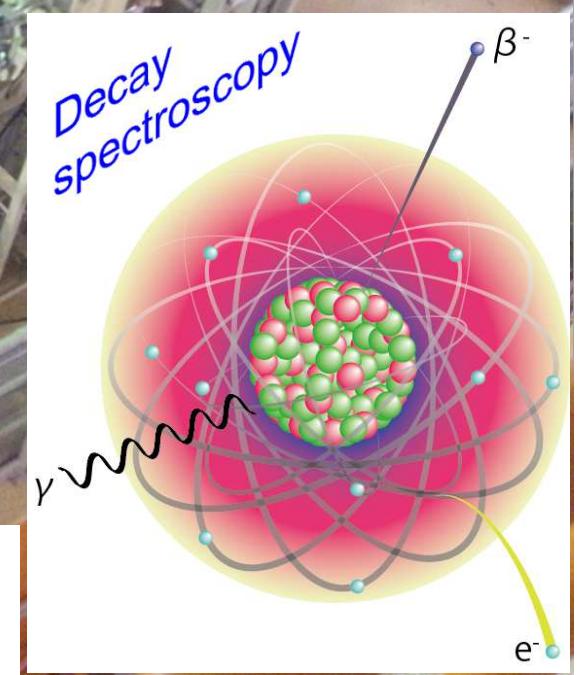
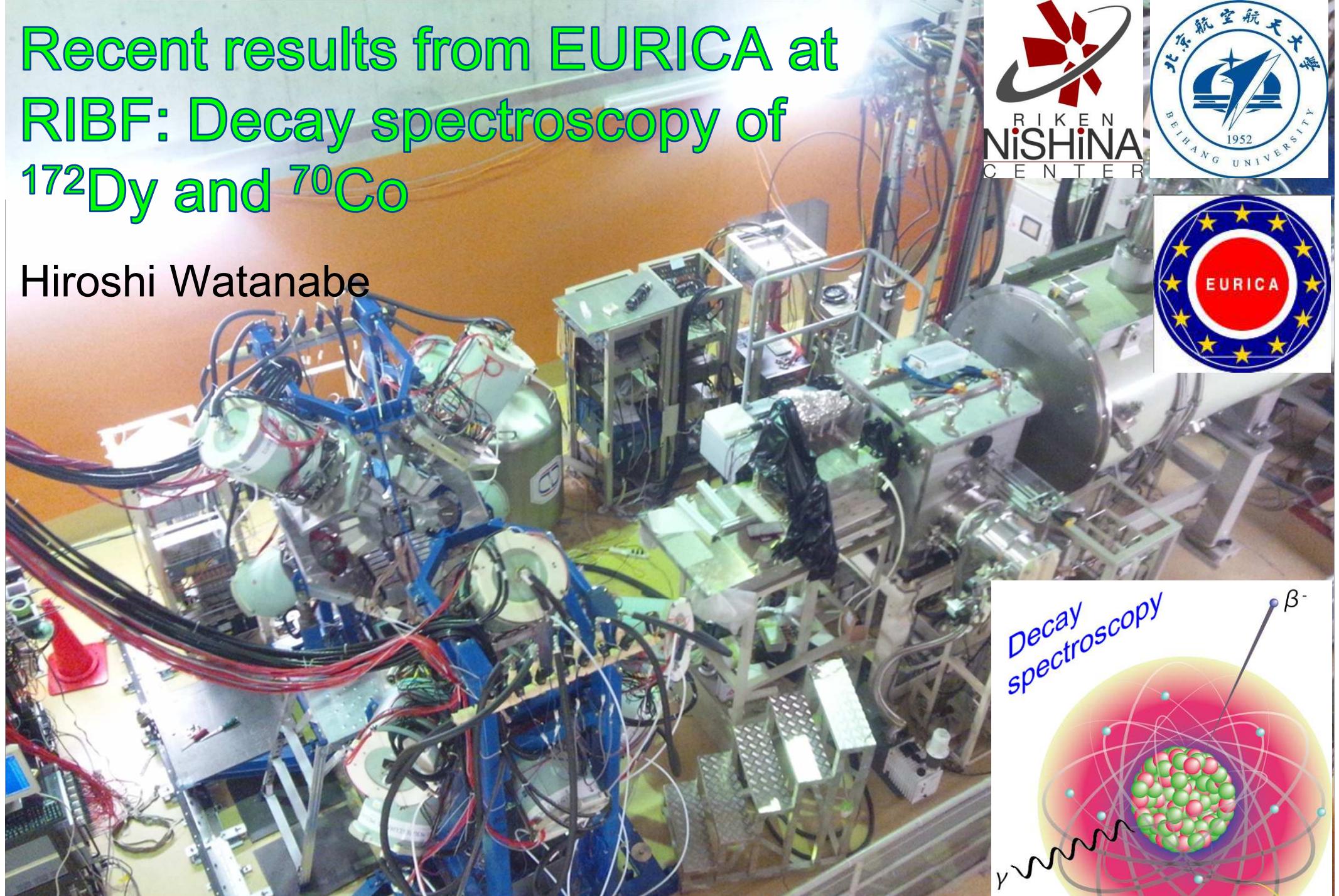


Recent results from EURICA at RIBF: Decay spectroscopy of ^{172}Dy and ^{70}Co

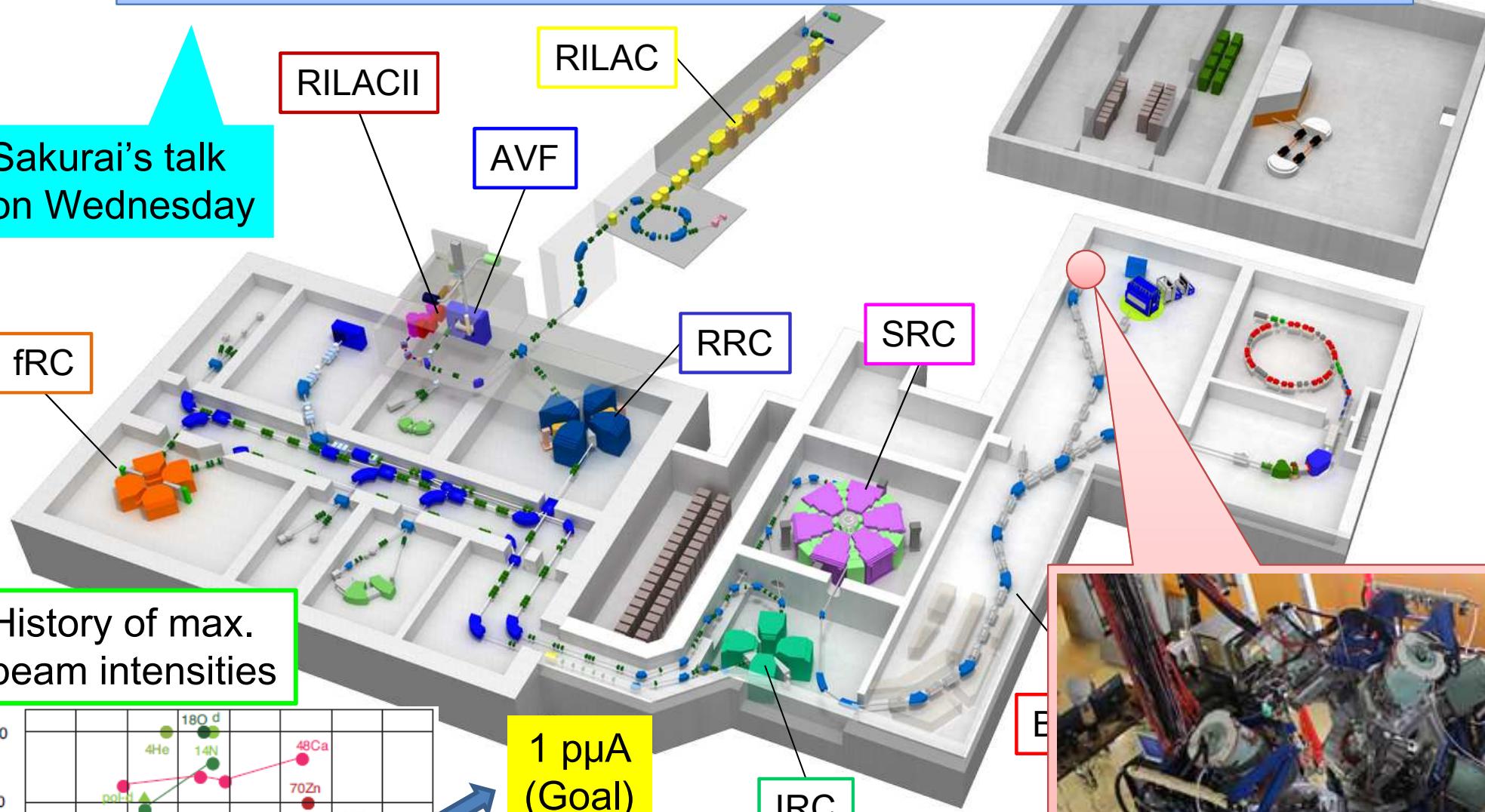
Hiroshi Watanabe



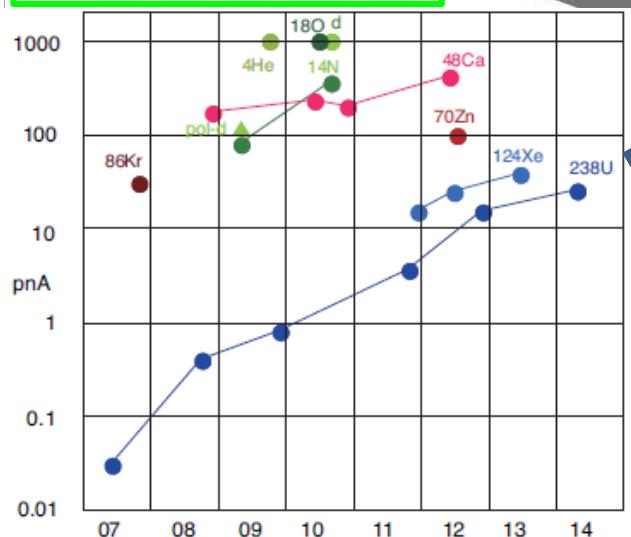
Shapes and Symmetries in Nuclei: from Experiment to Theory
(SSNET), November 7-11, 2016, CSNSM, Orsay, France

Radioactive Isotope-Beam Factory (RIBF) at RIKEN

Sakurai's talk
on Wednesday

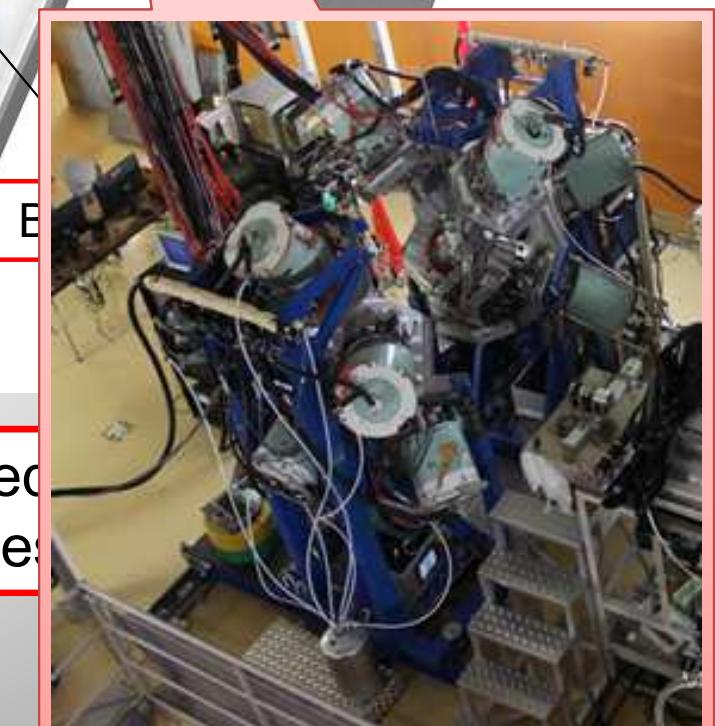


History of max.
beam intensities

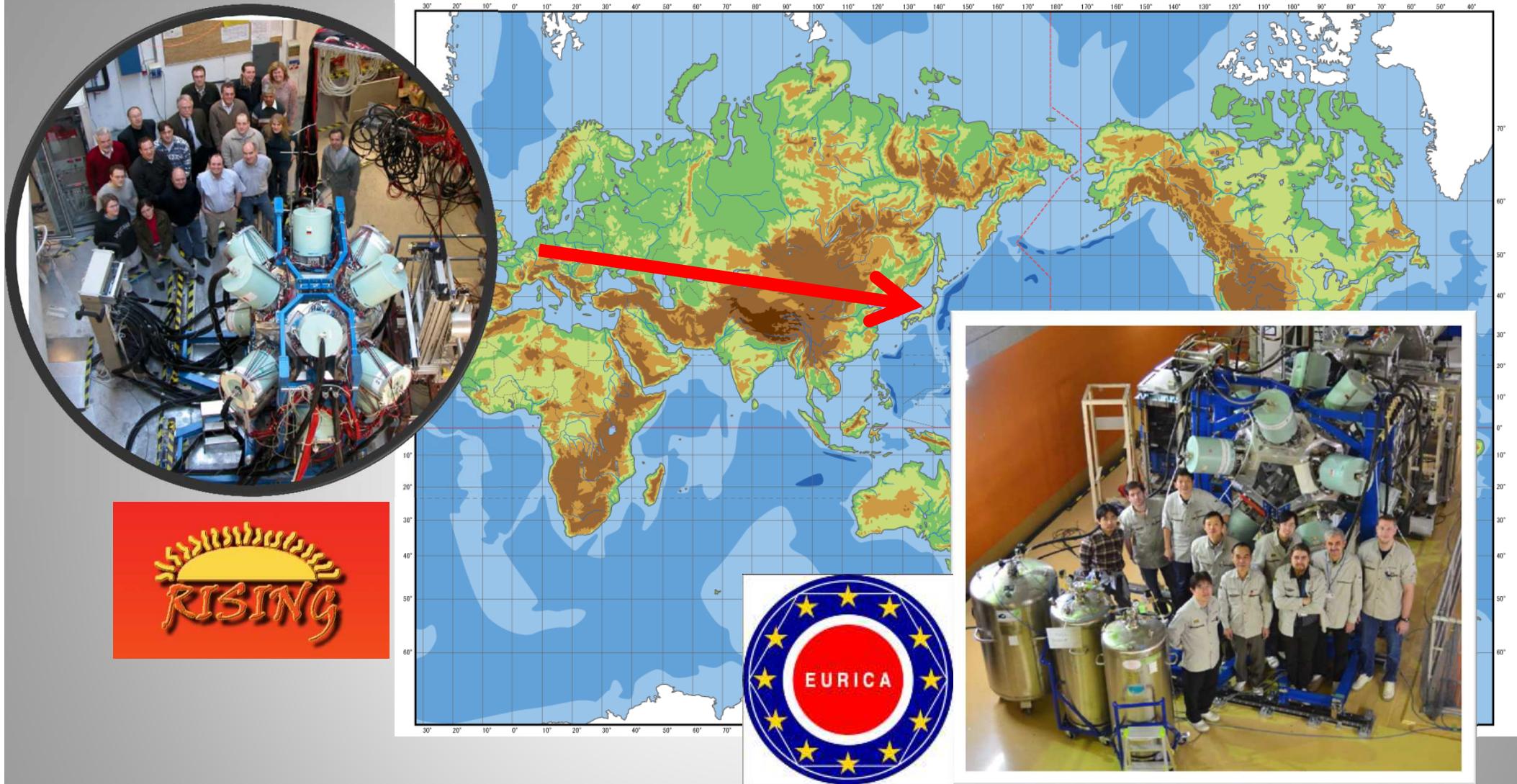


1 pμA
(Goal)

4000 species to be produced
(More than 1000 new isotopes)



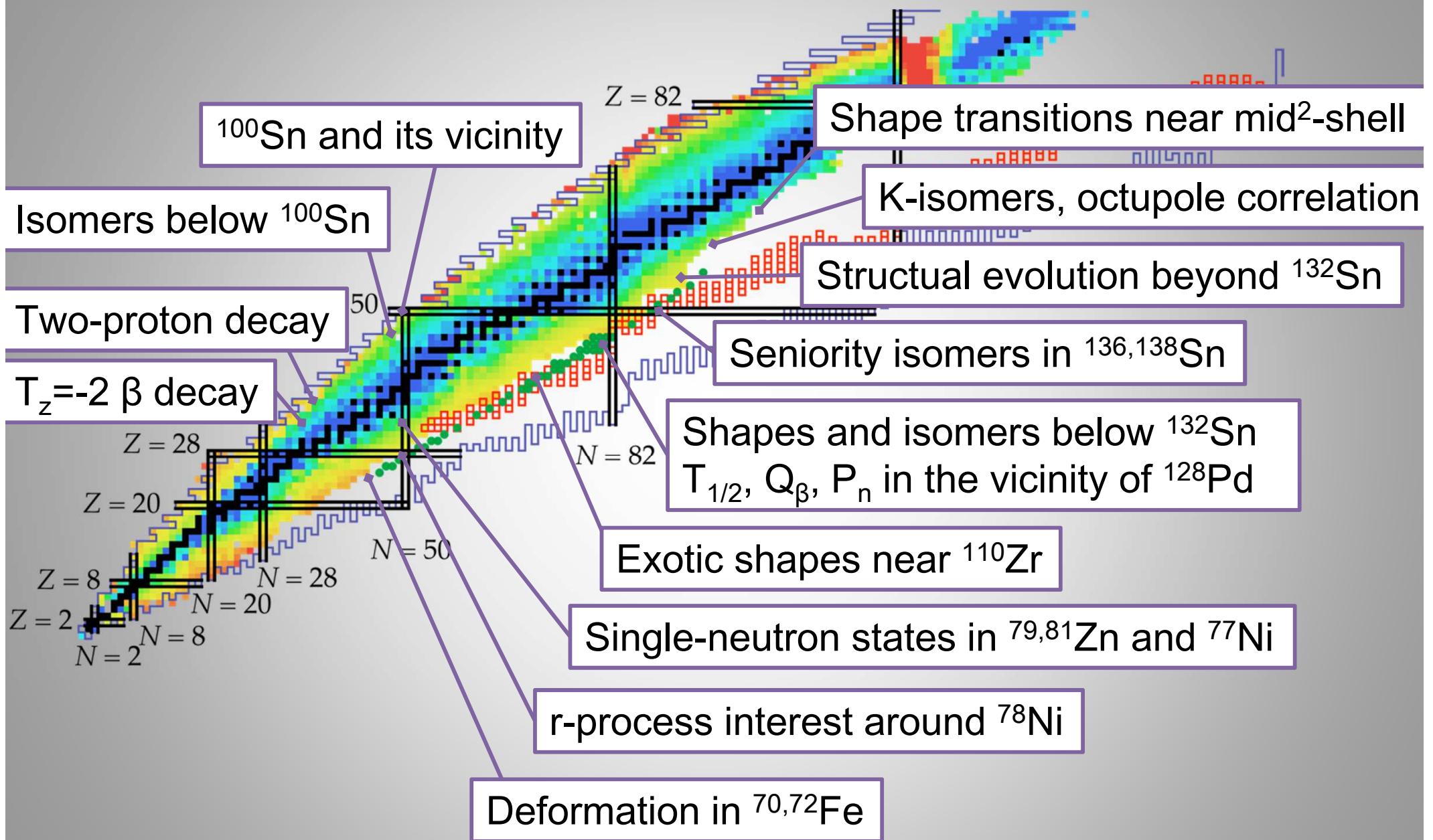
The EURICA (EUROBALL-RIKEN Cluster Array) project



