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"Nuclear Fission and Structure of Exotic Nuclei"
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Search for new isotopes and new isomers using in-flight fission of a 345 MeV/nucleon ^{238}U beam at RIKEN RI Beam Factory

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BigRIPS team
RIKEN Nishina Center, Japan

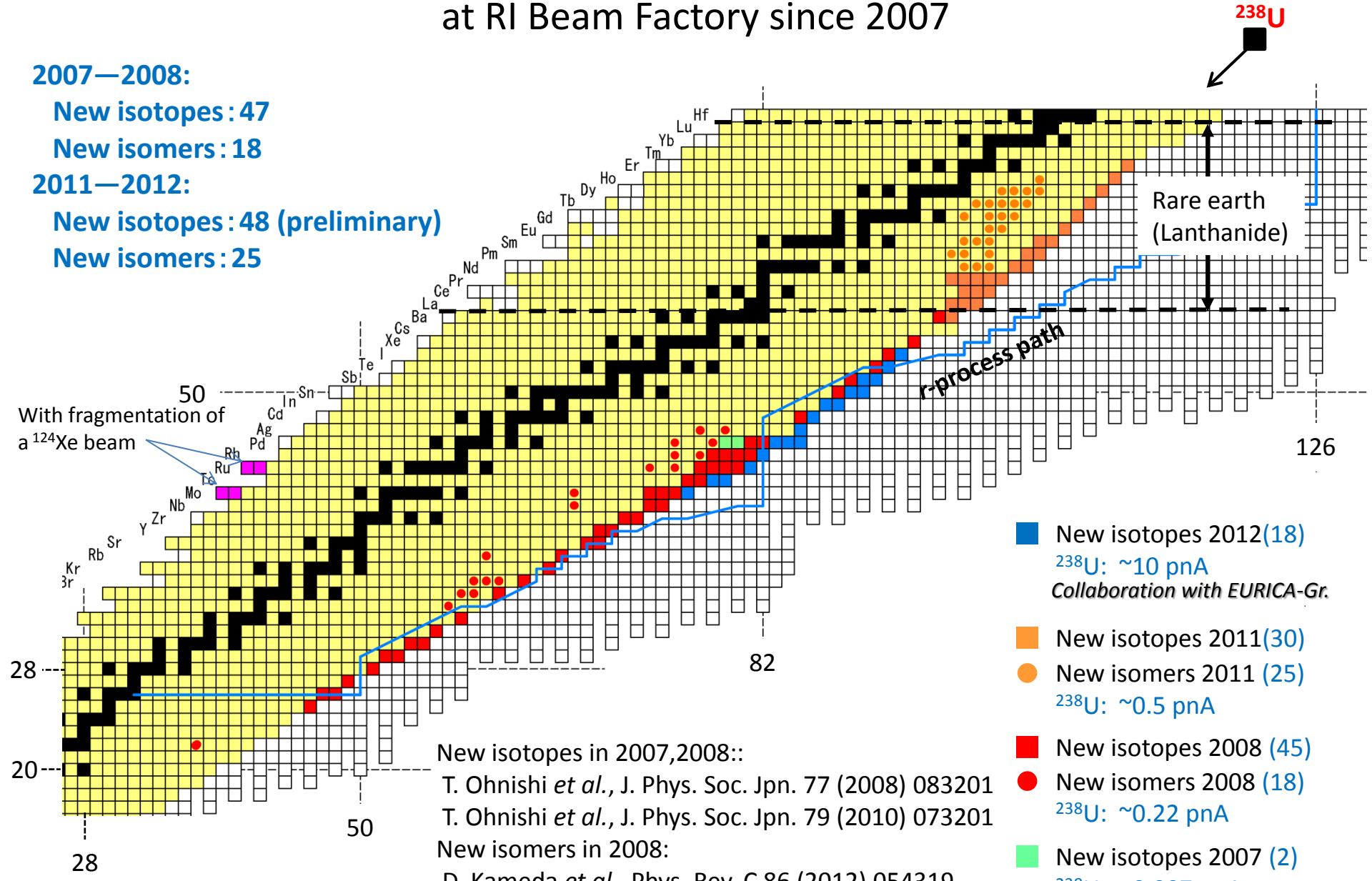
Outline

1. Overview of new isotope and new isomer search at RIBF
2. Experimental setup for the recent measurements in 2011
3. Experimental results
   - ✓ New isotopes and production cross section
   - ✓ New isomers and isomerism
4. Summary

Overview of the search for new isotopes and new isomers at RI Beam Factory since 2007

2007—2008:
- **New isotopes : 47**
- **New isomers : 18**

2011—2012:
- **New isotopes : 48 (preliminary)**
- **New isomers : 25**



New isotopes in 2007,2008::
T. Ohnishi *et al.*, J. Phys. Soc. Jpn. 77 (2008) 083201
T. Ohnishi *et al.*, J. Phys. Soc. Jpn. 79 (2010) 073201
New isomers in 2008:
D. Kameda *et al.*, Phys. Rev. C 86 (2012) 054319

- New isotopes 2012(18)
  ^{238}U: ~10 pnA
  Collaboration with EURICA-Gr.
- New isotopes 2011(30)
- New isomers 2011 (25)
  ^{238}U: ~0.5 pnA
- New isotopes 2008 (45)
- New isomers 2008 (18)
  ^{238}U: ~0.22 pnA
- New isotopes 2007 (2)
  ^{238}U: ~0.007 pnA

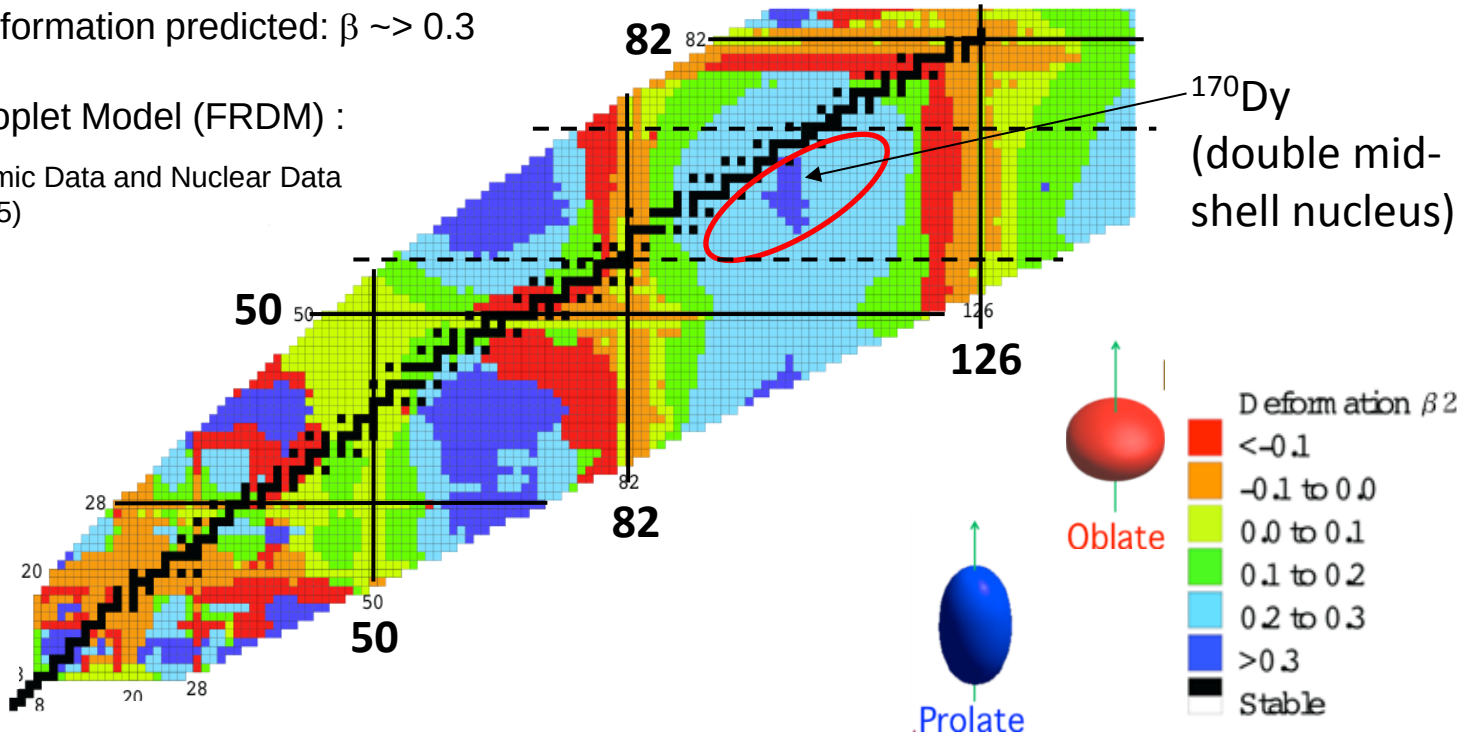
Neutron-rich rare earth nuclei

- Difficult to access by the traditional means
- Static prolate deformation in a wide range of the rare earth nuclei
- The large deformation in the double mid-shell region around ^{170}Dy
- Isomer systematics in well deformed nuclei: (high) *K* isomers…

Large prolate deformation predicted: β ~> 0.3

Finite Range Droplet Model (FRDM) :

P. Möller et al., Atomic Data and Nuclear Data Tables **59**,185 (1995)

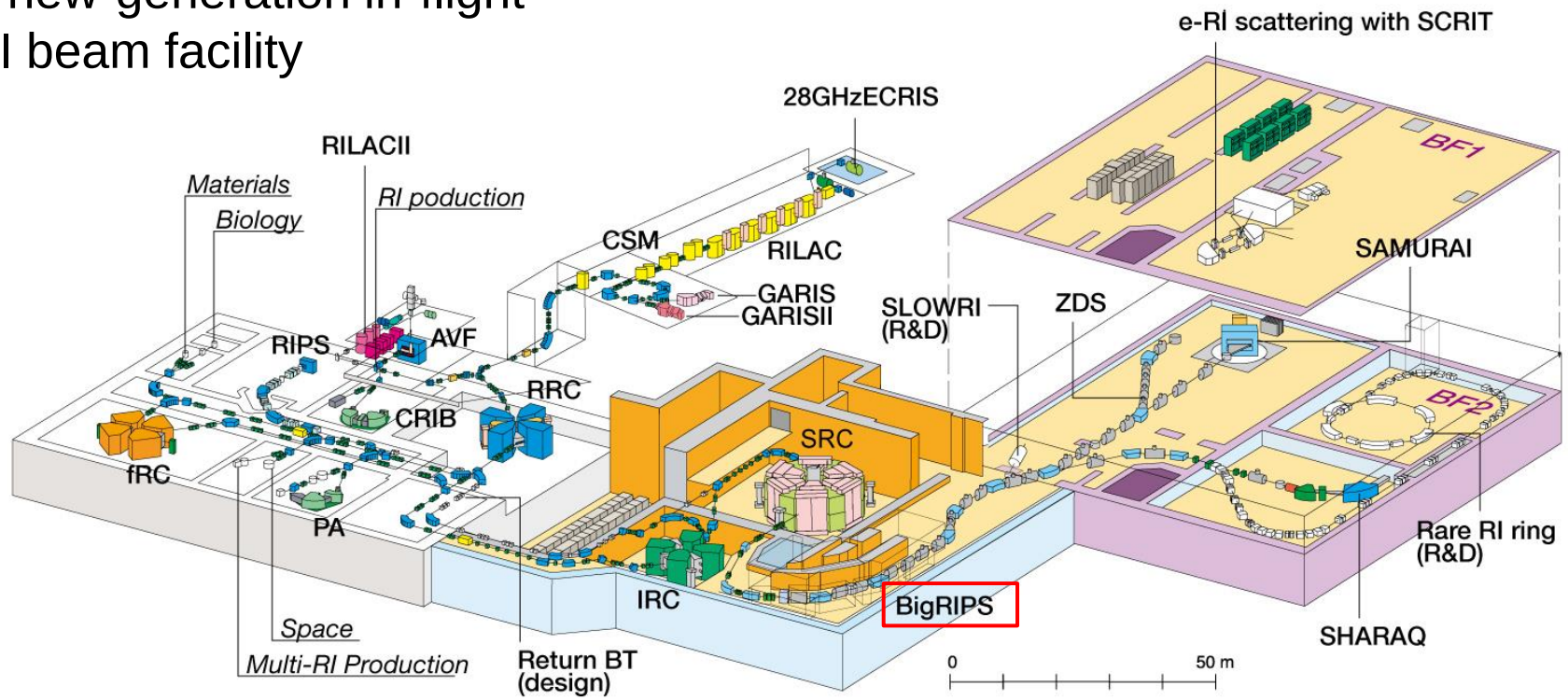


We have expanded the known frontier in this region with the new-generation in-flight separator BigRIPS at RIKEN

