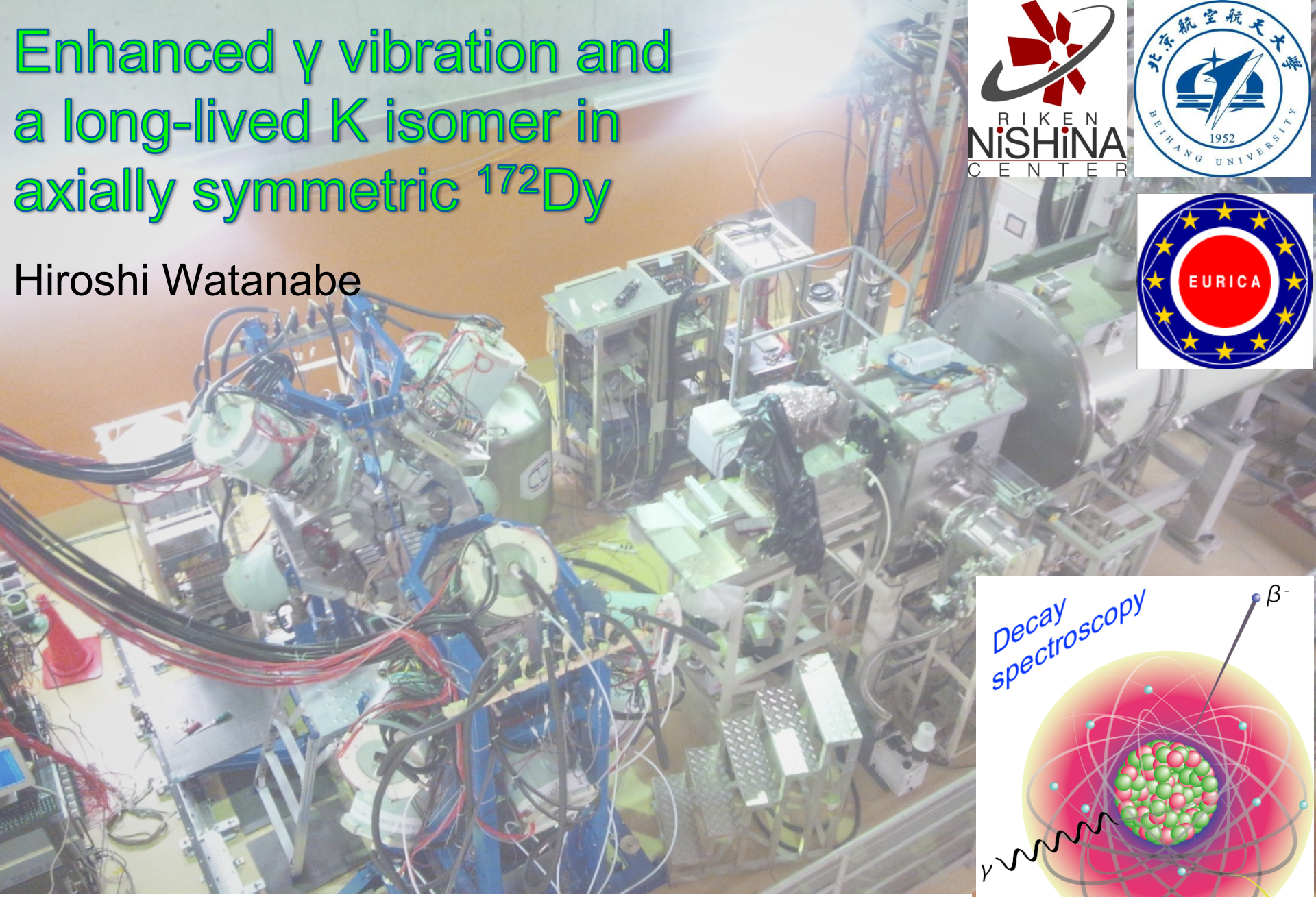
Enhanced γ vibration and a long-lived K isomer in axially symmetric ^{172}Dy

Hiroshi Watanabe



International Nuclear Physics Conference (INPC2016)
September 11-16, 2016, Adelaide Convention Centre, Australia

Outline

1. Introduction
   - Neutron-rich nuclei around double midshell
   - Collective vibration
   - High-K isomers
2. Experimental details
   - RIBF facility at RIKEN
   - EURICA decay spectroscopy setup
3. Results
   - ^{172}Dy
     - Long-lived $K^{\pi} = 8^{-}$ isomer
     - Ground-state and γ-vibrational bands
   - ^{168}Dy
4. Summary

Physics Letters B 760 (2016) 641–646

Contents lists available at ScienceDirect

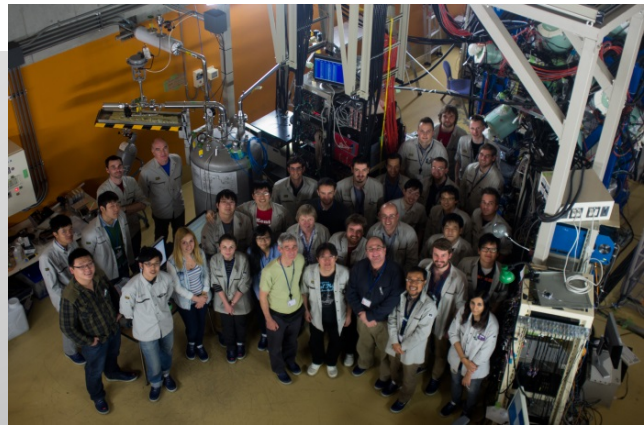
Physics Letters B

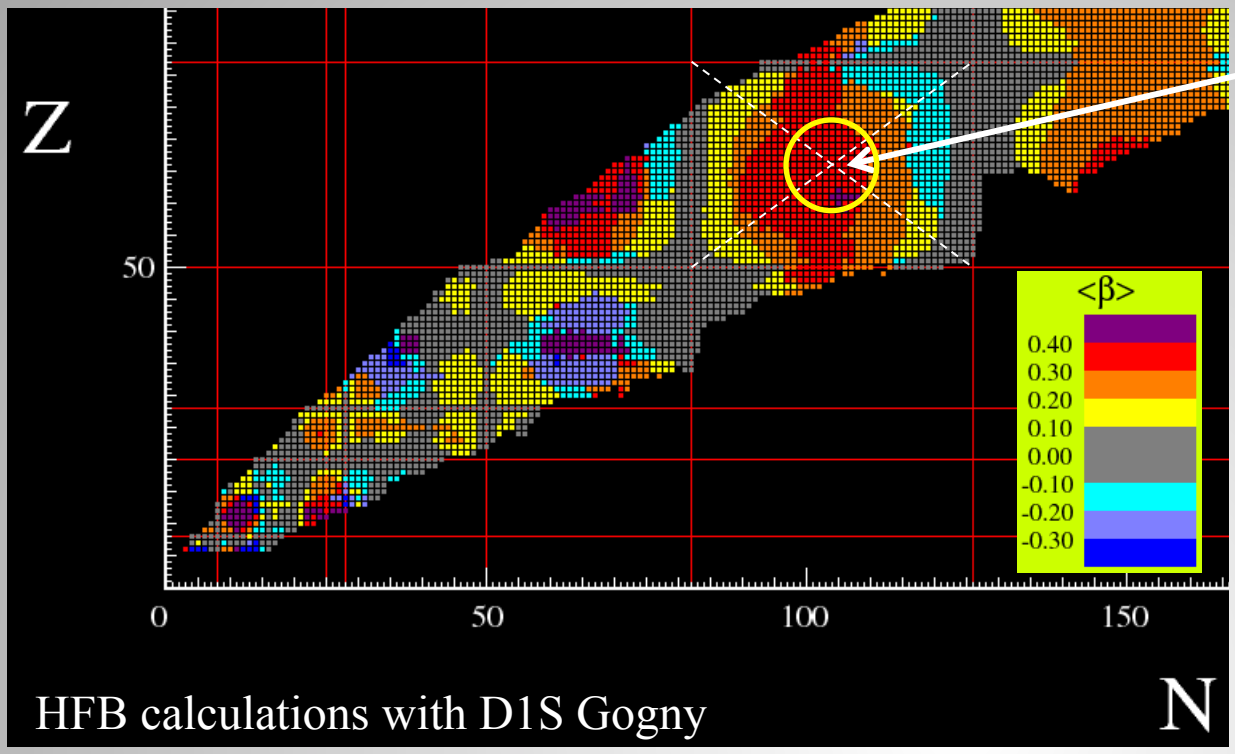
www.elsevier.com/locate/physletb

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





$^{170}_{66}Dy_{104}$

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

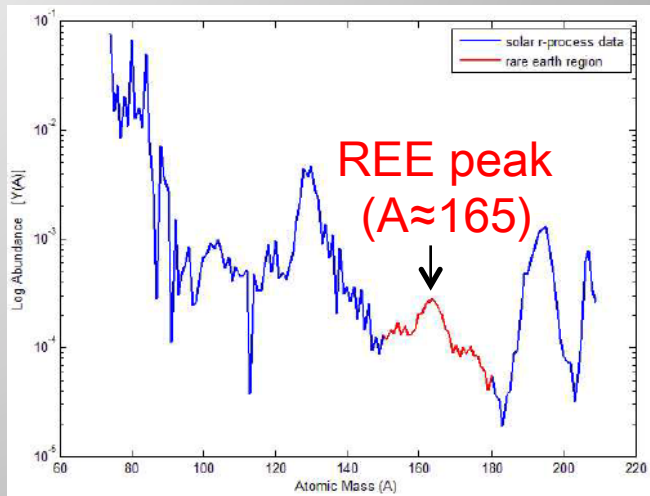
Maximum ground-state deformation?

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 peak in the r-process



Intrinsic excitations in deformed nuclei : Collective vibrations

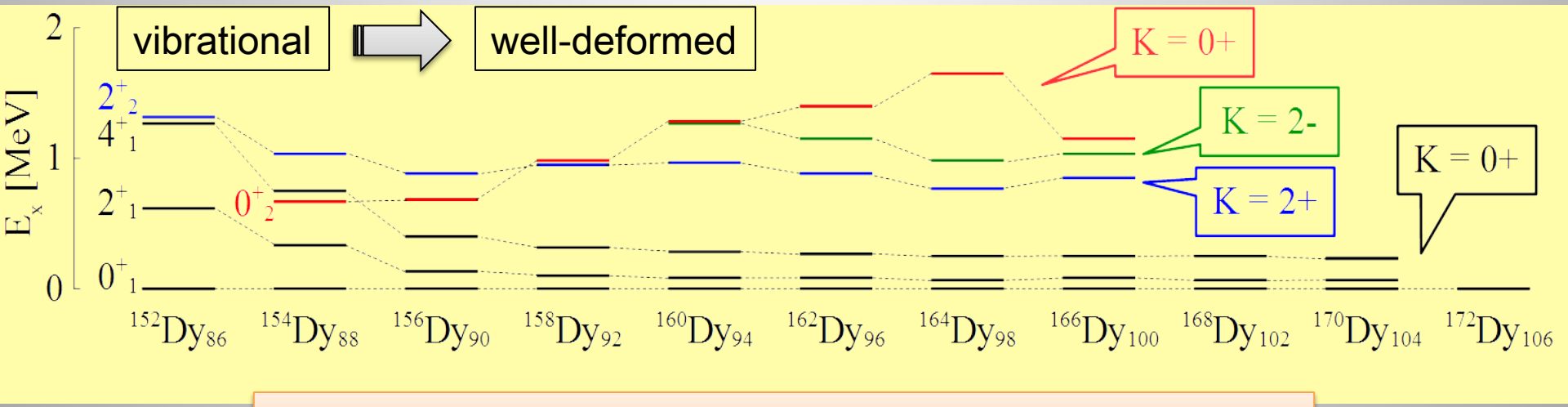
Single-particle orbitals near the Fermi surface ⇨ Intrinsic excitations

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

Intrinsic excitations in deformed nuclei : Collective vibrations

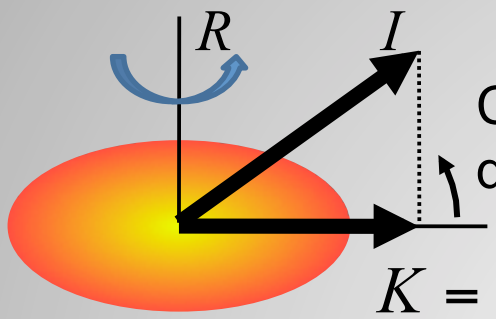
Single-particle orbitals near the Fermi surface ⇒ Intrinsic excitations

- $K^\pi = 2^+ \Rightarrow$ **γ 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
- $K^\pi = 0^+ \Rightarrow$ **β vibration**, pairing excitation, intruder states, shape coexistence .....
  - Axial symmetry preserved
- $K^\pi = 0^-, 1^-, 2^-, 3^- \Rightarrow$ **Octupole vibration** ($\Delta j = \Delta l = 3$)

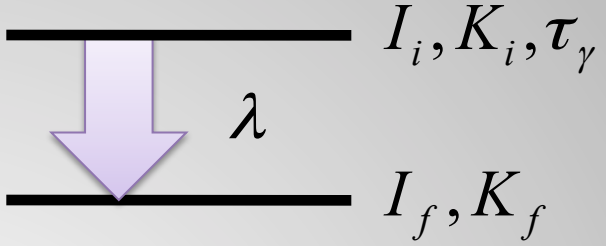


Good testing ground for collective model calculations

Intrinsic excitations in deformed nuclei : K isomer



$$K = \sum_j \Omega_j$$



$\lambda \geq |I_i - I_f|$ Spin selection … Yes

$\lambda \geq |K_i - K_f|$ K-selection … Sort of !

K hindered transitions

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

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

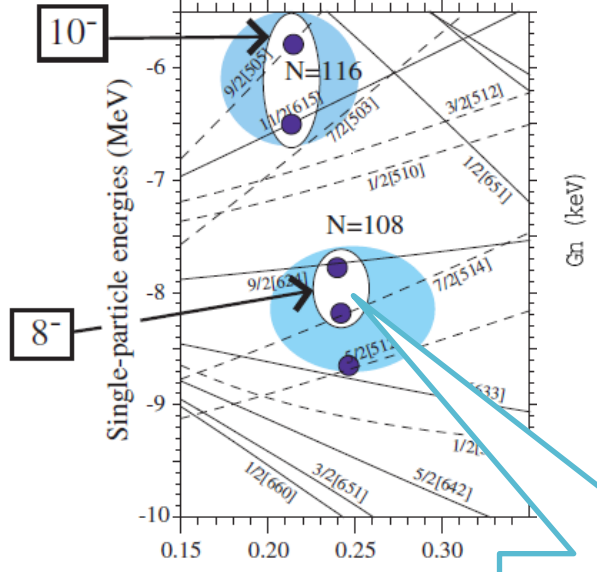
The degree of K forbiddenness $\nu = \Delta K - \lambda$

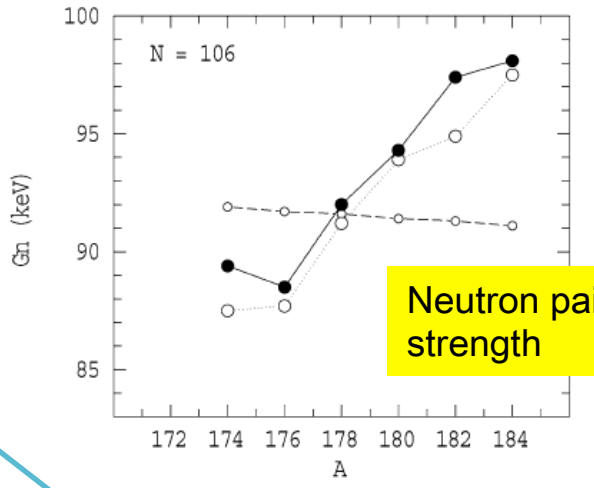
The identification and characterization of K-isomers provides information on

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

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

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





Neutron pairing strength

ν7/2⁻[514]ν9/2⁺[624]

