Discovery of 18 new isomers using in-flight fission of 345 MeV/u ^{238}U: Evolution of the shell structure and shape coexistence

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Outline

- Motivation
  - Richness of nuclear structure and isomerism in the neutron-rich region between ^{78}Ni and ^{132}Sn
  - Systematic study of the evolution of the shell structure and nuclear shapes
- Experimental approach
  - Separation and PID of fission fragments with a superconducting in-flight separator BigRIPS
  - Isomer spectroscopy with the particle-γ slow correlation technique
- Overview of our results
- Discussion of nuclear isomerism
  - Shape coexistence at Z~37, N~60
  - A variety of nuclear shapes and the coexistence at Z~40, N~68
  - New deformation and possible shape coexistence at Z~44, N~75
  - Shell evolution around the N=34 subshell gap with Z=22
- Summary

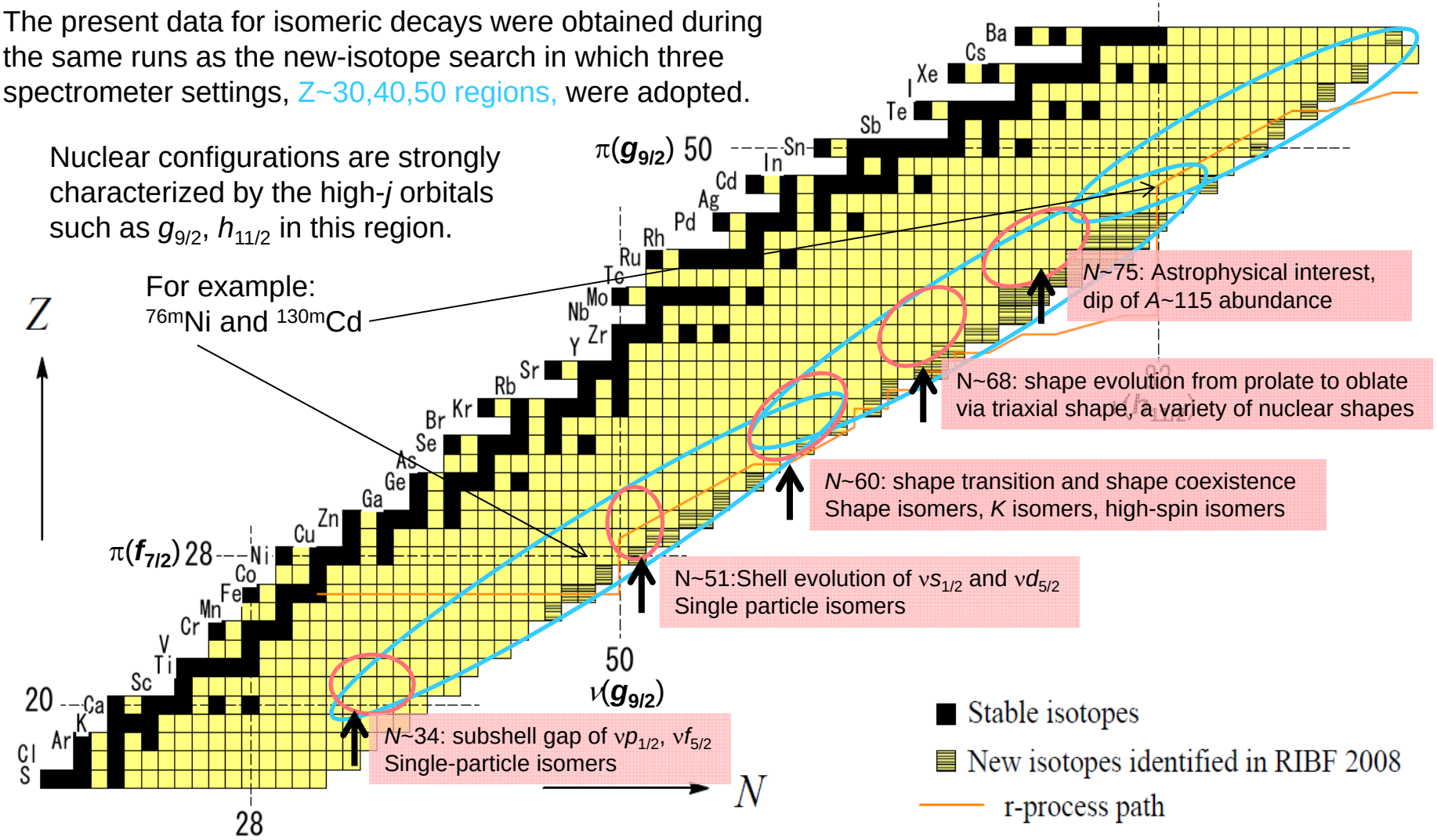
The region of the new-isotope/new-isomer search in RIKEN RI Beam Factory (RIBF) in 2008

New-isotope results: T. Ohnishi et al., J. Phys. Soc. Japan, 79, 073201, (2010).
New-isomer results: D. Kameda et al., submitted to Phys. Rev. C

The present data for isomeric decays were obtained during the same runs as the new-isotope search in which three spectrometer settings, Z~30,40,50 regions, were adopted.

Nuclear configurations are strongly characterized by the high-*j* orbitals such as $g_{9/2}$, $h_{11/2}$ in this region.

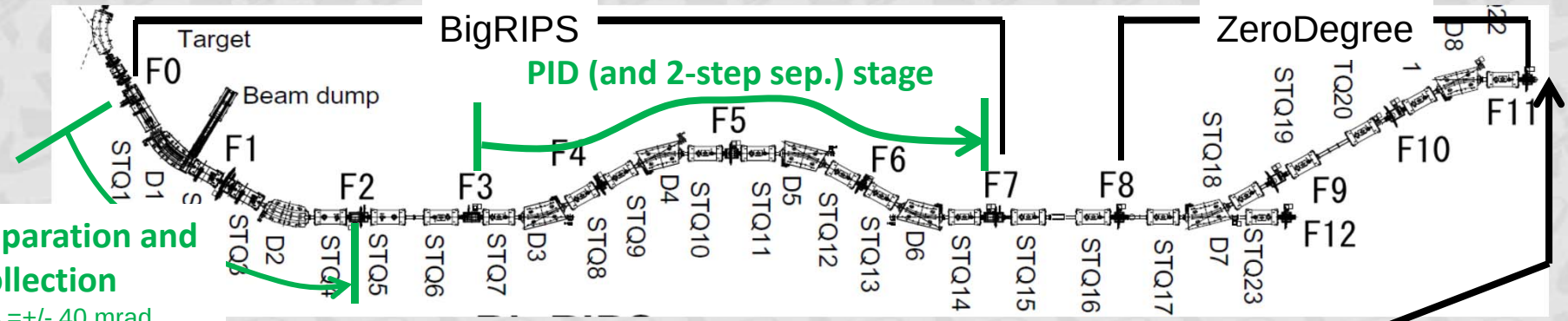
For example:
^{76m}Ni and ^{130m}Cd



Experimetal approach

Separation and Particle identification (PID) of fission fragments with BigRIPS:
(The detail in Ref. T. Ohinish et al., J. Phys. Soc. Japan, 79, 073201, (2010).)

- Separation and collection with large angular and momentum acceptances in the first stage
- *A/Q* deduced by the measured $B\rho$ and *TOF* at the second stage of BigRIPS
- *Z* deduced by the energy loss in an ionization chamber at the last focal plane (F11)
  (Time of flight from production target to stopper was in the range of 600-700 ns)

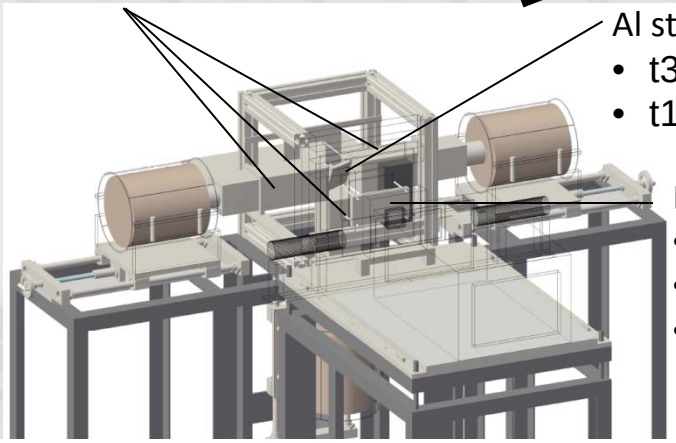


separation and collection
$\Delta\theta_h$=+/- 40 mrad
$\Delta\theta_v$=+/- 50 mrad
$\Delta p/p$=+/- 3 %