Layout of RI Beam Factory (RIBF)

E ~350 MeV/u up to U
(goal intensity ~1 pμA)

A new-generation in-flight
RI beam facility



- Major features of BigRIPS separator
- Large acceptances Comparable with the spreads of in-flight fission of ^{238}U
- Two-stage separator scheme with excellent particle identification (PID)

PID scheme based on TOF-Bρ-ΔE method with track reconstruction → Z and A/Q

A/Q resolution is high enough to identify charge state events

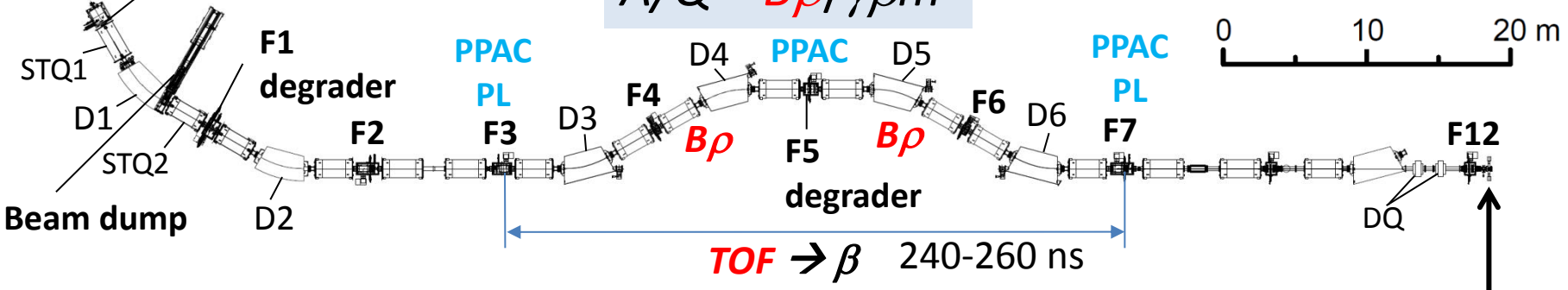
Particle identification (PID) by the TOF-$B\rho$-ΔE method

U beam
345 MeV/u, 0.5 pnA

The BigRIPS fragment separator

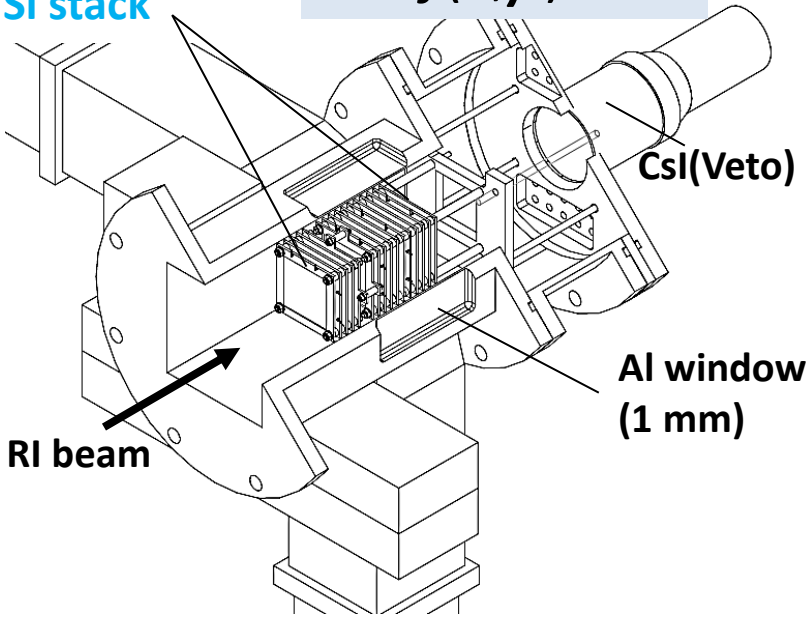
Be target:4mm, 5mm

$$A/Q = B\rho/\gamma\beta m$$

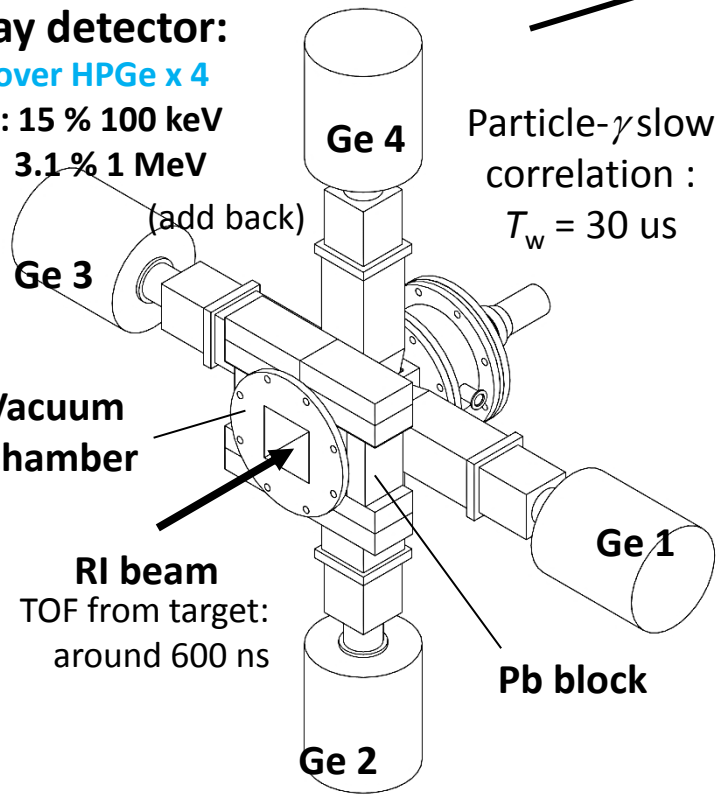


ΔE detector:
Si stack

$$\Delta E = f(Z,\beta) \rightarrow Z$$

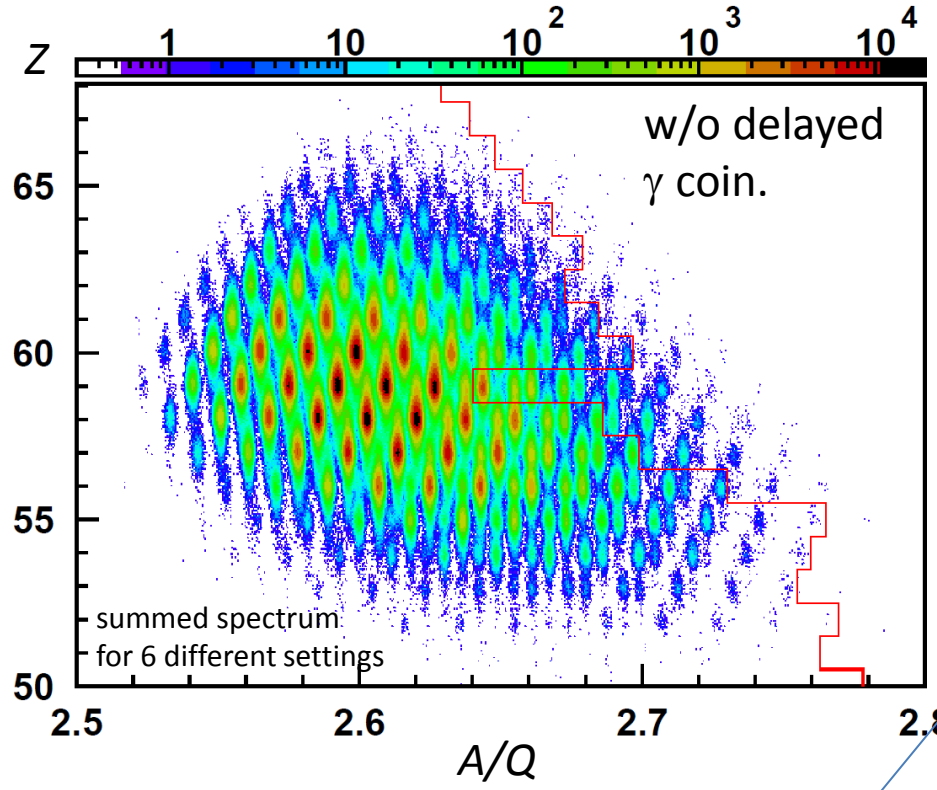


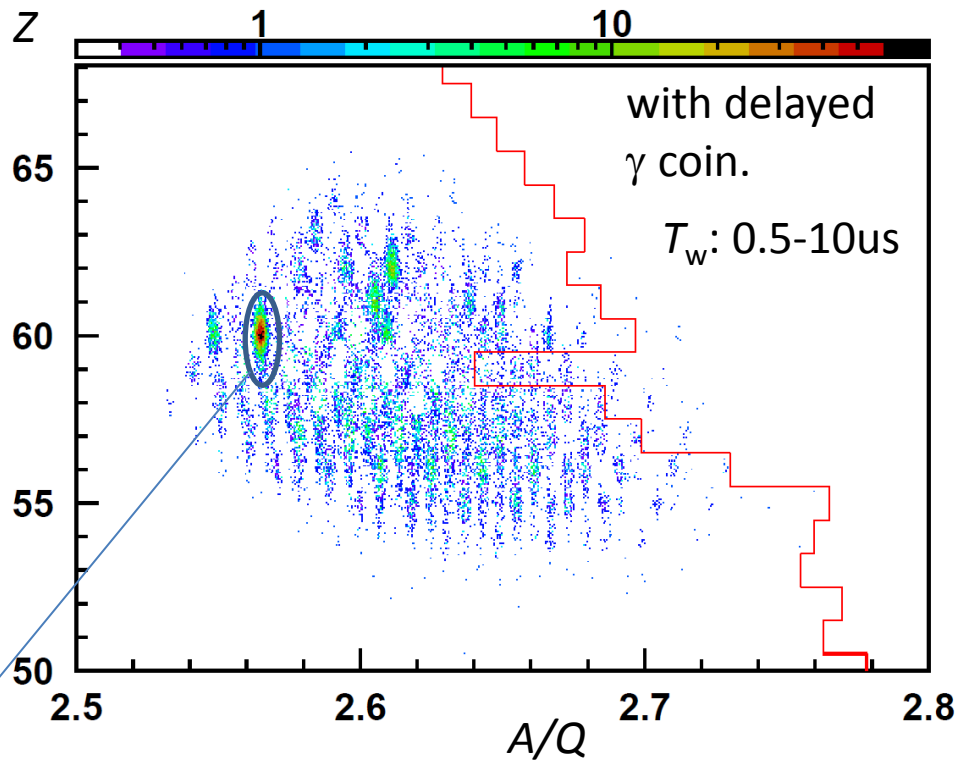
γ-ray detector:
Clover HPGe x 4
ε_γ: 15 % 100 keV
3.1 % 1 MeV