Studied by deep-inelastic reactions

Spherical-Oblate -Prolate Shape Co-existence

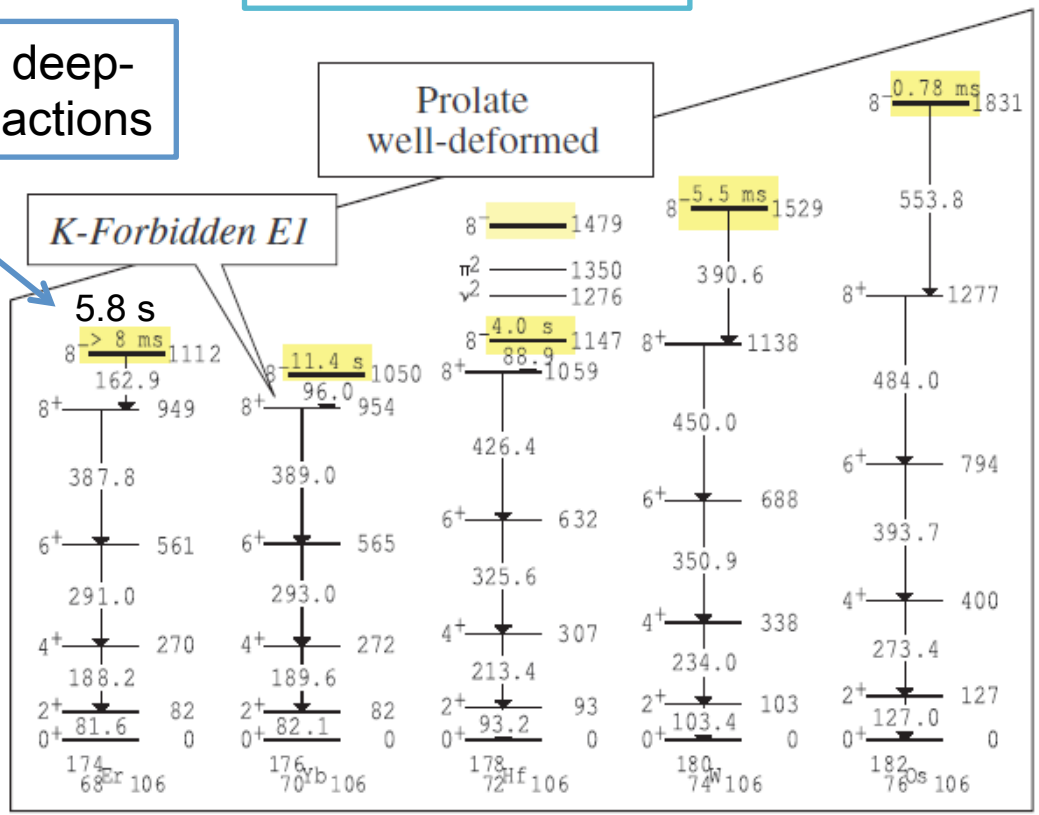
Oblate-Prolate Co-existence

Transitional

Prolate well-deformed

K-Forbidden E1

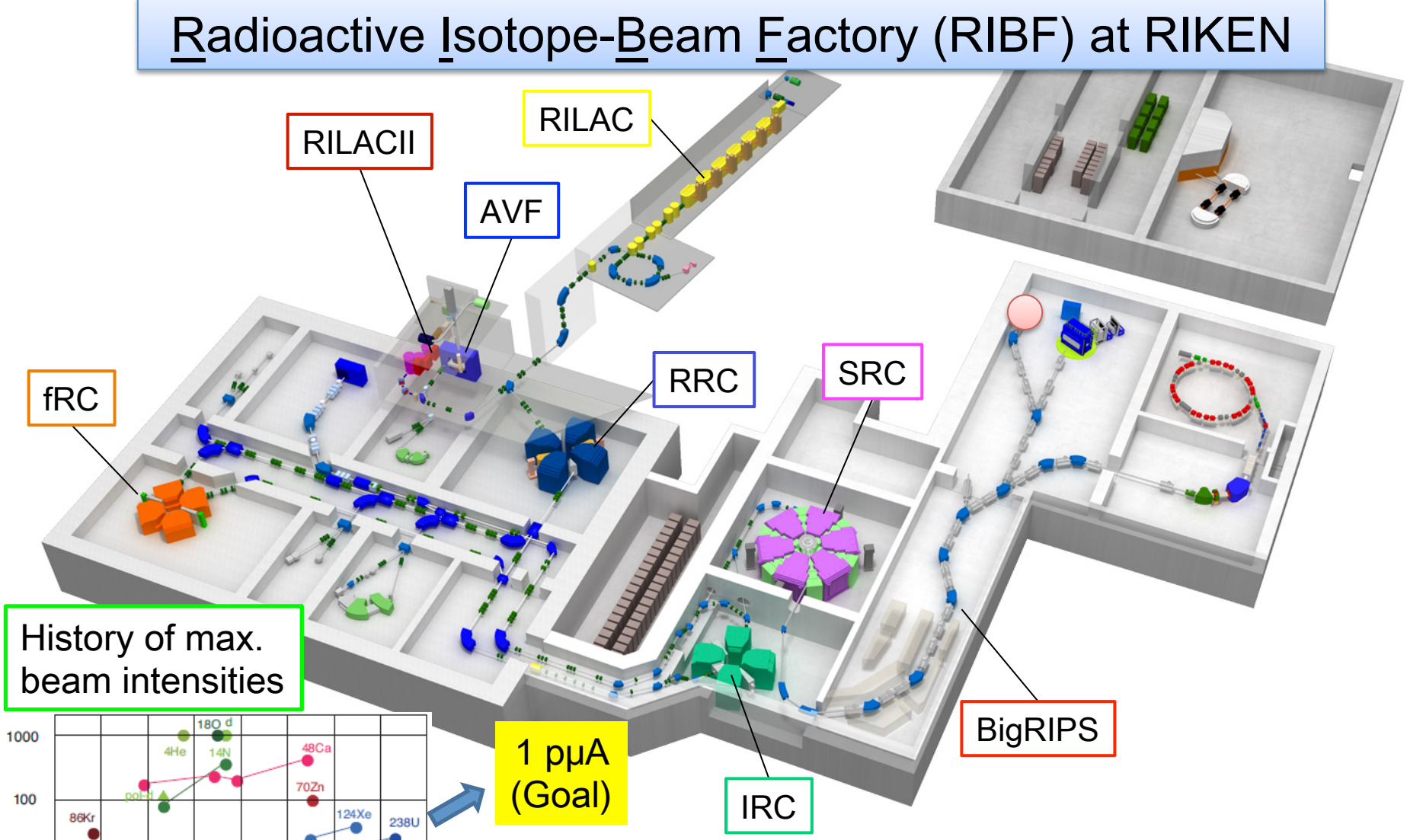
5.8 s



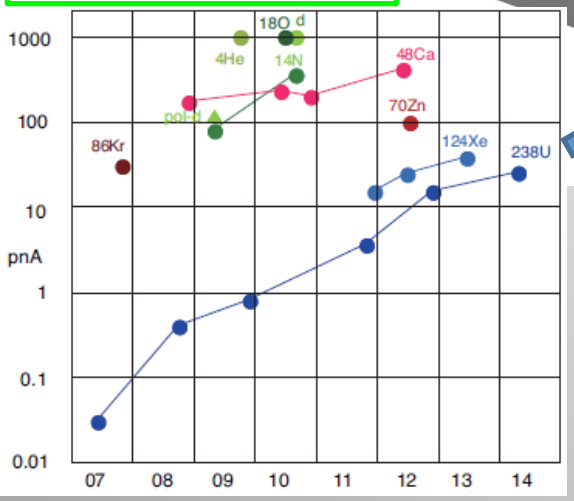
?

$^{172}_{66}Dy_{106}$

Radioactive Isotope-Beam Factory (RIBF) at RIKEN



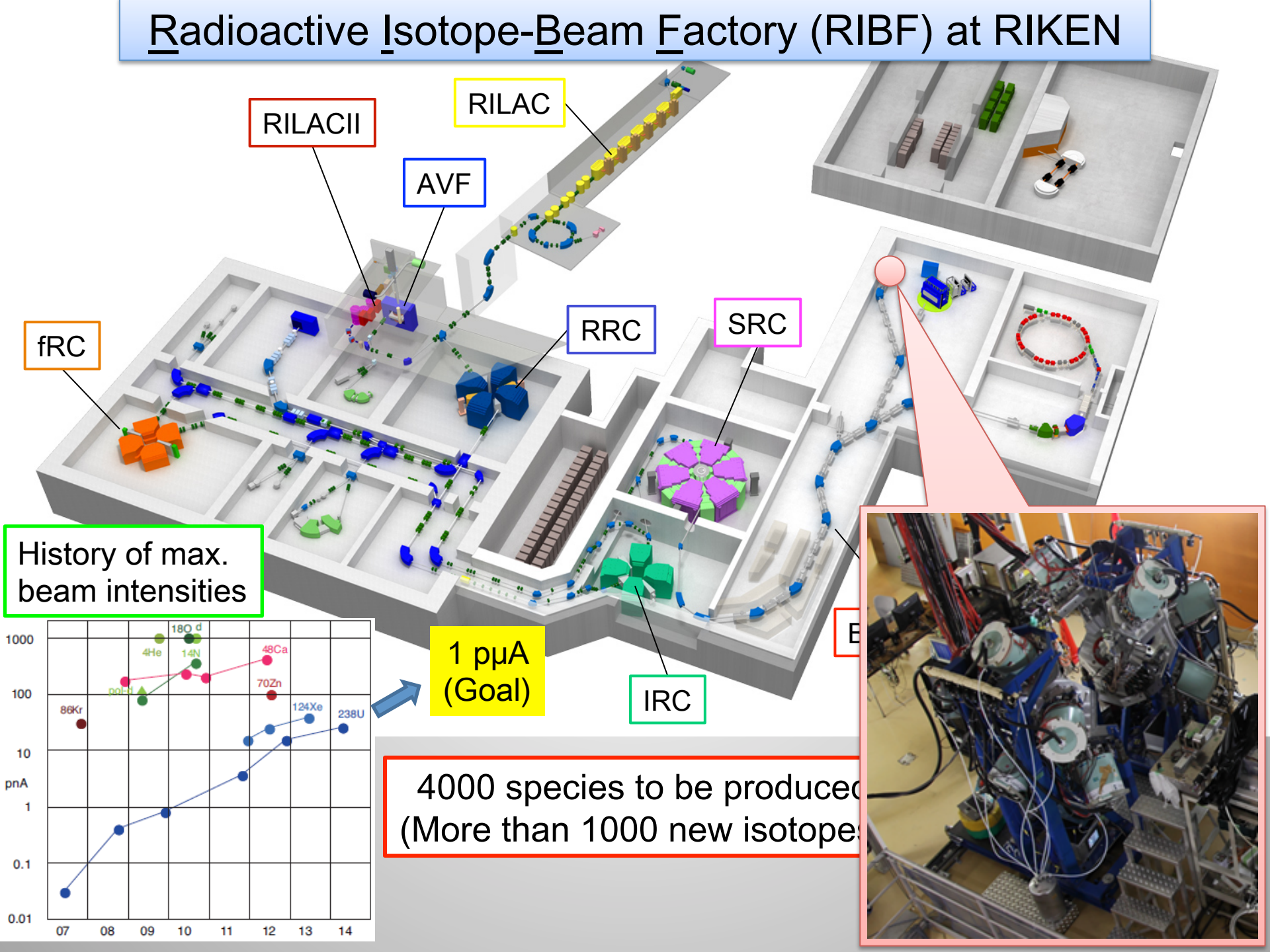
History of max. beam intensities



1 pμA (Goal)

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

Radioactive Isotope-Beam Factory (RIBF) at RIKEN



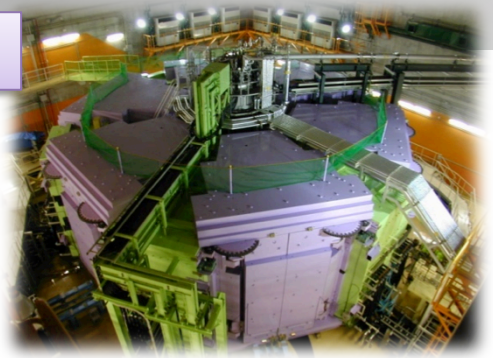
History of max. beam intensities

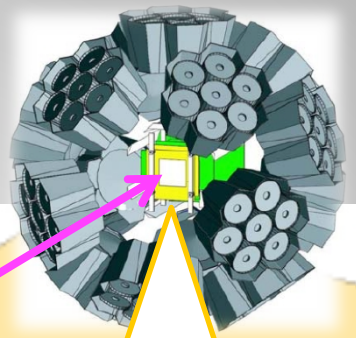
1 pμA (Goal)

4000 species to be produced
(More than 1000 new isotopes

Layout of the entire experimental setup

SRC





12 Clusters
(7 Ge each)
"EURICA"

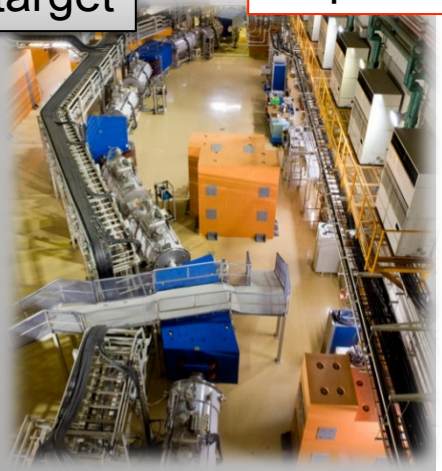
BigRIPS

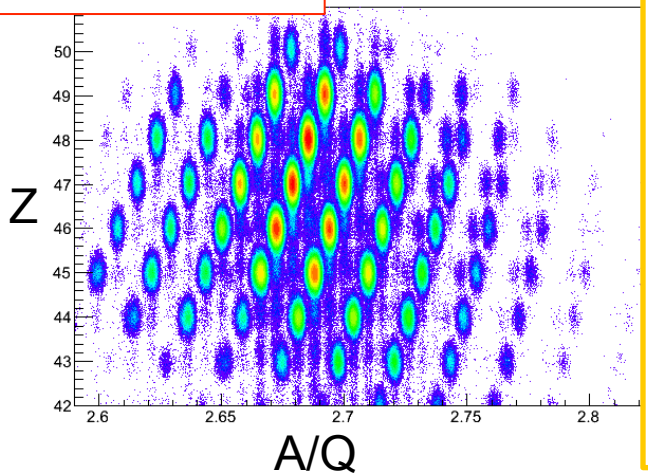
^{238}U beam
(345 AMeV)

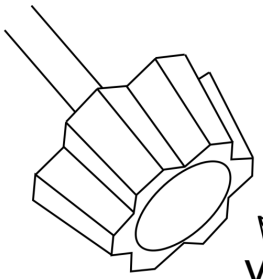
Identification and
further separation

Be target

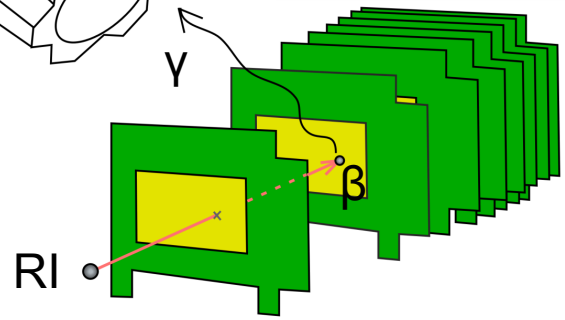
Separation of RI beam

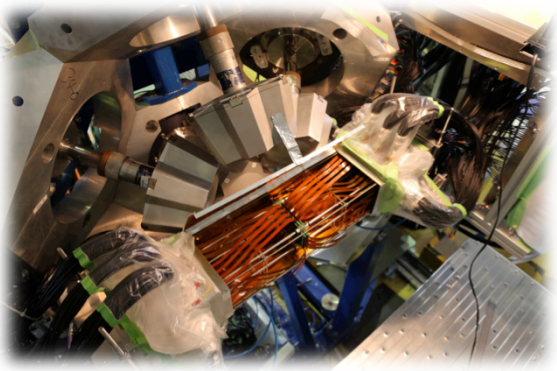




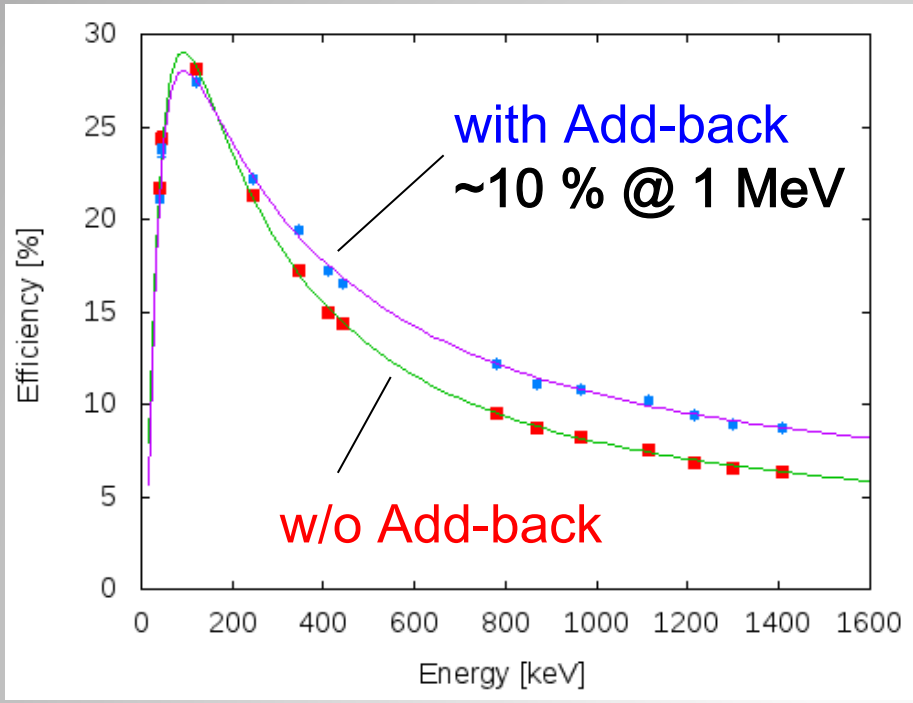


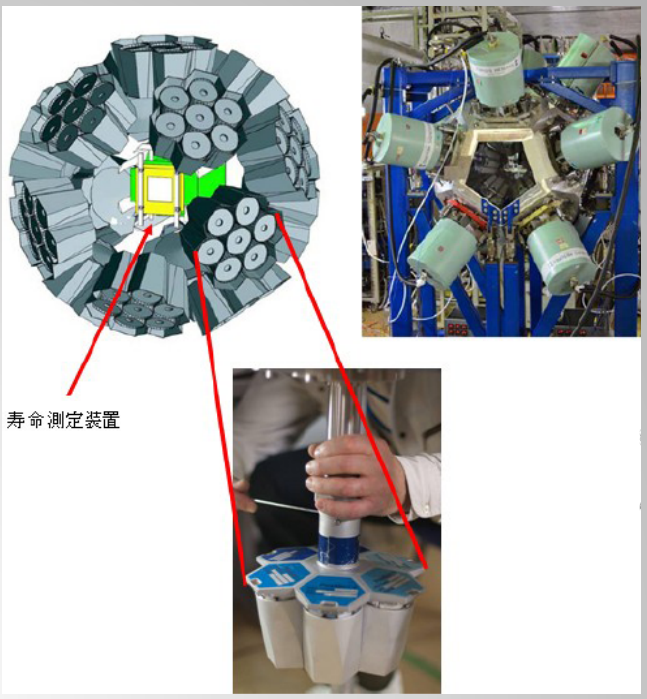
8 DSSSDs
(60×40 each)
"WAS3ABi"