Three clover-tye Ge detectors

γ-ray detection:

- Three clover-type Ge detectors
- Al stoppers (t10mm, t30mm)
- Energy degraders (Al)
- time window of 20 us following implantation

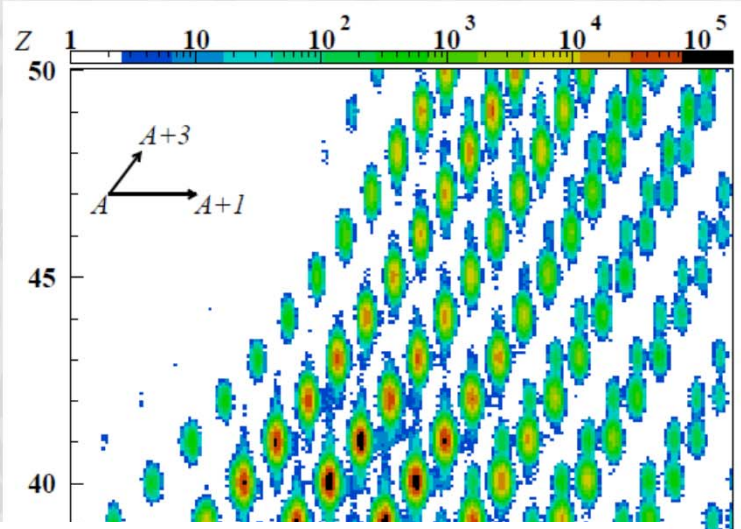


Al stopper with 90x90 mm^2
- t30 mm for Z~30
- t10 mm for Z~40,Z~50

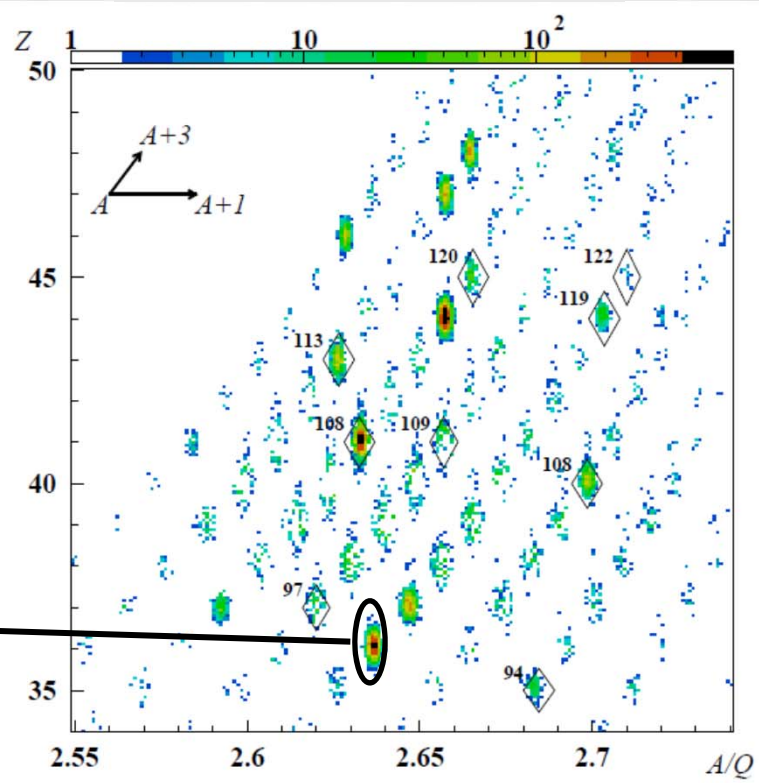
Energy deg. (Al)
- t15 mm for Z~30
- t10 mm for Z~40
- t8 mm for Z~50

Demonstration of PID in the case of Z~40 setting

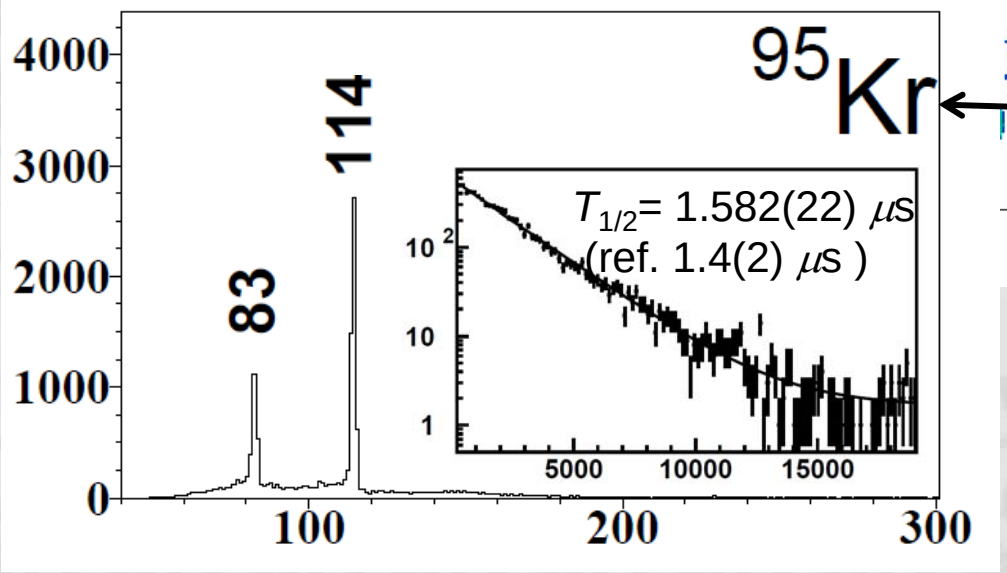
without a delayed γ-ray gate



with a delayed γ-ray gate
(Time window:0.2-5.0 μs)



(subtracted the accidental background)