In collaboration with

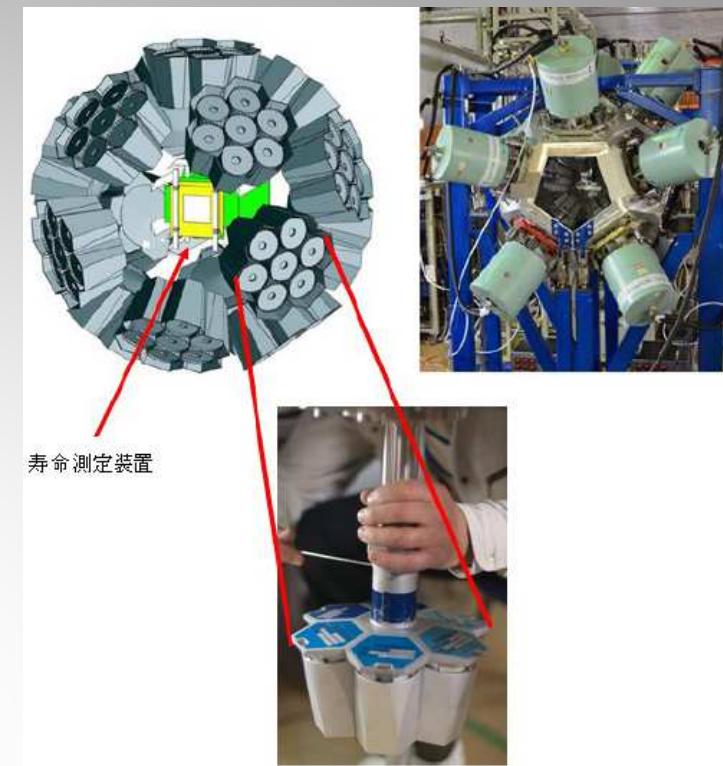
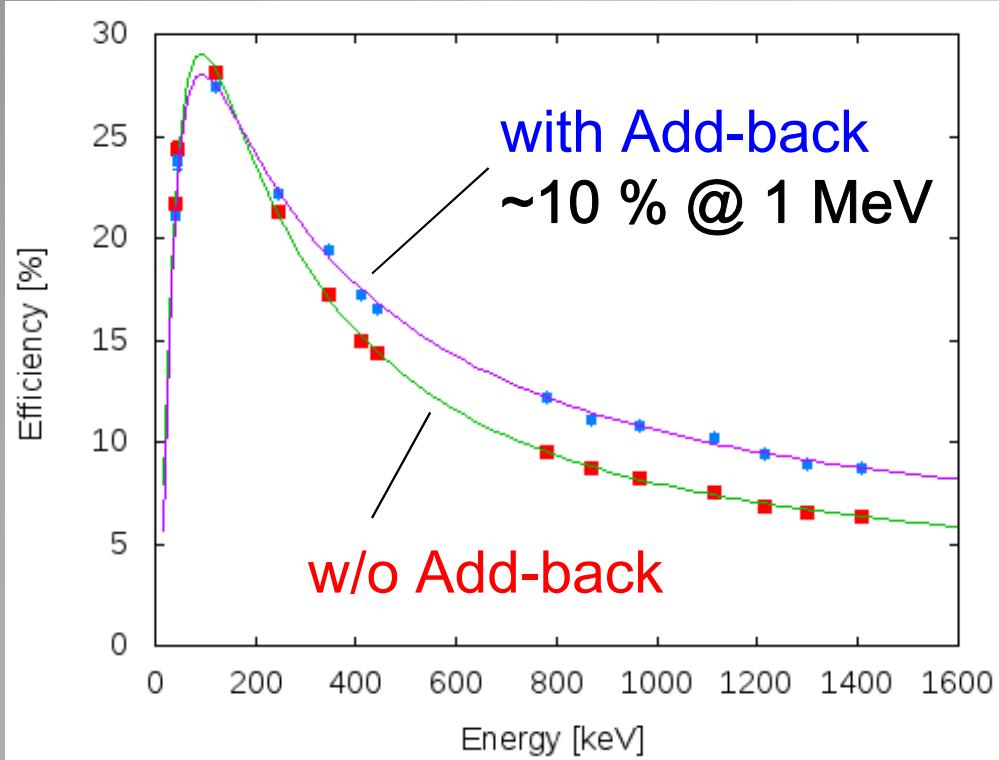
- Gammapool for 12 Cluster detectors
- RISING/PreSPEC for support structure and electronics

EURICA at RIBF in 2012-2016



Approved BT with Grade A or higher: ~100 days

7-element Cluster-type HPGe detectors $\times 12$

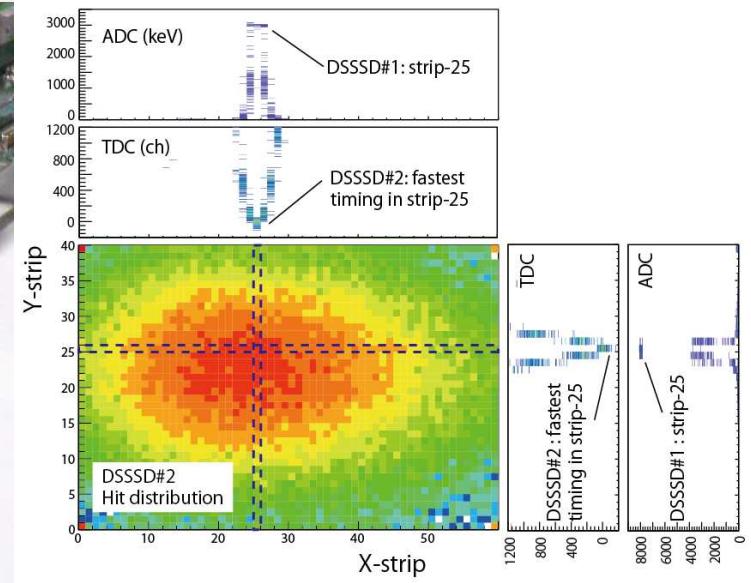
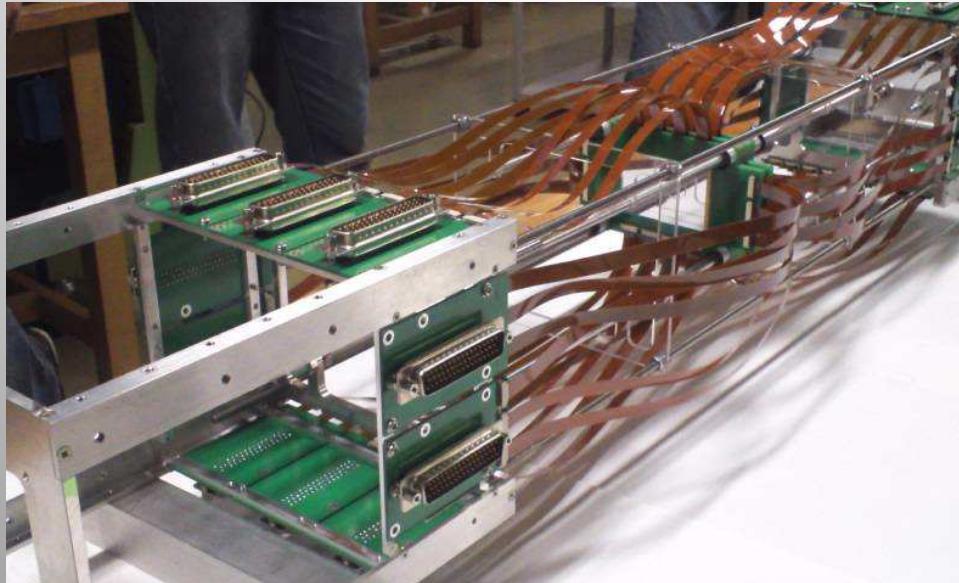


WAS3ABi: Wide-range Active Silicon-Strip Stopper Array for Beta and ion detection

DSSSD

- 60×40 strips
- 1-mm pitch

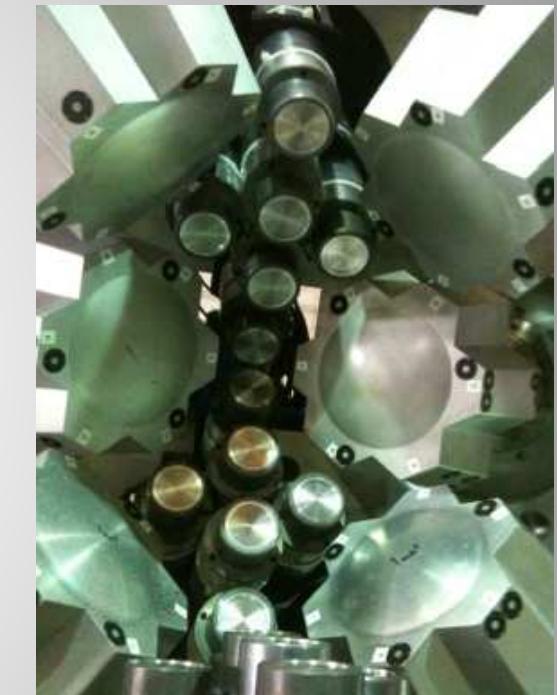
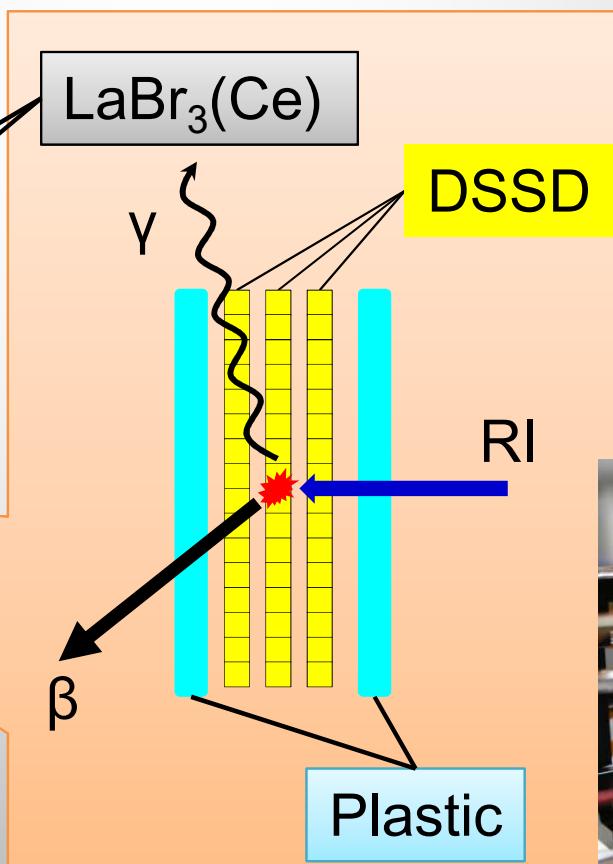
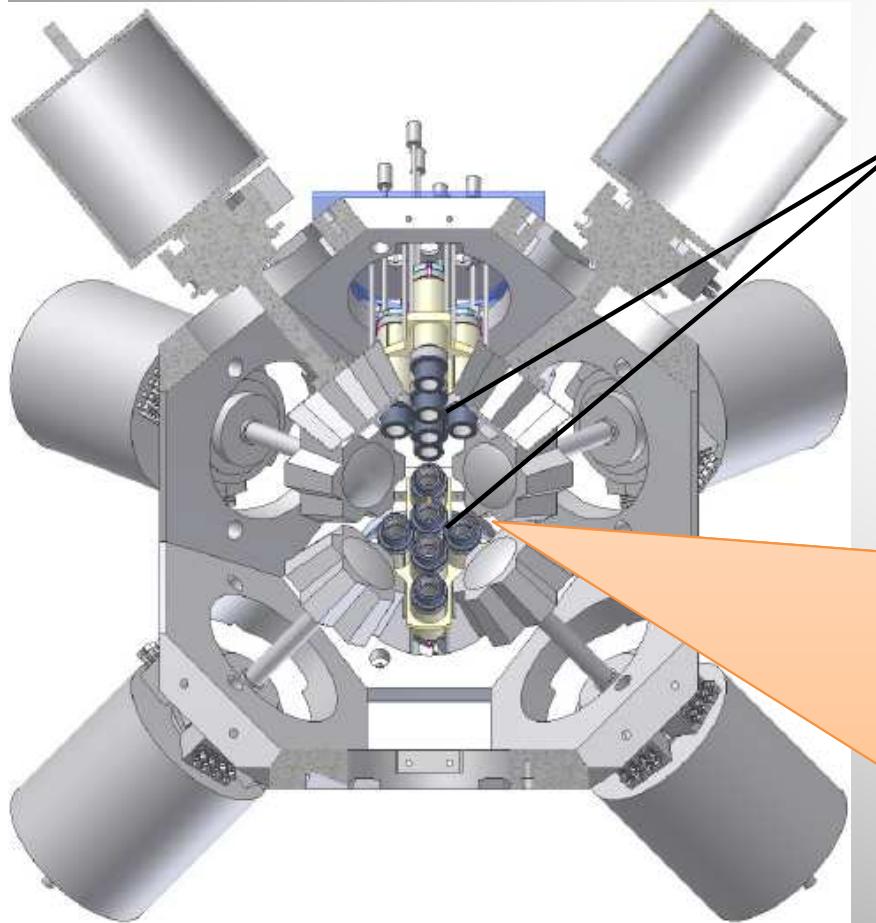
8 layers (2012)
5 layers (2013)



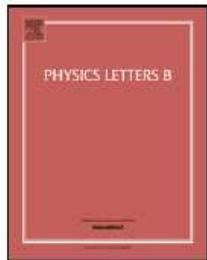
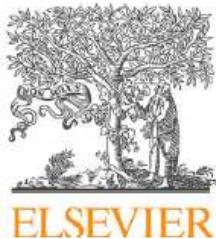
Fast timing demonstration with EURICA

- 18 LaBr₃(Ce) scintillators ($\Phi 1.5'' \times 2''$) on three vacant slots for γ rays
※ Contributed from U. of Surrey and Brighton
- BC-418 plastic counters (2-mm thick) beside the DSSDs for β rays

Fast-timing measurement



Decay spectroscopy of ^{172}Dy



Long-lived K isomer and enhanced γ vibration in the neutron-rich nucleus ^{172}Dy : Collectivity beyond double midshell

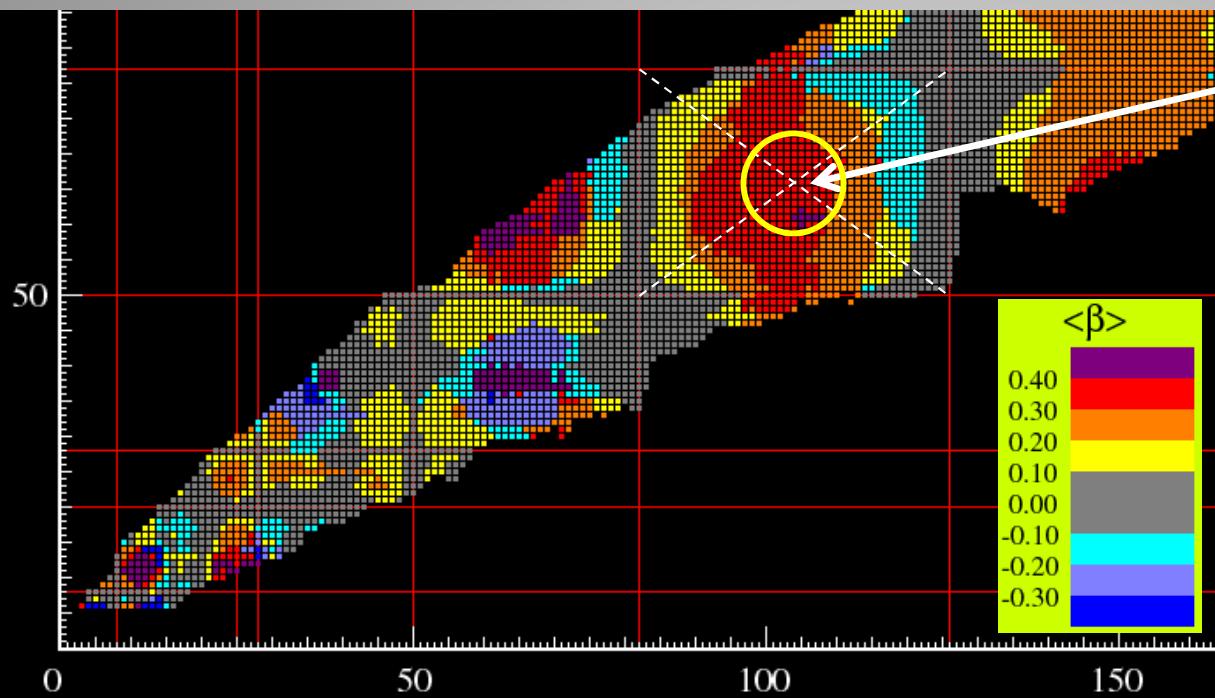


H. Watanabe ^{a,b,c,*}, G.X. Zhang ^{a,b}, K. Yoshida ^{d,e}, P.M. Walker ^f, J.J. Liu ^g, J. Wu ^{c,h},
 P.H. Regan ^{f,i}, P.-A. Söderström ^c, H. Kanaoka ^j, Z. Korkulu ^k, P.S. Lee ^l, S. Nishimura ^c,
 A. Yagi ^j, D.S. Ahn ^c, T. Alharbi ^m, H. Baba ^c, F. Browne ⁿ, A.M. Bruce ⁿ, R.J. Carroll ^f,
 K.Y. Chae ^o, Zs. Dombradi ^k, P. Doornenbal ^c, A. Estrade ^p, N. Fukuda ^c, C. Griffin ^p,
 E. Ideguchi ^q, N. Inabe ^c, T. Isobe ^c, S. Kanaya ^j, I. Kojouharov ^r, F.G. Kondev ^s, T. Kubo ^c,
 S. Kubono ^c, N. Kurz ^r, I. Kuti ^k, S. Lalkovski ^f, G.J. Lane ^t, C.S. Lee ^l, E.J. Lee ^o, G. Lorusso ^{c,f,i},
 G. Lotay ^f, C.-B. Moon ^u, I. Nishizuka ^v, C.R. Nita ^{n,w}, A. Odahara ^j, Z. Patel ^f, V.H. Phong ^{c,x},
 Zs. Podolyák ^f, O.J. Roberts ^y, H. Sakurai ^c, H. Schaffner ^r, C.M. Shand ^f, Y. Shimizu ^c,
 T. Sumikama ^v, H. Suzuki ^c, H. Takeda ^c, S. Terashima ^{a,b}, Zs. Vajta ^k, J.J. Valiente-Dóbon ^z,
 Z.Y. Xu ^g