7-element Cluster-type HPGe detectors × 12

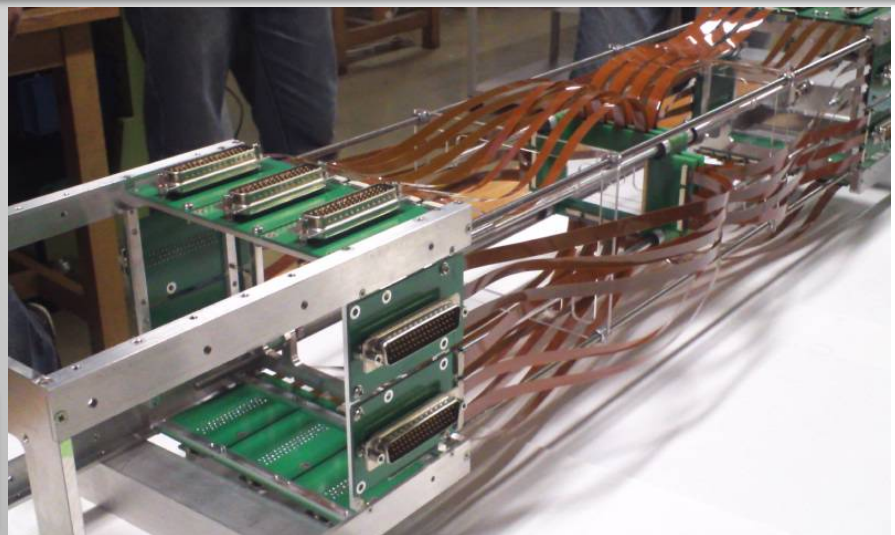


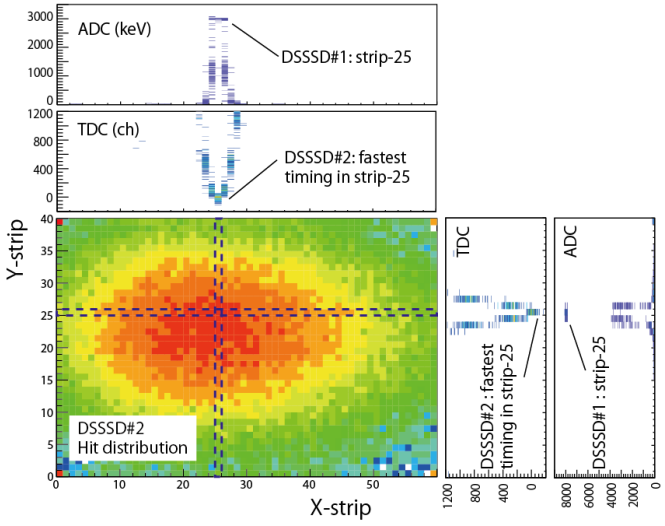


WAS3ABi: Wide-range Active Silicon-Strip Stopper Array for Beta and ion detection

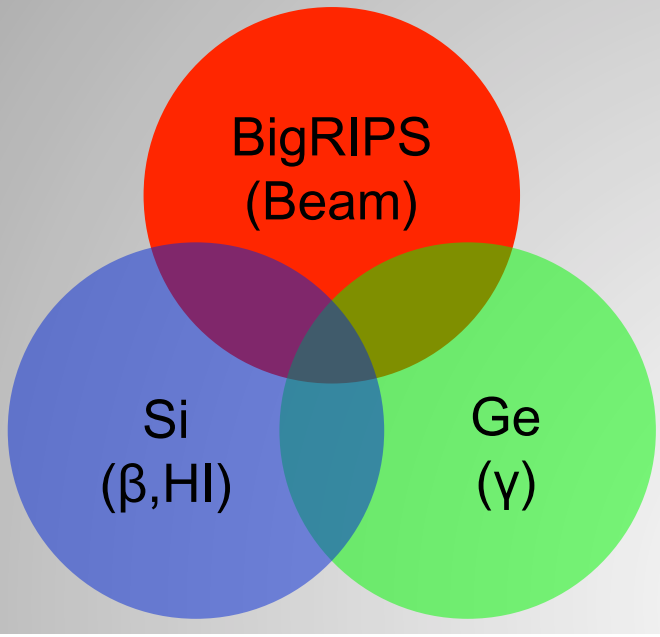
DSSSD
- 60×40 strips
- 1-mm pitch

8 layers (2012)
5 layers (2013)

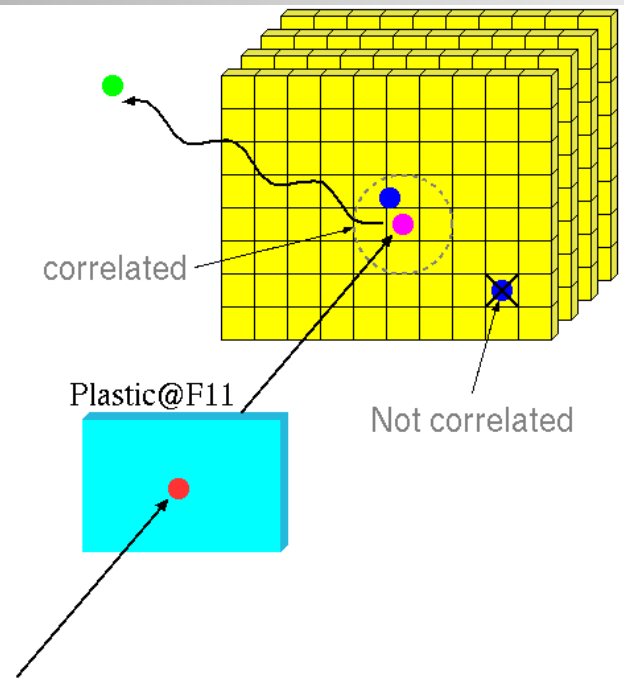


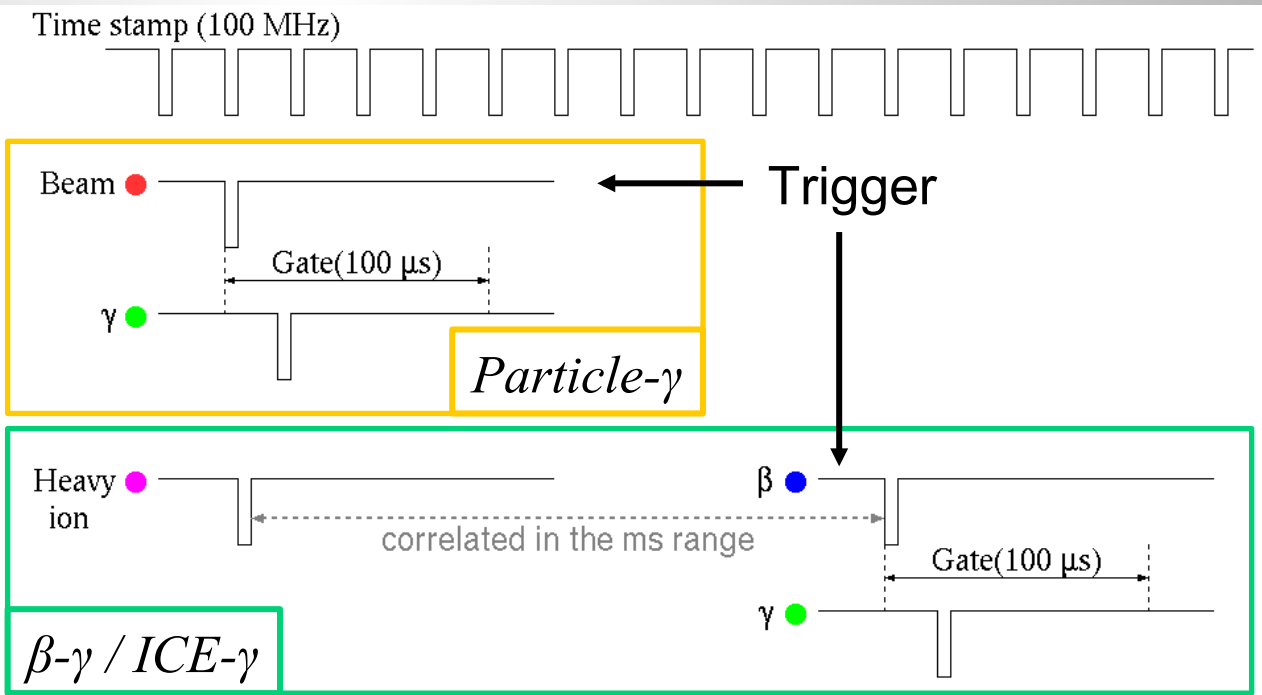


DAQ for decay spectroscopy experiment



- Independent DAQ systems
- Synchronized using time stamp
- Event build based on time stamp



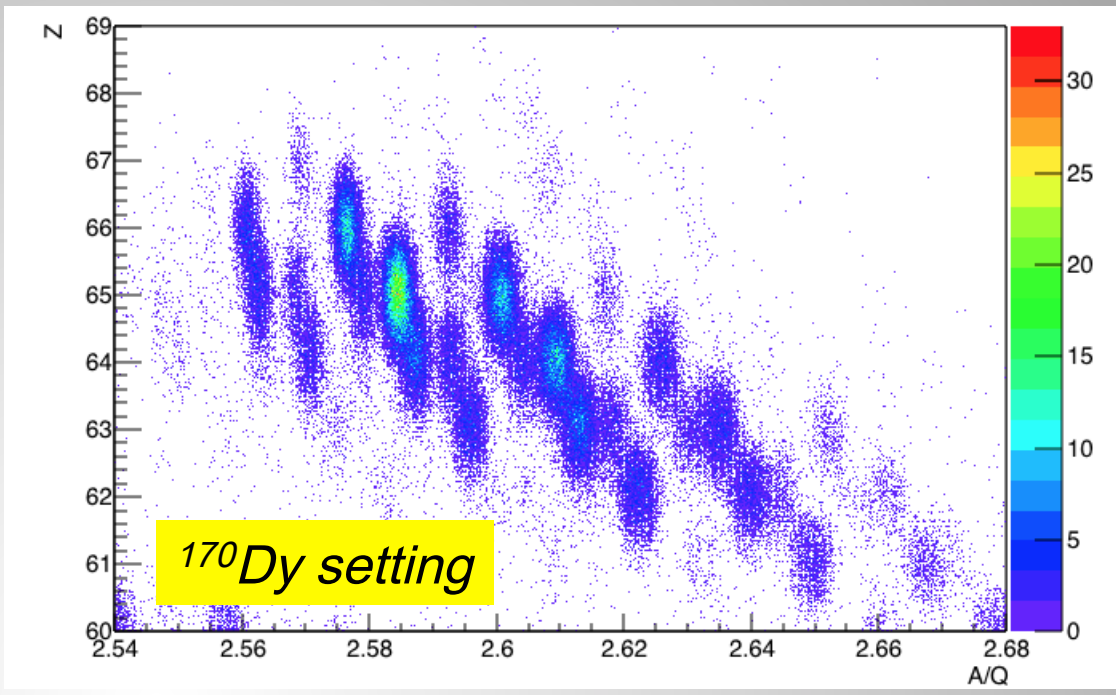


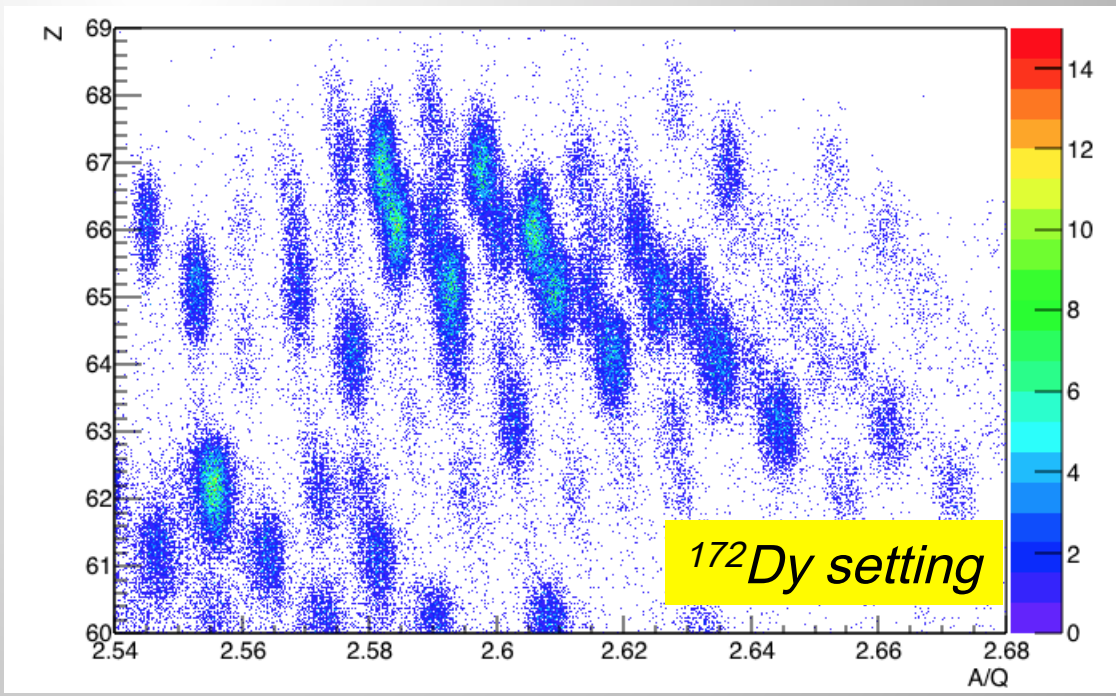
In-flight fission of ^{238}U + Isotope separation

Nov. 2014 (3 days)

- High intensity (10~15 pnA)
- Slits optimized for ^{170,172}Dy
- ΔA/Q ~ 0.05 %

  ⇒ Separate charge state





In-flight fission of ^{238}U + Isotope separation

Nov. 2014 (3 days)

- High intensity (10~15 pnA)
- Slits optimized for ^{170,172}Dy
- ΔA/Q ~ 0.05 %

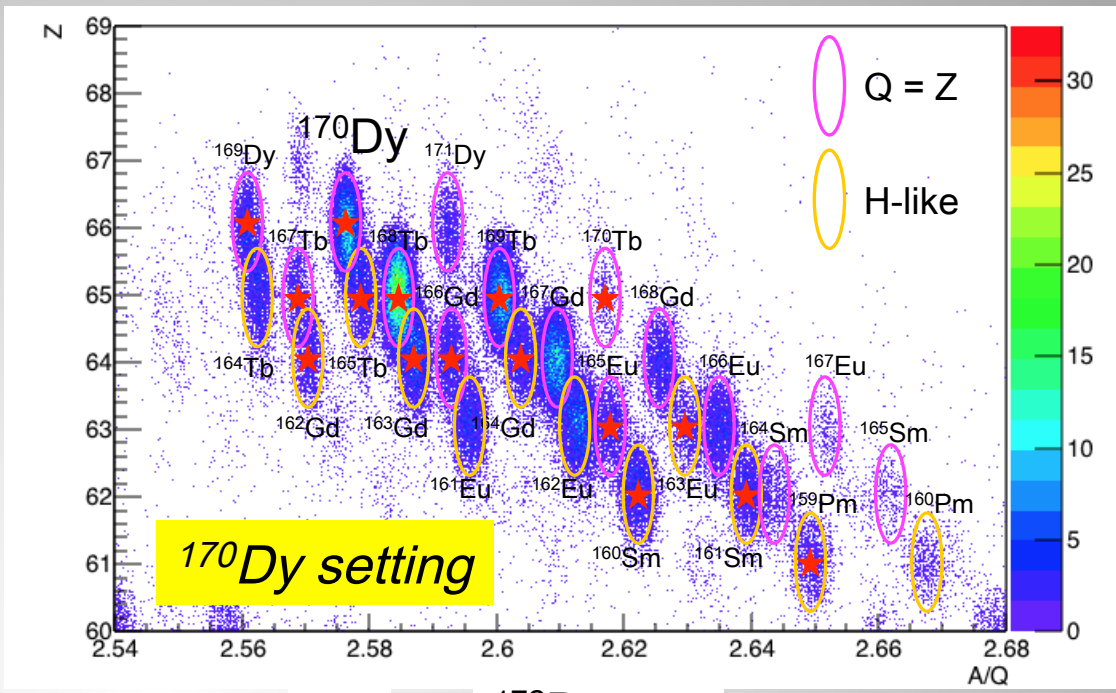
  ⇒ Separate charge state

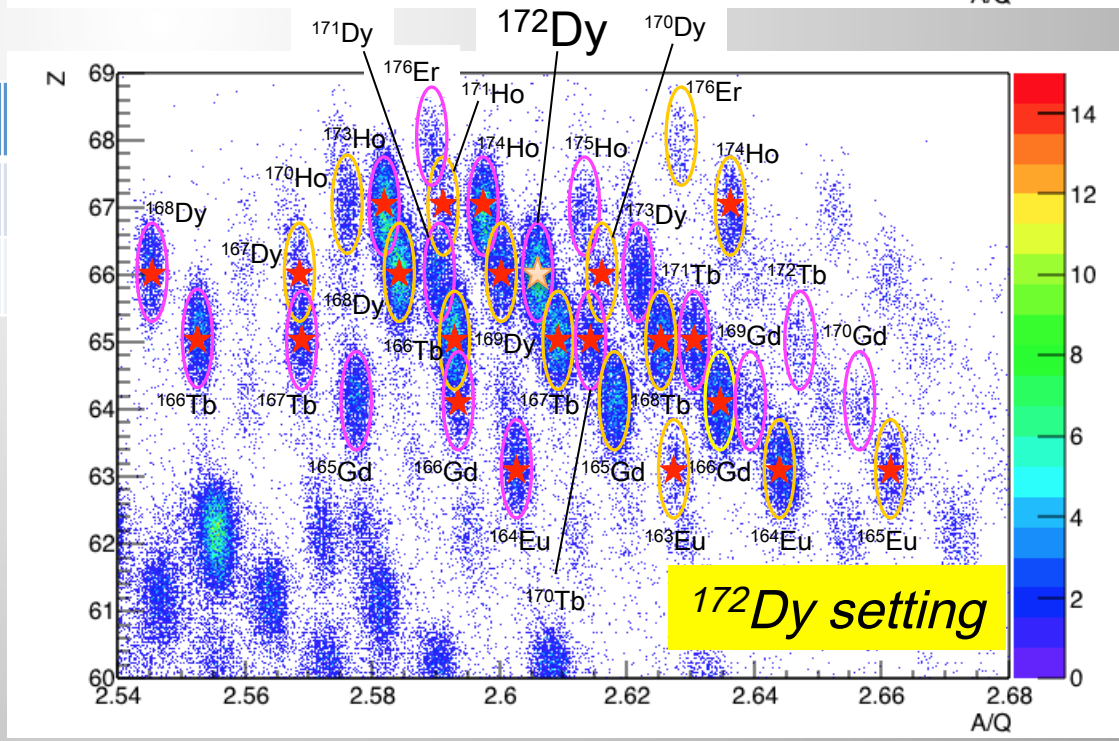
Ion	BigRIPS
^{170}Dy^{66+}	12932
^{172}Dy^{66+}	8272