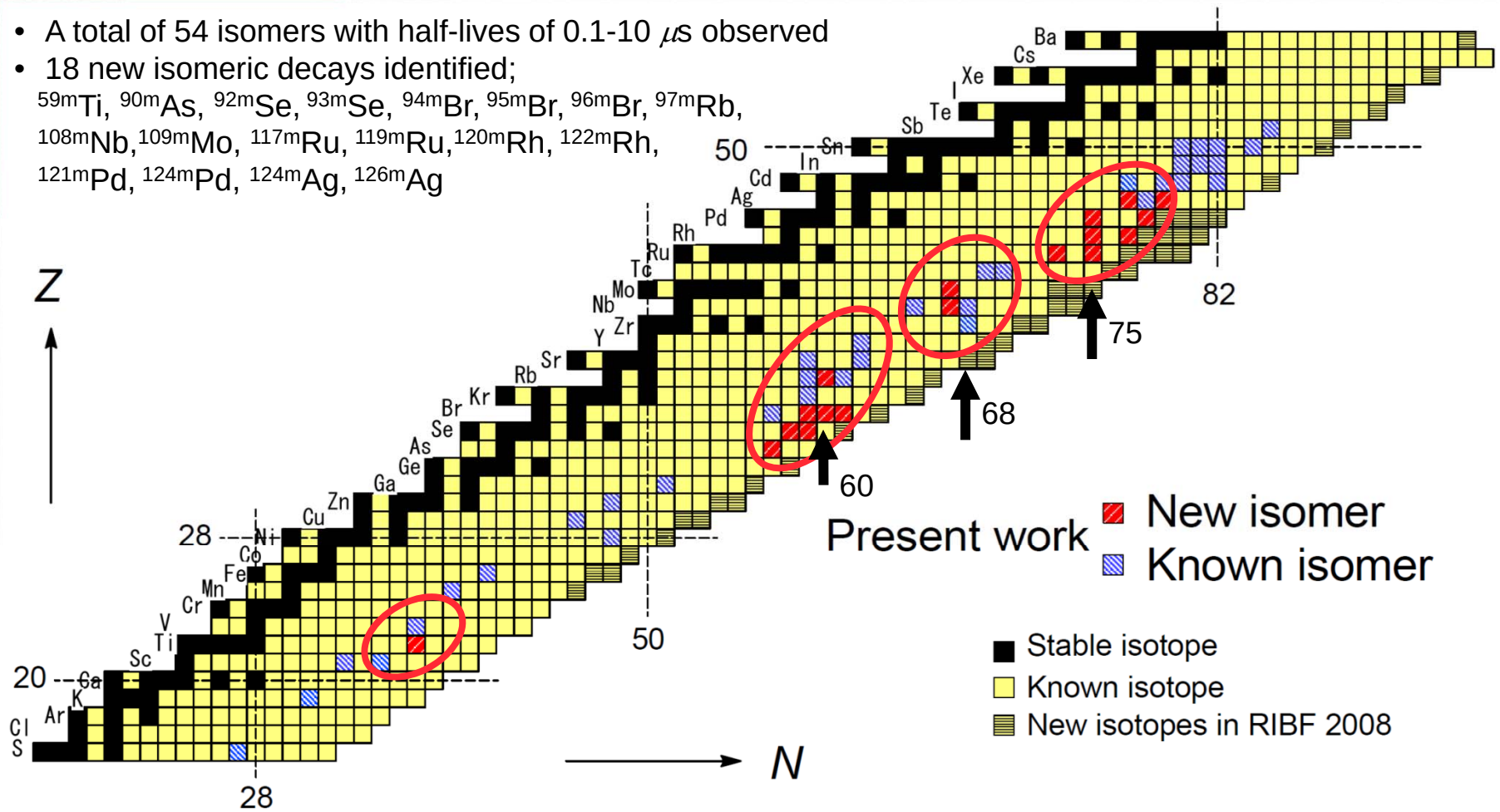


Decay curve: single exponential plus constant background
(the Maximum-likelihood method)

ref. J. Genevey et al., PRC73, 037308 (2006).

Overview of results

- A total of 54 isomers with half-lives of 0.1-10 μs observed
- 18 new isomeric decays identified;
  ^{59m}Ti, ^{90m}As, ^{92m}Se, ^{93m}Se, ^{94m}Br, ^{95m}Br, ^{96m}Br, ^{97m}Rb, ^{108m}Nb, ^{109m}Mo, ^{117m}Ru, ^{119m}Ru, ^{120m}Rh, ^{122m}Rh, ^{121m}Pd, ^{124m}Pd, ^{124m}Ag, ^{126m}Ag



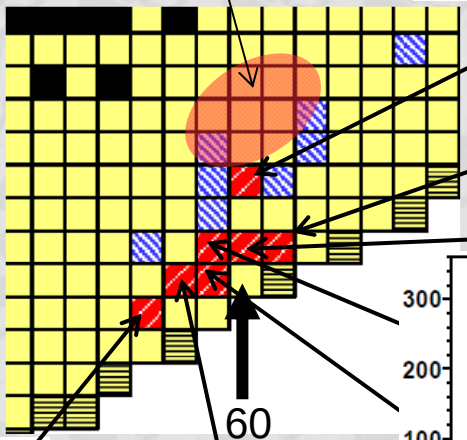
- New information for 5 known isomers;
  ^{92m}Br($T_{1/2}$,new γ rays), ^{82m}Ga($T_{1/2}$), ^{98m}Rb,^{108m}Zr(new γ rays), ^{125m}Ag(new γ rays)
- Level schemes are proposed for 12 new isomers: ^{59m}Ti, ^{94m}Br, ^{95m}Br, ^{97m}Rb, ^{108m}Nb,^{109m}Mo, ^{117m}Ru,^{119m}Ru,^{120m}Rh, ^{122m}Rh, ^{121m}Pd, ^{124m}Ag, based on the relative intensity and $\gamma\gamma$ coincidence as well as the γ-ray energies and half -lives
- Level schemes are extended or newly proposed for the 5 known isomers

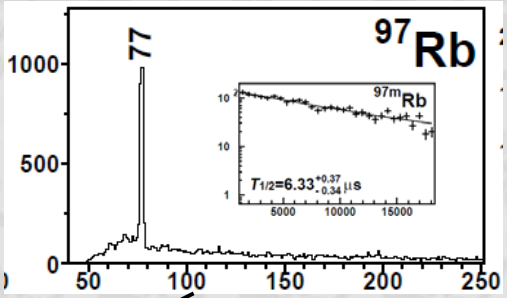
Energy and time spectra for new isomers in the region of *N*~60

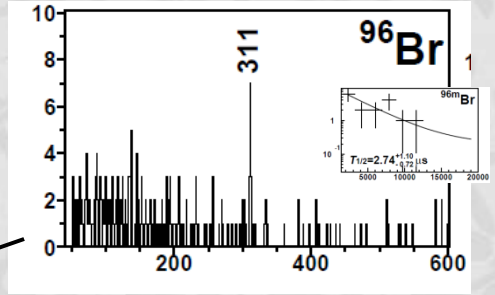
Shape transition and shape coexistence for Z>=38 and N=58-60 is well known since 1970's

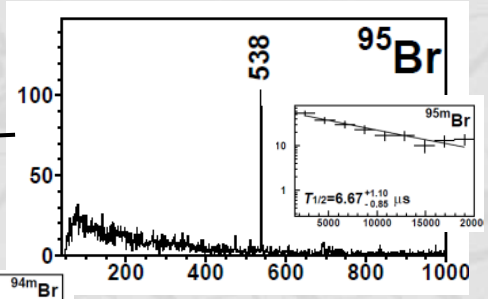
Our interest:
The evolution of shape coexistence in more neutron-rich region with Z<38 ?

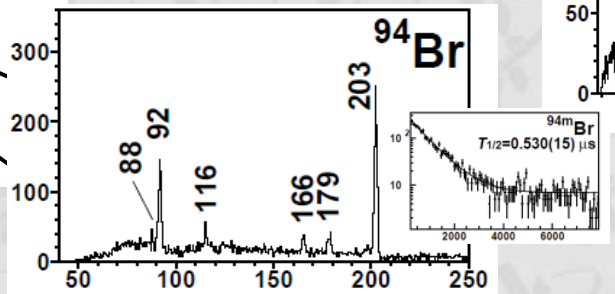
The observed isomers may provide a clue to elucidating the evolution of shape coexistence…

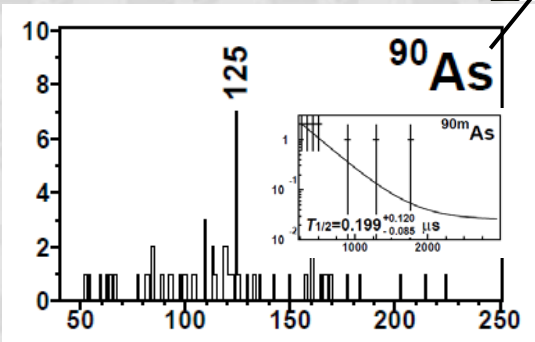


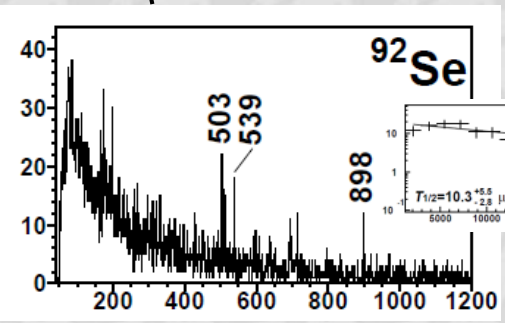


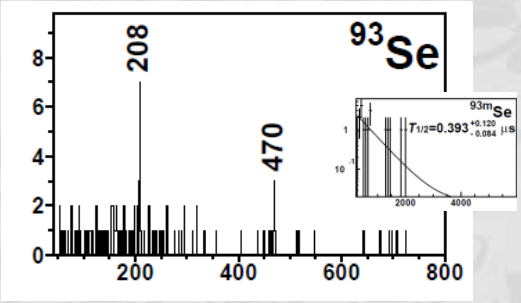




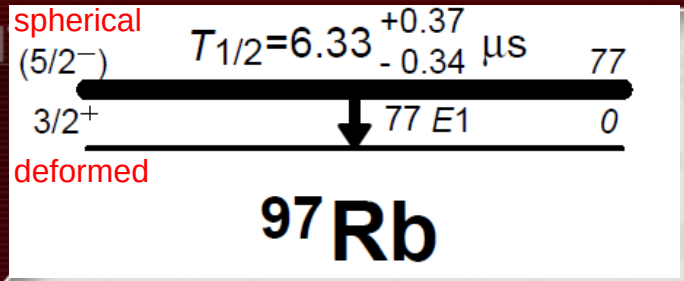








Shape isomerism at N=60 : ^{97m}Rb(Z=37,N=60)



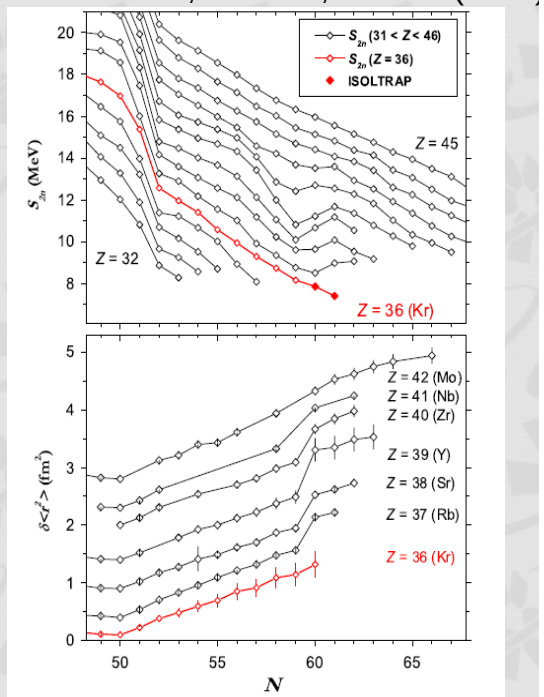
$B(E1) = 9.37^{+0.61}_{-0.56}$ W.u.