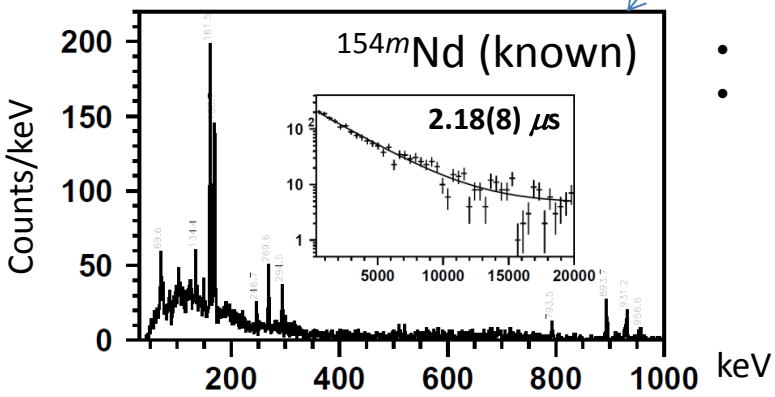


Particle-γ slow correlation :
T_w = 30 us

PID plots in the BigRIPS setting for *Z~59* region





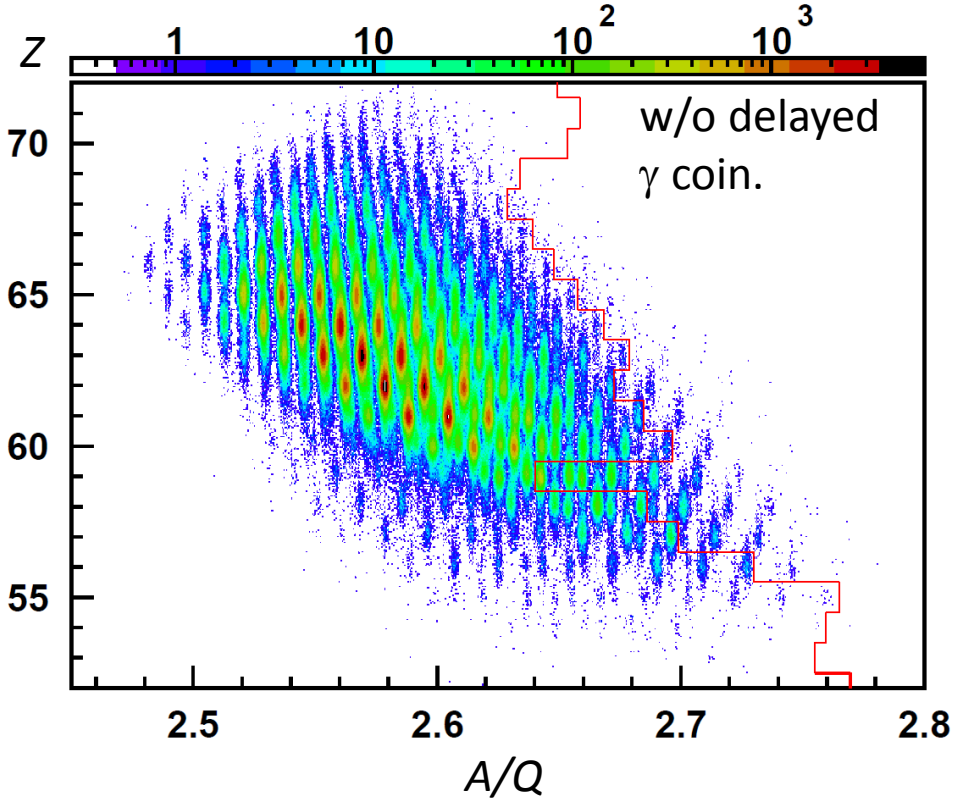


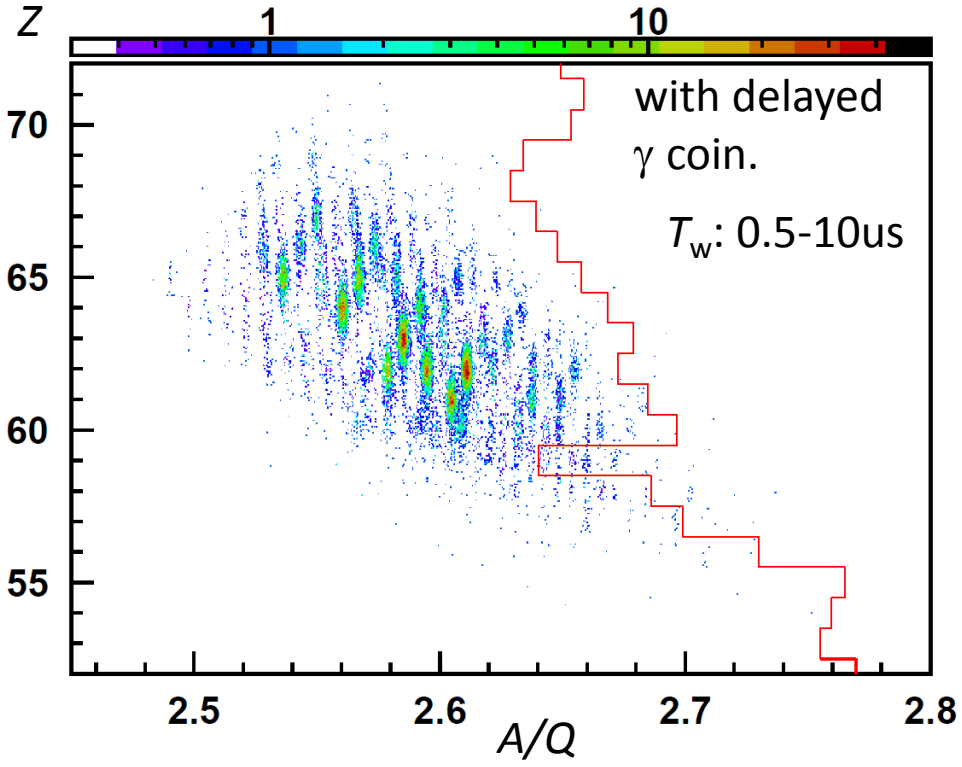
- **We observed all the previously-reported γ-rays of ^{154m}Nd**
- **The present half-life fairly agrees with the previouly-reported value of 3.8 us.**

G. Simpson et al., PRC80(2009)024304

→ confirm our particle identification (isomer tagging)

PID plots in the setting for a *Z*~64 region

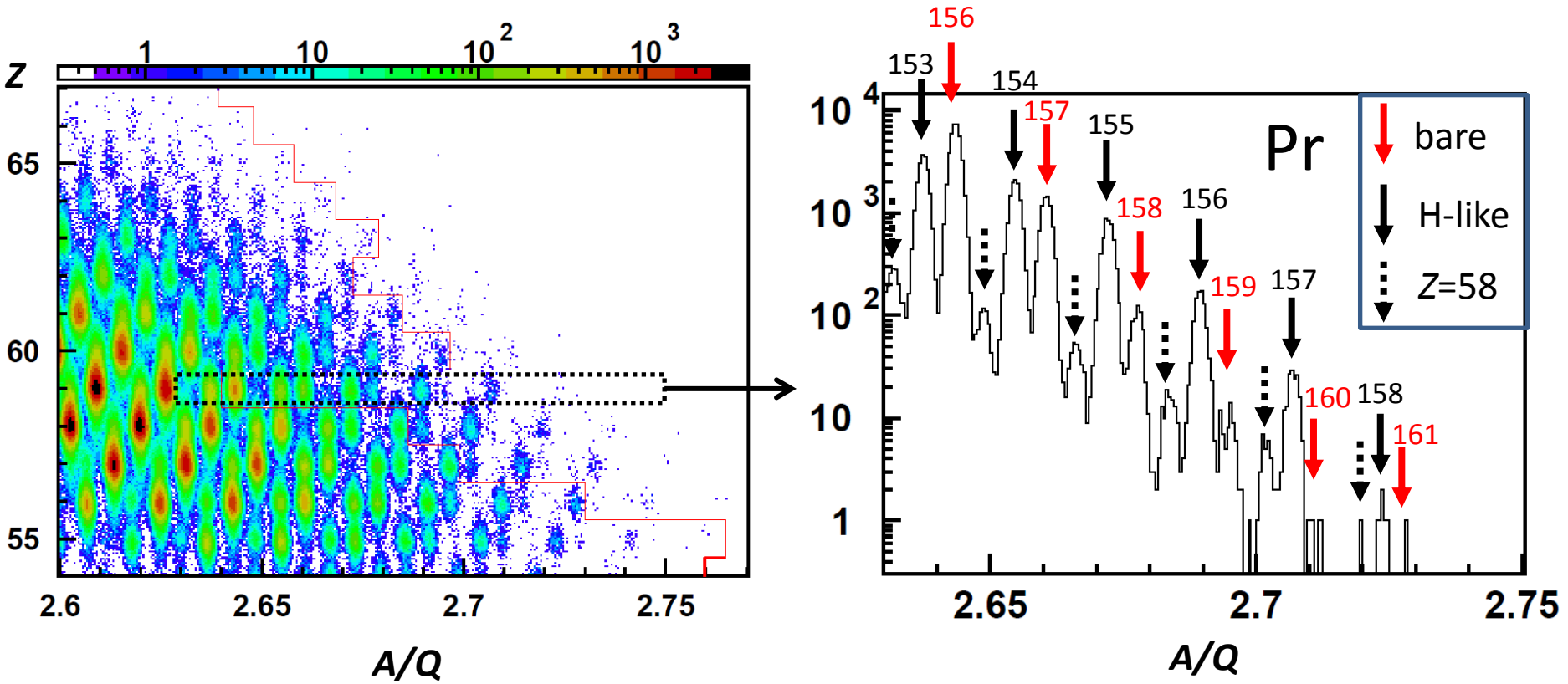




We observed a number of unknown isomers along with several previously reported isomers such as ^{159m}Sm and ^{156m}Nd

Identification of charge states

Case of the Pr(Z=59) isotopes:



A/Q resolution: 0.04 %

Z resolution: 0.4 %

The fully-stripped events are identified as well as the H-like and neighboring isotope events with different *Z* numbers