Heaviest isotope spectroscopic study done so far at RIBF

★ Isomer in μs

☆ Isomer in ms

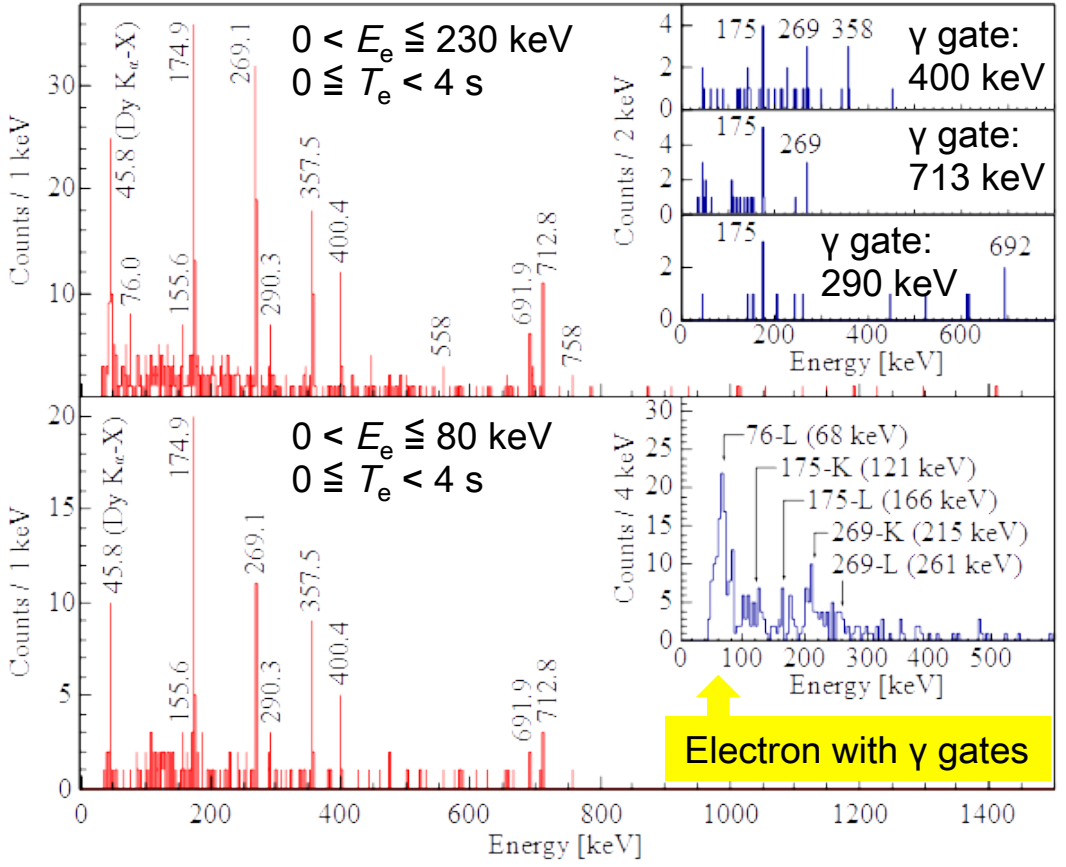


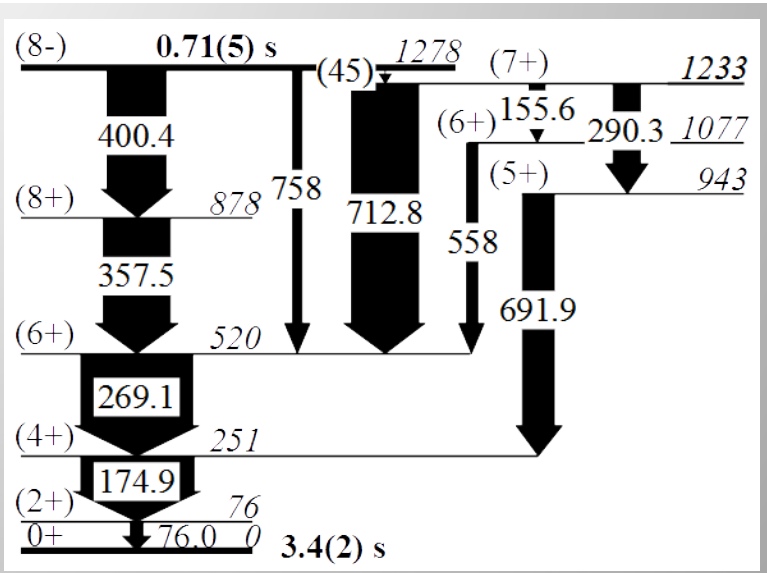


$^{172}_{66}Dy_{106}$

H. Watanabe et al.,
PLB 760 (2016) 641

- 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 $E_e \leqq 80$ 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

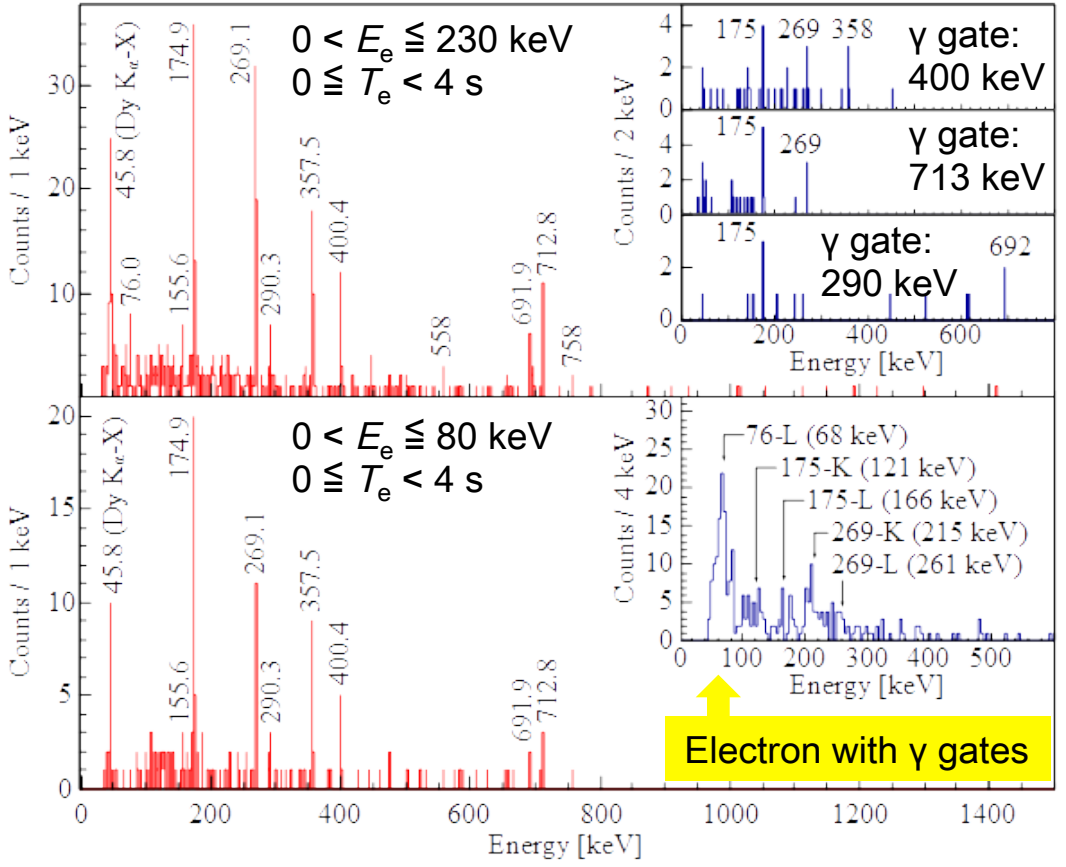


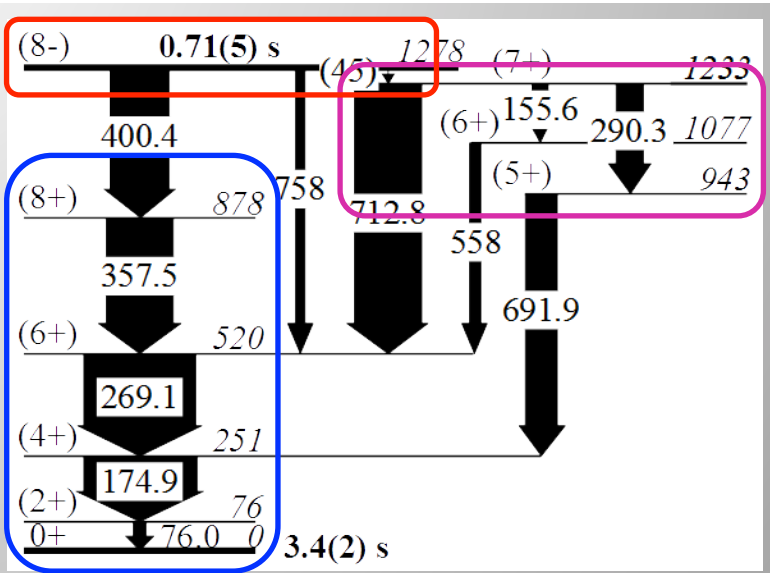


$^{172}_{66}Dy_{106}$

H. Watanabe et al.,
PLB 760 (2016) 641

- 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 $E_e \leqq 80$ 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

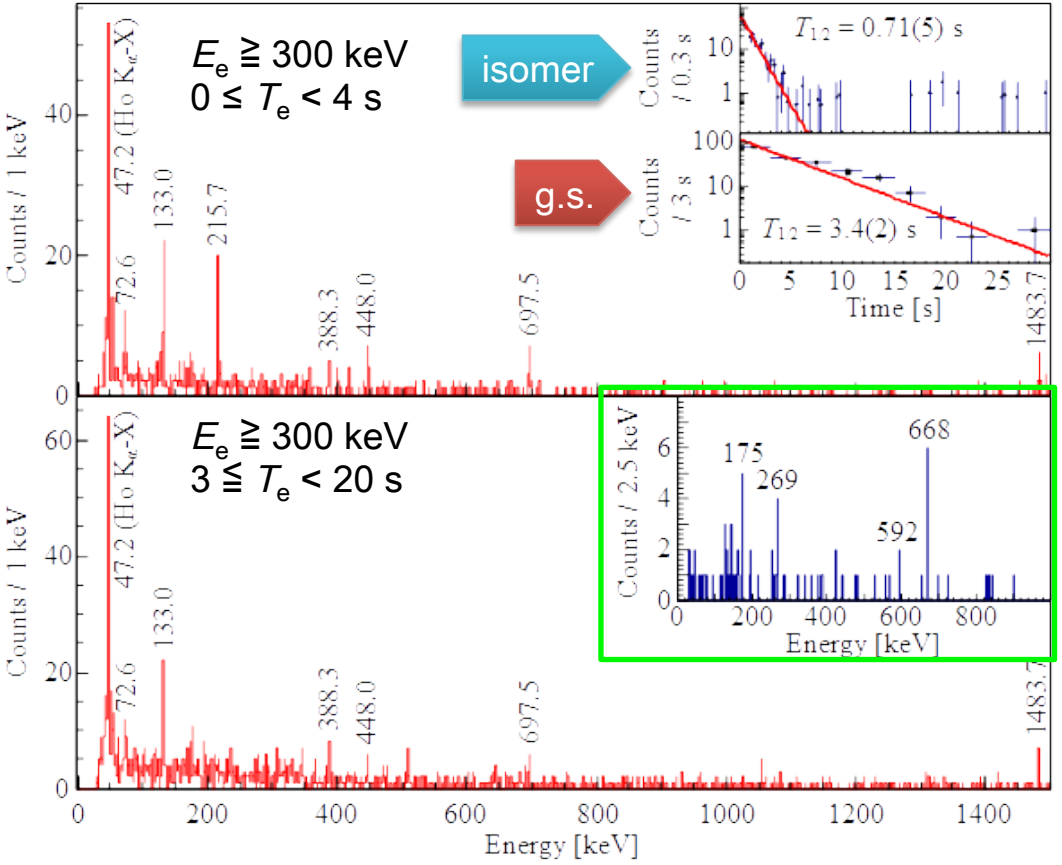




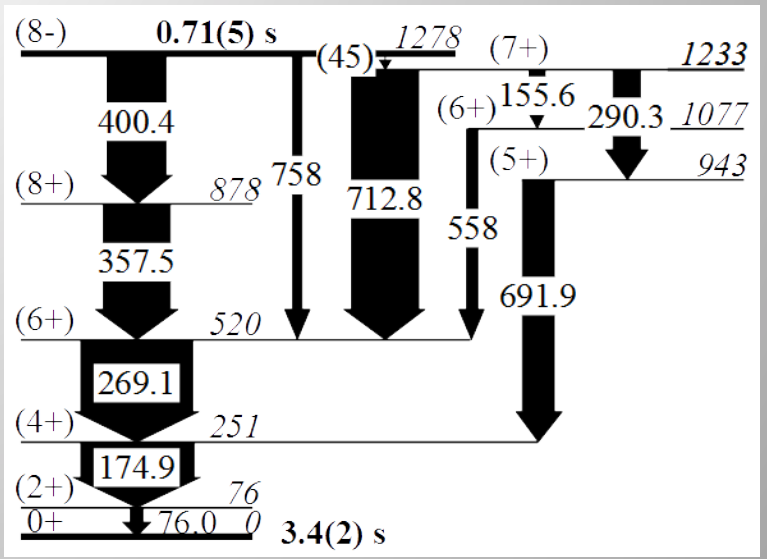
$^{172}_{66}Dy_{106}$

H. Watanabe et al.,
PLB 760 (2016) 641

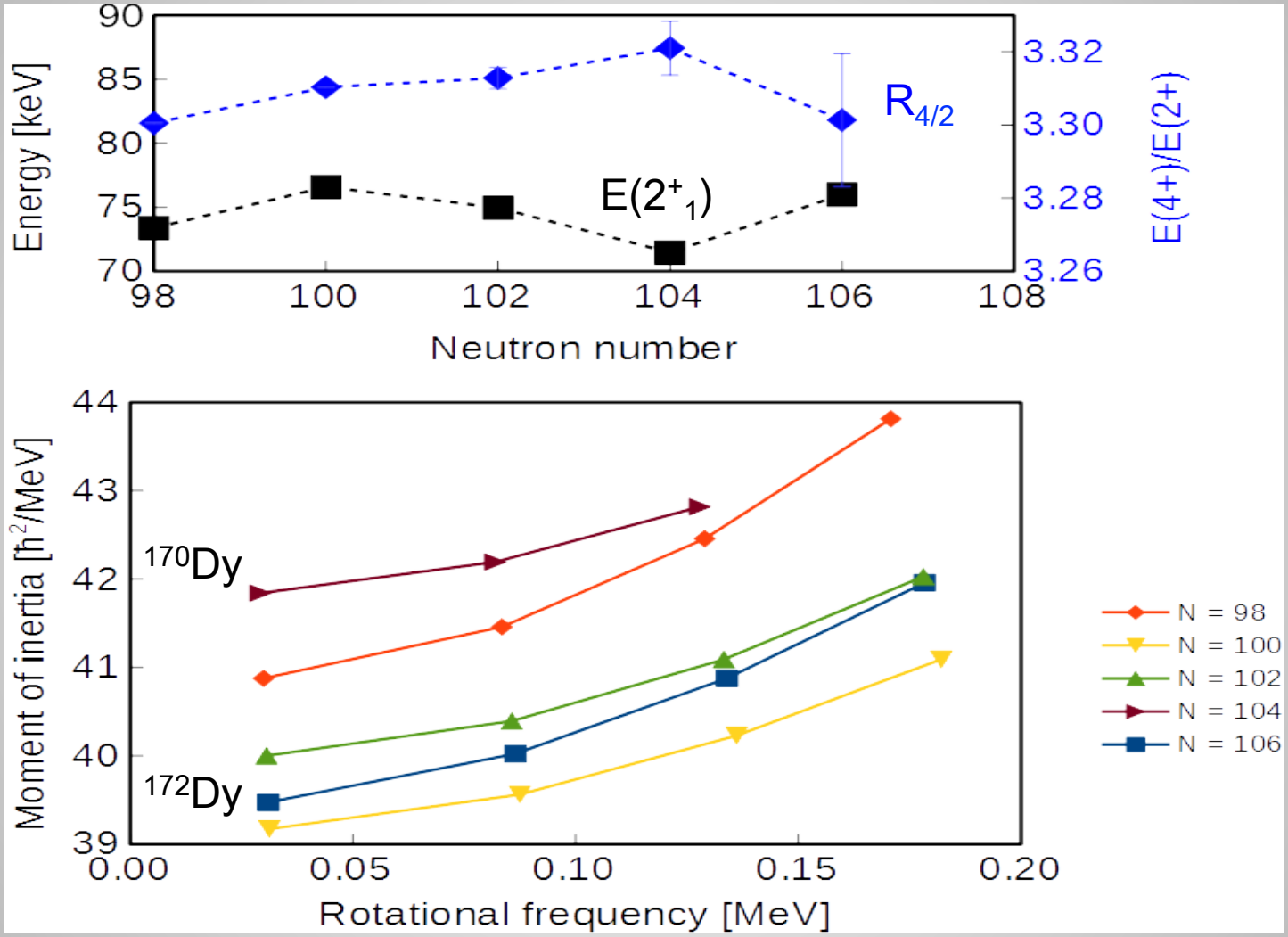
- β decay from the $K^{\pi} = 8^-$ isomer
  - Ho K_α-X ray (47.2 keV) observed with $E_e \geqq 300$ keV
  - 216-keV γ ray disappears for a longer-time window
    - ⇒ β decay of the isomer
      - $I_\beta = 19(3)$ %
      - **$\log ft = 5.0(2)$** *allowed transition*
  - Other peaks arise from the β decay of the g.s. ($T_{1/2}$ = 3.4 s)