$F_W = (T_{1/2})_{exp.}/(T_{1/2})_{W.u.} = 1.1 \times 10^7$

Spherical configuration based on the systematics of ^{93,95}Rb$_{g.s.}$(I^{π}=5/2$^-$)
G. Simpson et al., PRC82, 024302 (2010)

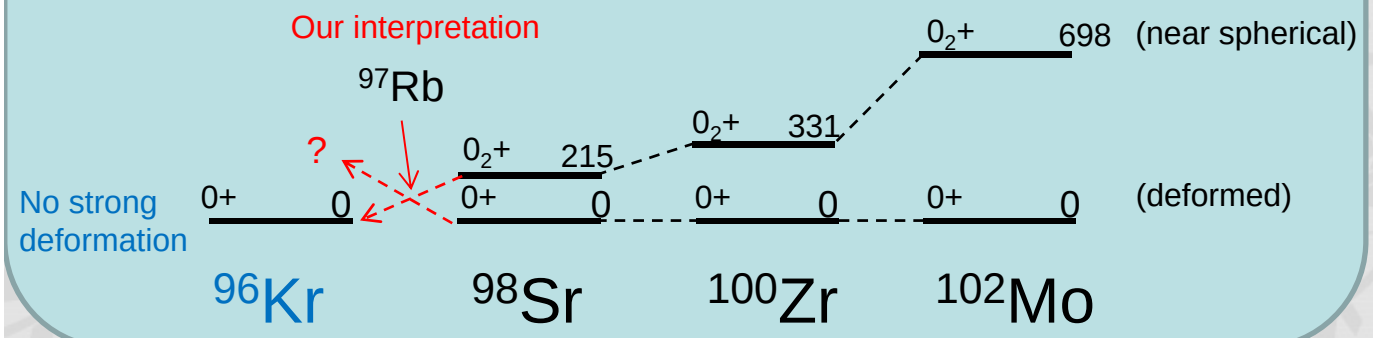
- **Strong prolate deformation in ^{97}Rb$_{g.s.}$ [431]3/2$^+$**
  C. Thibault et al., PRC23,2720 (1981).
- **Shape coexistence in ^{98}Sr(0_2+) and ^{100}Zr(0_2+)**
  F. Schussler et al., Nucl. Phys. A 339, 415 (1980).
  F. K. Wohn et al., PRC33, 677 (1986).
- **Candidate for a spherical state at 599 keV in the deformed odd-nucleus ^{99}Y**
  R. Petry et al., PRC31, 621 (1985).
- **Shape coexistence in ^{96}Rb**
  J. A. Pinston et al., PRC71, 054304 (2003).

S. Naimi et al., PRL105, 032502 (2010)

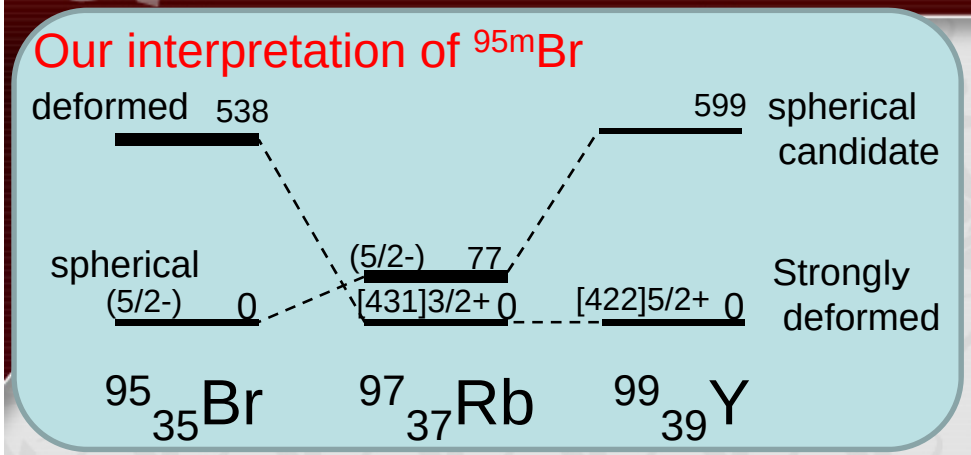


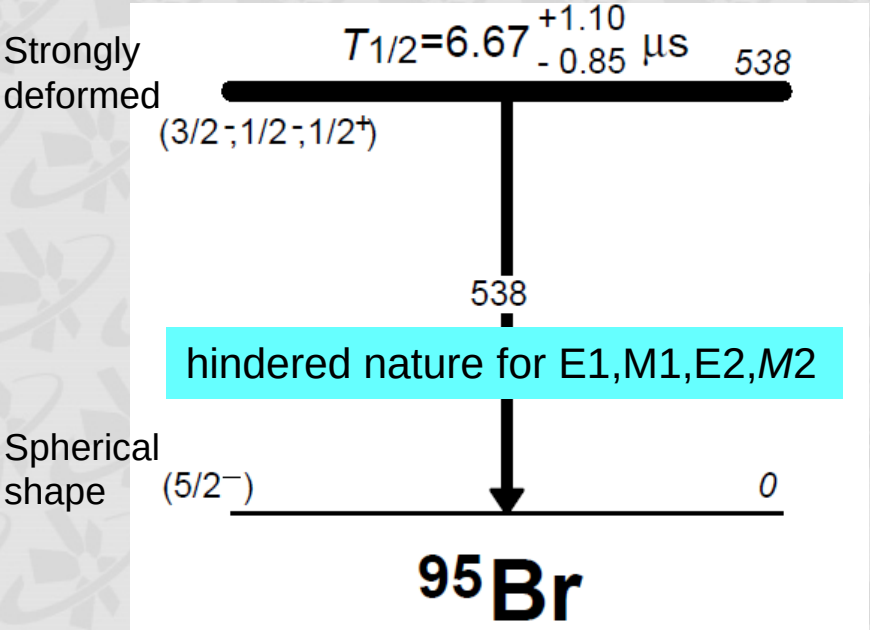
Indication of narrowing energy gap between strongly deformed and spherical states:

^{96}Kr:
S. Naimi et al., PRL105, 032502 (2010).
M. Albers et al., PRL108, 062701 (2012).