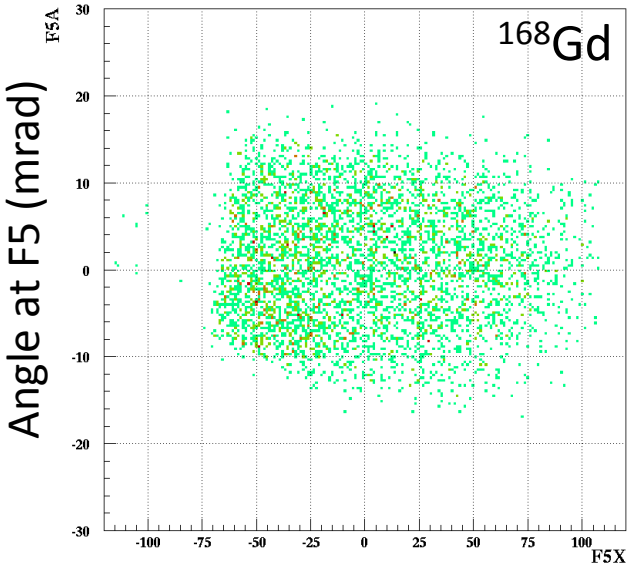
A total of 30 new isotopes has been identified:

^{179,180}Er, ^{177,178}Ho, ^{175,176}Dy, ^{173,174}Tb, ^{171}Gd, ^{169}Eu, ^{166,167}Sm, ^{164,165}Pm, ^{162,163}Nd, ^{156,157,158,159,160,161}Pr, ^{156,157,158}Ce, ^{154,155,156}La

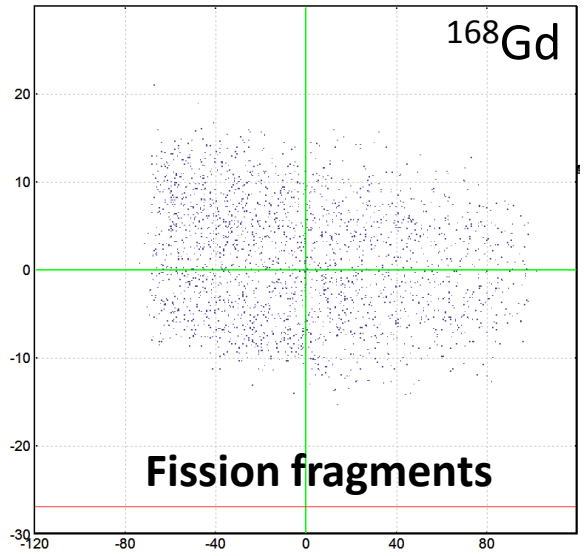
Kinematics of fragments

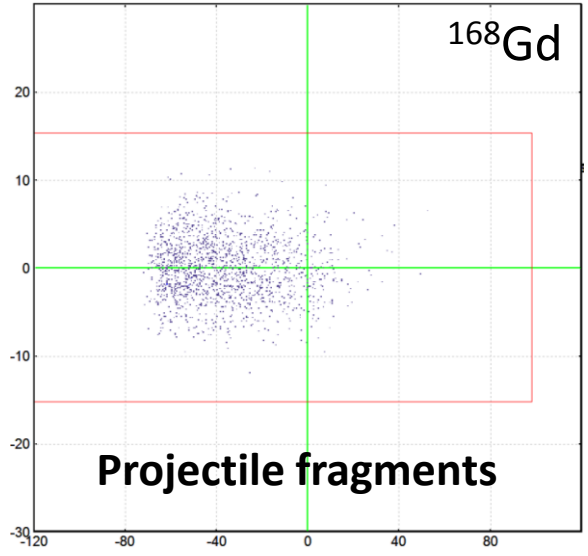
- Phase space at the dispersive focal plane (F5) -

Experiment



Simulation with LISE++:



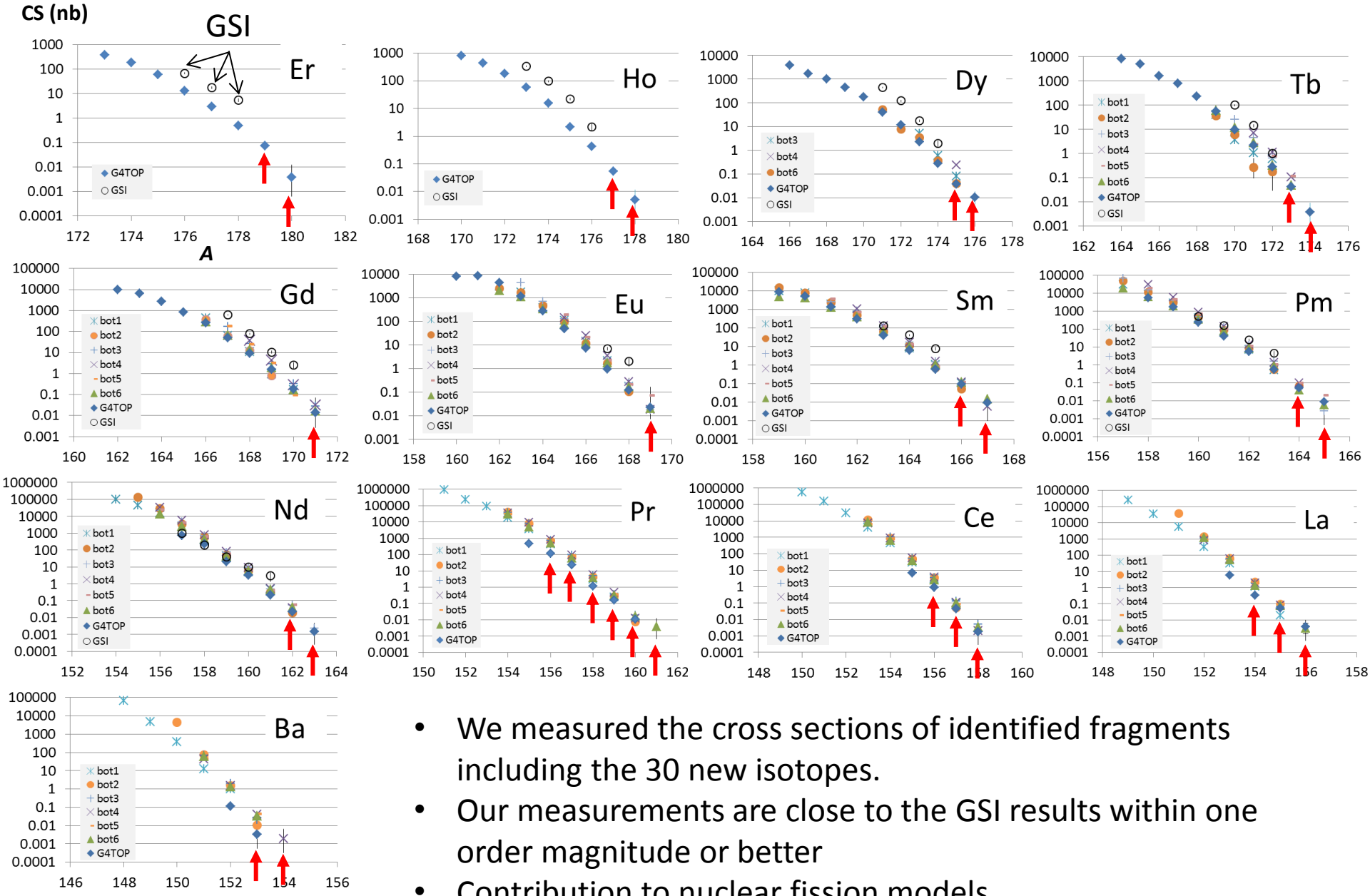


LISE++ code (ver 9.8.32):
O.B. Tarasov and D. Bazin, NIM B 266, 4657 (2008).

The momentum and angular spreads are fairly well reproduced by the kinematics of fission → Dominance of the fission process

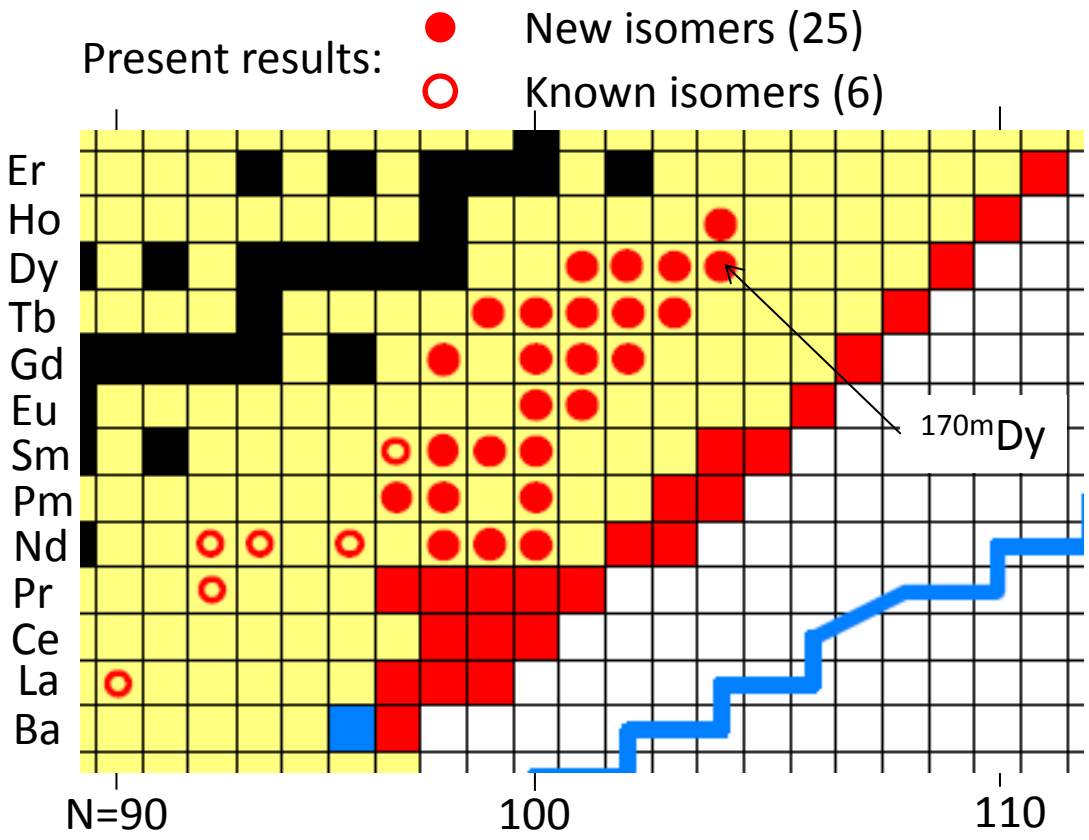
Consistent with the GSI experiment for *Z*=60-69 fragments produced with a 1GeV/u ^{238}U beam:
J. Kurcewicz et al., Phys. Lett. B 717 (2012) 371.