- β decay from ^{172}Tb
  - 175- and 269-keV γ rays are visible
    - ⇒ β-decaying state with 5^+, 6^+, or 7^+
    - ※ The g.s. of ^{172}Tb expected to have $J^{\pi} = 6^+$; $\pi 3/2^+[411] \otimes \nu 9/2^+[624]$
    - ※ Anti-parallel coupling results in $J^{\pi} = 3^+$
  - γ rays at 668 and 592keV, the former in agreement with the extrapolated energy of the 2^+_γ state (671 keV)

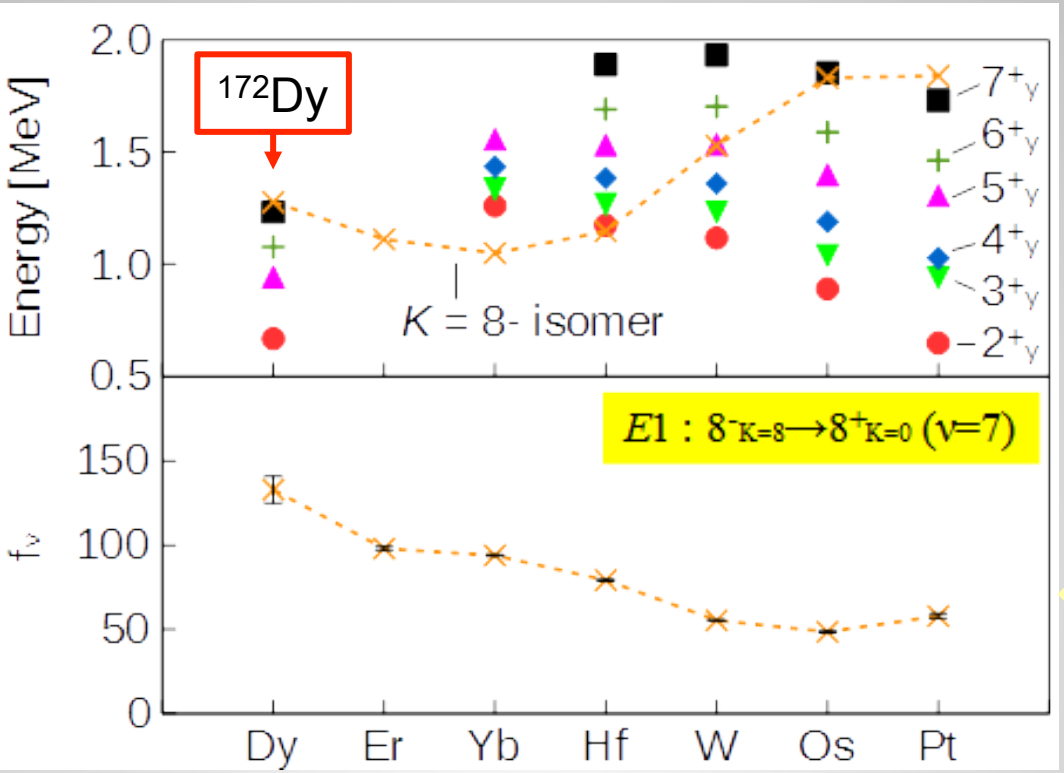


Systematics of the ground-state rotational band of Dy isotopes



Maximum deformation of the Dy isotopes occurs in ^{170}Dy (N = 104) ?

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



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

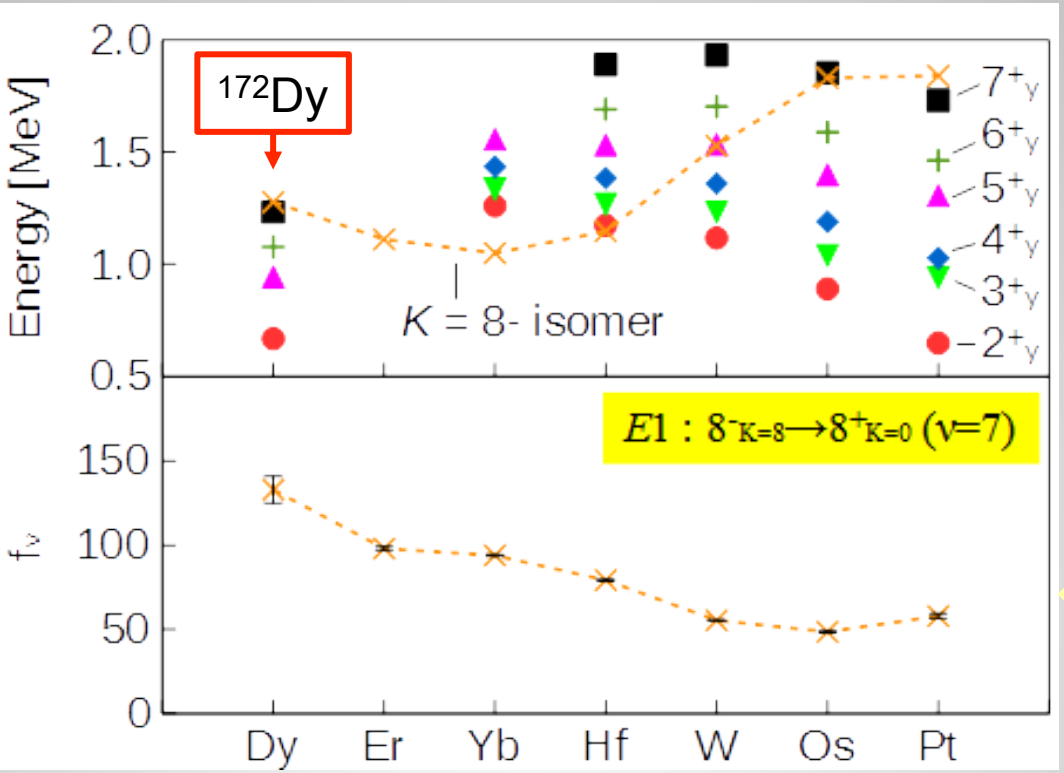
$$f_\nu = F^{1/\nu}$$

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

- $K^{\pi} = 8^-$ isomers in N = 106 isotones
  - Neutron two-quasiparticle configuration: $\nu 7/2^-[514]\nu 9/2^+[624]$
  - The energy systematics interpreted in terms of the variation of the neutron pairing strength
  - The isomerism ascribed to the large difference in the K quantum number

- E1 transition from the $K^{\pi} = 8^-$ isomer to the 8^+ state in the g.s. band
  - **f_ν follows the upward trend**
    - ⇒ K is rather robust, as expected for axially symmetric nuclei

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



$$F = \tau_{\gamma}^{\exp} / \tau_{W}$$

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

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

- $K^{\pi} = 2^{+}$ 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

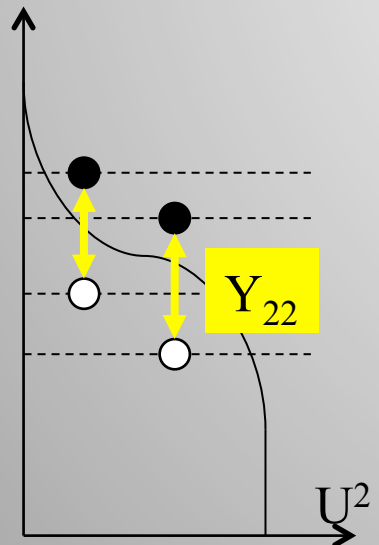
Skyrme + pairing energy-density functional (EDF)

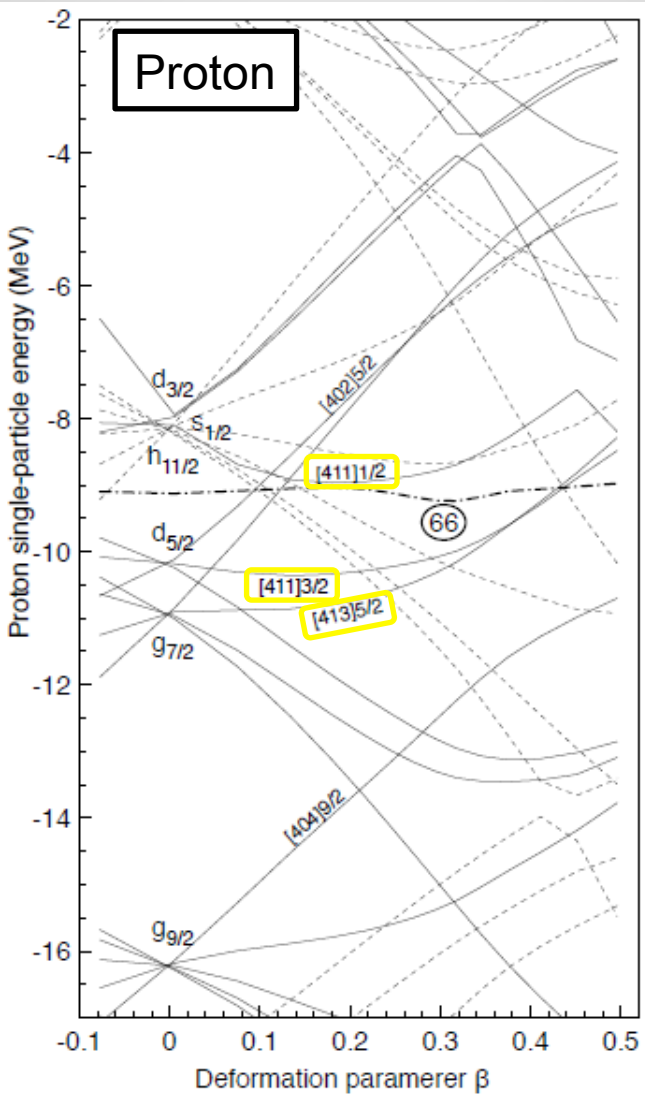
- HFB for the ground state
- QRPA for the intrinsic excitations

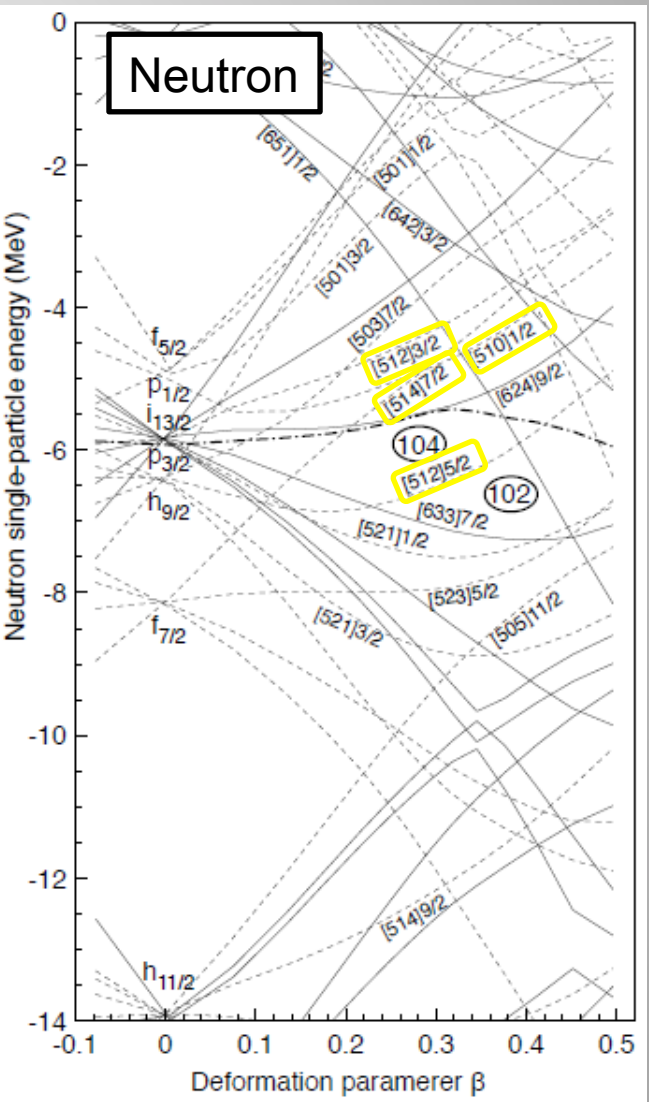
K. Yoshida and H. Watanabe
arXiv:1607.07111

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

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



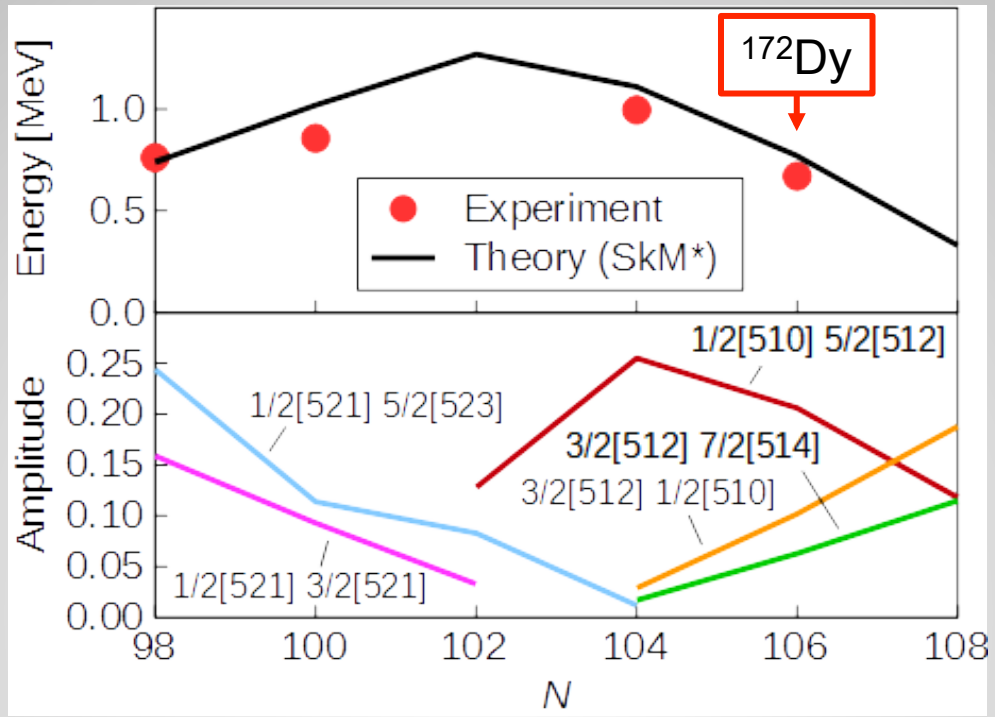




Interpretation of γ vibration in the framework of Nuclear DFT

$E(2^+_\gamma)$

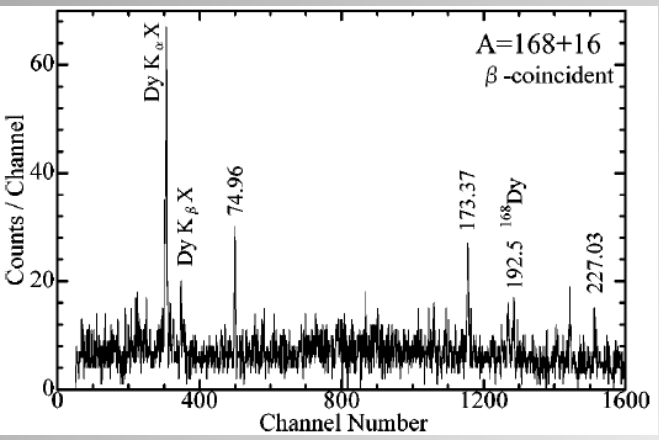
Neutron 2qp components in 2^+_γ

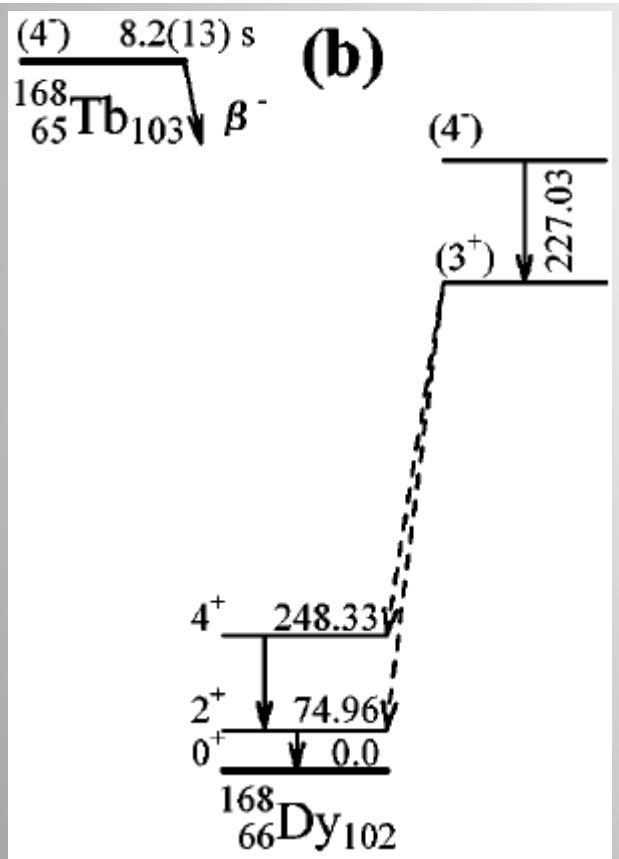


- **HFB+QRPA calculation well reproduces the experimental results**
  - Decreasing trend of the 2^+_γ energies from $^{170}Dy_{104}$ to $^{172}Dy_{106}$
  - [Significant 2qp components in QRPA]
    - **Proton** ⇒ *Not change so much with the neutron number*
      - $\pi^2 1/2^+[411]\otimes 3/2^+[411]$ (~0.25), $\pi^2 1/2^+[411]\otimes 5/2^+[413]$ (~0.19)
    - **Neutron** ⇒ *Isotopic dependence of the 2^+_γ energies*
      - 3 components play dominant roles beyond midshell (N > 104)