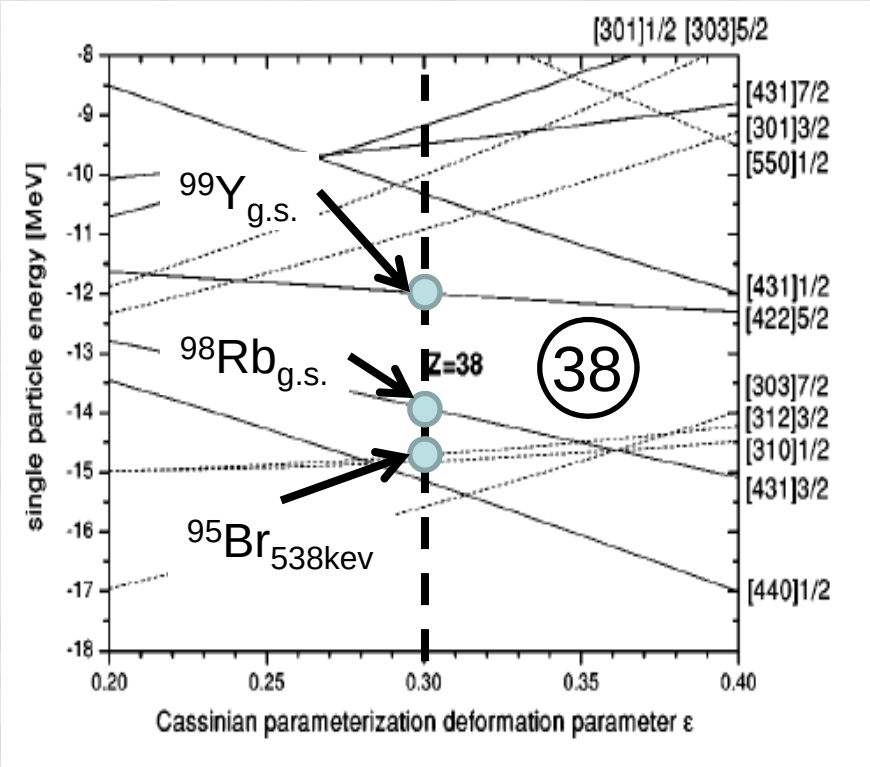


Shape isomerism: ^{95m}Br(Z=35, N=60)



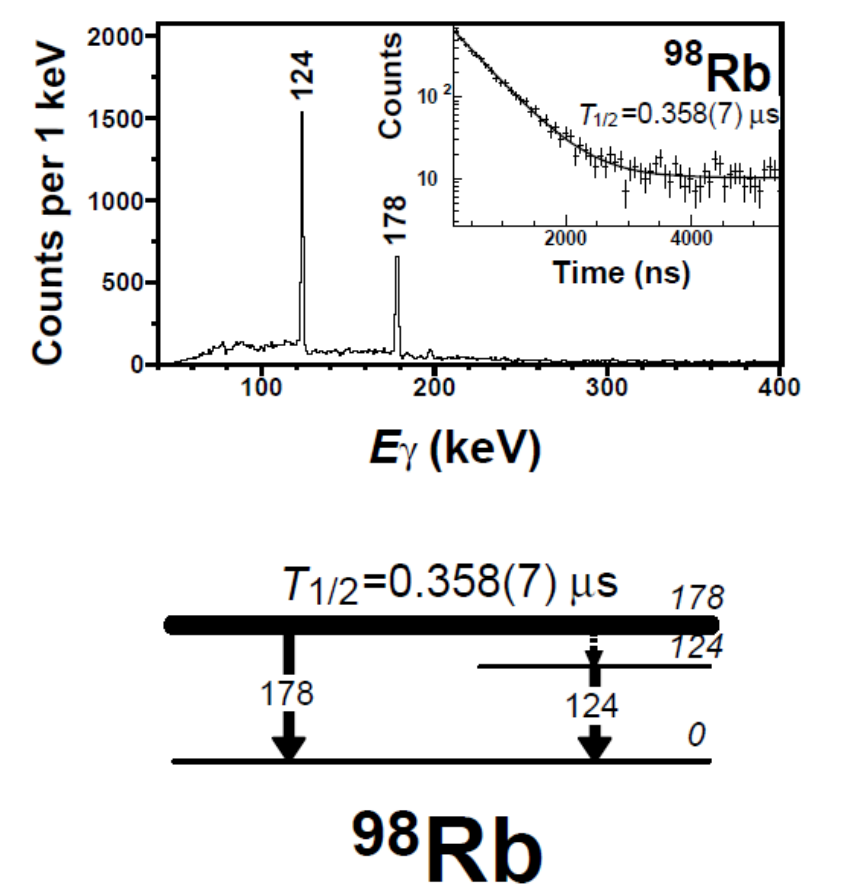


The Recommended Upper Limit (RUL) excludes the possible of $\sigma\lambda > M3$



G. Lhersonneau et al., PRC65, 024318 (2002).

Shape isomerism : ^{98m}Rb(Z=37,N=61)



Level scheme proposed for the first time

- Absence of the116-keV γ-ray
  C.M. Folden et al., PRC79,064318 (2009).
- More precise half-life
- No $\gamma\gamma$ coincidence

Hindered nature of 178-keV transition:

- $F_w(E1) = 2.0 \times 10^7$
- $F_w(M1) = 3.0 \times 10^5$
- $F_w(E2) = 1.0 \times 10^1$

The relative intensity:
178 keV : 45(2)%
124 keV : 100(2)%

Strong candidate for a shape isomer

Reverse ordering of the 54- and124-keV γ-rays could be possible.
(The 54-keV γ-ray was not detected due to our energy threshold or decaying to the long-lived isomer out of our time window)

Energy and time spectra in the region of *N*~68

Interests:

→ A variety of nuclear shapes; prolate, oblate, triaxial, tetrahedral shapes

→ Shape coexistence and shape isomerism

Previously-reported isomers

- ^{112m,113m}Tc: Triaxial shape proposed

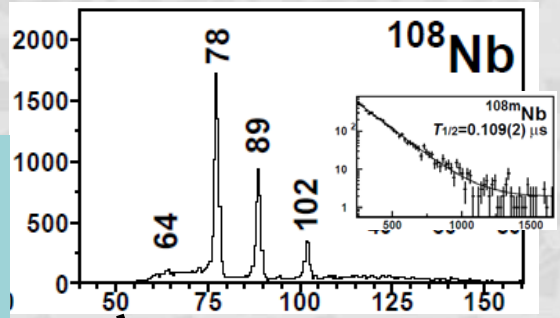
A.M. Bruce et al., PRC82, 044311(2010).

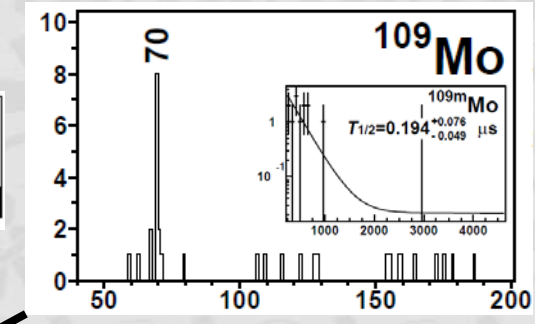
- ^{109m}Nb: Oblate shape proposed

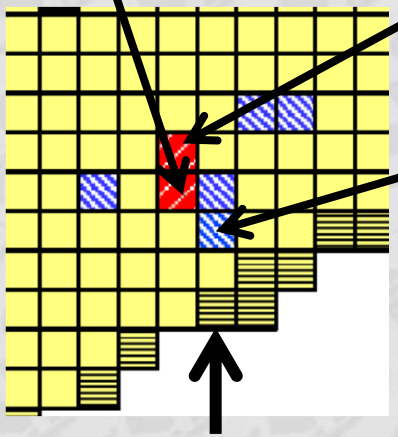
H. Watanabe et al., Phys. Lett. B 696, 186 (2011).