**EURICA experimental campaign at RIBF
in November, 2014**



Z



HFB calculations with D1S Gogny

$^{170}_{\text{66}}\text{Dy}_{104}$

Middle of the major shells
between ^{132}Sn and ^{208}Pb



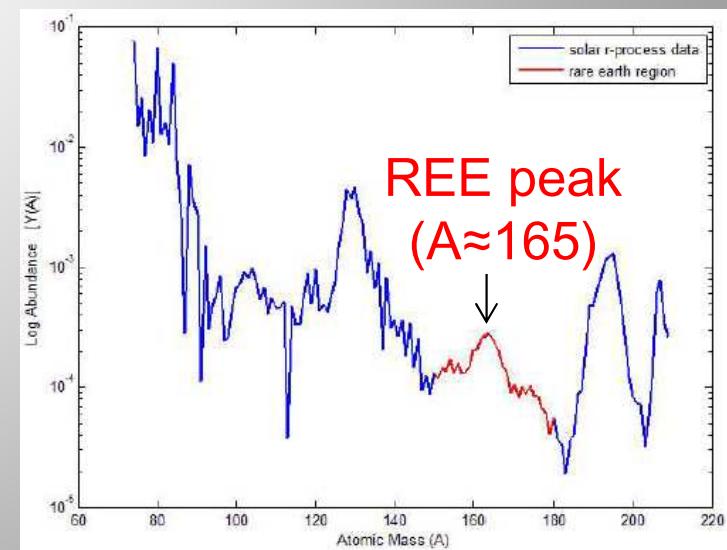
Maximum
ground-state
deformation?

Nuclear Physics

- Where does the largest deformation occur?
- How the neutron excess affect shapes, pairing?
- Sub-shell closures stabilize the shape?

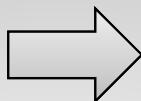
Nuclear Astrophysics

- ◆ Formation of the rare-earth element (REE) peak in the r-process



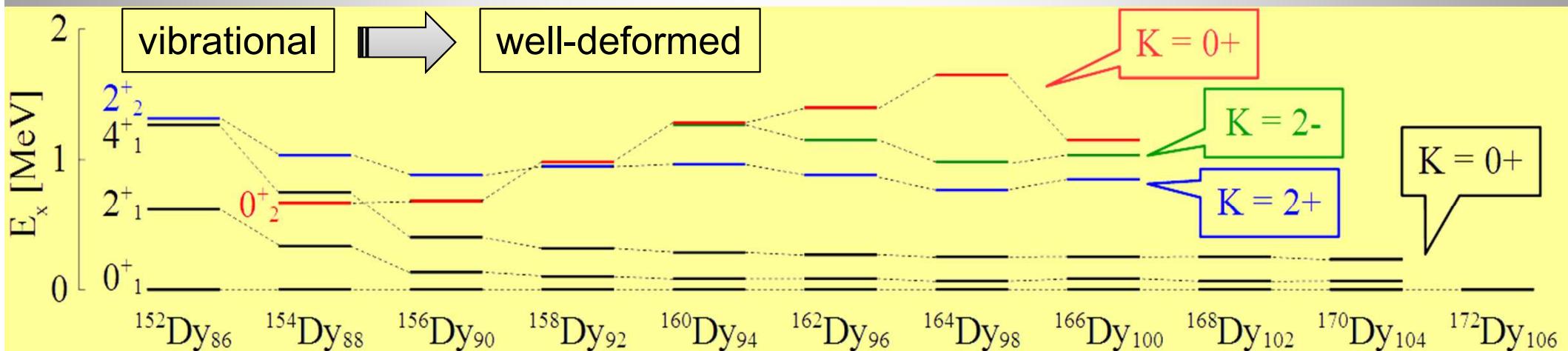
Intrinsic excitations in deformed nuclei : Collective vibrations

Single-particle orbitals
near the Fermi surface



Intrinsic excitations

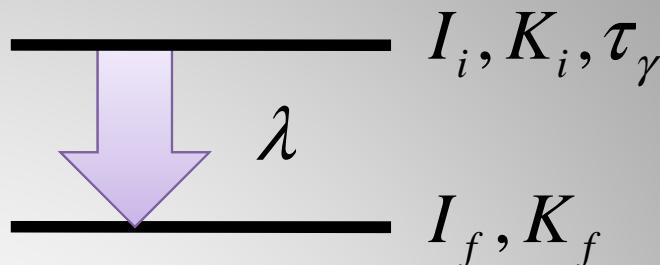
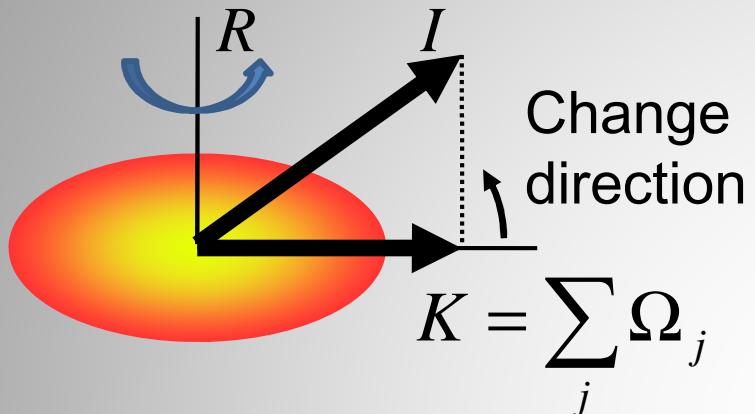
- $K^\pi = 2^+$ $\Rightarrow \gamma$ vibration ($\Delta N = 0$ or ± 2 , $\Delta n_z = 0$, $\Delta \Lambda = \Delta K = \pm 2$)
 - Instantaneous breaking of axial symmetry
 - Soft mode of γ instability or rigid triaxial deformation
- $K^\pi = 0^+$ $\Rightarrow \beta$ vibration, pairing excitation, intruder states, shape coexistence
 - Axial symmetry preserved
- $K^\pi = 0^-, 1^-, 2^-, 3^-$ \Rightarrow Octupole vibration ($\Delta j = \Delta l = 3$)



Good testing ground for collective model calculations

Intrinsic excitations in deformed nuclei : K isomer

Phil Walker's talk
on Monday



$$\lambda \geq |I_i - I_f| \quad \text{Spin selection ... Yes}$$
$$\lambda \geq |K_i - K_f| \quad \text{K-selection ... Sort of !}$$

K hindered
transitions

Weisskopf hindrance

$$F = \tau_\gamma^{\text{exp}} / \tau_W$$

Reduced hindrance

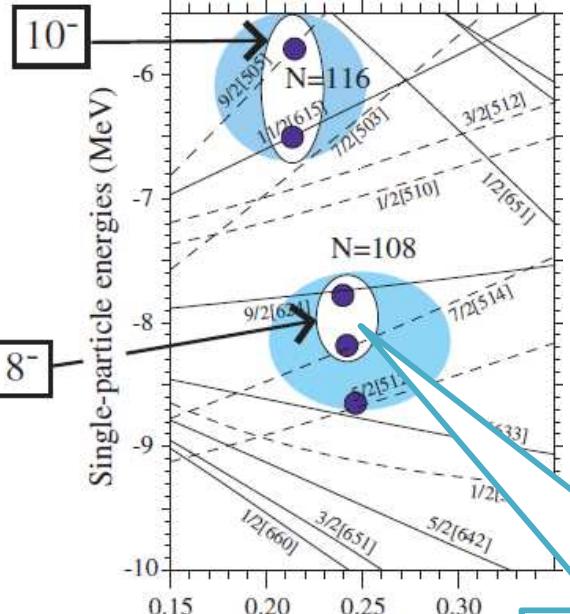
$$f_\nu = F^{1/\nu}$$

The degree of K forbiddenness

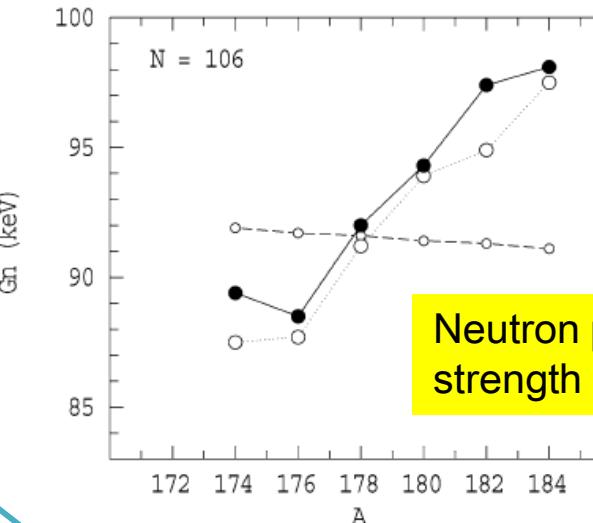
$$\nu = \Delta K - \lambda$$

Identification and characterization of K-isomers provides information on

- Single-particle orbits near the Fermi surface
- Pairing and other residual interactions
- Axial (a)symmetry (γ degree of freedom)



$v7/2-[514]v9/2+[624]$



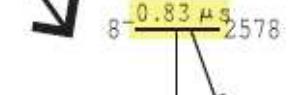
$K^\pi = 8^-$ isomers in $N = 106$

G.D. Dracoulis,
Phys. Scr. T152, 014015 (2013)

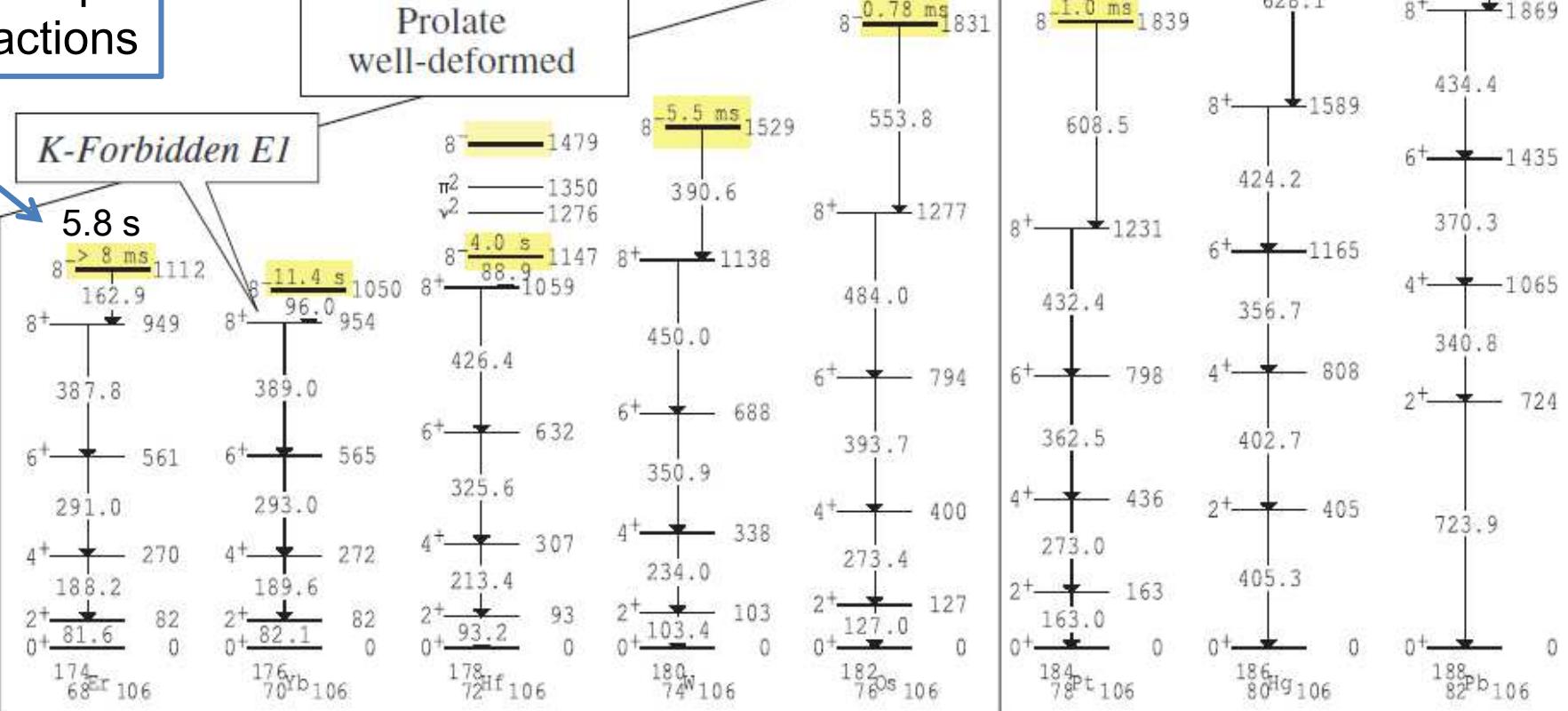
Spherical-Oblate
-Prolate
Shape Co-existence

Oblate-Prolate
Co-existence

Transitional



Studied by deep-inelastic reactions



In-flight fission of ^{238}U +

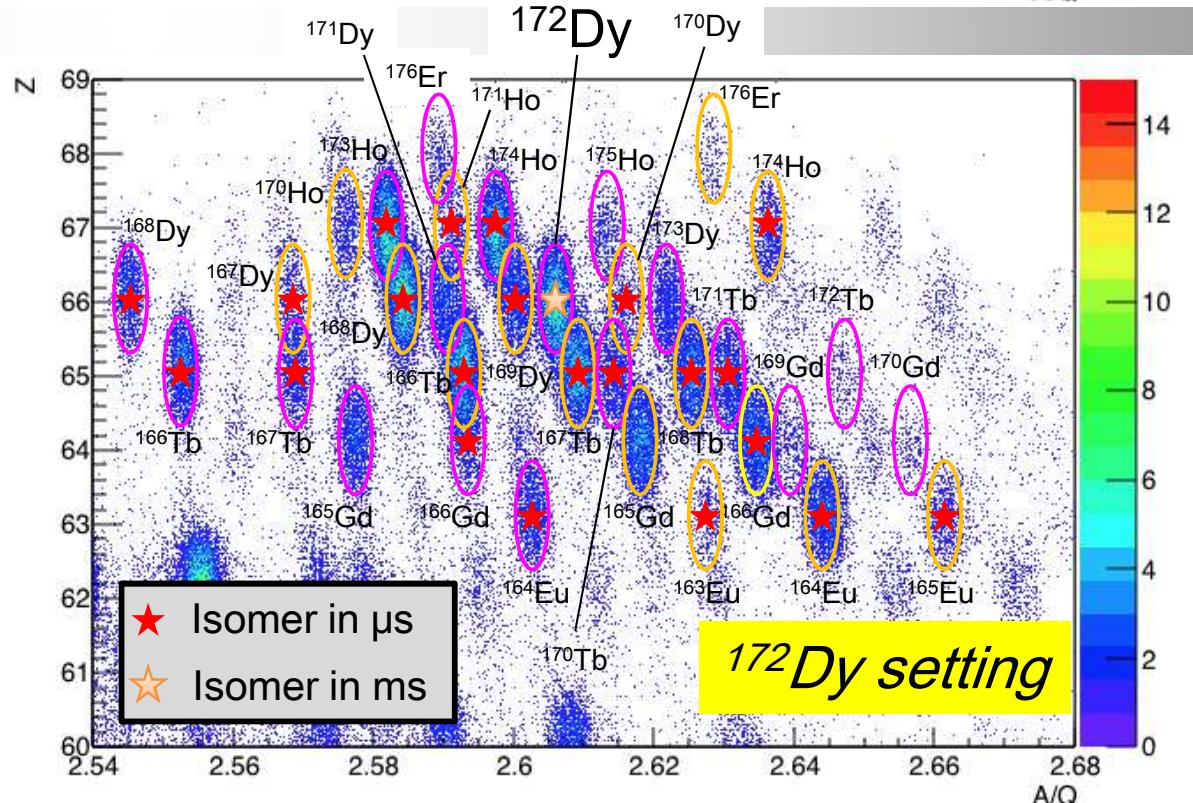
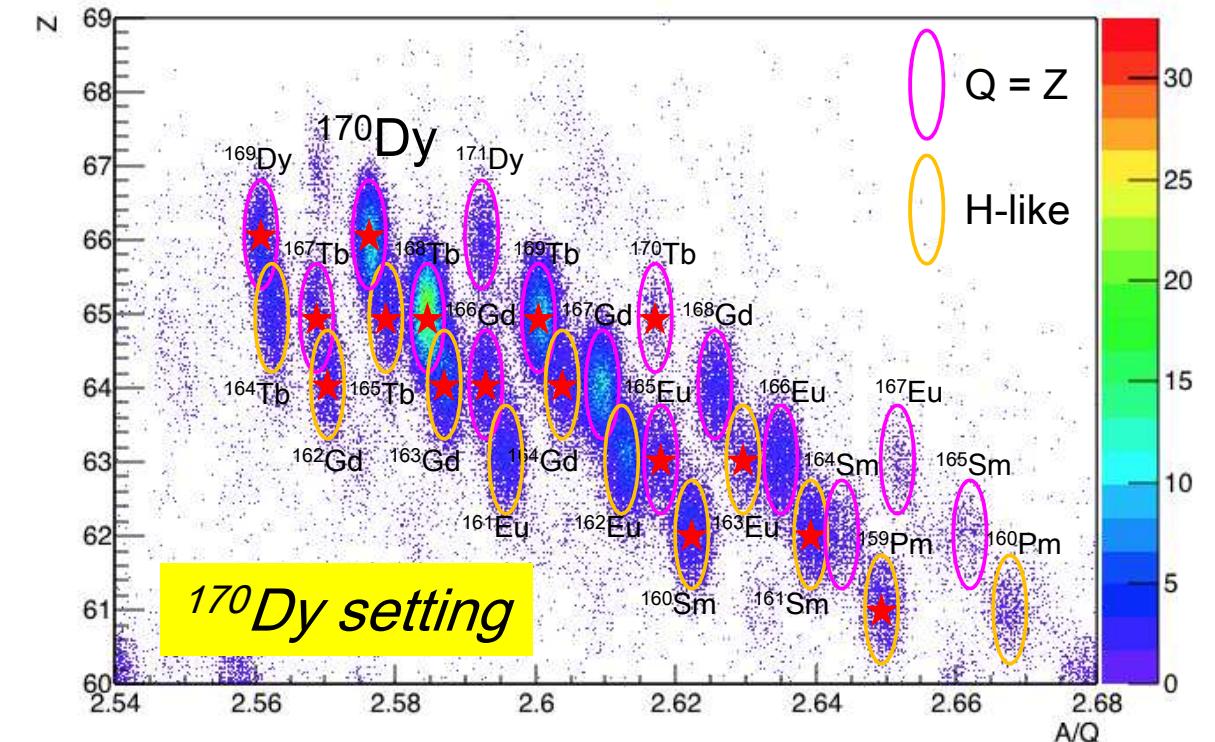
Isotope separation

