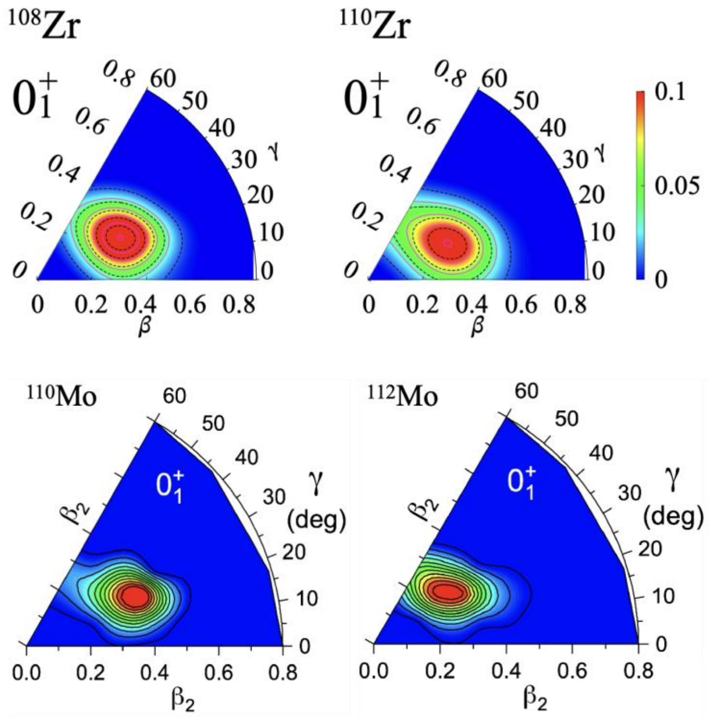


Triaxial shape in Zr and Mo isotopes

Measurement of E2 transition strengths clarified the development after the critical point at N = 60.

- **Reducing E2 strength** indicates triaxiality is selected in the ground state.
- **γ fluctuations develop into triaxial shape both in Zr and Mo.**





HFB-SCCM with Gogny interaction

Courtesy: B. Moon (IBS)

B. Moon et al., PLB 858, 139047 (2024)

B. Moon *et al.*, PLB 870, 139904 (2025)

Summary

- Shape transition is a unique emergent phenomenon of finite nuclei.
- In-beam gamma-ray spectroscopy with RI beam is a key experimental technique.
- Gamma-ray tracking technology will advance shape studies to the next step.
- Fluctuation, freeze-out and interferences are our interest in recent HiCARI project a,on-going experimental studies;