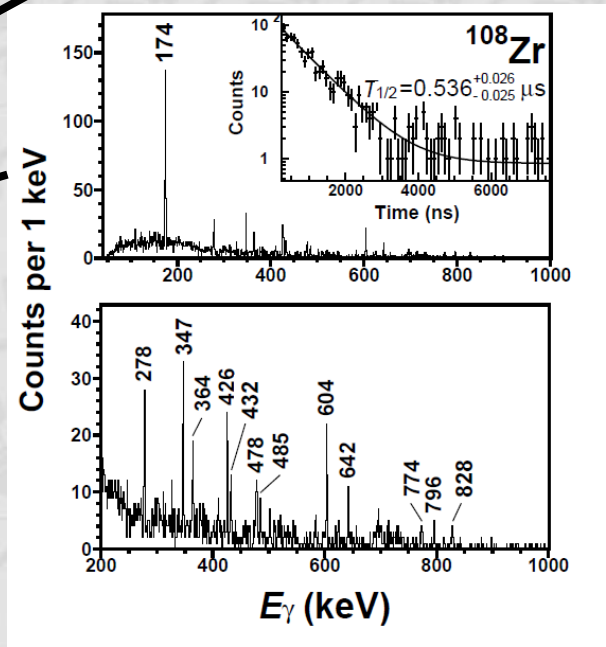
- ^{108m}Zr: Tetrahedral shape proposed

T. Sumikama et al., PRC82, 202501 (2011).

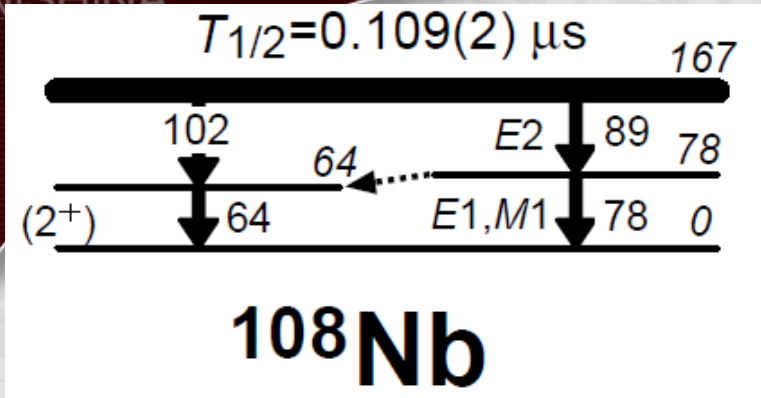








Proposed level scheme: ^{108m}Nb, ^{109m}Mo



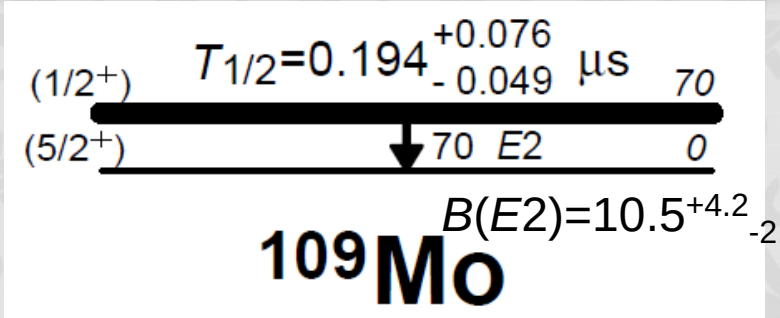
Two possible isomerism:

1. Small energy transition with *E*2 between deformed states in different bands.
2. Oblate-deformed shape isomer similar to the case of ^{109m}Nb

- $\gamma\gamma$: 89-78 keV, 102-64 keV, 89-64 keV
- Intensity balance suggests the multi-polarity of (89,78)-keV cascade to be (E2, E1 or M1).

β-decay spectroscopy:
H. Penttila et al., PRC54, 2760 (1996).

- The spin-party of ^{108}Nb$_{g.s.}$ to be 2+ with π[422]5/2+ ν[411]1/2



The isomerism may be due to the small energy transition with *E*2 decay between deformed states in different bands.

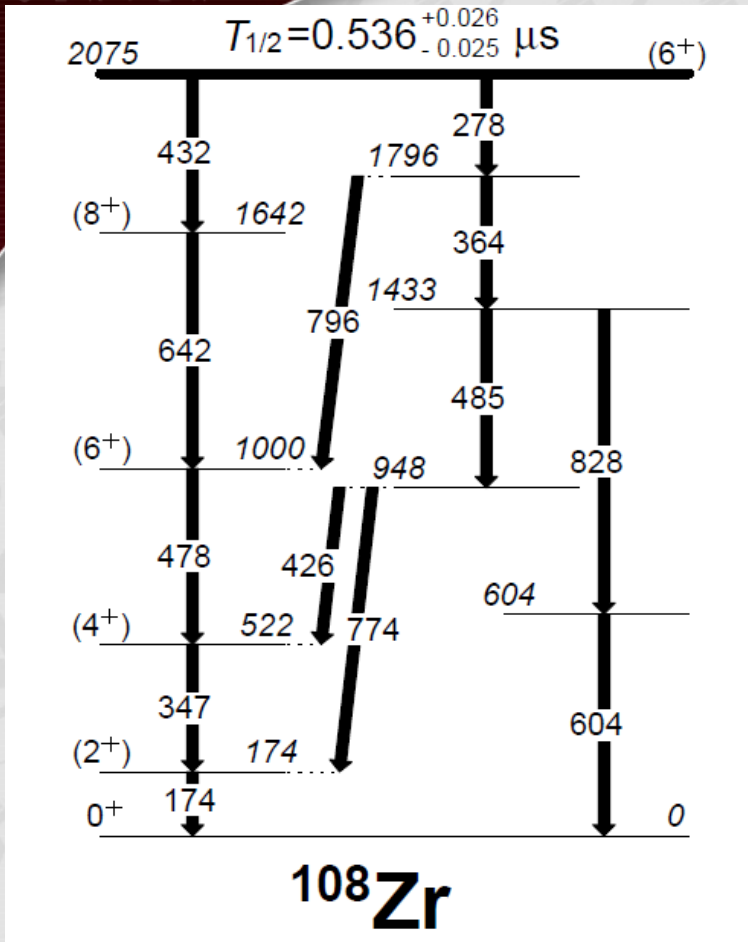
Fission spectroscopy:
W. Urban et al., PRC73, 037302 (2006).

- The ^{109}Mo$_{g.s.}$ is assigned to be [402]5/2+ (prolate) and the band head at 222 keV to be [523]7/2- (prolate)

The presence of E2 isomer in ^{107m}Mo
J. Pinston et al., PRC74, 064304 (2006).

- Isomeric state to be a triaxial deformed state originating from [411]1/2+. B(E2)=5.9(5) W.u.

^{108m}Zr: *K*-isomerism



The level scheme is constructed based on the energy sum. There is some inconsistency in the relative intensity and $\gamma\gamma$ relation of 426 keV.

Previous report: T. Sumikama et al., PRL 106, 202501 (2011).

- 174-, 278-, 347-, 478-, and 604-keV γ-rays were observed.
- The g.s. rotational band was proposed up to the 4^+ member based on the level systematics in the lighter Zr isotopes
- The tetrahedral shape was discussed as the isomerism.

This work :

- New peaks at 364, 426, 432, 485, 642, 774, 796 and 828 keV
- $\gamma\gamma$: 174-347 keV, 174-478 keV
- In the newly proposed level scheme, the g.s. band is extended up to the 8+ member
- All the observed γ-rays are uniquely assigned to the level scheme.
- The isomeric state is tentatively assigned to be the level at 2075 keV.

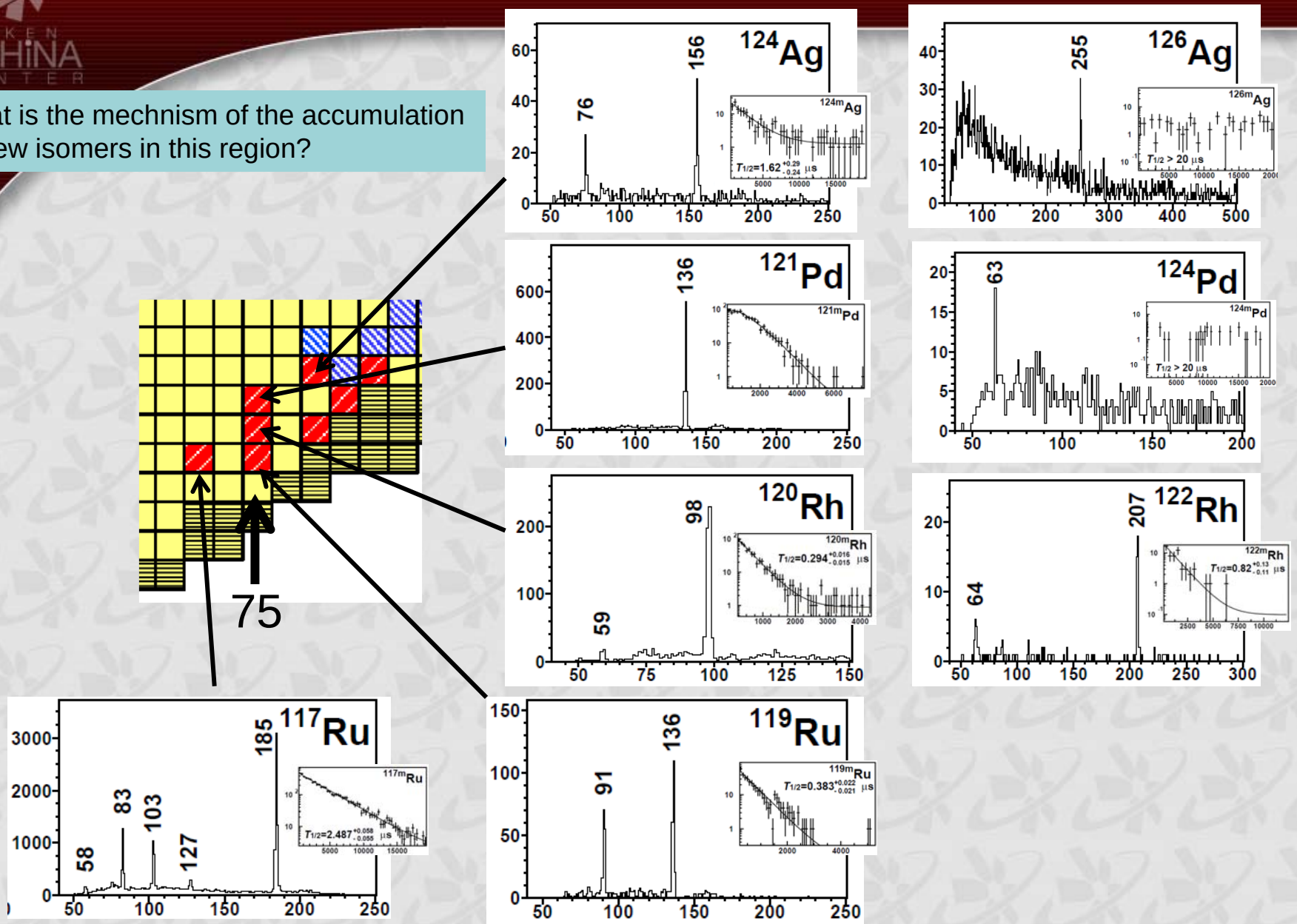
The level of isomeric state is close to the predicted level of high *K* state (6^+) implying the *K* isomerism in ^{108}Zr.