Nov. 2014 (3 days)

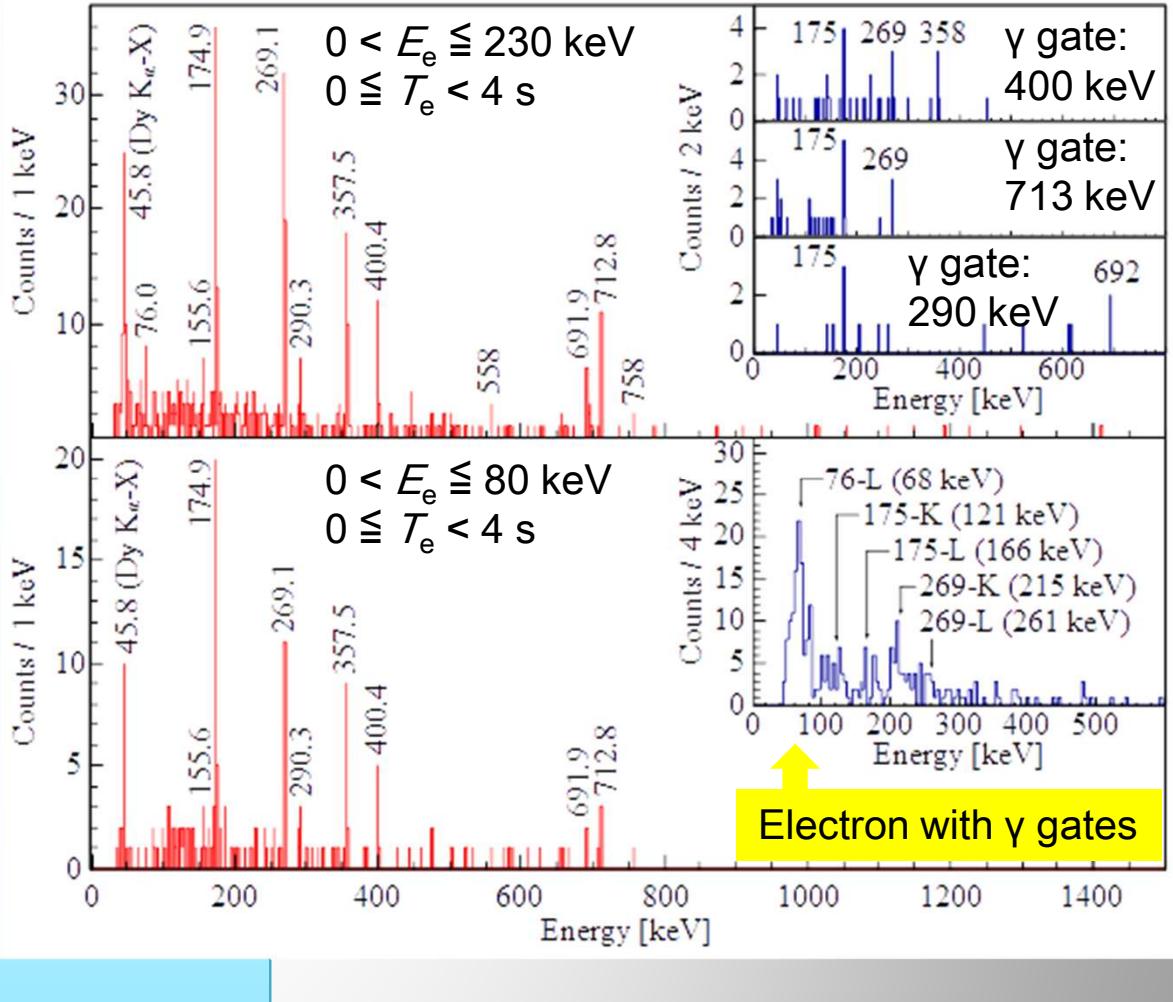
- High intensity (10~15 pnA)
- Slits optimized for $^{170,172}\text{Dy}$
- $\Delta A/Q \sim 0.05\%$
⇒ Separate charge state

Ion	BigRIPS	On DSSD
$^{170}\text{Dy}^{66+}$	12932	5483
$^{172}\text{Dy}^{66+}$	8272	7096

Heaviest isotope
spectroscopic study
done so far at RIBF



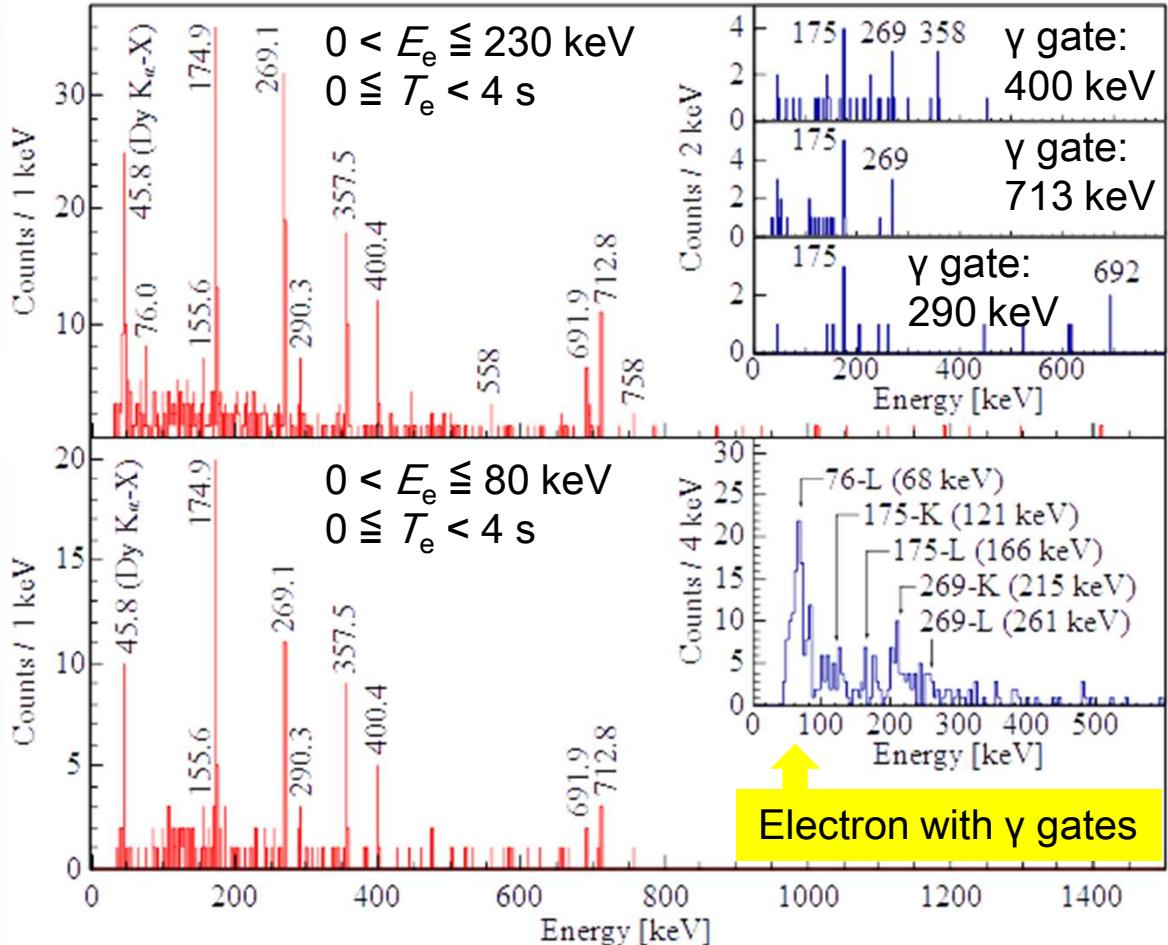
- No level information before
- 11 new γ rays observed by gating on low-energy electrons
 - Coincidence with internal-conversion (IC) electrons
 - Decay from a long-lived isomer
 - Observation of the Dy K_a-X ray at 45.8 keV
 - 76-keV γ ray disappears for $E_e \leq 80$ keV



□ No level information before

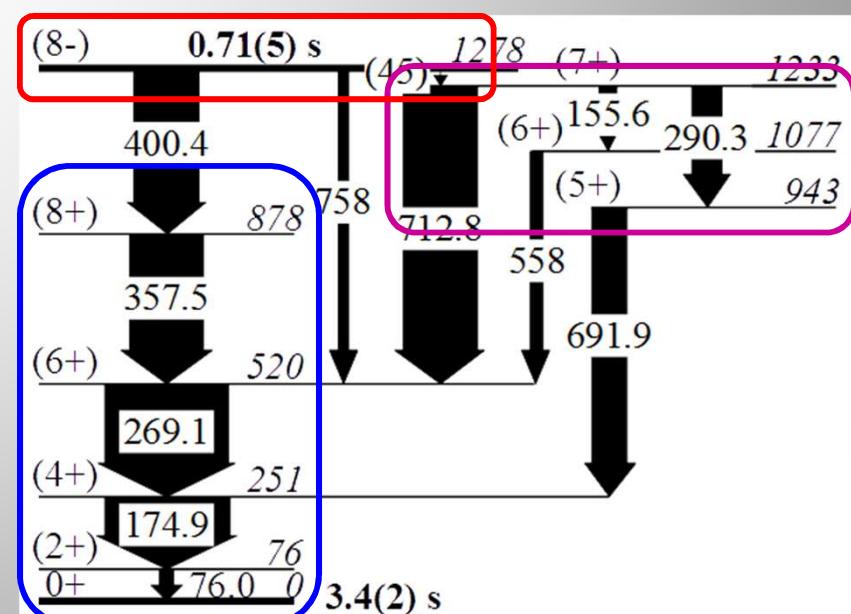
□ 11 new γ rays observed by gating on low-energy electrons

- Coincidence with internal-conversion (IC) electrons
- Decay from a long-lived isomer
- Observation of the Dy K _{α} -X ray at 45.8 keV
- 76-keV γ ray disappears for $E_e \leq 80$ keV

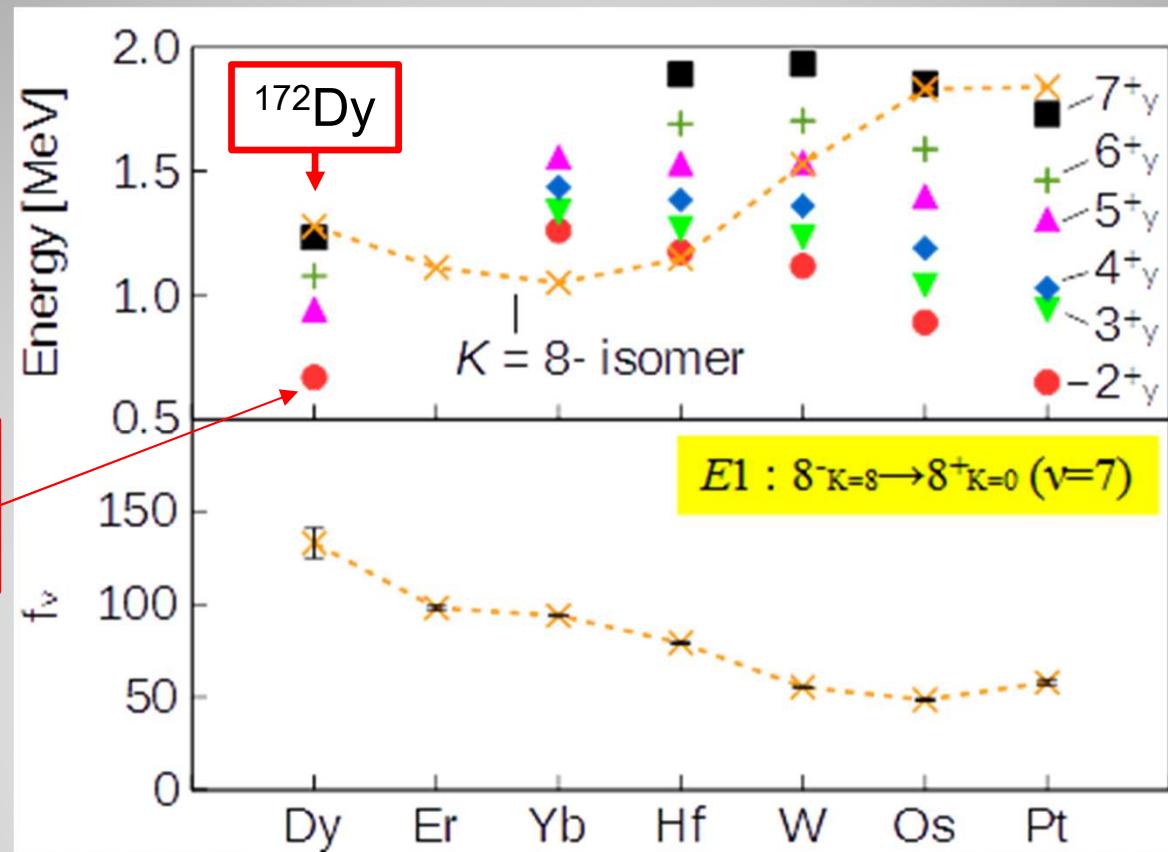


□ Level scheme constructed based on γ - γ coincidence, energy matching, feeding patterns, and systematics

- $K^\pi = 8^-$ isomer ($T_{1/2} = 0.75$ s) at 1278 keV
- Ground-state (g.s.) rotational band
- γ -vibrational band
- ✓ Band assignment supported by the moment of inertia and g.s.- γ band mixing



$K^\pi = 8^-$ isomers and γ -vibrational states in $N = 106$ isotones



□ $K^\pi = 2^+$ γ -vibrational levels in ^{172}Dy

- ※ Unusually low excitation energy, compared to the heavier isotones (^{176}Yb , ^{178}Hf)
- Extrapolated energy of the 2^+_{γ} state (671 keV)
 - As low as the 2^+_{γ} state in the γ -unstable nucleus ^{184}Pt
 - Sufficiently higher than the 4^+_1 state ⇒ Axially-symmetric structure

- γ -vibrational motion is remarkably enhanced
- Microscopic effect on the non-axial collectivity is significant