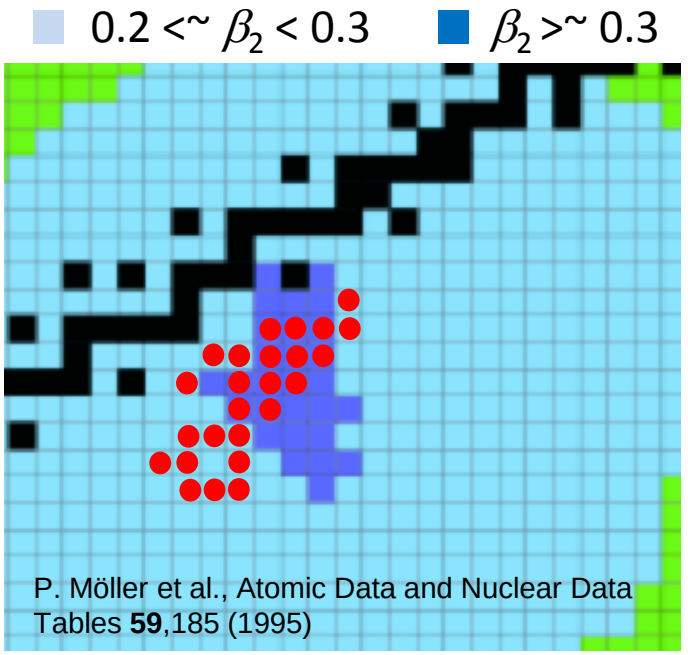
Production cross sections (Preliminary)



- We measured the cross sections of identified fragments including the 30 new isotopes.
- Our measurements are close to the GSI results within one order magnitude or better
- Contribution to nuclear fission models

Overview of isomer results





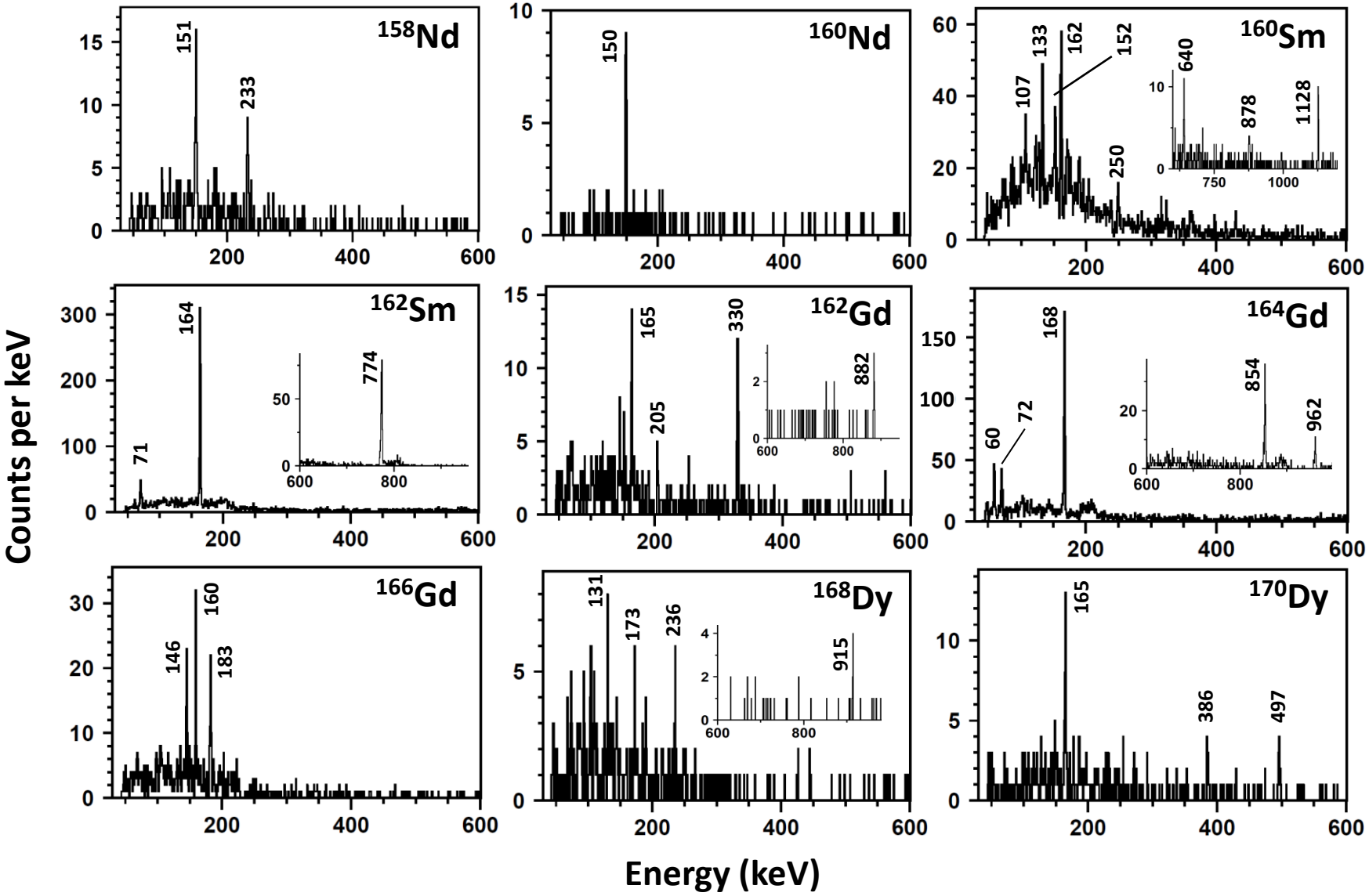
We observed a total of 25 new isomers with microsecond half-lives in well-deformed nuclei:
^{158m}Nd, ^{159m}Nd, ^{160m}Nd, ^{158m}Pm, ^{159m}Pm, ^{161m}Pm, ^{160m}Sm, ^{161m}Sm, ^{162m}Sm, ^{163m}Eu, ^{164m1,m2}Eu, ^{162m}Gd, ^{164m}Gd, ^{165m}Gd, ^{166m}Gd, ^{164m}Tb, ^{165m}Tb, ^{166m}Tb, ^{167m}Tb, ^{168m}Tb, ^{167m}Dy, ^{168m}Dy, ^{169m}Dy, ^{170m}Dy, ^{171m}Ho

We observed 6 previously-reported isomers in this region: ^{148m}La, ^{152m}Pr, ^{153m}Nd, ^{154m}Nd, ^{156m}Nd, ^{159m}Sm → confirmation of our PID (Isomer tagging)

Spectroscopic studies of new isomers are in progress.

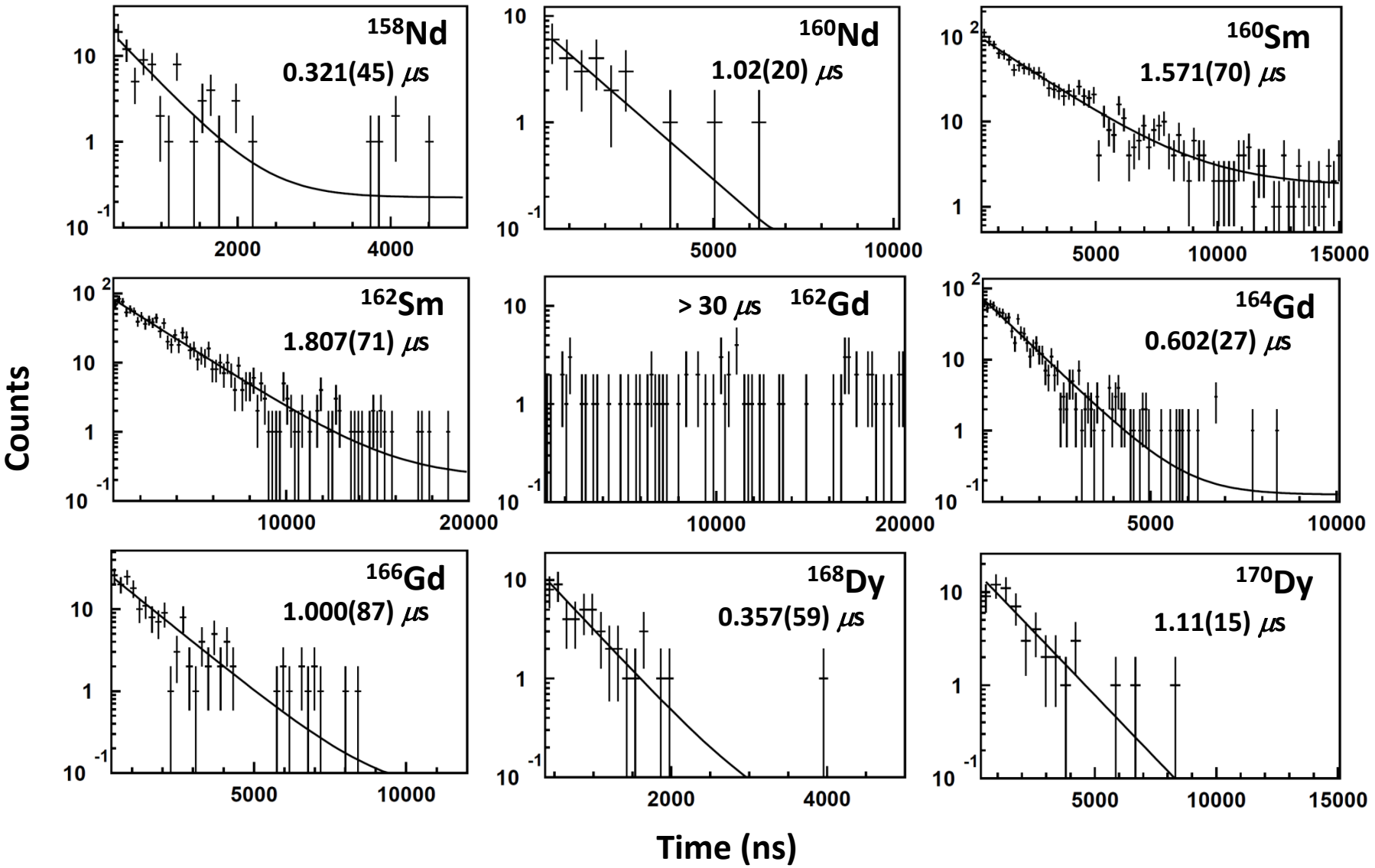
Energy spectra of new isomers

even-even nuclei



Time spectra of new isomers

even-even nuclei



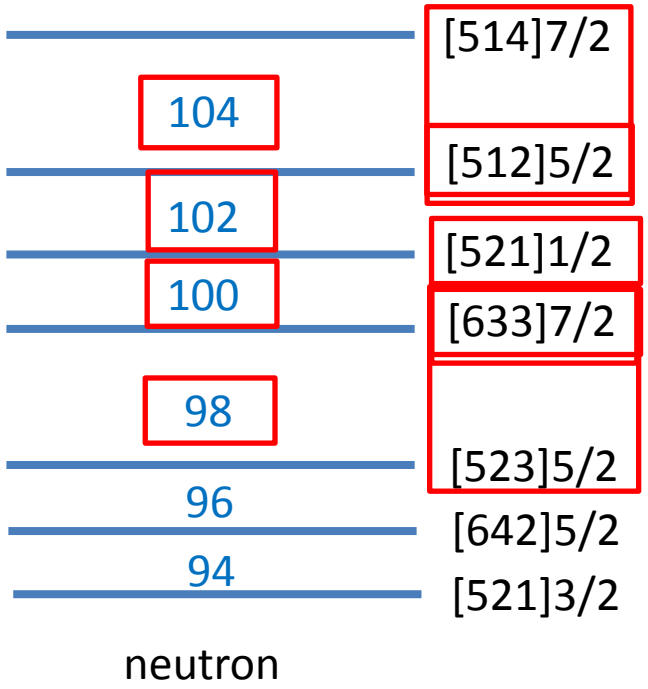
High *K* isomerism
- even-even nuclei -

- *N*=104 : ^{170m}Dy
  → *K*=6+, ν([514]7/2[512]5/2)
  – Analogous isomer in *N* = 104 isotones: ^{172m}Er, ^{174m}Yb, ^{176m}Hf