Y. Shi et al., PRC85, 027307 (2012).

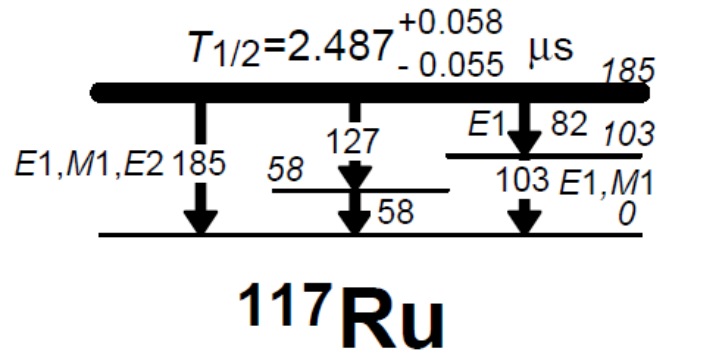
^{108}Zr	0^+	vacuum	0.353	1.0	−0.03	0.0
	4^-	$\nu\frac{7}{2}^-[523]\otimes\frac{1}{2}^+[411]$	0.357	1.5	−0.03	1.414
	6^+	$\nu\frac{7}{2}^-[523]\otimes\frac{5}{2}^-[532]$	0.333	0.0	−0.04	1.997
	3^+	$\nu\frac{5}{2}^+[402]\otimes\frac{1}{2}^+[411]$	0.327	5.6	−0.02	2.165
	5^-	$\nu\frac{5}{2}^+[402]\otimes\frac{5}{2}^-[532]$	0.309	0.1	−0.03	2.561
	4^-	$\pi\frac{3}{2}^-[301]\otimes\frac{5}{2}^+[422]$	0.322	0.0	−0.03	2.326
	5^-	$\pi\frac{5}{2}^-[303]\otimes\frac{5}{2}^+[422]$	0.313	1.2	−0.02	2.726
	3^-	$\pi\frac{3}{2}^-[301]\otimes\frac{3}{2}^+[431]$	0.307	0.3	−0.03	3.421

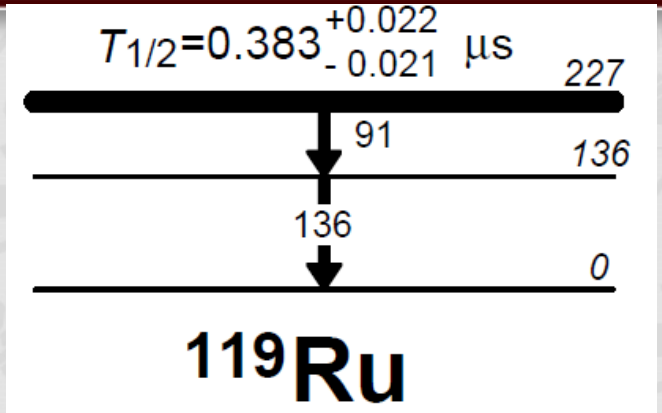
Energy and time spectra in the region of *N*~75:

What is the mechnism of the accumulation of new isomers in this region?



Shape isomerism for ^{117m}Ru and ^{119m}Ru





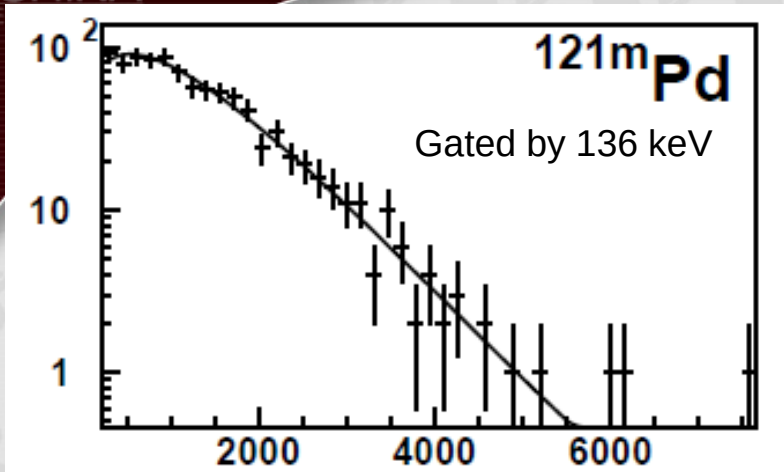
The shape isomerism is proposed for ^{117m}Ru from the observation

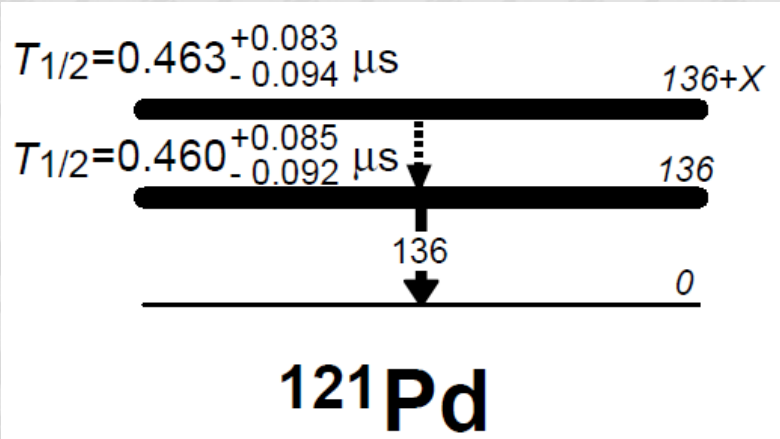
- $\gamma\gamma$: 82-103 keV
- The multipolarity of 82- and 103-keV γ-rays to be (*E*1, *E*1 or *M*1) from intensity balance
- The hindered nature of the 185-keV transition

The shape isomerism is also proposed for ^{119m}Ru from the observation

- $\gamma\gamma$: 91-136 keV
- The RUL exclude the possibility of $\sigma\lambda$ > *M*2 for both the γ transitions.
- The possibility of *E*2 is not likely due to the intensity balance
- Hindered nature of *E*1 or *M*1 decay regardless of the ordering of the γ-rays in the level scheme

^{121m}Pd

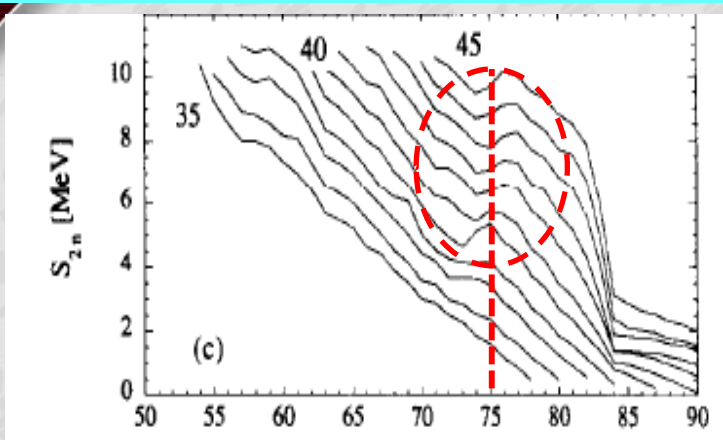




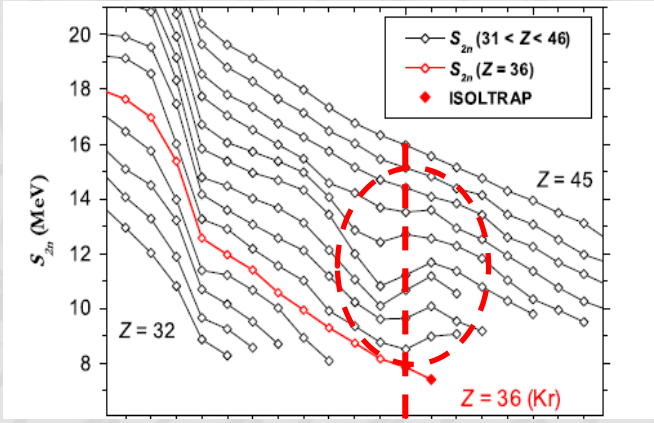
- The decay curve is not consistent with the single decay component plus constant background.
- The double-decay component plus constant B.G. was well fit to the decay curve
- The 136-keV transition:
  *E*1,*M*1 → hindered nature
  *E*2 → normal W.u.