Interpretation of γ vibration in the framework of Nuclear DFT

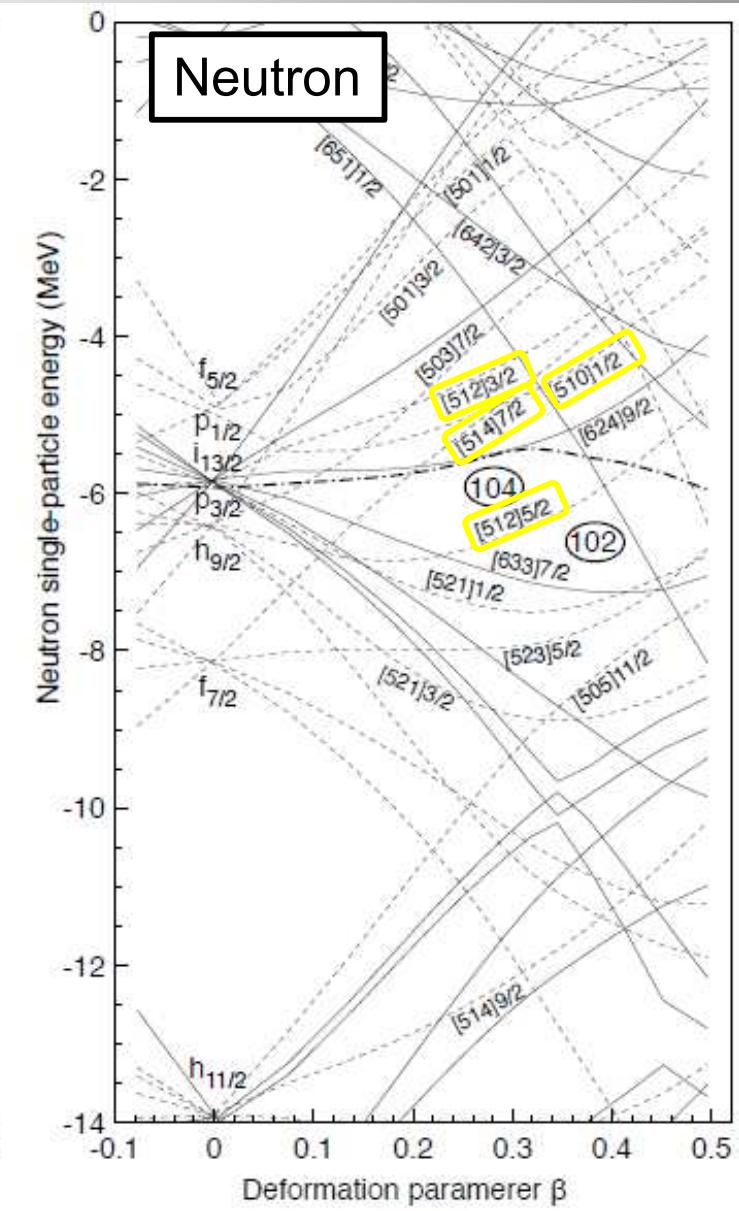
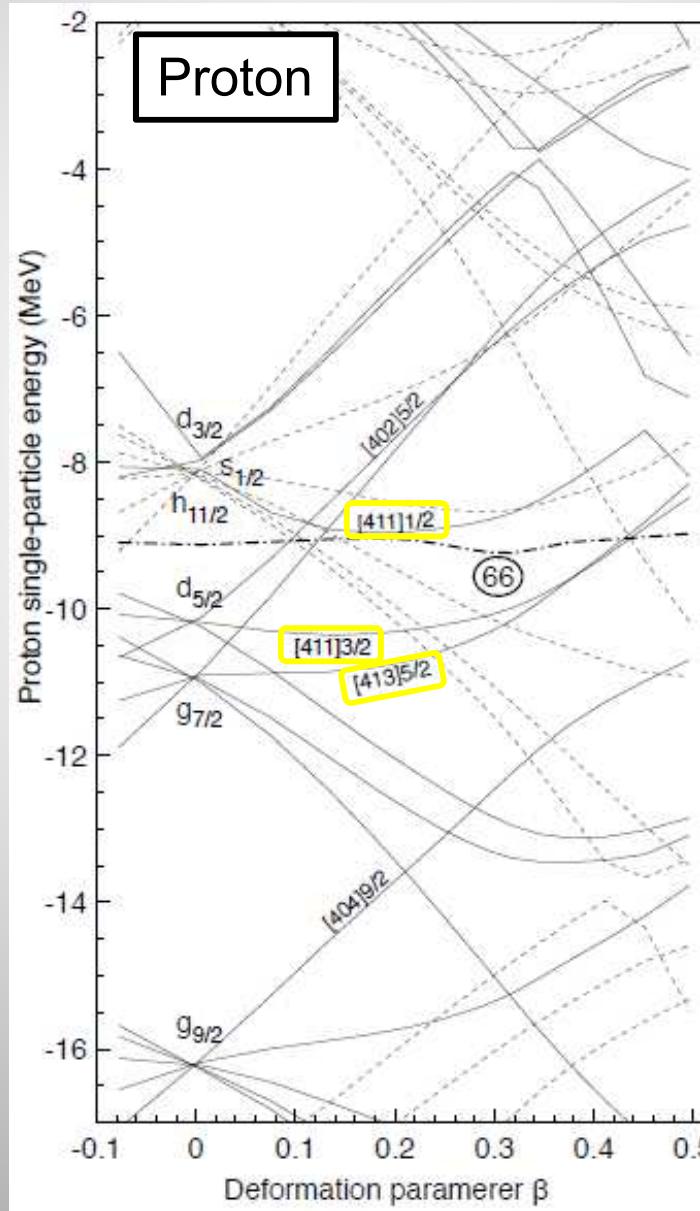
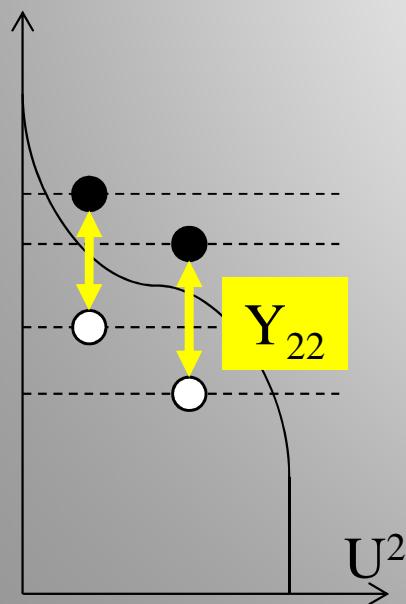
Skyrme + pairing energy-density functional (EDF)

- HFB for the ground state
- QRPA for the intrinsic excitations

K. Yoshida and H. Watanabe
arXiv:1607.07111
PTEP in press

Selection rules for
the non-axial quadrupole
matrix elements (Y_{22})

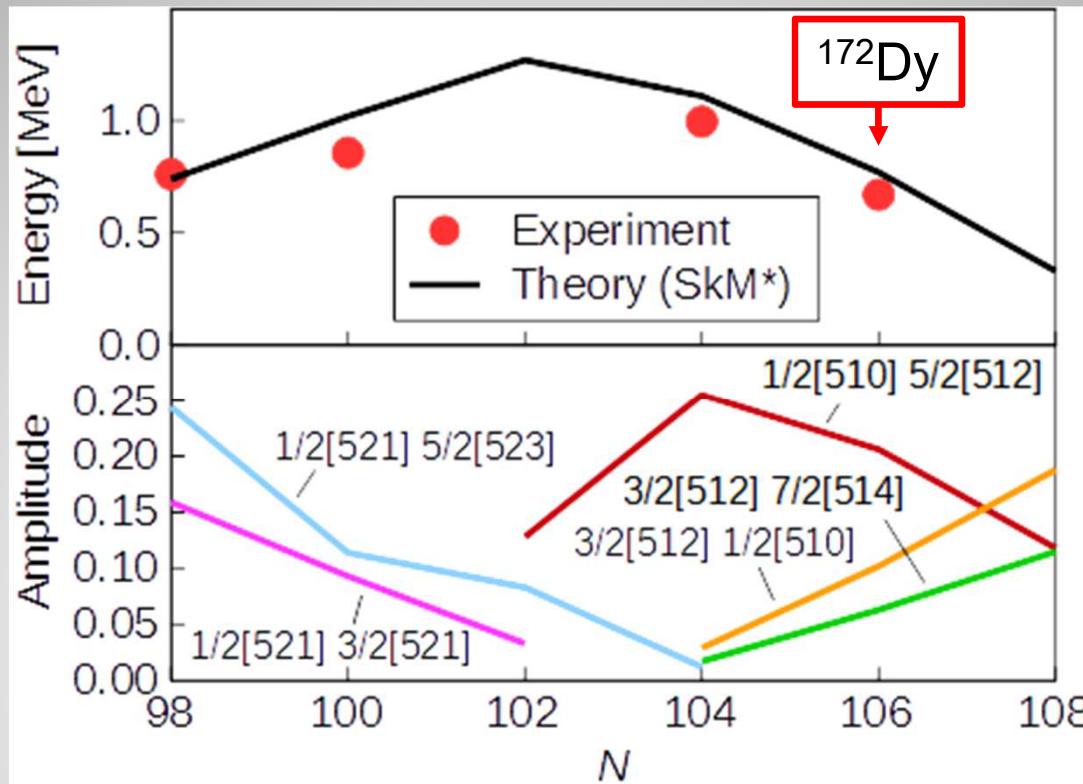
- $\Delta N = 0$ or ± 2 ,
- $\Delta n_z = 0$,
- $\Delta \Lambda = \Delta K = \pm 2$



Interpretation of γ vibration in the framework of Nuclear DFT

$E(2^+_\gamma)$

Neutron 2qp components in 2^+_γ



- ◆ HFB+QRPA calculation well reproduces the experimental results
Decreasing trend of the 2^+_γ energies from $^{170}\text{Dy}_{104}$ to $^{172}\text{Dy}_{106}$

- ◆ Significant 2qp components in QRPA
 - Proton \Rightarrow Not change so much with the neutron number
 $\pi^2 1/2^+[411] \otimes 3/2^+[411]$ (~0.25), $\pi^2 1/2^+[411] \otimes 5/2^+[413]$ (~0.19)
 - Neutron \Rightarrow Isotopic dependence of the 2^+_γ energies
3 components play dominant roles beyond midshell ($N > 104$)

Decay spectroscopy of ^{70}Co

COLLABORATION

A.I. Morales, G. Benzoni, H. Watanabe, Y. Tsunoda, T. Otsuka, S. Nishimura, F. Brown, R. Daido, P. Doornenbal, Y. Fang, G. Lorusso, Z. Patel, S. Rice, L. Sinclairl, P.-A. Söderström, T. Sumikama, J. Wu, Z.Y. Xu, L. Coraggio, N. Itaco, A. Gargano A. Yagi, R. Yokoyama, H. Baba, R. Avigo, F.L. Bello Garrote, N. Blasi, A. Bracco, F. Camera, S. Ceruti, F.C.L. Crespi, G. de Angelis, M.-C. Delattre, Zs. Dombradi, A. Gottardo, T. Isobe, I. Kojouharov, N. Kurz, I. Kuti, K. Matsui, B. Melon, D. Mengoni, T. Miyazaki, V. Modamio-Hoybjor, S. Momiyama, D.R. Napoli, M. Niikura, R. Orlandi, H. Sakurai, E. Sahin, D. Sohler, H. Schaffner, R. Taniuchi, J. Taprogge, Zs. Vajta, J.J. Valiente-Dobo`n, O. Wieland, M. Yalcinkaya ,

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Department of Physics, Istanbul University, 34134 Istanbul, Turkey

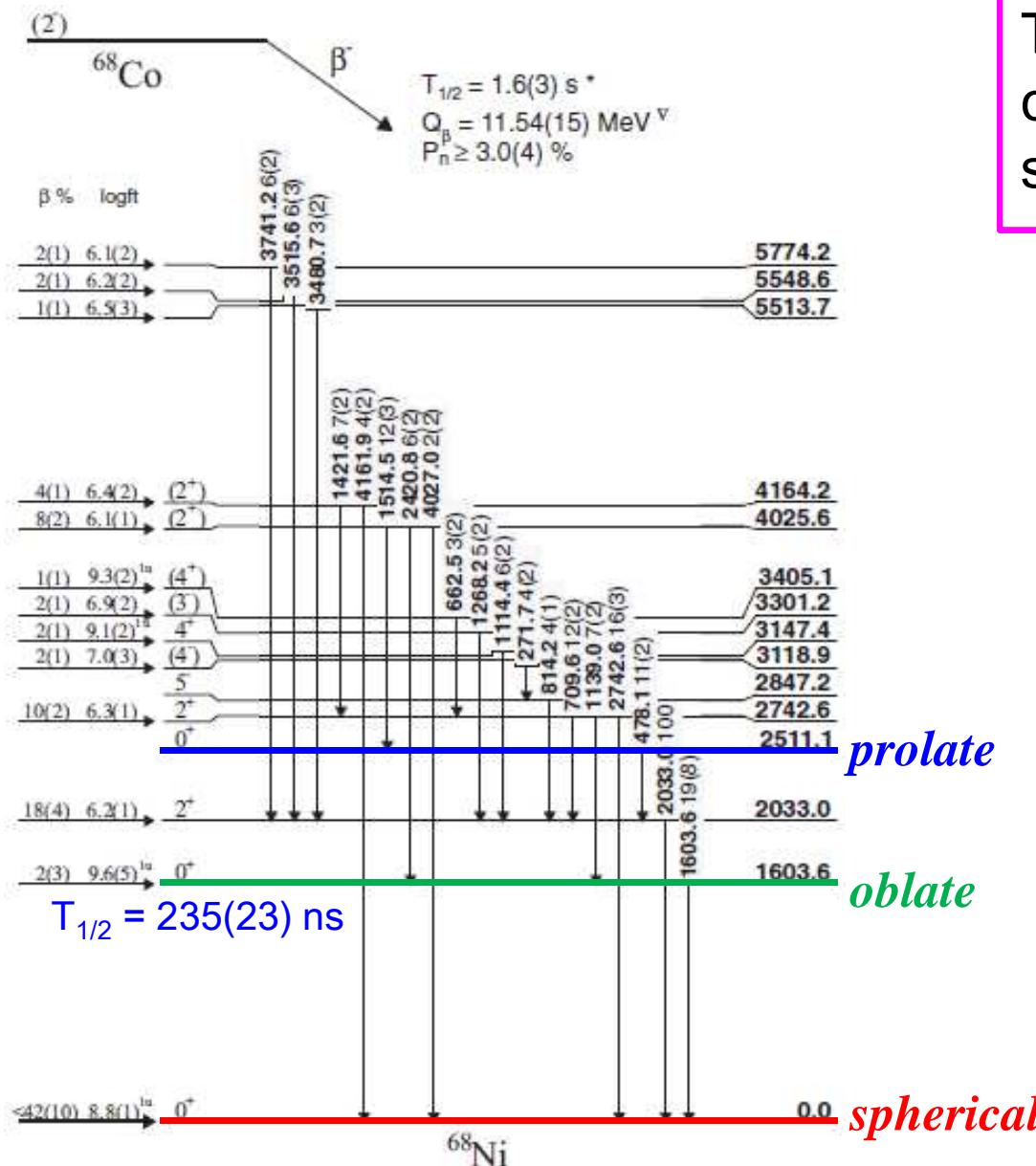
Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Napoli, Italy f

Dipartimento di Fisica dell'Università di Napoli Federico II, Napoli, Italy

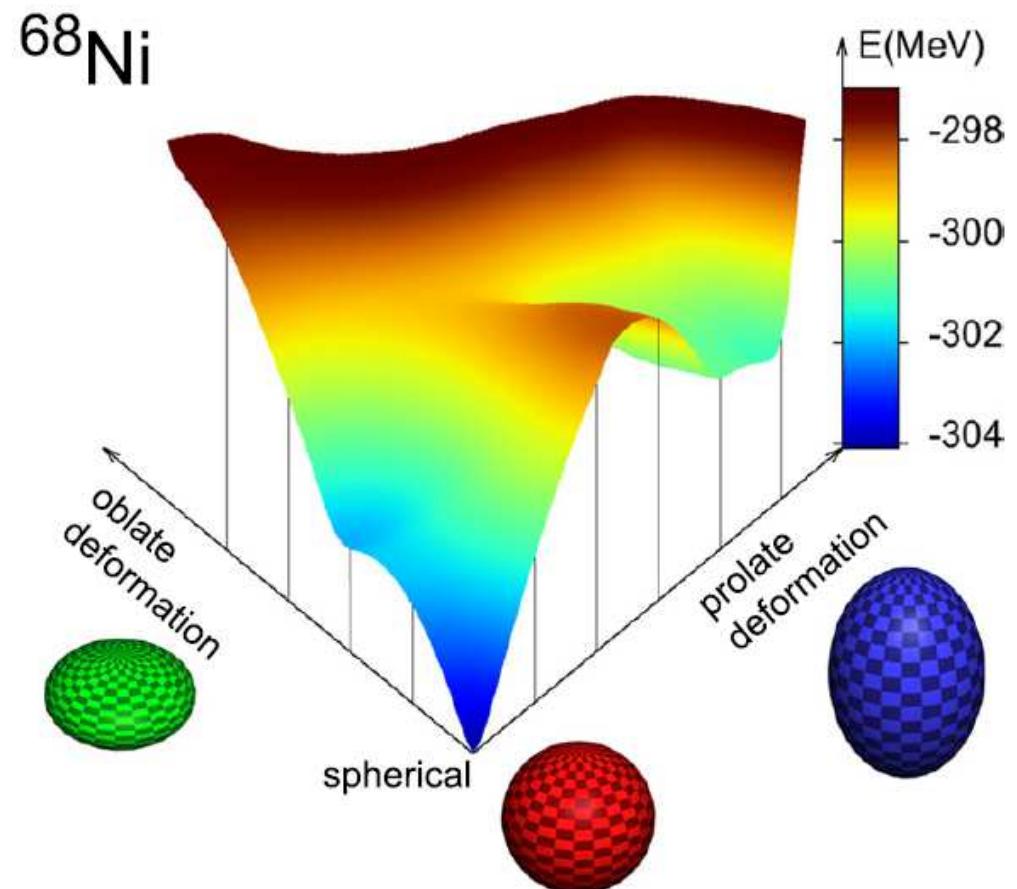
**EURICA experimental
campaign at RIBF
in May, 2013**

Triple shape coexistence in ^{68}Ni

Shape transition and shell evolution also take place within the same nucleus



Three 0^+ states below 3 MeV in ^{68}Ni , corresponding to local minima at spherical, oblate, and prolate shapes