- *N*=102 : ^{168m}Dy, ^{166m}Gd
  → *K*=6-, ν([633]7/2 [512]5/2)
  – Analogous isomer in *N* = 102 isotones: ^{170m}Er^{m}, ^{172m}Yb

- *N* = 100 : ^{164m}Gd, ^{162m}Sm, ^{160m}Nd
  → *K*=4-, ν([633]7/2[521]1/2)
  – Analogous isomer in *N* = 100 isotones: ^{168m}Er, ^{170m}Yb
  – Prediction by Y.C. Yang et al., JPG37(2010)085110

- *N*=98 : ^{162m}Gd, ^{160m}Sm, ^{158m}Nd
  → not clear
  – *K*=6-, ν([633]7/2[523]5/2)
  – *K*=5-, ν([642]5/2[523]5/2) proposed in ^{160m}Sm
    G. Simpson et al., PRC80(2009)024304
  – *K*=4-, ν([633]7/2[521]1/2) predicted
    Y.C. Yang et al., JPG37(2010)085110

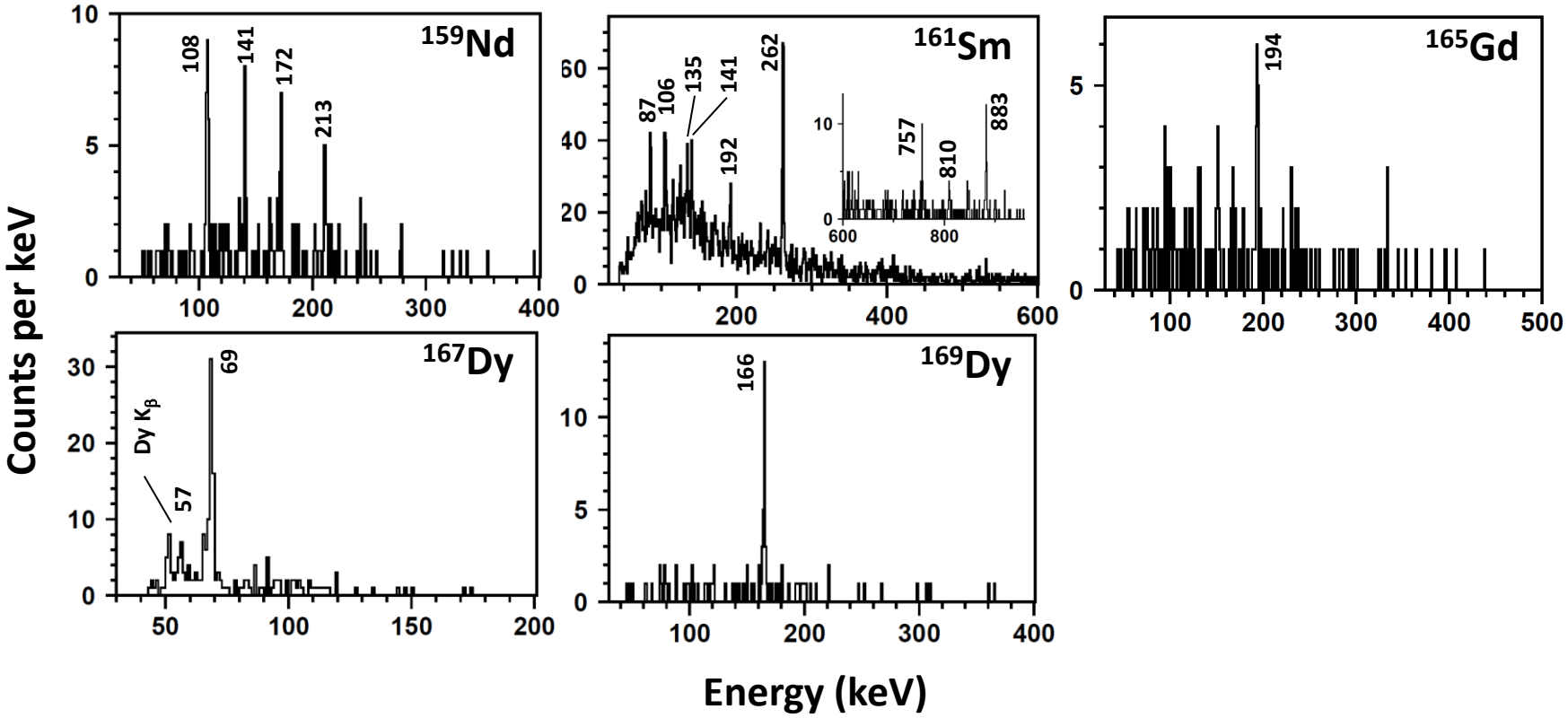


The ordering of the Nilsson orbits with $\beta_2 \sim 0.3$

A.K. Jain et al., Rev. Mod. Phys. 62 (1990) 393.