- **Even lower energy predicted for $^{174}Dy_{108}$**
  - to be investigated in future experiments using more intense RI beams

$^{168}_{66}Dy_{102}$





β-decay study on ^{168}Dy

M. Asai et al., Phys. Rev. C 59, 3060 (1999)

- ^{168}Tb
  - $T_{1/2}$ = 8.2(13) s
  - J^{π} = (4^-); $\pi 3/2^+[411] \otimes \nu 5/2^-[512]$

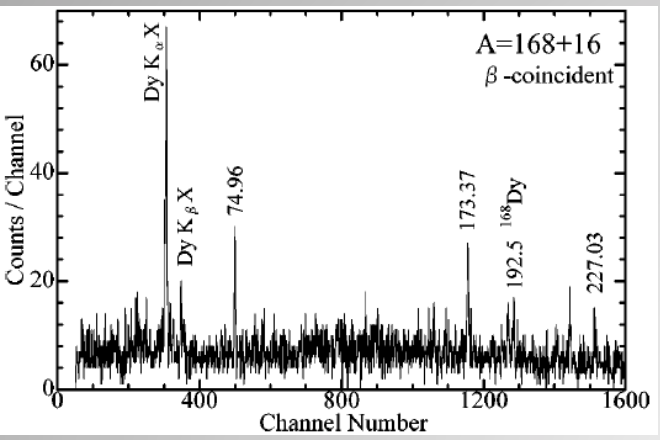
Tb (Z=65) isotopes

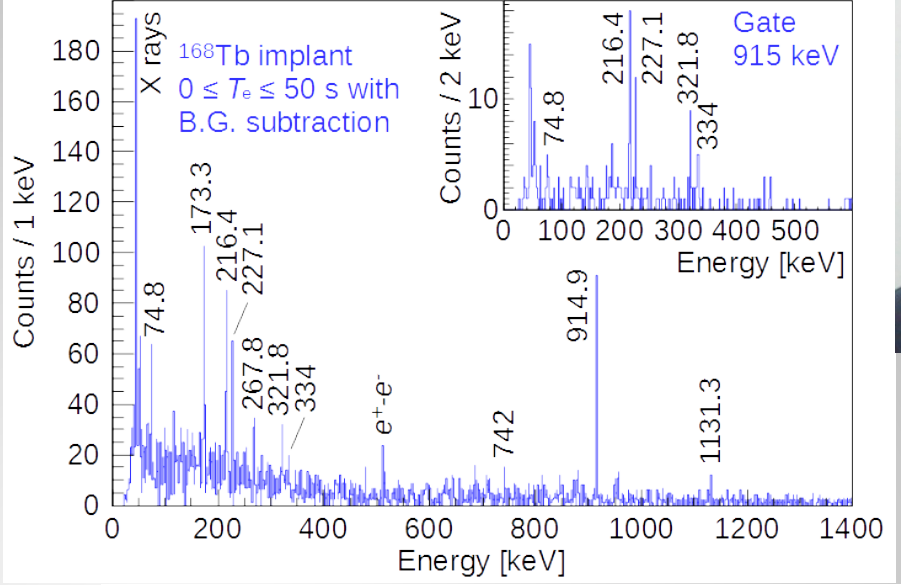
N=103 isones

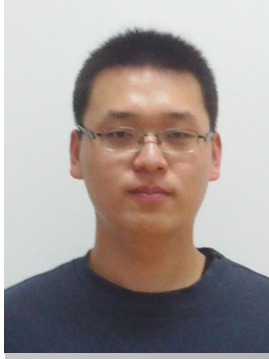
- Three γ transitions assigned to ^{168}Dy
  - 75 keV ($2^+ \rightarrow 0^+$)
  - 173 keV ($4^+ \rightarrow 2^+$)
  - 227 keV ($4^- \rightarrow 3^+_{\gamma}$)

  Interband transitions towards the ground-state band were not observed

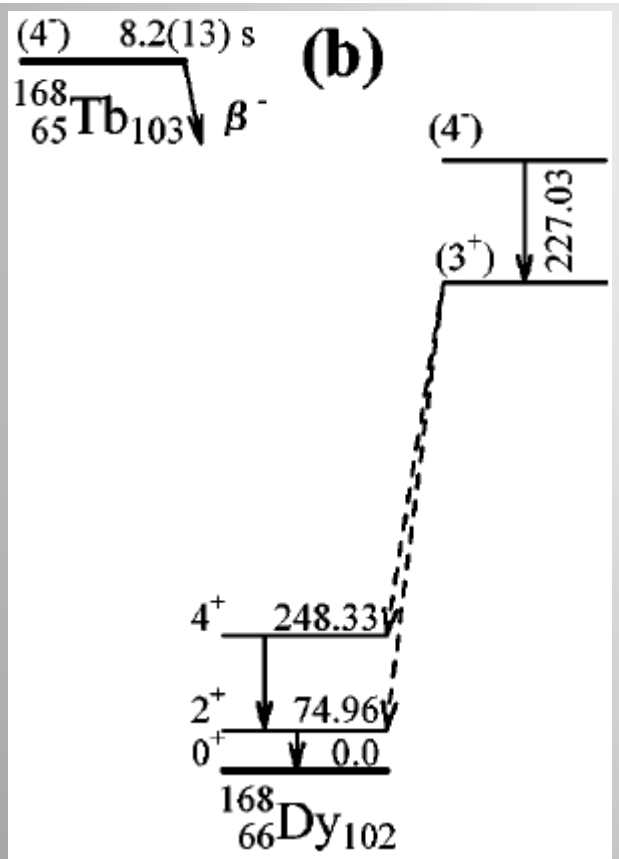
$^{168}_{66}Dy_{102}$

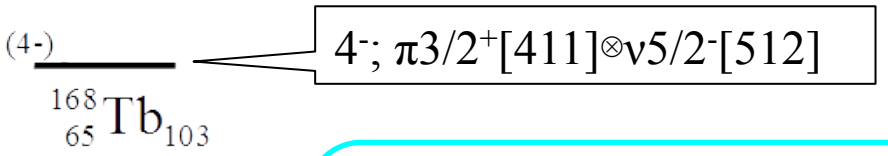




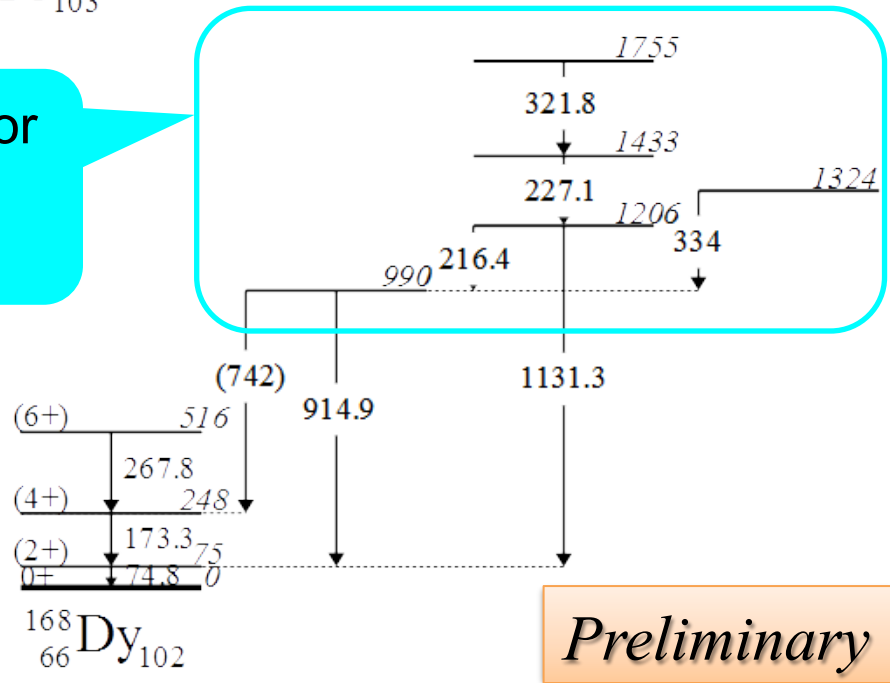


G.X. Zhang
Beihang Univ.



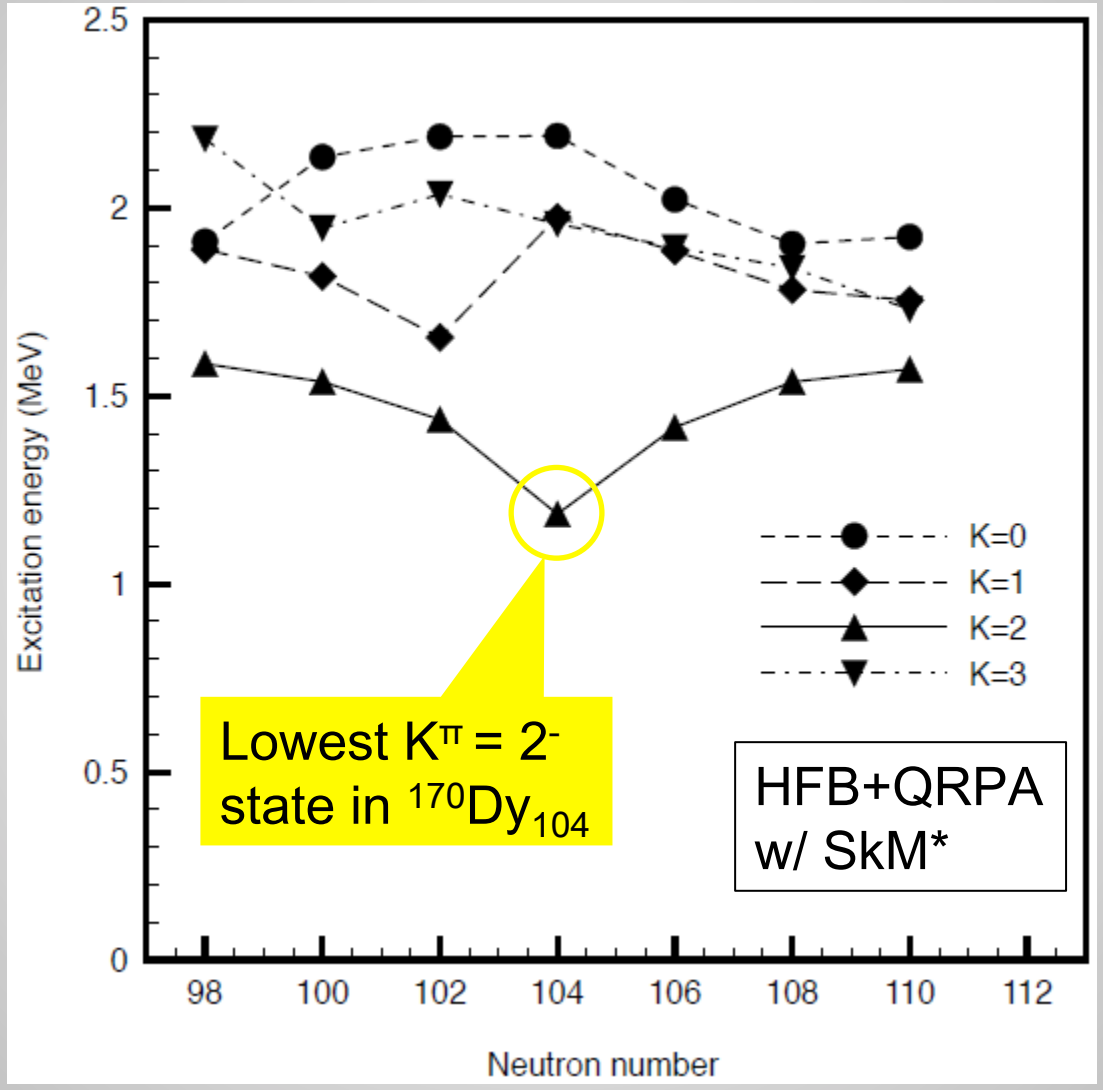


Candidates for
$K^{\pi} = 2^{+}$ or 2^{-}
states



Preliminary

Prediction of octupole-vibrational states in Dy isotopes



Summary

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

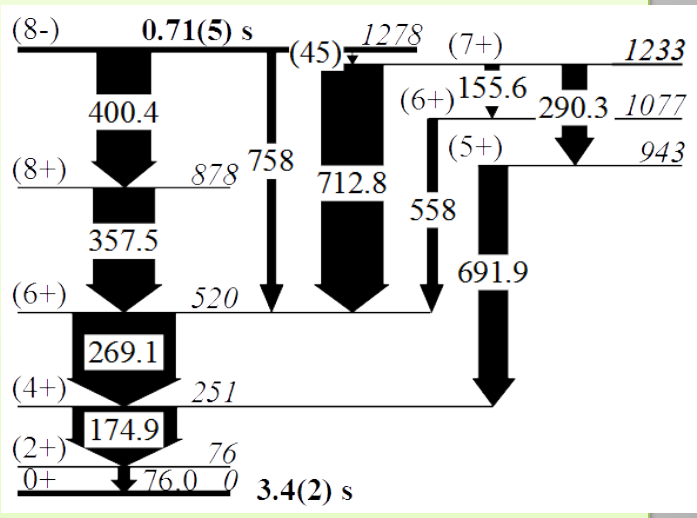
^{172}Dy (N = 106)

- 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



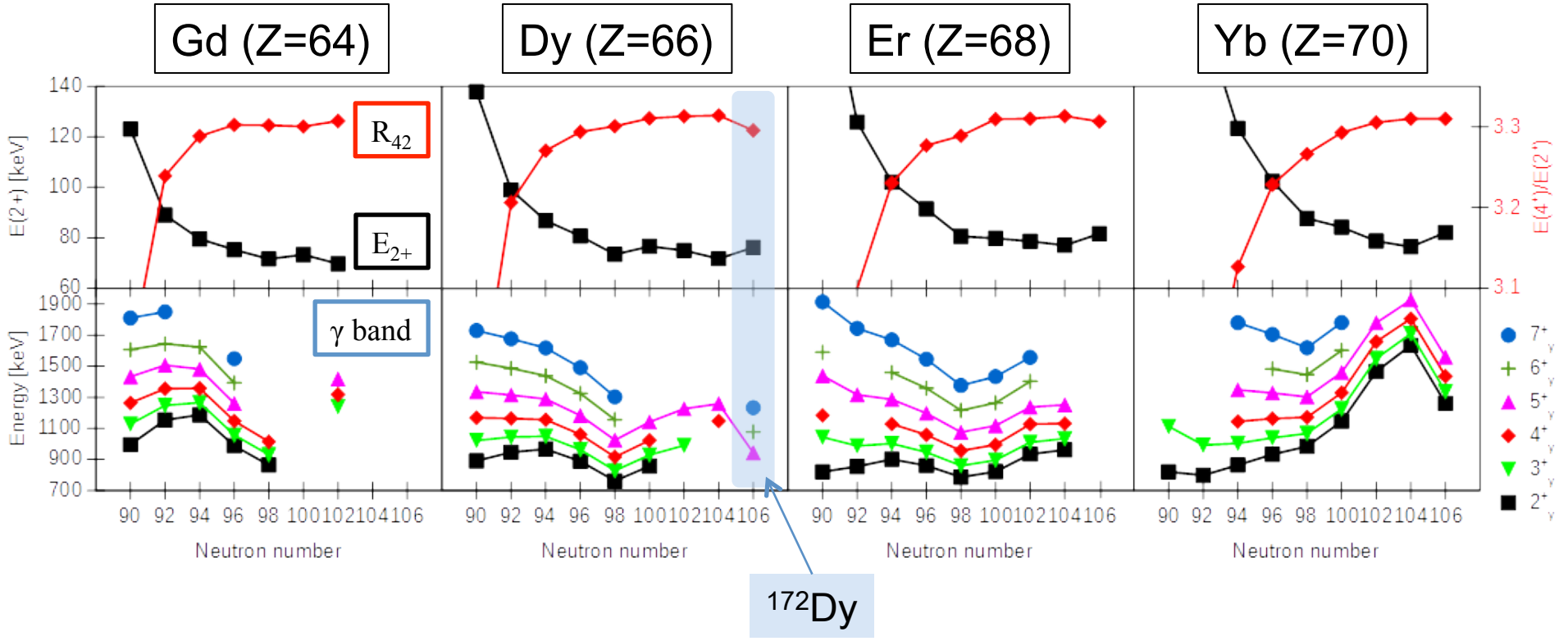
^{168}Dy (N = 102)