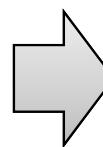


Shape coexistence

Development of shape coexistence in ^{70}Ni

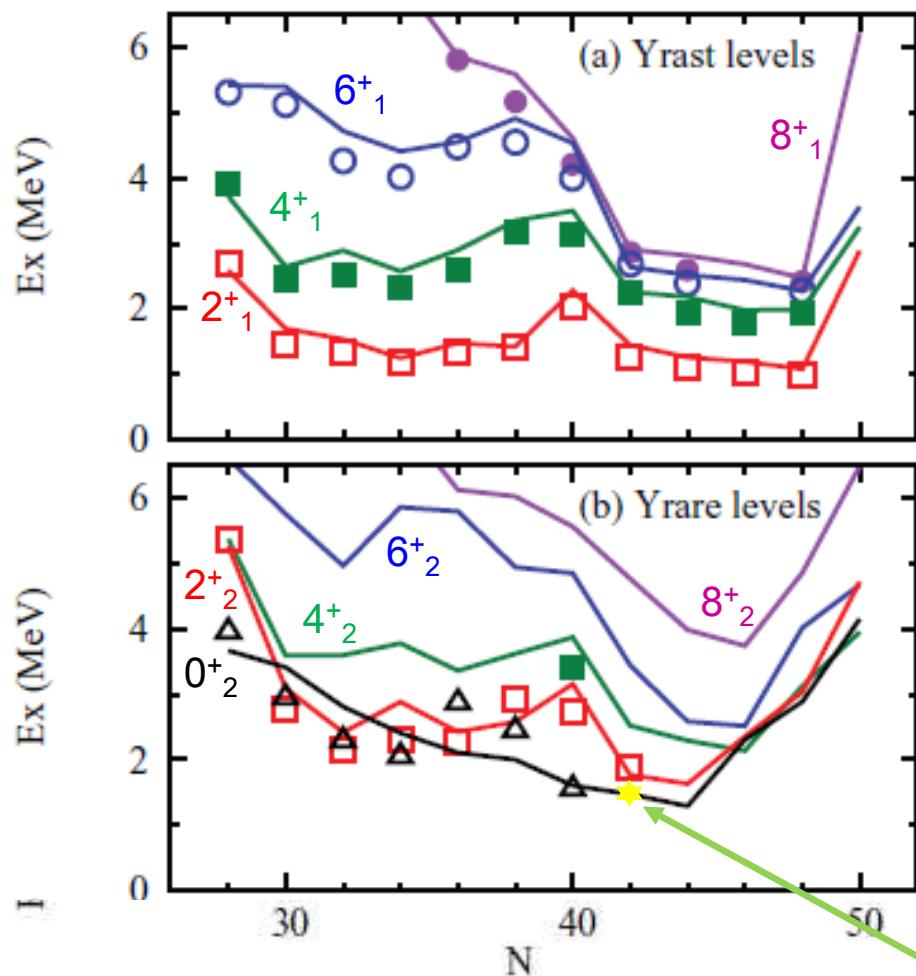
Monte Carlo shell-model (MCSM)

- Full pf-g9/2-d5/2 model space
- A3DA Hamiltonian

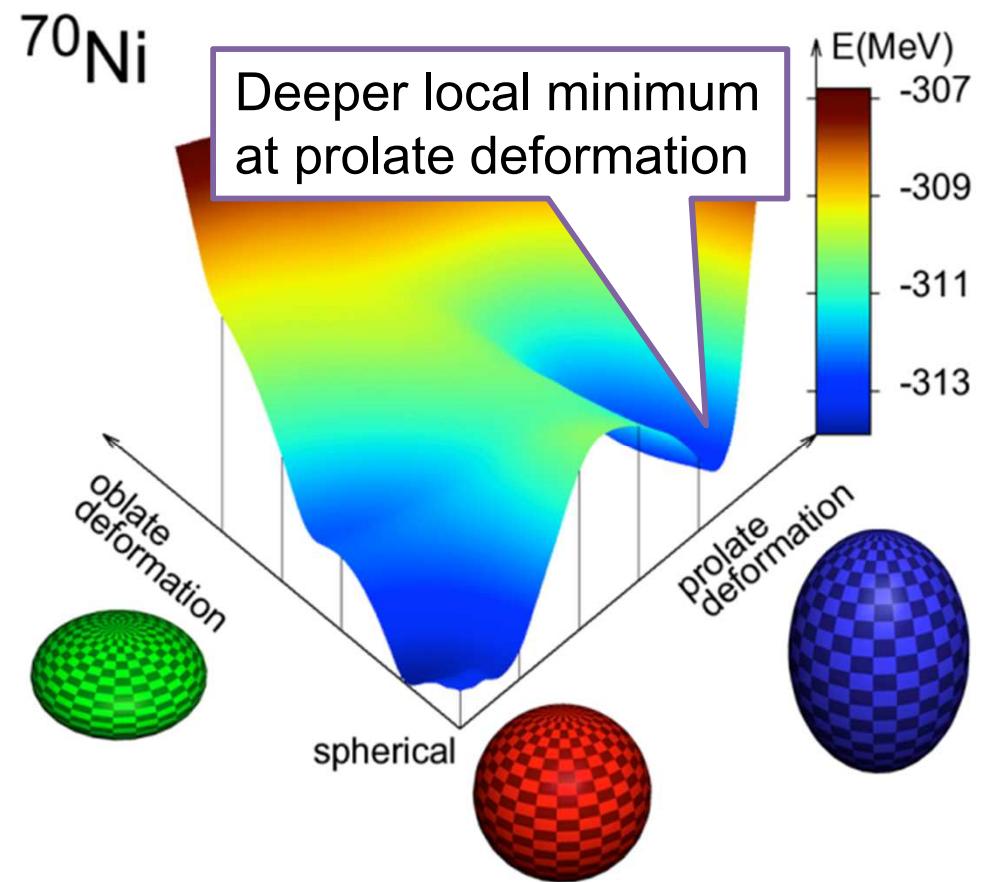


Combined effect of the proton-neutron tensor force and changes of major configurations is crucial for driving the shape coexistence

Y. Tsunoda et al., PRC 89, 031301(R) (2014)



Type-II shell evolution



0^+_2 level at 1566 keV in ^{70}Ni

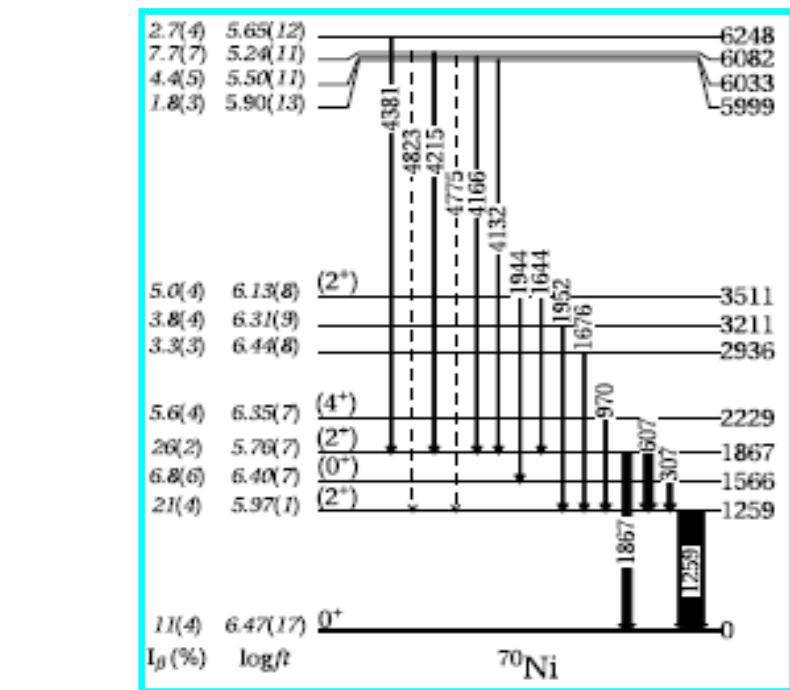
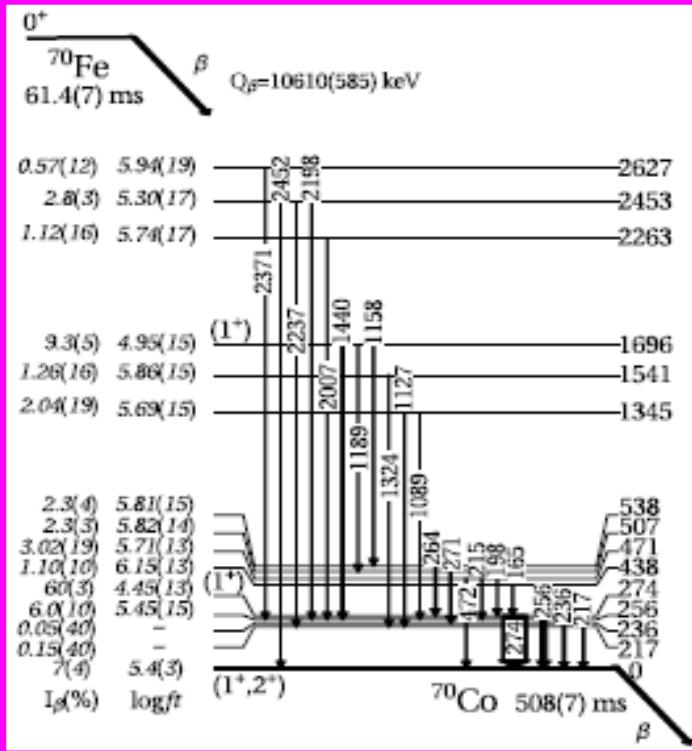
C.J. Prokop et al., PRC92, 061302 (2015)

Purpose of this work

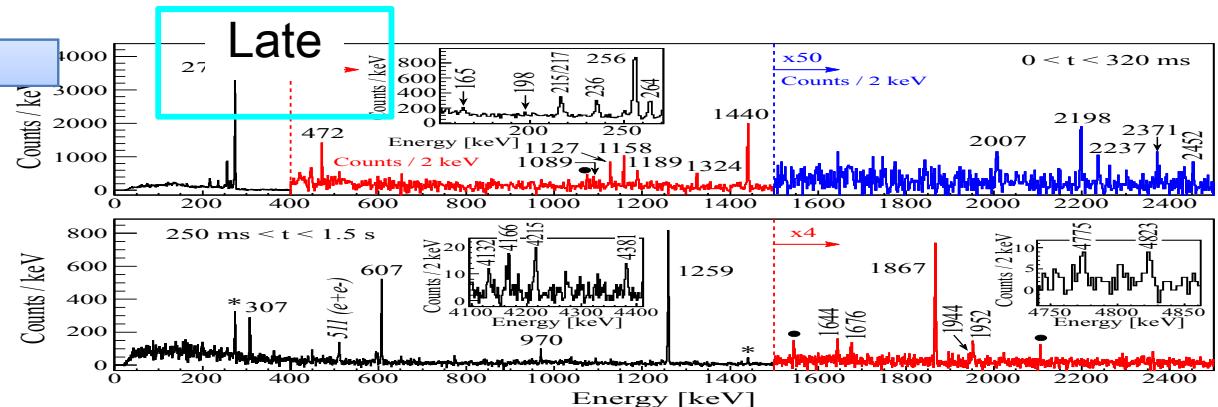
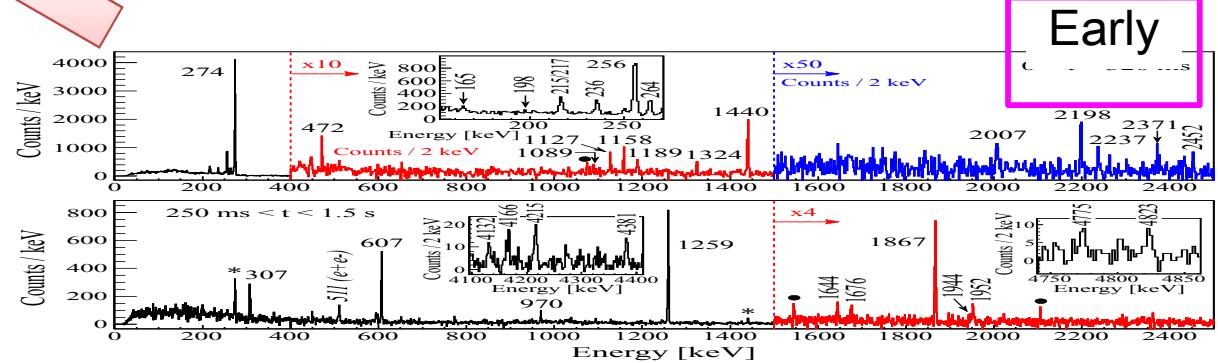
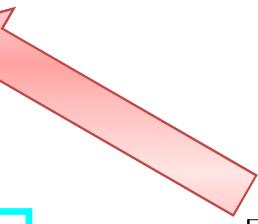
How does the β decay of the “transitional” $A = 70$ nuclei proceed from **the new island of inversion** to **the $Z = 28$ closed-shell regime?**

- ^{70}Fe ($Z = 26$, $N = 44$) \Rightarrow Deformed
 - » EURICA: G. Benzoni et al., PLB751 (2015) 107
 - » SEASTER: C. Santamaria et al., PRL115 (2015) 192501
 - ^{70}Ni ($Z = 28$, $N = 42$) \Rightarrow Shape coexistence
 - ^{70}Co ($Z = 27$, $N = 43$) \Rightarrow ?
-
- Selectivity to populate different shapes?
 - Shape/Shell evolution along the isobaric decay chain?

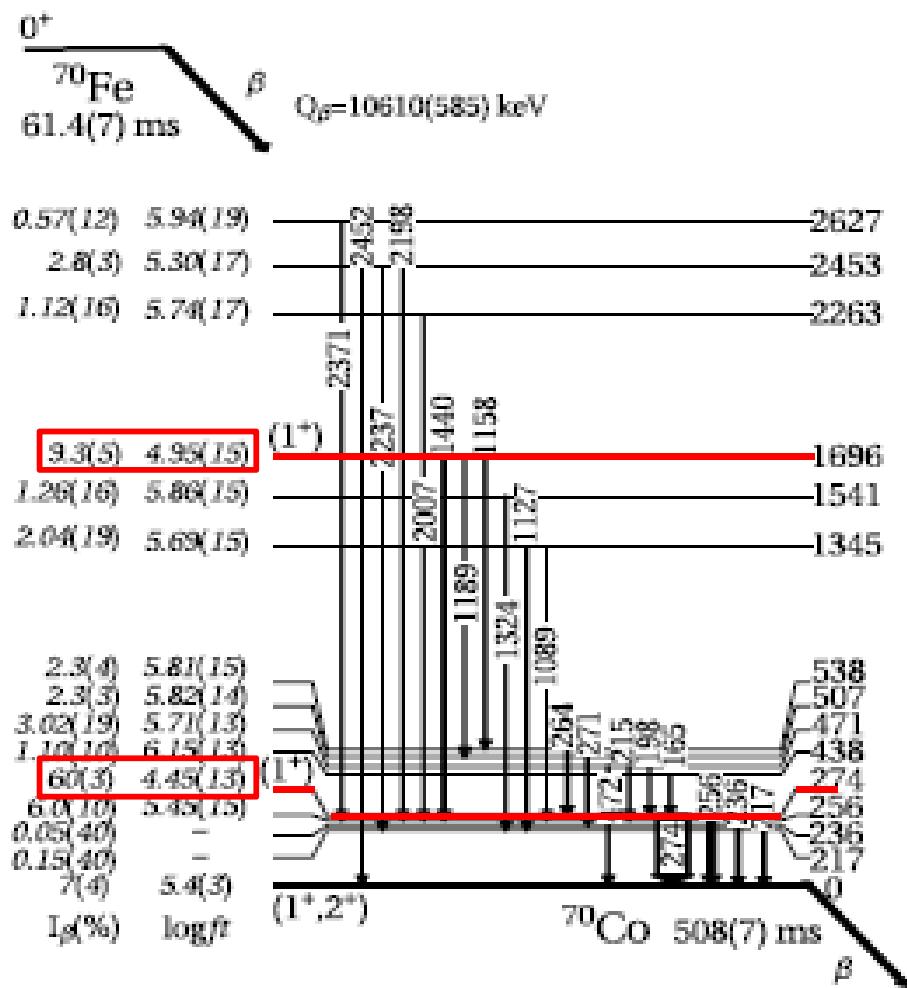
β decay in the A = 70 isobaric chain



- Two long-lived β-decaying states at high and low spins in ^{70}Co
- Low-spin β-decaying state in ^{70}Co isolated via the β decay of ^{70}Fe
- Selectively populate low-spin states in ^{70}Ni



$^{70}\text{Fe} \rightarrow ^{70}\text{Co}$: Deformed structure at low excitation energy in ^{70}Co



If spherical,

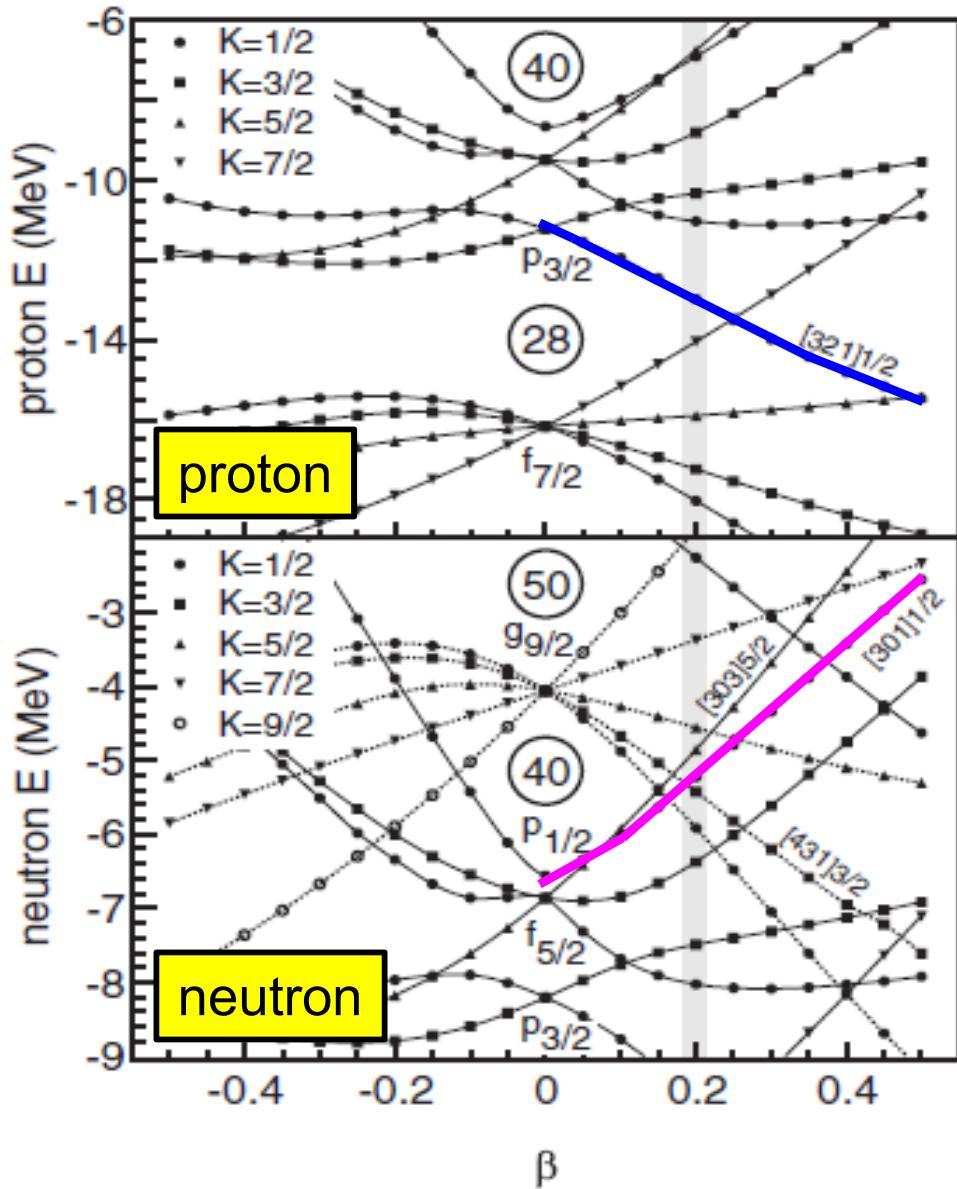
- Low-lying levels: $\pi f_{7/2}^{-1} \otimes \nu g_{9/2}$
⇒ Negative parity
- 1⁺ state: $\pi f_{7/2}^{-1} \otimes \nu f_{5/2}^{-1}$
⇒ $E_x \sim 1 \text{ MeV}$