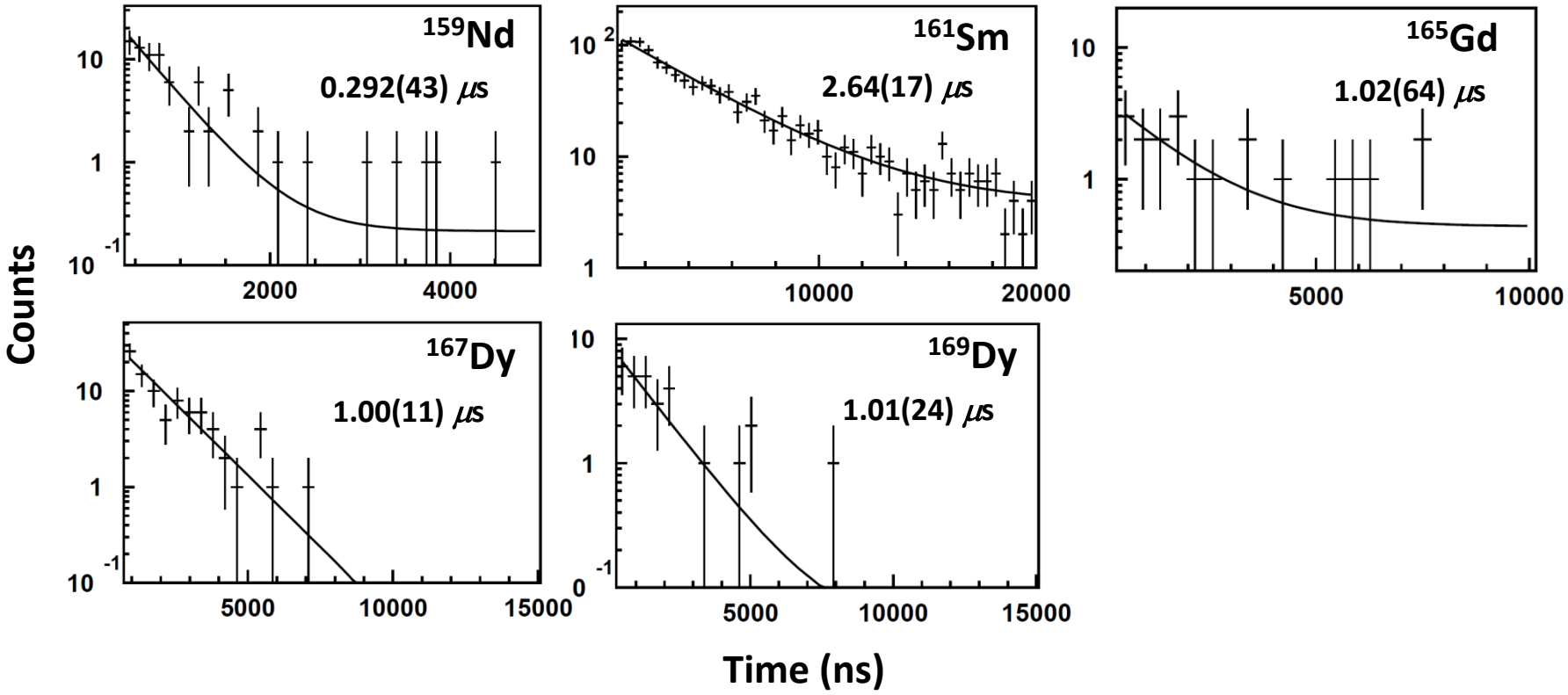
Energy spectra of new isomers

even-Z odd-N nuclei



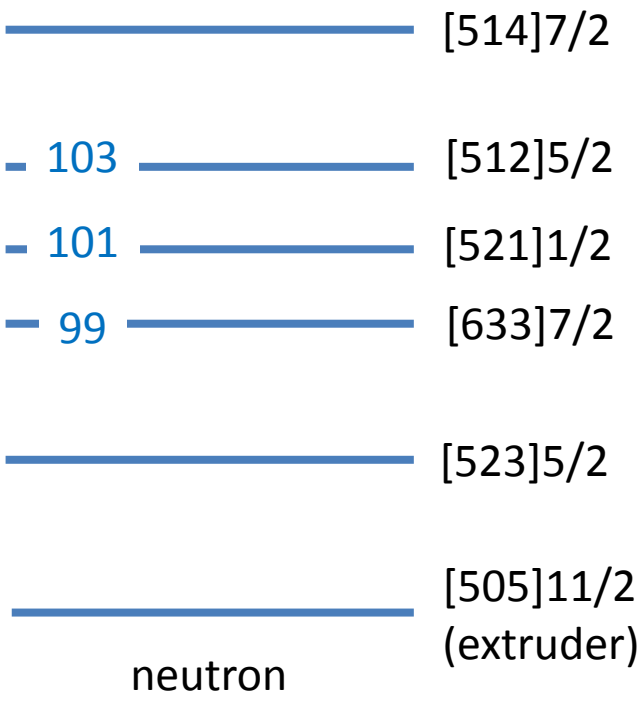
Time spectra of new isomers

even-Z odd-N nuclei



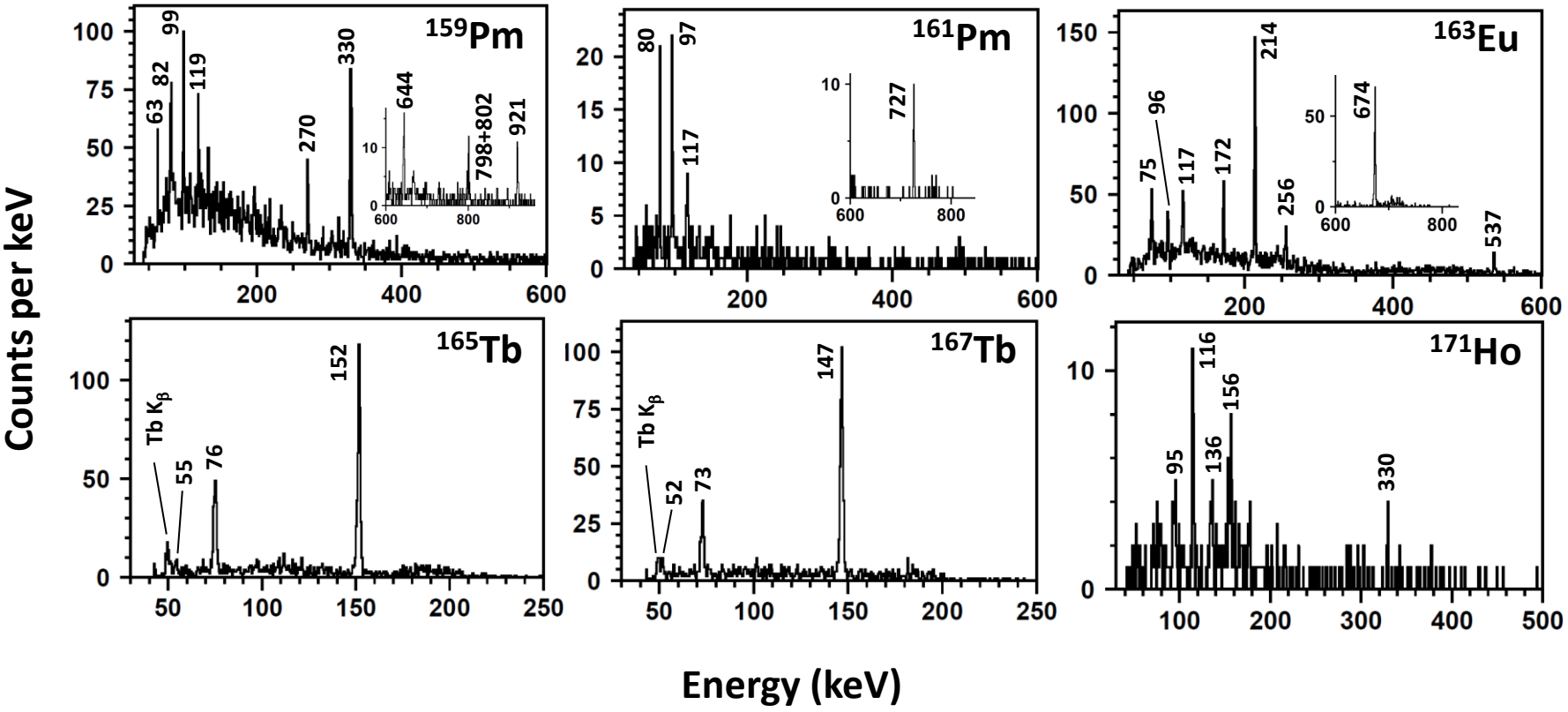
Proposed isomerism
- even-*Z* odd-*N* nuclei -

- *N*=103 : ^{169m}Dy
  → *K*=1/2-, ν[521]1/2 (hole state), forbidden E2
  - Analogous isomers in *N* = 103 isotones: ^{171m}Er, ^{173m}Yb
- *N*=101 : ^{167m}Dy, ^{165m}Gd
  → *K*=5/2-, ν[512]5/2
  - Analogous isomers in *N* = 101 isotones : ^{169m}Er, ^{171m}Yb, ^{173m}Hf
- *N*=99 : ^{161m}Sm, ^{159m}Nd
  → *K*=11/2-, ν[505]11/2 (extruder state)
  - Analogous isomers in neighboring nuclei:^{159m}Sm, ^{165m}Er



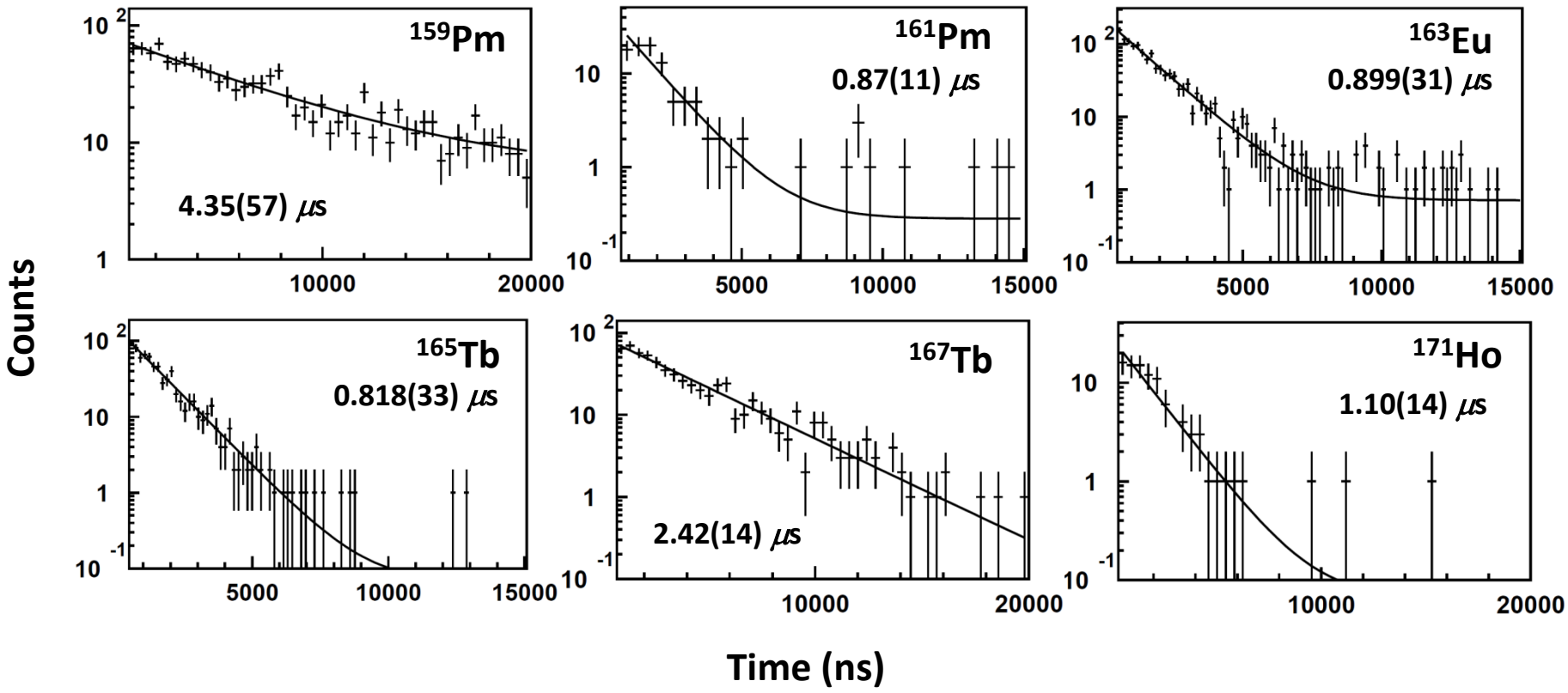
Energy spectra of new isomers

odd-Z even-N nuclei



Time spectra of new isomers

odd-Z even-N nuclei



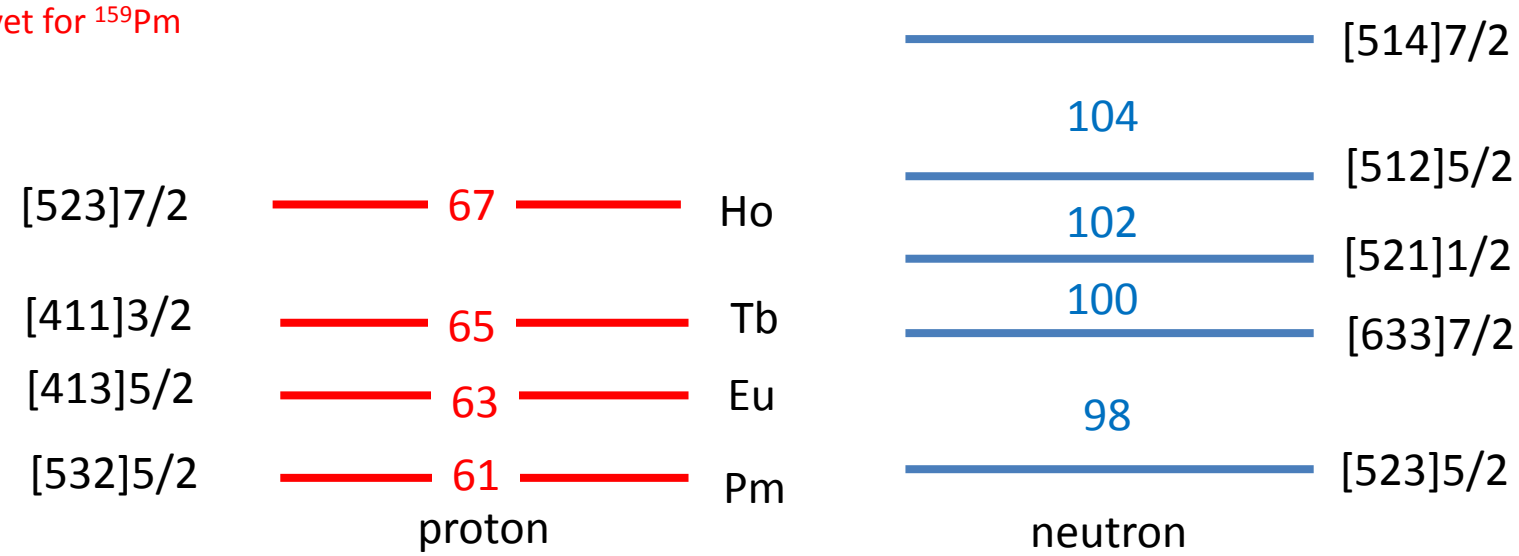
Proposed isomerism of new isomers
- odd-*Z* even-*N* nuclei -

- Ho(Z=67) isotope: $^{171m}Ho_{104}$
  → *K*=19/2-, π[523]7/2 ν([512]5/2 [514]7/2)$^{6+}$
  – Analogous Isomers in *N*=104 isotones: ^{173m}Tm, ^{172m}Er, ^{174m}Yb

- Tb(Z=65) isotopes : $^{165m}Tb_{100}$, $^{167m}Tb_{102}$
  → *K*=7/2-, π[523]7/2 or, *K*=9/2+- isomer, π[404]7/2