Implication of the occurrence of the shape coexistence at *N*~75

The S_{2n} systematics by the ETFSI-Q model: J.M. Pearson et al., PLB 387, 455 (1996).



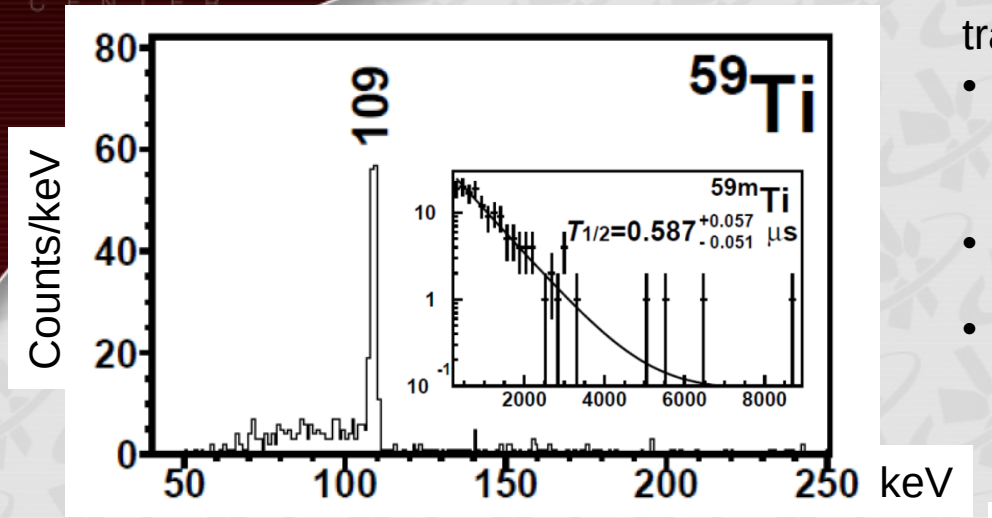
The experimental systematics of S_{2n} at *N*~60: S. Naimi et al., PRL105, 032502 (2010).

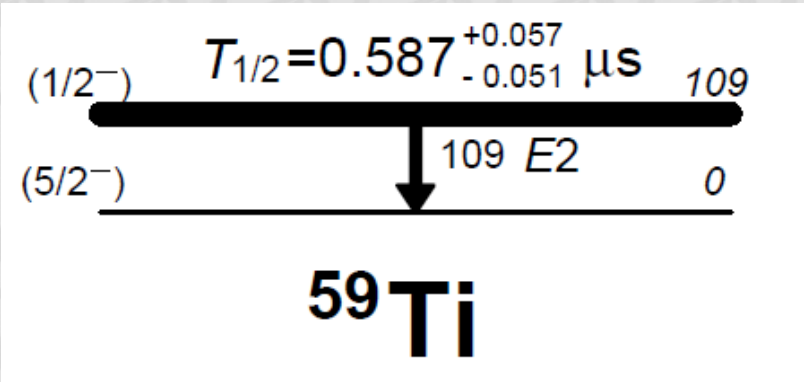


N=60

- The clear humps are predicted by the ETFSI-Q mass model.
- These humps are similar to that observed in the region of *N*=60.
- This might be indication of shape transition and shape coexistence at *N*=75, resulting in the appearance of new shape isomers such as ^{117m}Ru and ^{119m}Rh, like the case of *N*=60.

^{59m}Ti : single particle isomer of spherical shape





$B(E2) = 3.68^{+0.37}_{-0.34}$ W.u.

We propose a spherical *E2* isomer with a small transition energy.

- Level systematics in $^{55,\,57}$Ti
  S. Liddick et al., Phys. Rev. C **72**, 054321 (2005).
  H. L. Crawford et al., Phys. Rev. C **82**, 014311 (2010).
  P. Maierbeck et al., Phys. Lett. B **675**, 22 (2009).
- Isomers with spherical shape: ^{54m}Sc, ^{56m}Sc
  H. L. Crawford et al., Phys. Rev. C **82**, 014311 (2010).
- Strongly attractive monopole interaction between $\pi f_{7/2}$ and $\pi f_{5/2}$
  T. Otsuka et al., Phys. Rev. Lett. 104, 012501 (2010) and reference therein.

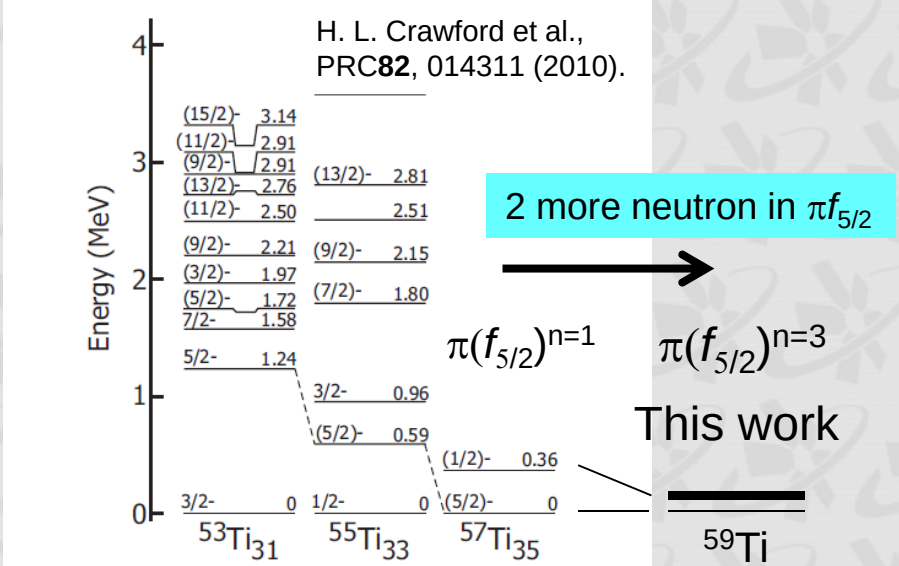


FIG. 17. Experimentally determined levels below 4 MeV for odd-*A* ^{53,55,57}Ti isotopes.

Collaboration

Search for new isotopes and isomers in RIBF 2008

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Summary

- A comprehensive search for new isomers among fission fragments from 345 MeV/u ^{238}U was performed using the in-flight separator BigRIPS that exploited the advantageous feature of the in-flight fission, large cross production sections of neutron-rich nuclei over the wide range of *Z* number
- This made it possible to observe a number of new and known isomeric decays and allows systematic investigation of nuclear structure and isomerism in this region
- Nuclear isomerism is discussed in some particular regions
  - *N*=60 region: Shape isomerism for ^{97m}Rb, ^{95m}Br, ^{98m}Rb
  - *N*=68 region: *K*-isomerism for ^{108m}Zr, Isomeric transition between deformed states in different bands for ^{108m}Nb, ^{109m}Mo, shape isomerism for ^{108m}Nb
  - *N*=75 region: Shape isomerism for ^{117m}Ru, ^{119m}Ru. The origin is also discussed in terms of the mass systematics predicted by the ETFSI-Q model.
  - *N*=34 region: Isomeric *E*2 decay due to the narrowing of the N=34 subshell in ^{59m}T
- The results will provide future opportunities for experimental and theoretical investigation of nuclear structure and isomerism in this region.

Thank you for your attention.