■ Strong population of the states at

- 274 keV: $\log ft = 4.45(13)$
- 1696 keV: $\log ft = 4.95(15)$

➤ Gamow-Teller transition $\Rightarrow J^\pi = 1^+$

$^{70}\text{Fe} \rightarrow ^{70}\text{Co}$: Deformed structure at low excitation energy in ^{70}Co



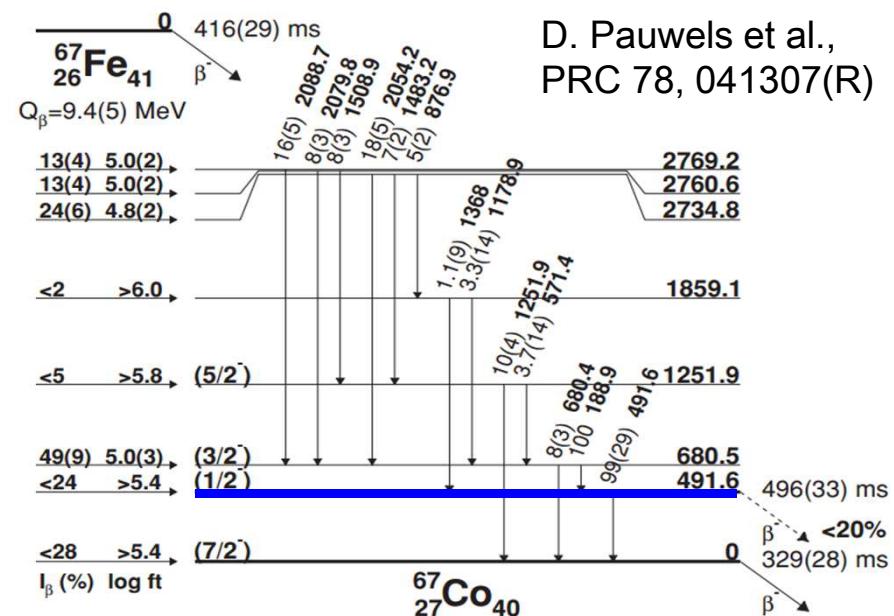
1⁺ state at 274 keV
 ⇒ Evidence for a deformed configuration

If spherical,

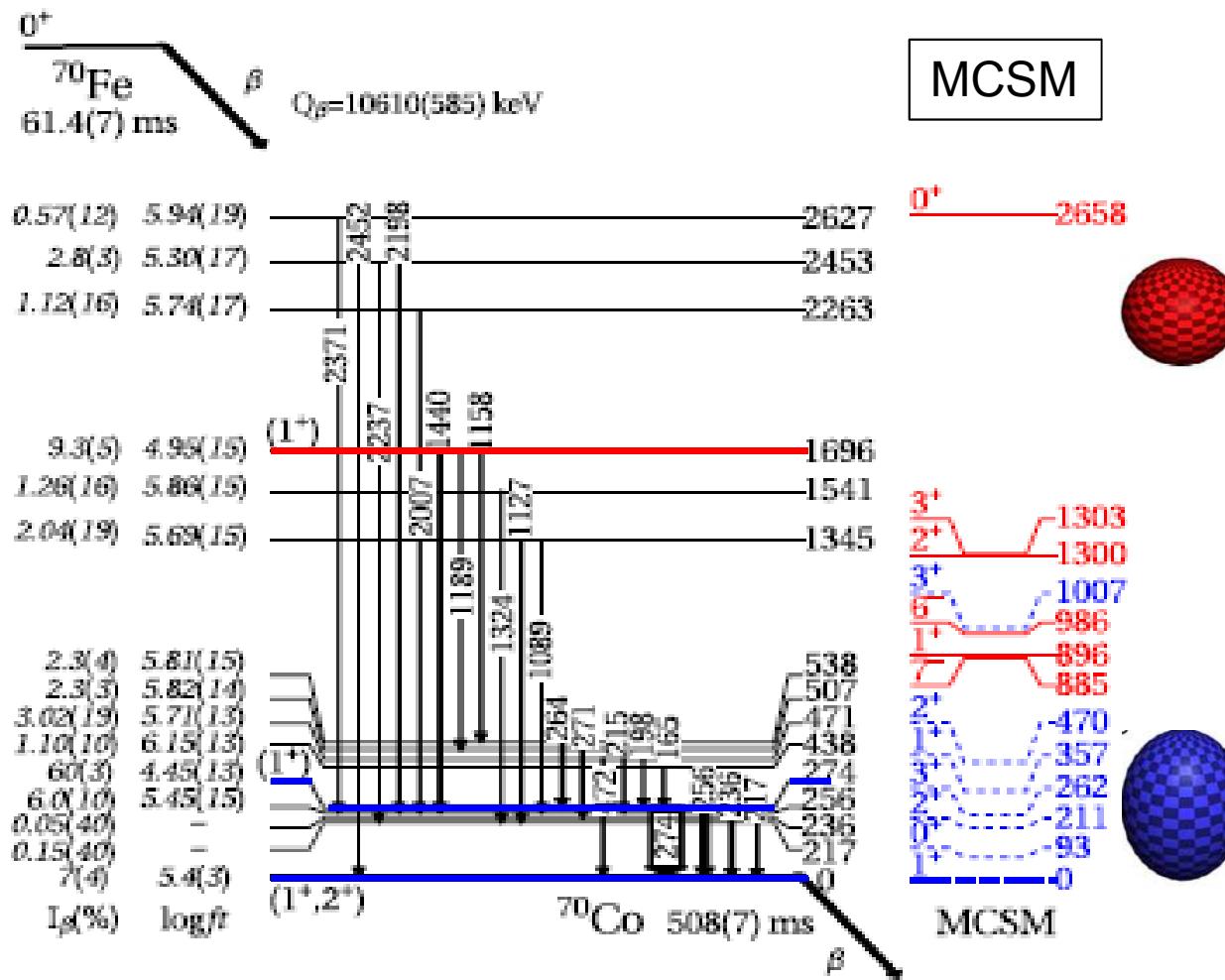
- Low-lying levels: $\pi f_{7/2}^{-1} \otimes \nu g_{9/2}$
 ⇒ Negative parity
- 1⁺ state: $\pi f_{7/2}^{-1} \otimes \nu f_{5/2}^{-1}$
 ⇒ $E_x \sim 1 \text{ MeV}$

If deformed,

- Proton: 1/2-[321]
- Neutron: 1/2-[301]
- Odd-odd ⇒ $K^\pi = 1^+, 2^+$



$^{70}\text{Fe} \rightarrow ^{70}\text{Co}$: Interpretation by Monte-Carlo shell-model calculations



MCSM calculations

- A3DA Hamiltonian
- pf + g_{9/2} + d_{5/2} orbitals

- Low-lying levels dominated by prolate-deformed configurations
- States characterized by small deformation appear at ≥ 900 keV

■ Logft

- Strong population of the 1⁺₂ and 1⁺₃ states
- Highly hindered β feeding to the 1⁺₁ ground state

⇒ consistent with the observed decay pattern

Hindered



logft (MCSM)

logft (exp.)

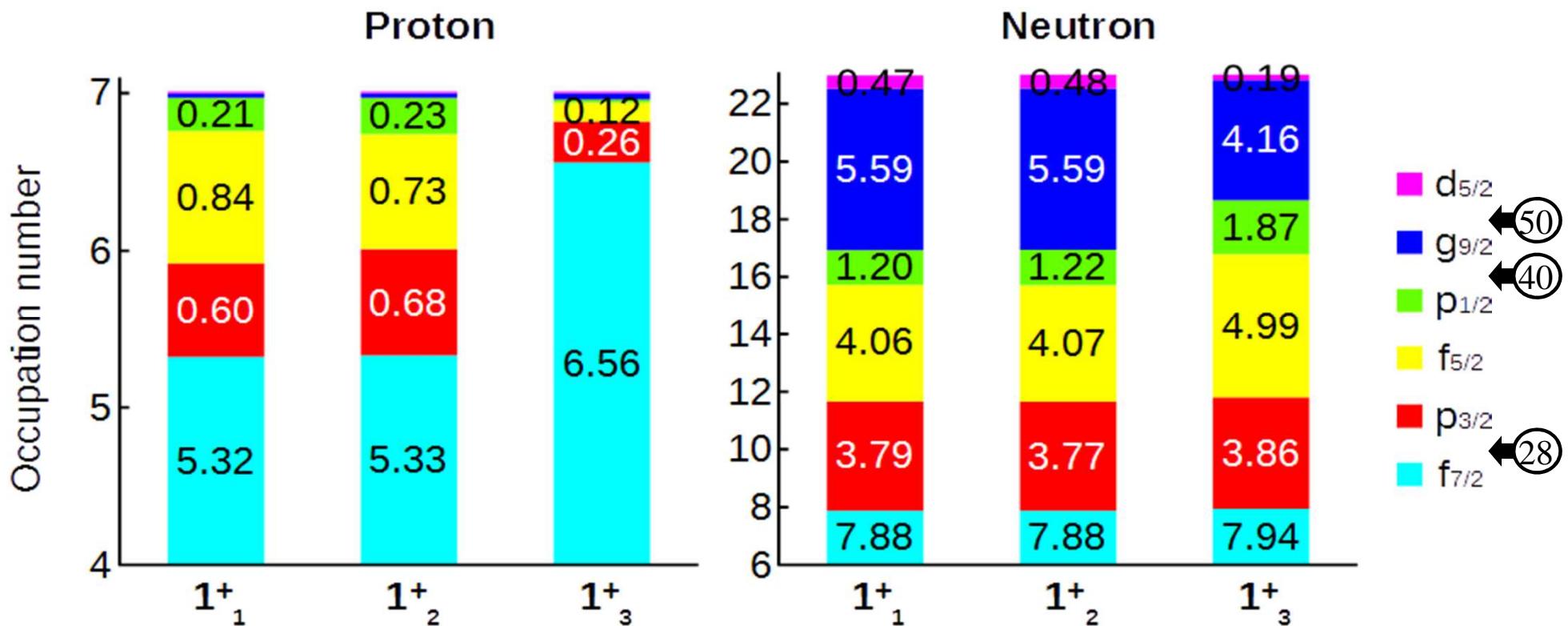
Favored



	logft (MCSM)	logft (exp.)
Hindered	1 ⁺ ₁	7.9
Favored	1 ⁺ ₂	>4.45(13)
Favored	1 ⁺ ₃	>4.95(15)

$^{70}\text{Fe} \rightarrow ^{70}\text{Co}$: Interpretation by Monte-Carlo shell-model calculations

Occupancies of single-particle orbitals for the three 1^+ levels of ^{70}Co



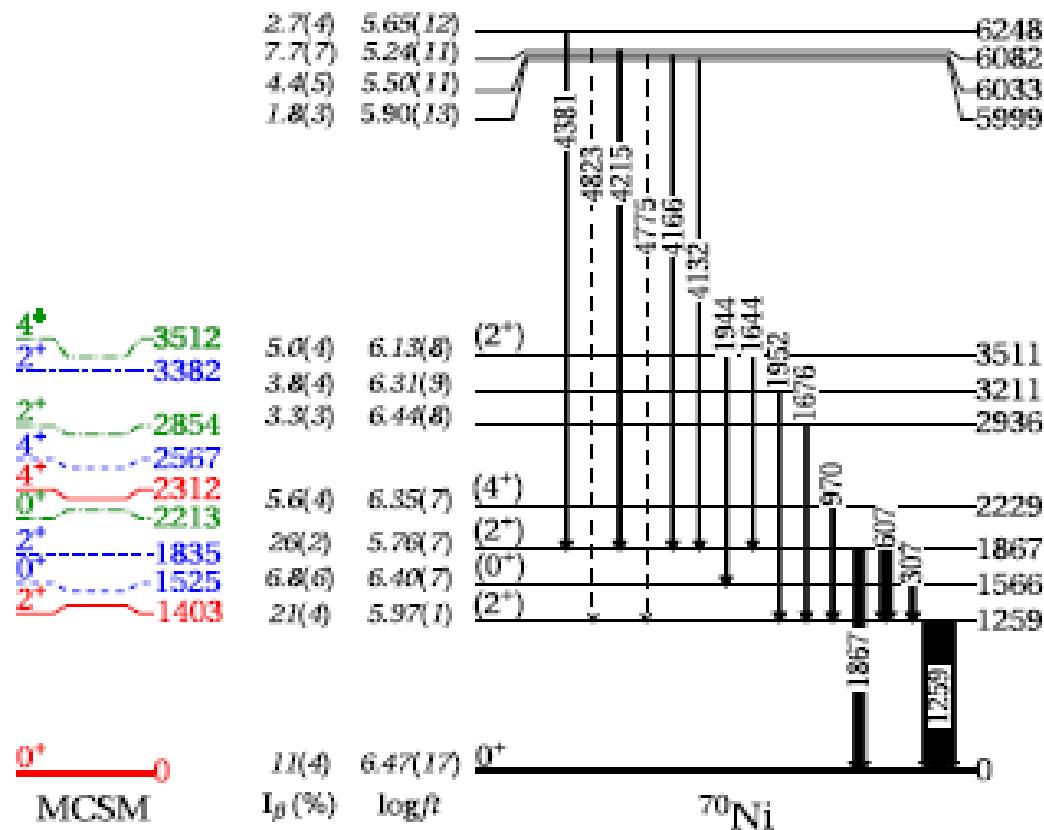
MCSM wave functions of the three 1^+ states in ^{70}Co

- $1^+_{1,2}$: almost identical, involving multiple p-h excitations across the $Z = 28$ and $N = 40$ gaps (Type-II shell evolution) \Rightarrow Largely prolate deformed shape
- 1^+_3 : dominated by $\pi f_{7/2}^{-1} v f_{5/2}^{-1} g_{9/2}^{+4}$ $\xrightarrow{\text{Gamow-Teller}}$ Near spherical shape

Gamow-Teller

$^{70}\text{Co} \rightarrow ^{70}\text{Ni}$: Shape-selective β decay

low spin
 ^{70}Co



MCSM prediction

$J^\pi(^{70}\text{Co})$	$J^\pi(^{70}\text{Ni})$	$\log ft$
0^+_1	0^+_1	9.2
0^+_2	0^+_2	7.8
1^+_1	2^+_1	7.7
2^+_2	2^+_2	5.90
2^+_1	2^+_1	8.6
2^+_2	2^+_2	6.31
2^+_1	2^+_1	9.7
2^+_2	2^+_2	7.5
3^+_1	4^+_1	8.4
4^+_2	4^+_2	5.7



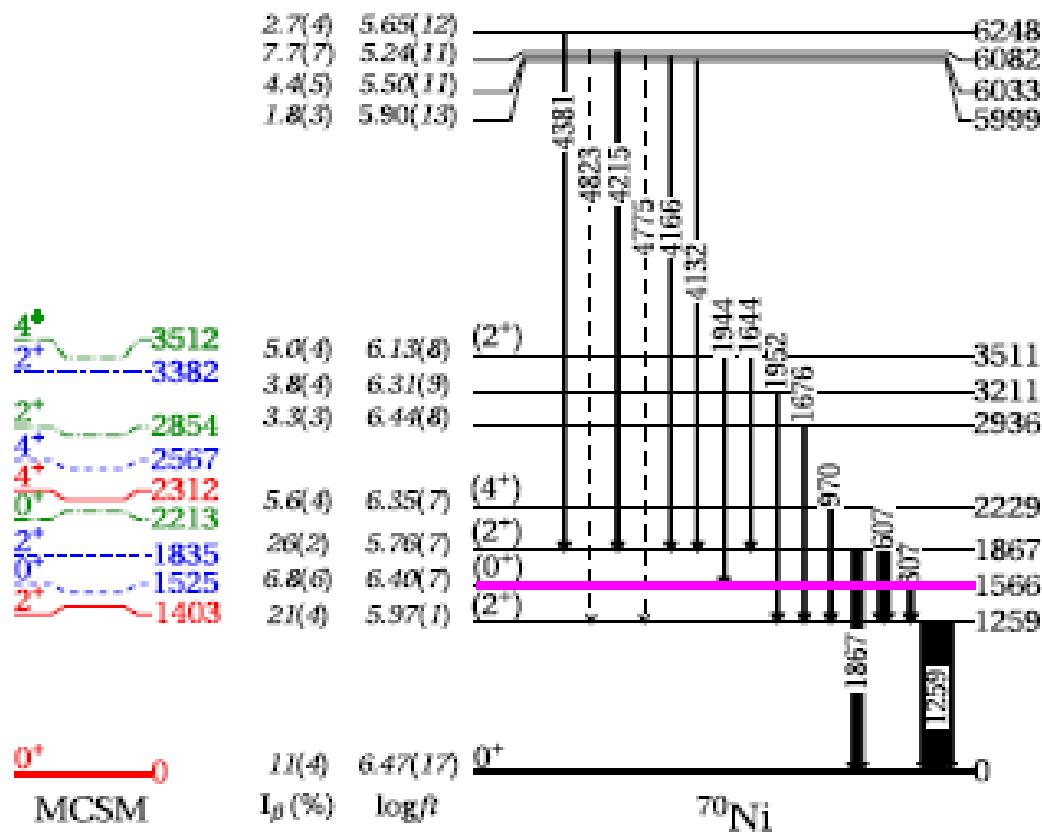
- Strong feeding to the two 2^+ states in ^{70}Ni
 $\log ft = 5.97(1)$ for 2^+_1 , $5.76(7)$ for 2^+_2
- $J^\pi = 1^+, 2^+, \text{ or } 3^+$ possible for the low-spin β -decaying state in ^{70}Co

Low-spin β -decaying state of ^{70}Co expected to have $J^\pi = 1^+ \text{ or } 2^+$.