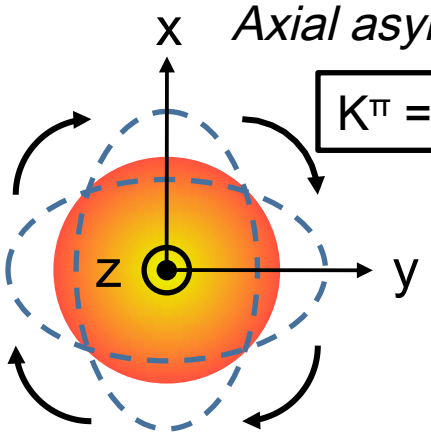
- Analysis is still ongoing

Thank you for your attention!

backup

Systematics of γ-vibrational band in well-deformed rare-earth nuclei around double mid-shell





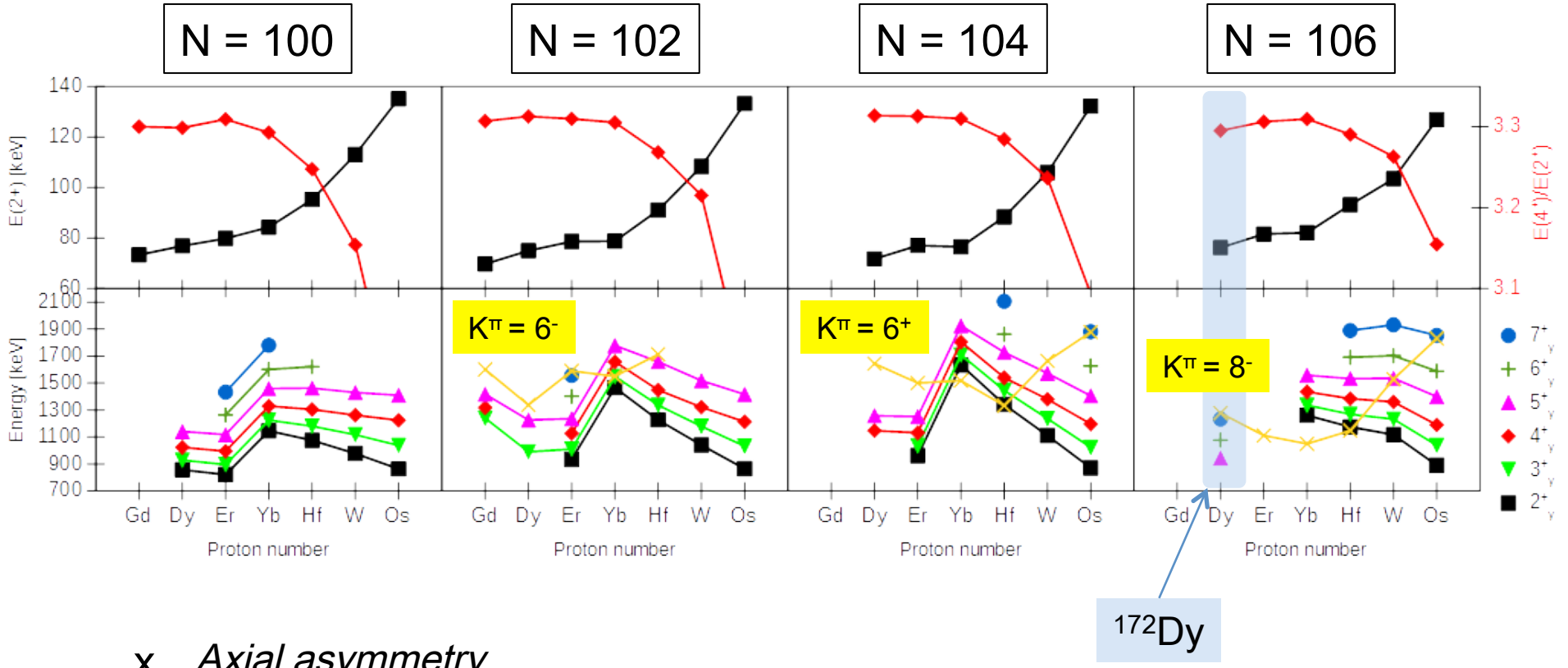
Axial asymmetry

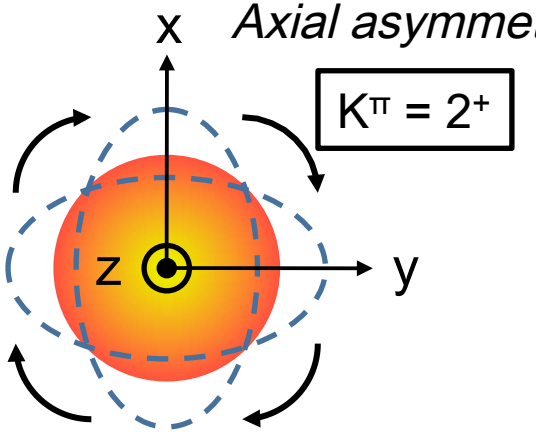
$K^{\pi} = 2^{+}$

Levels in γ-vibrational band fall at

N = 106

Systematics of γ-vibrational band in well-deformed rare-earth nuclei around double mid-shell



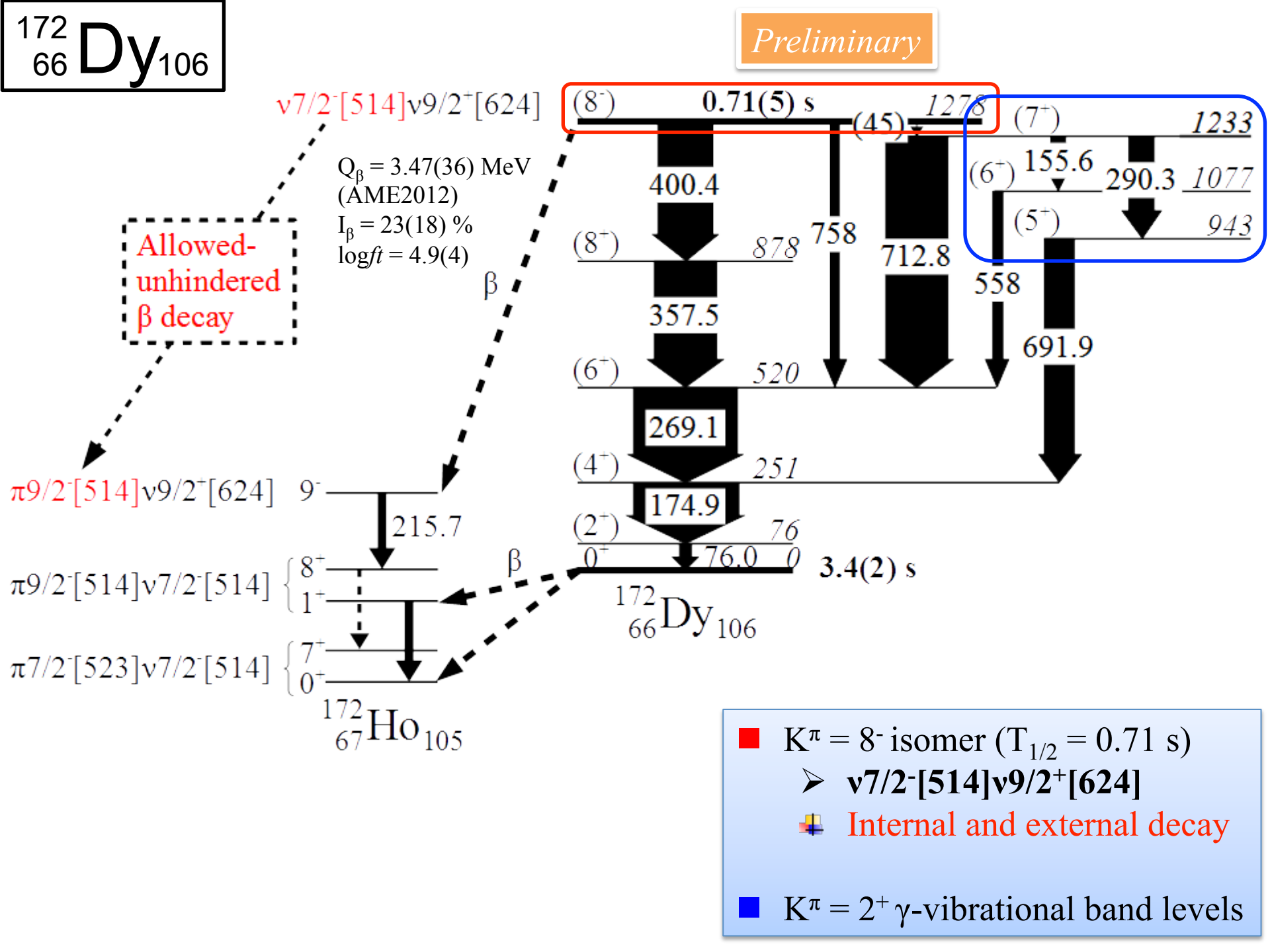


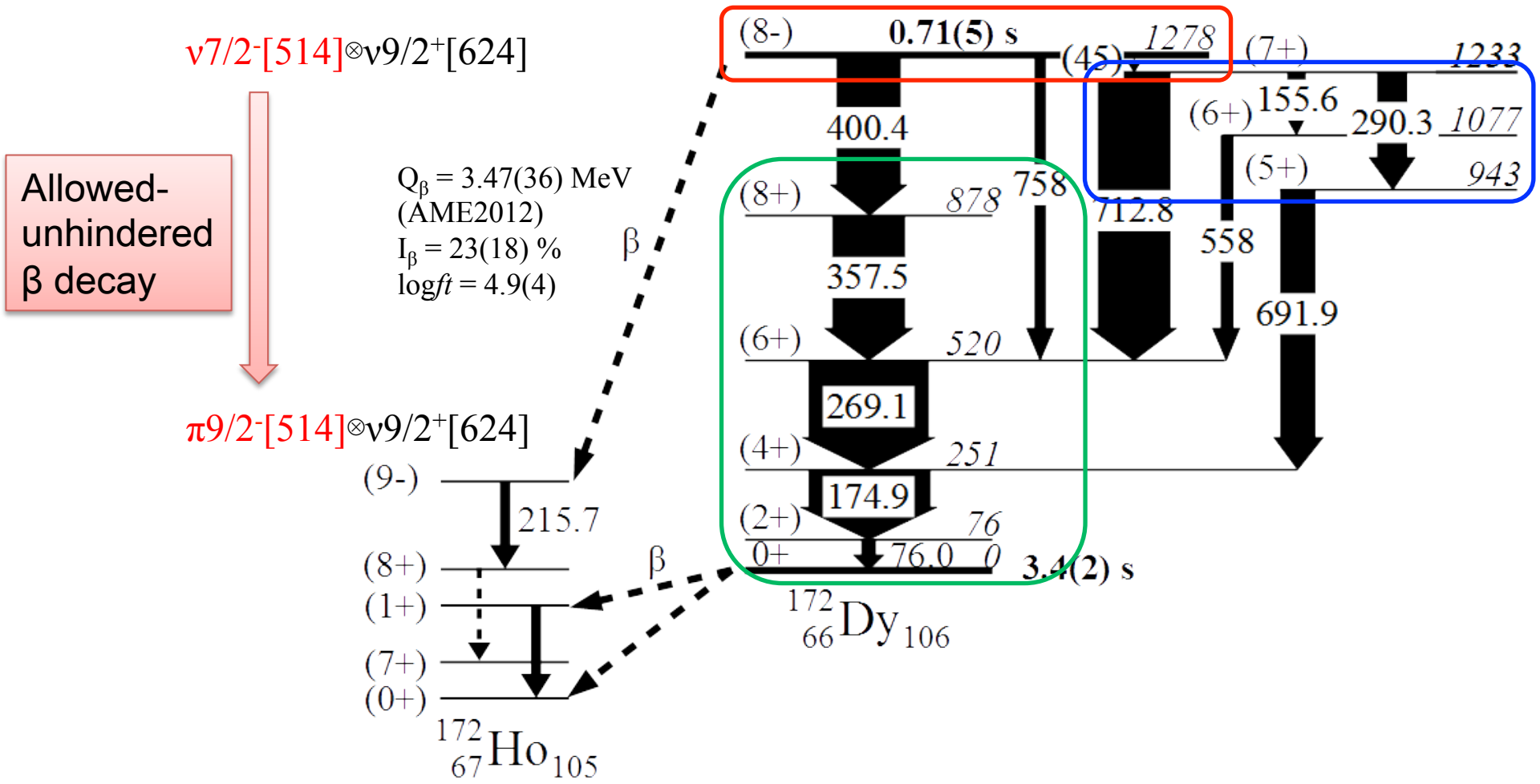
Levels in γ-vibrational band fall at

N = 106

$_{66}$Dy (and $_{68}$Er)

Enhanced γ vibration in $^{172}Dy_{106}$


172 66 Dy106
Preliminary
ν7/2⁻[514]ν9/2⁺[624]
(8⁻)
0.71(5) s
1278
(45)
(7⁺)
1233
(6⁺)
155.6
290.3
1077
(5⁻)
943
Q_β = 3.47(36) MeV
(AME2012)
I_β = 23(18) %
logft = 4.9(4)
400.4
758
712.8
558
691.9
(8⁺)
878
357.5
(6⁺)
520
269.1
(4⁺)
251
174.9
(2⁺)
76
0⁻
76.0
0
3.4(2) s
β
Allowed-unhindered β decay
π9/2⁻[514]ν9/2⁺[624]
9⁻
215.7
π9/2⁻[514]ν7/2⁻[514]
8⁻
1⁻
π7/2⁻[523]ν7/2⁻[514]
7⁻
0⁺
172 67 Ho105
172 66 Dy106
Kπ = 8⁻ isomer (T1/2 = 0.71 s)
ν7/2⁻[514]ν9/2⁺[624]
Internal and external decay
Kπ = 2⁺ γ-vibrational band levels



Long-lived isomer ($T_{1/2}$ = 0.71 s)

K-hindered internal transitions compete with allowed-unhindered β decay

Transition	I (γ/β)	σλ	B(σλ) [W.u.]	ν	f_ν
400.4 keV	100(41)	E1	$1.1(6)\times10^{-15}$	7	137(26)
758 keV	17(12)	M2	$2.3(18)\times10^{-10}$	6	40(13)
45 keV	144(52)	E1	$1.1(5)\times10^{-12}$	5	245(50)
β	94(70)	-	-	-	-