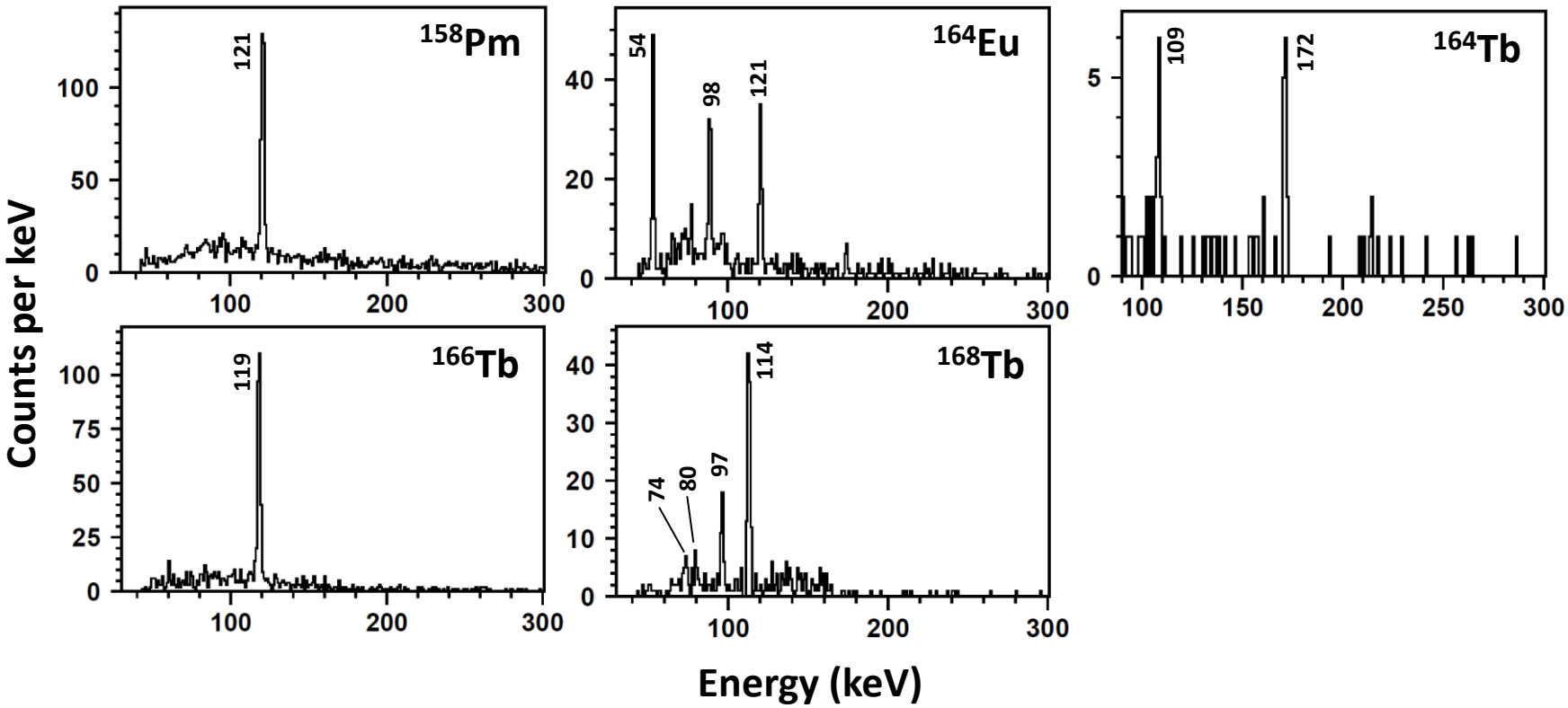
- Eu(Z=63) isotope: $^{163m}Eu_{100}$
  → *K*=13/2-, π[413]5/2 ν([633]7/2 [521]1/2)$^{4-}$
  – Analogous Isomers in *N* = 100 isotones:^{162m}Sm(new), ^{164m}Gd(new),^{168}Er^{m}, ^{170m}Yb

- Pm(Z=61) isotopes: $^{159m}Pm_{98}$, $^{161m}Pm_{100}$
  → *K*=13/2+ isomer, π[532]5/2 ν([633]7/2 [521]1/2)$^{4-}$ for ^{161m}Pm
  – Isomer systematics of *N* = 100 isotones:^{162m}Sm(new), ^{164m}Gd(new),^{168m}Er, ^{170m}Yb
  → Not clear yet for ^{159}Pm



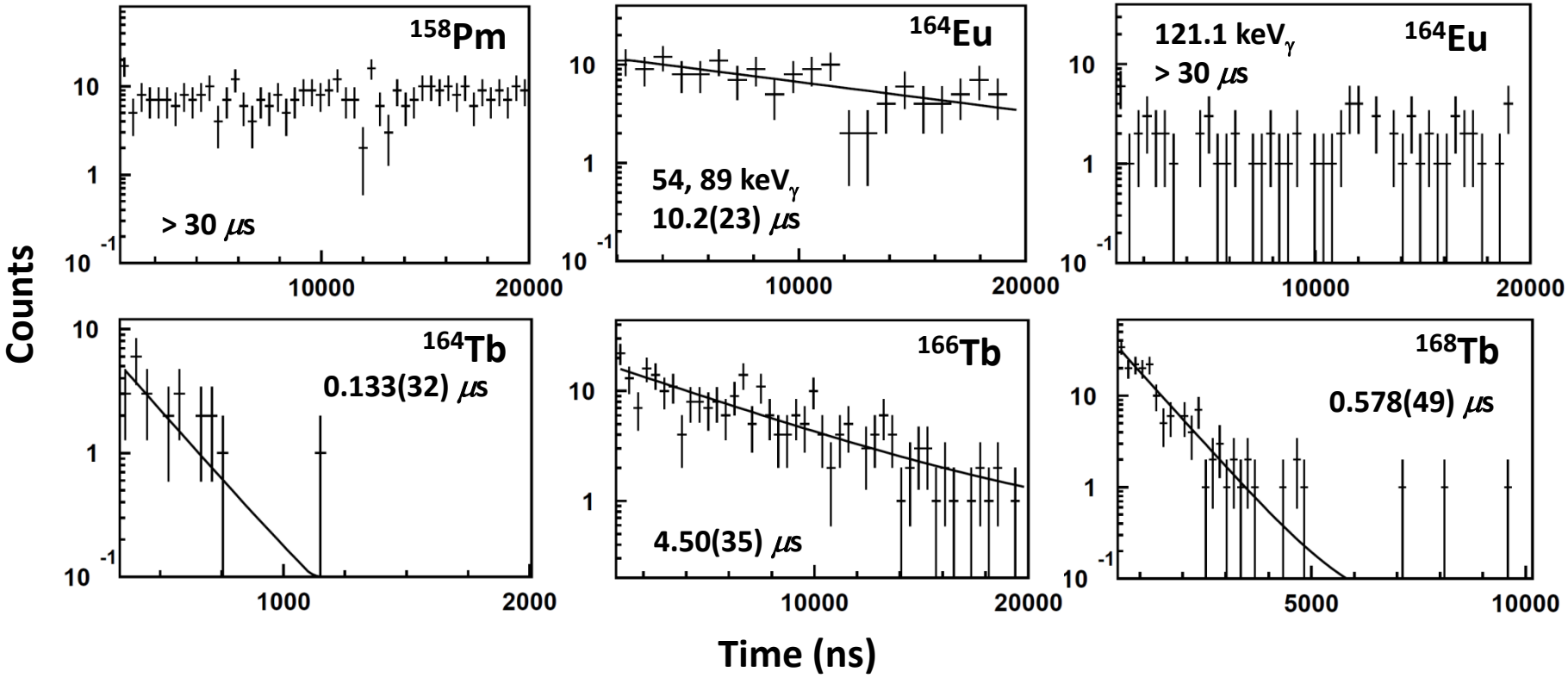
Energy spectra of new isomers

odd-Z odd-N nuclei



Time spectra of new isomers

odd-Z odd-N nuclei



Proposed isomerism of new isomers
- odd-*Z* odd-*N* nuclei -

No data for investigating isomer systematics…

Summary of the proposed isomerism

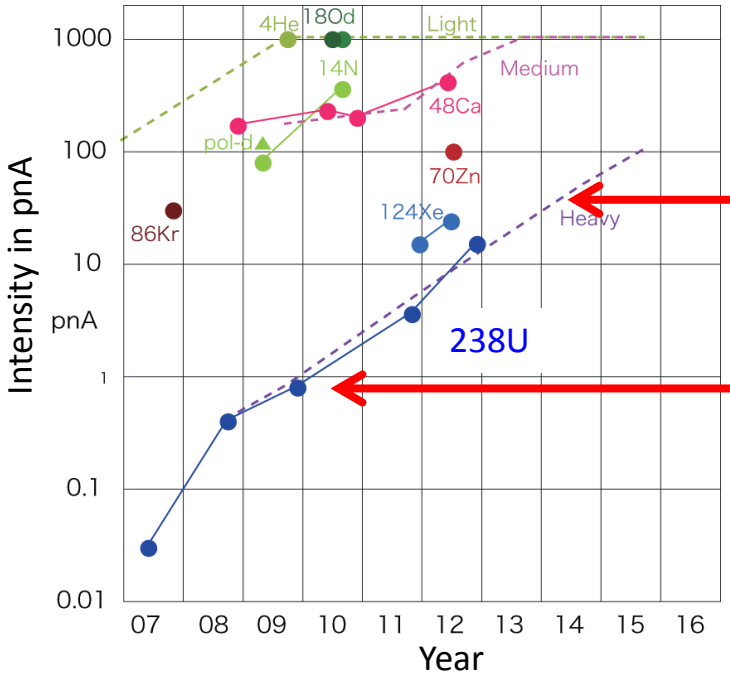
New Known • Known but not observed in this work

68	92	93	94	95	96	97	98	99	100	101	102	103	104	105
67	159Ho	160Ho	161Ho	162Ho	163Ho	164Ho		166Ho	167Ho	168Ho	169Ho High *K*	170Ho	171Ho High *K*	172Ho
66		159Dy						165Dy	166Dy	167Dy *K*	168Dy High *K*	169Dy forbid *E*2	170Dy High *K*	171Dy
65	157Tb	158Tb		160Tb	161Tb	162Tb	163Tb	164Tb ?	165Tb *K* ?	166Tb ?	167Tb *K* ?	168Tb ?	169Tb	170Tb
64	156Gd	157Gd	158Gd	159Gd		161Gd	162Gd High *K*	163Gd	164Gd High *K*	165Gd ?	166Gd High *K*	167Gd	168Gd	169Gd
63	155Eu	156Eu	157Eu	158Eu	159Eu	160Eu	161Eu	162Eu	163Eu High *K*	164Eu ?	165Eu	166Eu	167Eu	168Eu
62		155Sm *E*1	156Sm High *K*	157Sm	158Sm High *K*	159Sm High *K*	160Sm High *K*	161Sm High *K*	162Sm High *K*	163Sm	164Sm	165Sm	166Sm	167Sm
61	153Pm	154Pm	155Pm	156Pm	157Pm	158Pm ?	159Pm High *K*	160Pm	161Pm High *K*	162Pm	163Pm	164Pm	165Pm	166Pm
60	152Nd	153Nd *E*1	154Nd High *K*	155Nd	156Nd High *K*	157Nd	158Nd High *K*	159Nd ?	160Nd High *K*	161Nd	162Nd	163Nd	164Nd	
59	151Pr	152Pr ?	153Pr	154Pr	155Pr	156Pr	157Pr	158Pr	159Pr	160Pr	161Pr	162Pr	163Pr	
58	150Ce	151Ce	152Ce	153Ce	154Ce	155Ce	156Ce	157Ce	158Ce	159Ce	160Ce			

Summary

- The recent results of search for new isotopes and new isomers using BigRIPS separator at RIKEN RI Beam Factory (RIBF) have been reviewed.
- The region of accessible exotic nuclei is expanding at RIBF with increasing beam intensity (e.g. ~10 pnA ^{238}U) and the research on exotic nuclei is being promoted.

Planned schedule of intensity upgrade at RIBF



From RIKEN accelerator group

This year

Present results in 2011

Collaboration on search for new isotopes and isomers with U beam in 2011 at RIBF

RIKEN Nishina Center, Japan

T. Kubo, N. Inabe, N. Fukuda, H. Takeda, D. Kameda, H. Suzuki, K. Yoshida, K. Kusaka, K. Tanaka, Y. Yanagisawa, M. Ohtake, H. Sato, Y. Shimizu, H. Baba, M. Kurokawa, D. Nishimura, T. Ohnishi

Center for Nuclear Study (CNS), University of Tokyo, Japan

S. Go, R. Yokoyama, T. Fujii, E. Ideguchi

Tohoku University, Japan

A. Chiba, T. Yamada, N. Iwasa

Rikkyo University, Japan

D. Murai, K. Ieki

Kochi University of Technology, Japan

S. Momota

Osaka University, Japan,

H. Nishibata

NSCL/MSU, U.S.A.

O. B. Tarasov, D. J. Morrissey, B. M. Sherrill

Seoul University, South Korea

J. Hwang, S. Kim, Y. Sato

LPSC-IN2P3, France

G. Simpson

Thank you for your attention