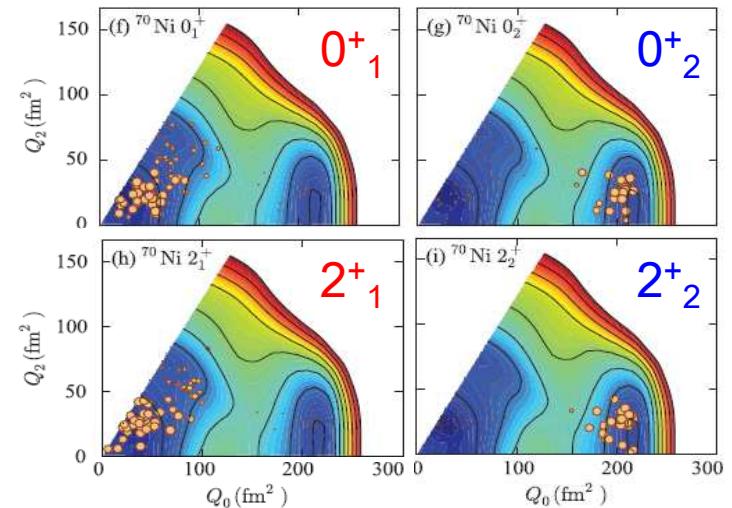
$^{70}\text{Co} \rightarrow ^{70}\text{Ni}$: Shape-selective β decay

$(1^+, 2^+)$
 ^{70}Co

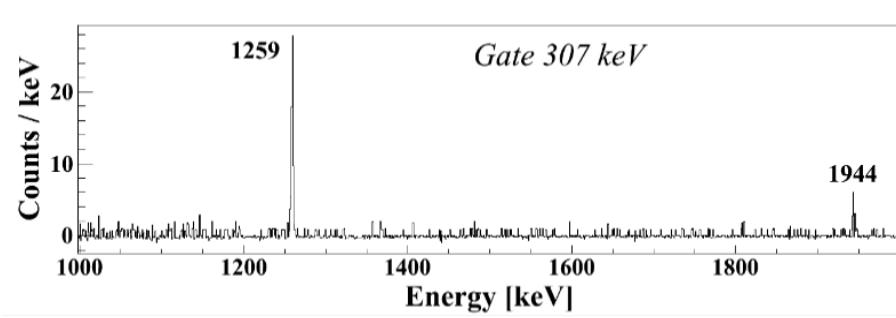
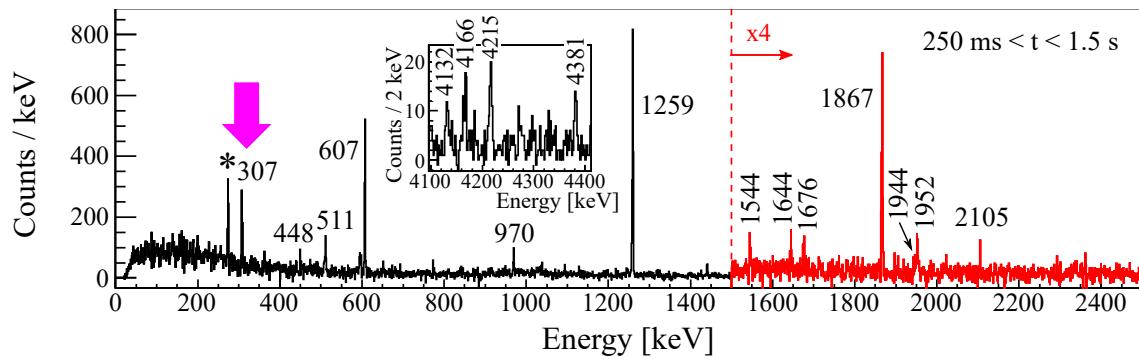
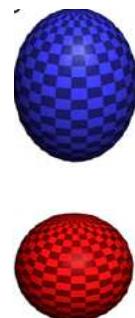
Observation of
a candidate for 0^+_2



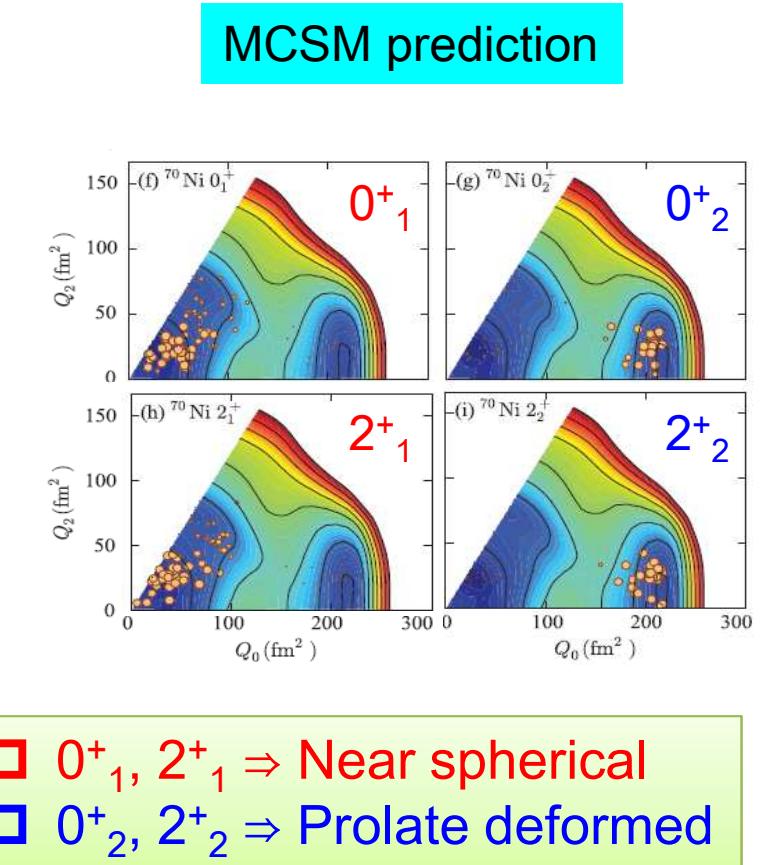
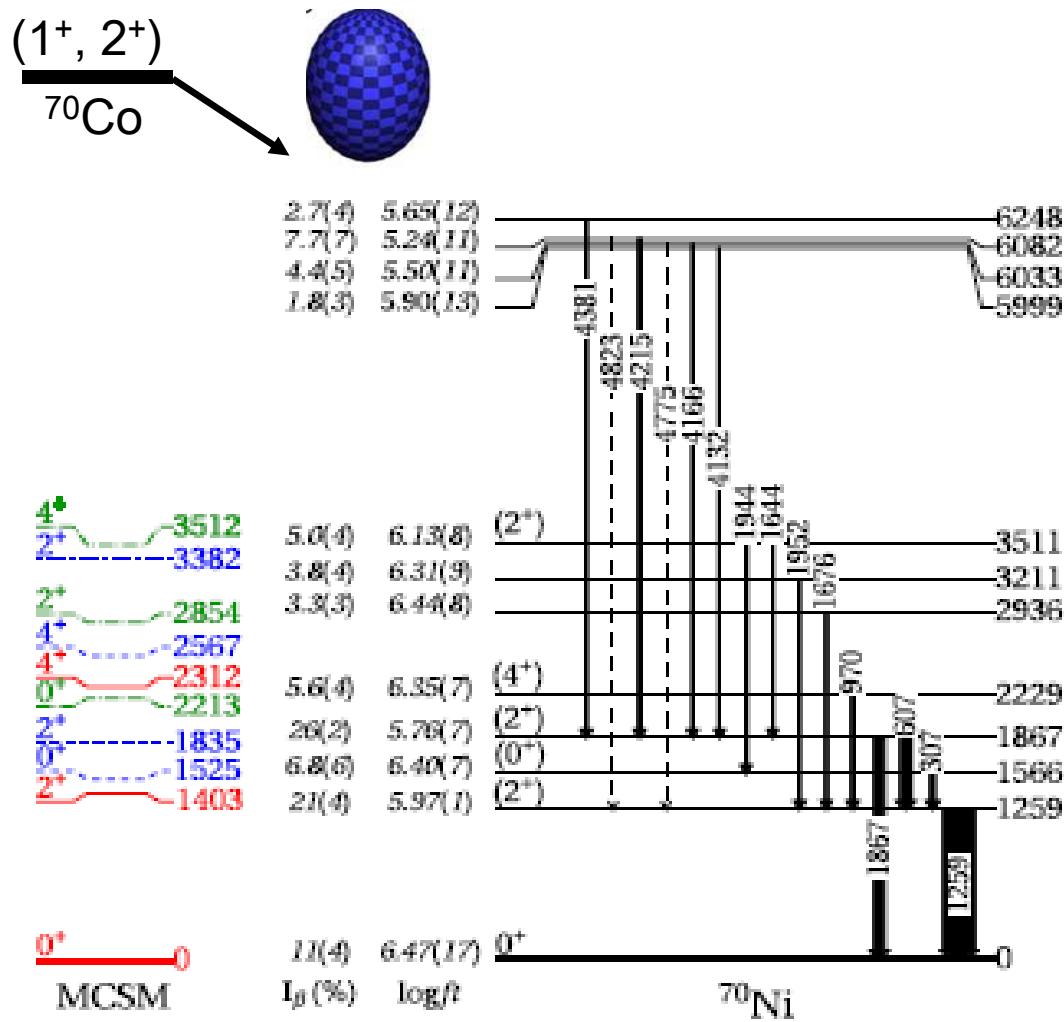
MCSM prediction



◻ $0^+_1, 2^+_1 \Rightarrow$ Near spherical
 ◻ $0^+_2, 2^+_2 \Rightarrow$ Prolate deformed



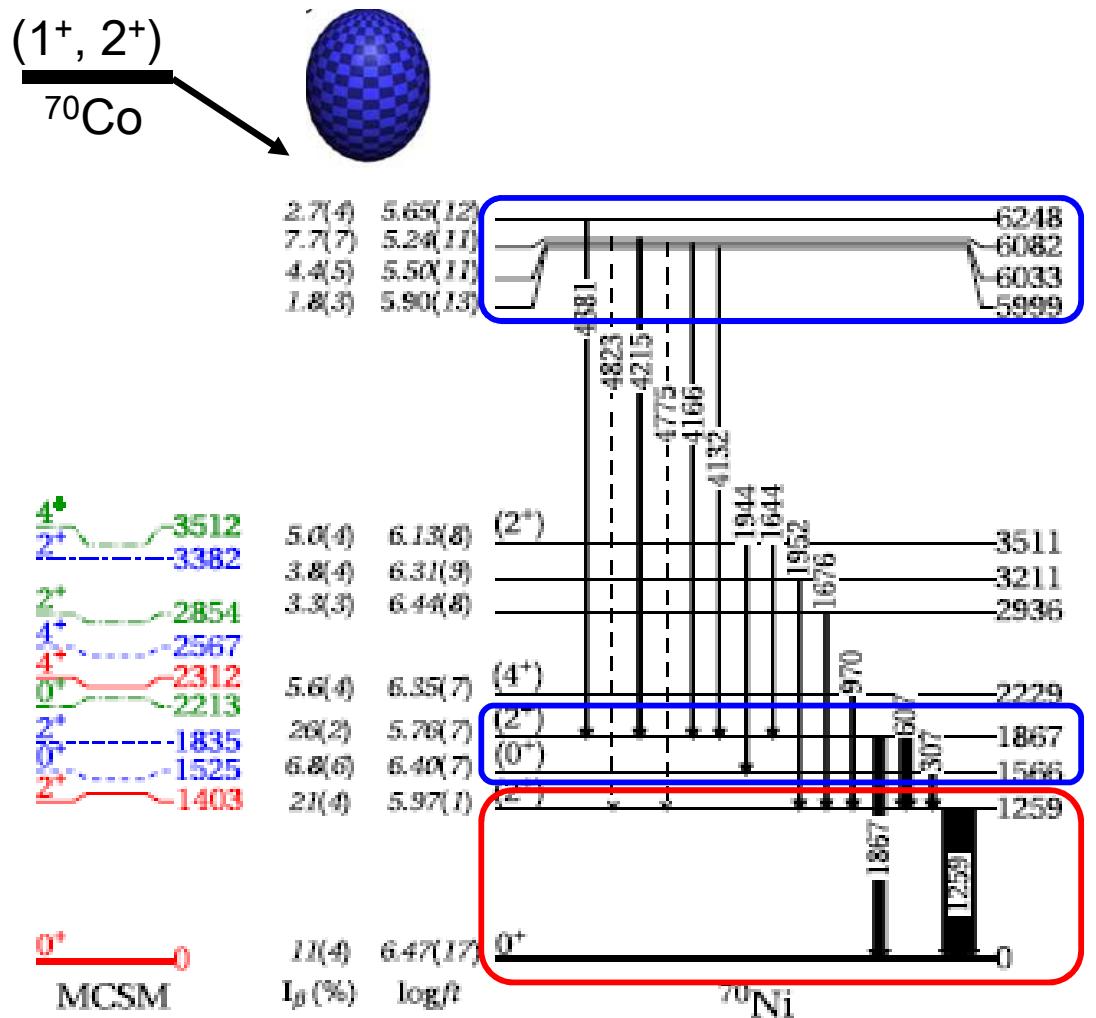
$^{70}\text{Co} \rightarrow ^{70}\text{Ni}$: Shape-selective β decay



^{70}Co (low spin) \rightarrow ^{70}Ni

- MCSM \Rightarrow Much higher population of 2^+_2 than 2^+_1
- Experiment \Rightarrow Slightly prefer to feed 2^+_2 than 2^+_1 , but almost comparable

$^{70}\text{Co} \rightarrow ^{70}\text{Ni}$: Shape-selective β decay



Four new excited states around 6 MeV

- Populated with $\log ft \sim 5.7$
- Preferentially feed the 2^+_2 state



- Similar deformed structure
- Proton 2qp configurations with $K^\pi = 0^+, 1^+, 2^+$

^{70}Co (low spin) \rightarrow ^{70}Ni

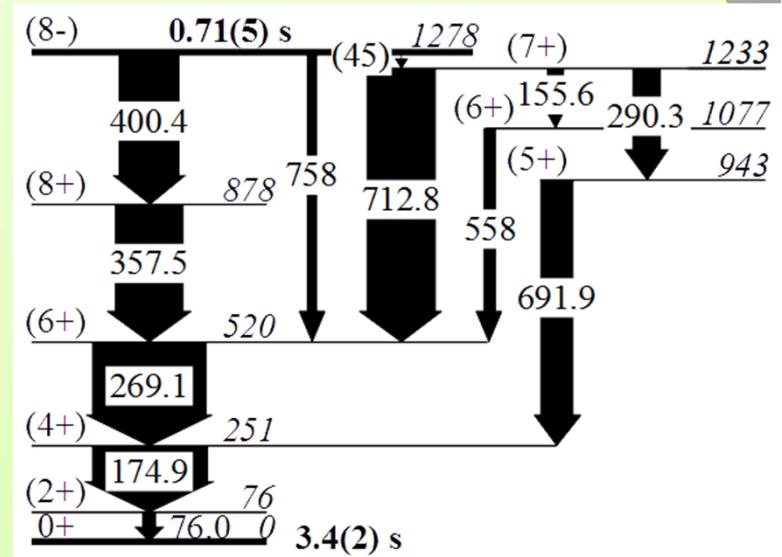
- MCSM \Rightarrow Much higher population of 2^+_2 than 2^+_1
- Experiment \Rightarrow Slightly prefer to feed 2^+_2 than 2^+_1 , but almost comparable

Summary (part 1)

Neutron-rich Dy isotopes have been explored at RIBF as part of the EURICA decay spectroscopy campaign.

^{172}Dy ($N = 106$)

- The most neutron-rich Dy isotope studied to date
 - So far, the heaviest isotope any spectroscopic information obtained at RIBF
-
- $K^\pi = 8^-$ isomer ($E_x = 1278$ keV, $T_{1/2} = 0.71$ s)
 - Ground-state rotational band
 - ⇒ Axial symmetry
 - $K^\pi = 2^+$ states at low excitation energy
 - ⇒ Enhanced γ vibration
 - ◆ Interpretation by Nuclear DFT (HFB+QRPA)
 - 3 neutron 2qp components significant beyond double midshell



^{168}Dy ($N = 102$)

- Analysis is still ongoing

Summary (part 2)

- ◆ The level structures of ^{70}Co and ^{70}Ni , populated from the decay of ^{70}Fe , have been investigated using β -delayed γ -ray spectroscopy following in-flight fission of a ^{238}U beam as part of the EURICA campaign in 2013.
- ◆ The experimental results are compared to Monte-Carlo shell-model calculations including the pf+g_{9/2}+d_{5/2} orbitals.

^{70}Co ($Z = 27$, $N = 43$)

- Low-spin β -decaying (ground) state with $J^\pi = 1^+$ or 2^+
- (1^+) state at $E_x = 274$ keV
 - ⇒ Prolate-deformed configuration
- High-spin β -decaying state with $J^\pi = (7^-)$
 - ⇒ Spherical shape

^{70}Ni ($Z = 28$, $N = 42$)

- 0^+_2 state at 1566 keV
- 2^+_2 (1867 keV) and higher-lying levels (~6 MeV) preferentially populated in ^{70}Co (low spin) → ^{70}Ni

Thank you for your attention