β⁻-decay of deformed nuclei in the rare-earth region

Allowed β⁻ decay : **Gamow-Teller (GT) transition**

$$\Delta I = 0,1 \quad \Delta\pi = no$$

deformed

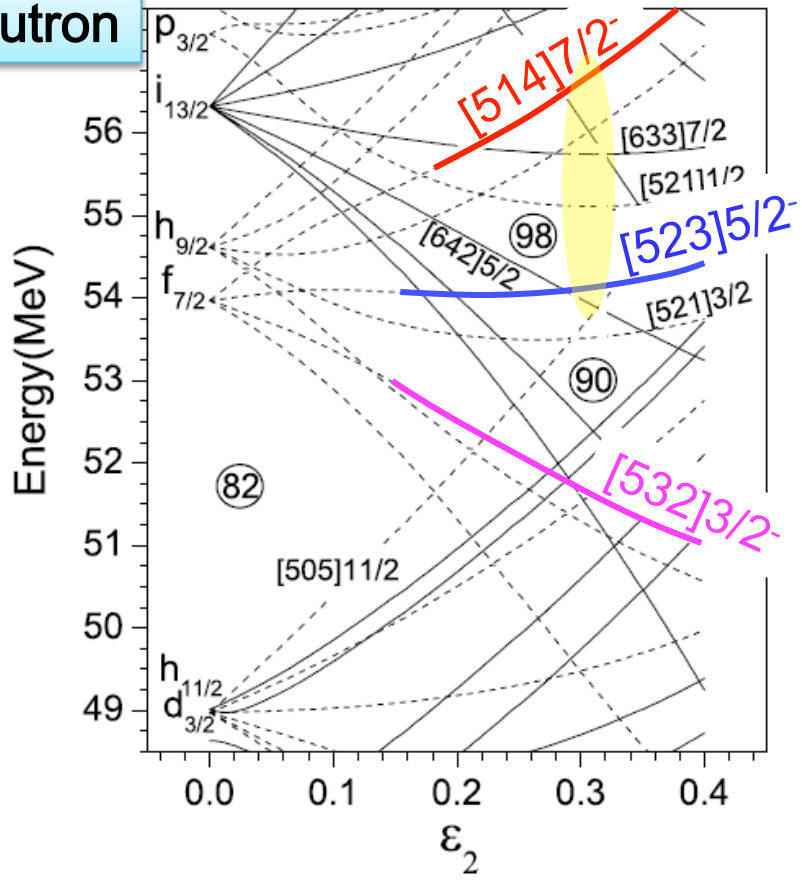
Allowed-unhindered (au) transitions

$$\Delta N = \Delta n_z = \Delta\Lambda = 0$$
$$\Delta K = 1^+$$

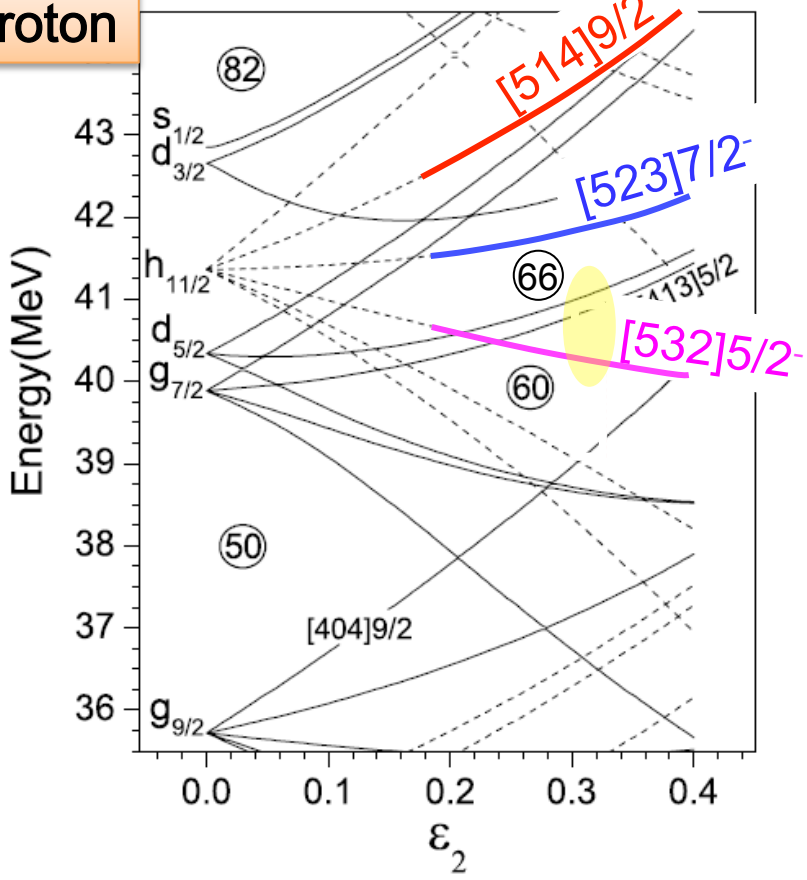
$$\log ft \le 5$$

Neutron	→	Proton
[532]3/2⁻	→	[532]5/2⁻
[523]5/2⁻	→	[523]7/2⁻
[514]7/2⁻	→	[514]9/2⁻

Neutron

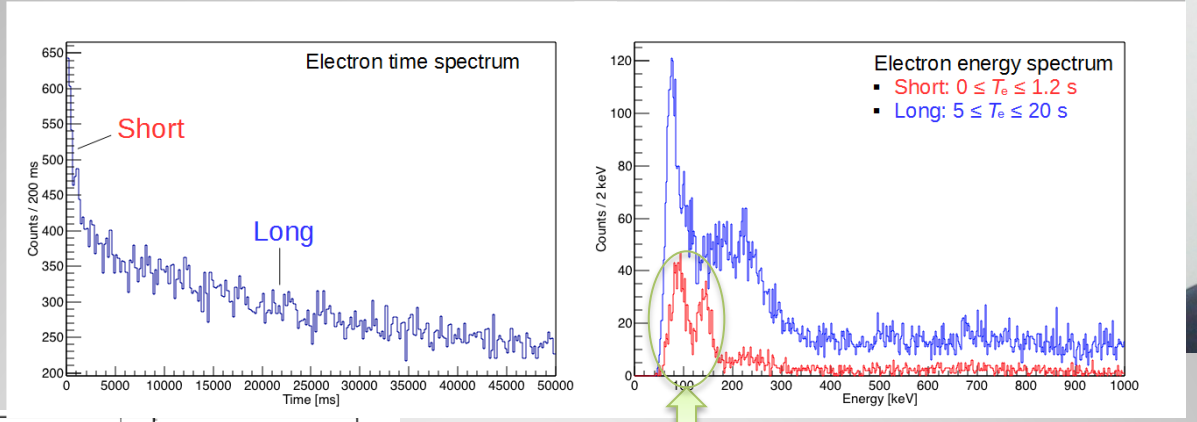


Proton



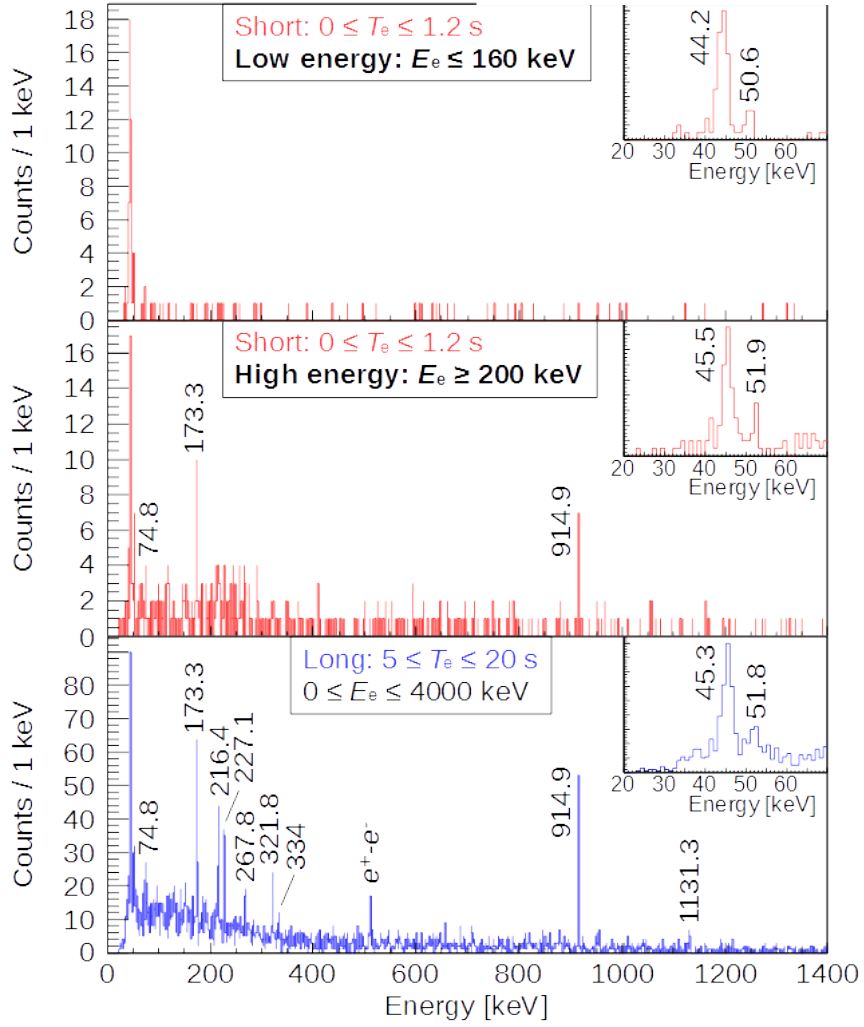
$^{168}_{66}Dy_{102}$

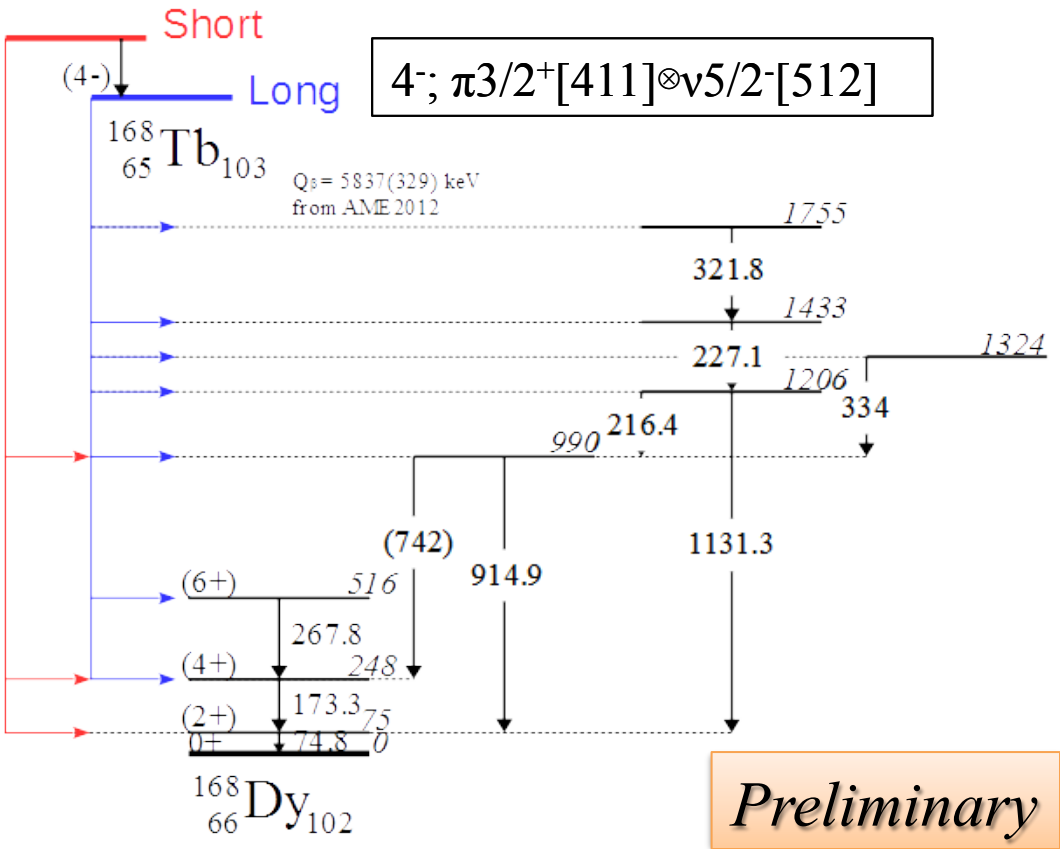
K_α X-ray energies
- Tb: 44.2 keV
- Dy: 45.7 keV



G.X. Zhang
Beihang Univ.

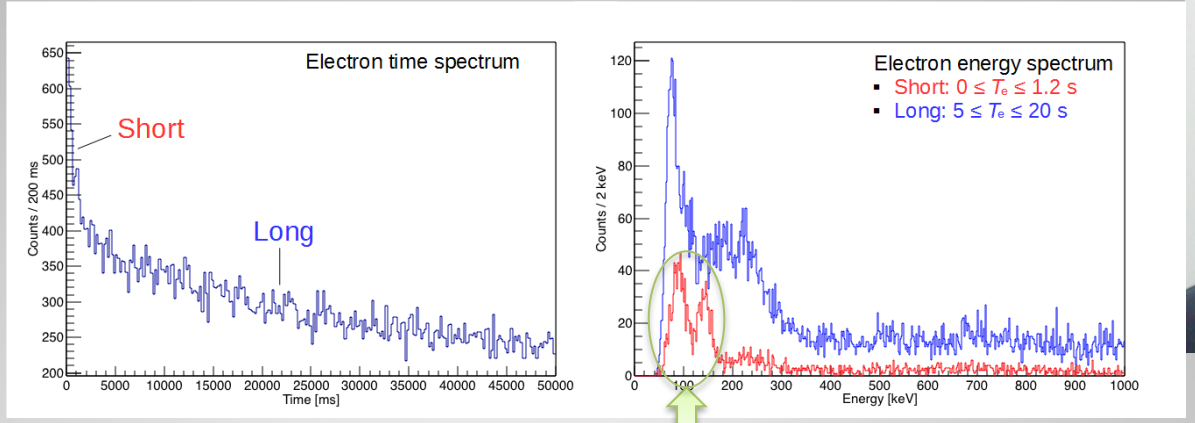
K -and L-conversion electrons?





Preliminary

$^{168}_{66}Dy_{102}$

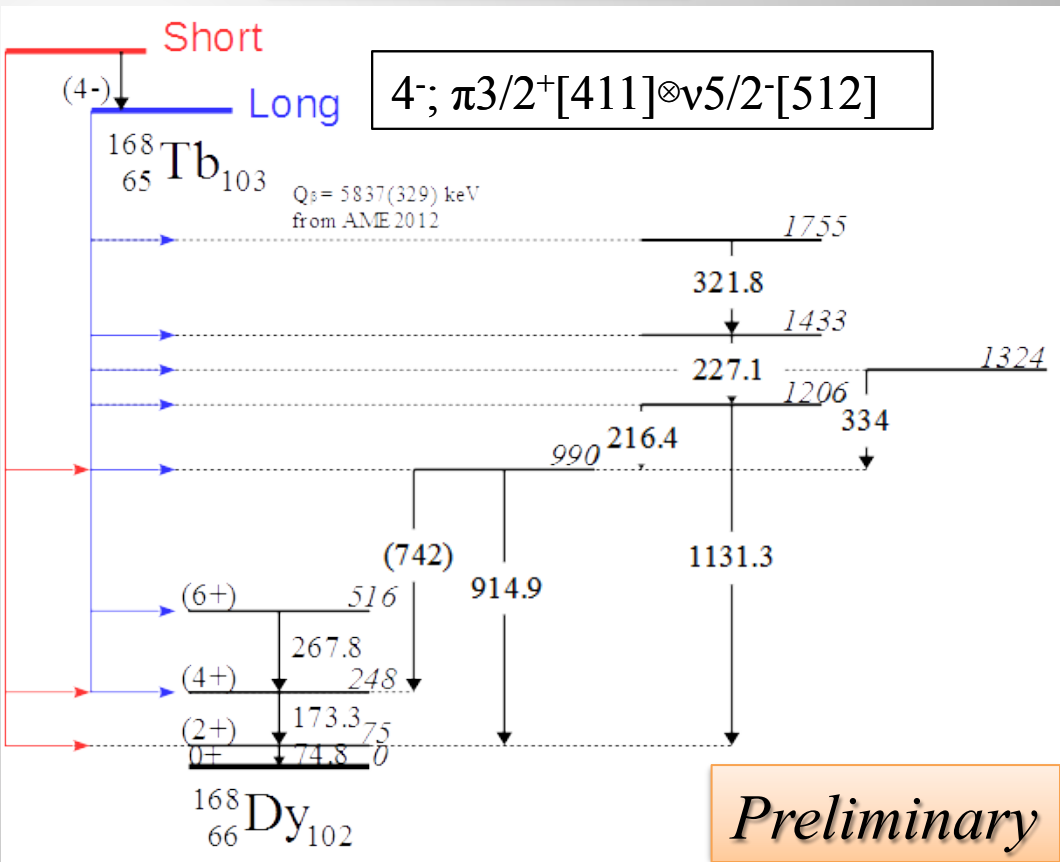


G.X. Zhang
Beihang Univ.

K -and L-conversion electrons?

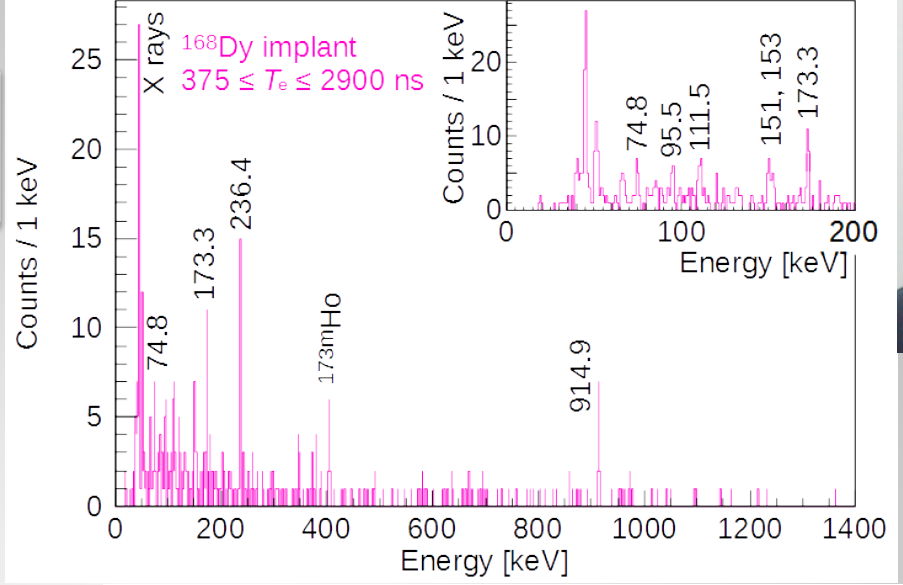
Data analysis still ongoing

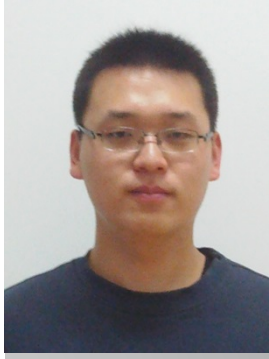
- **Lifetimes** of short- and long-lived states in ^{168}Tb
- **log*ft*** values
  ⇒ Spin-parity assignment



$^{168}_{66}Dy_{102}$

Beam-γ coincidence





G.X. Zhang
Beihang Univ.

Data analysis still ongoing

- **Lifetimes** of short- and long-lived states in ^{168}Tb
- **log*ft*** values
  - ⇒ Spin-parity assignment
- New isomer in the μs range
  - ➢ $K^{\pi} = 6^-$ from the N = 102 systematics?