Decay Spectroscopy of Mo Isotopes

A Quest to Exotic Nuclear Shapes

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IBS, Daejeon, Korea

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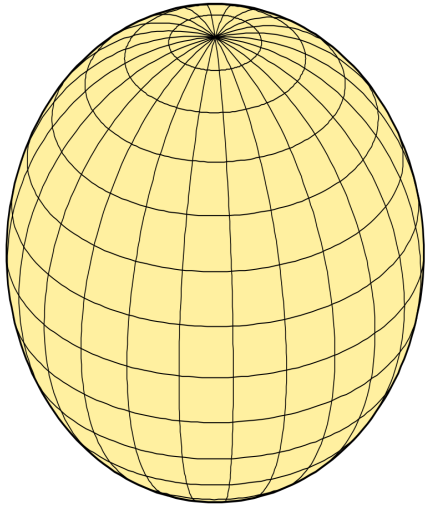
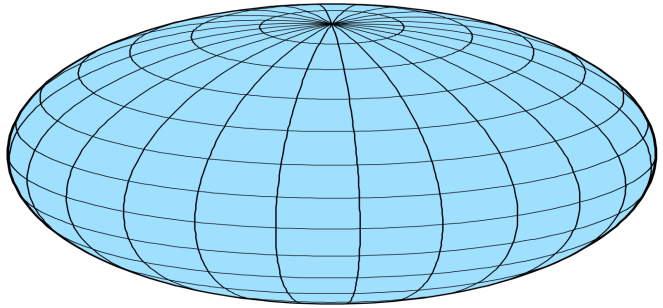
Shapes of Atomic Nuclei

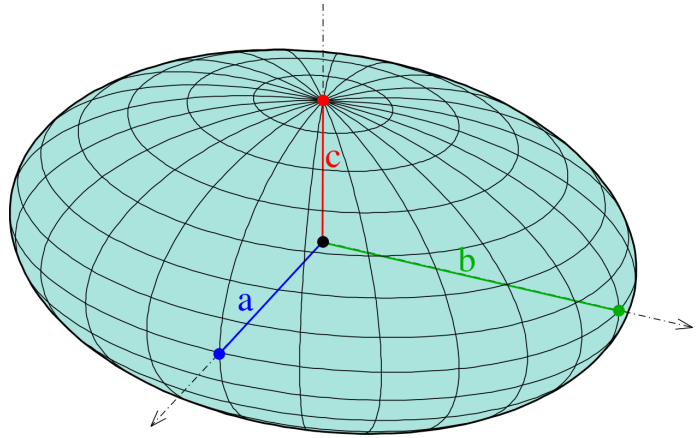
Possible shapes of deformed nuclei



Prolate



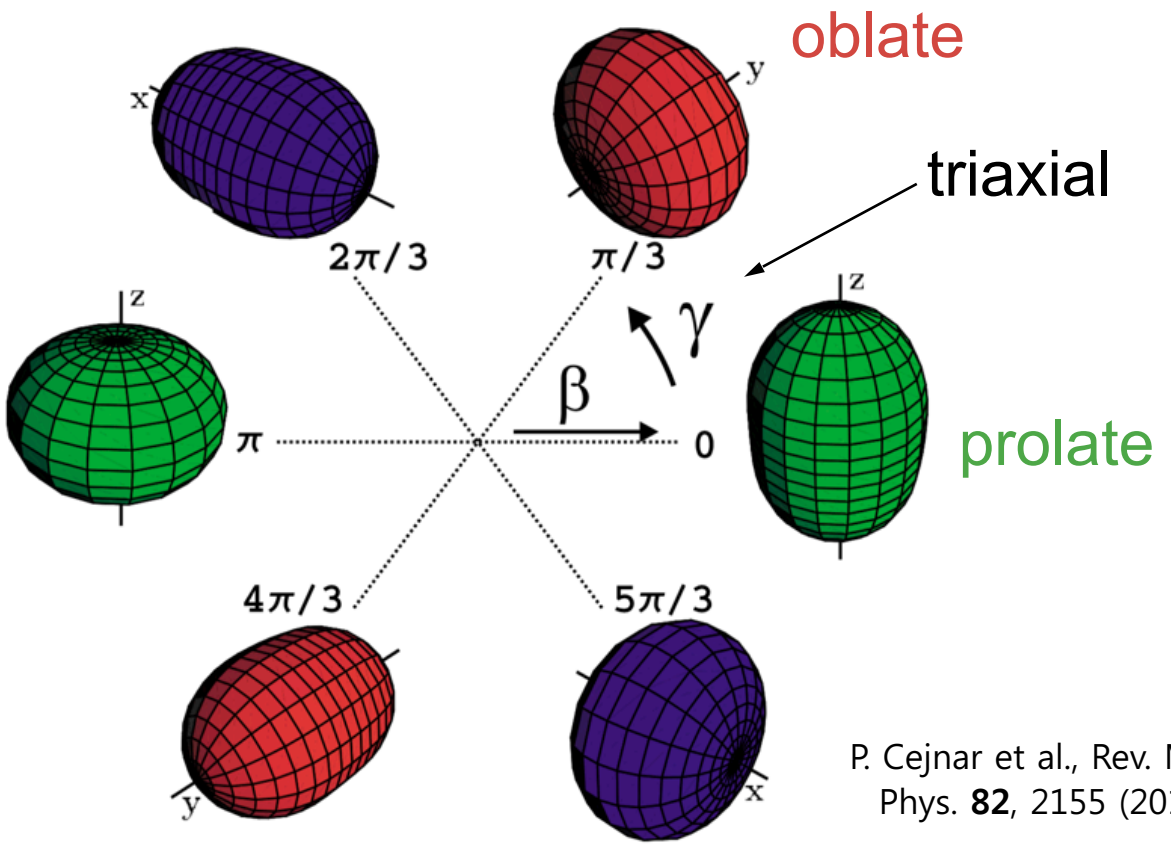
Oblate



Triaxial

Shapes of Atomic Nuclei

Coordinate: ‘Hill-Wheeler’ coordinate



P. Cejnar et al., Rev. Mod. Phys. **82**, 2155 (2010)

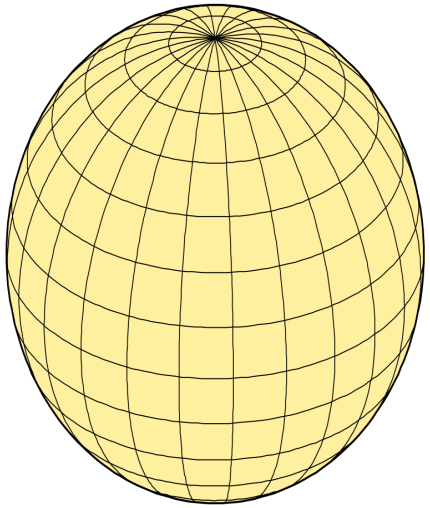
Parametrization of Quadrupole Deformation

$$R = R_0(1 + a_{2m}Y_{2m}(\theta, \phi))$$

$$a_{20} = \beta\cos\gamma, \qquad a_{22} = \frac{1}{\sqrt{2}}\beta\sin\gamma$$

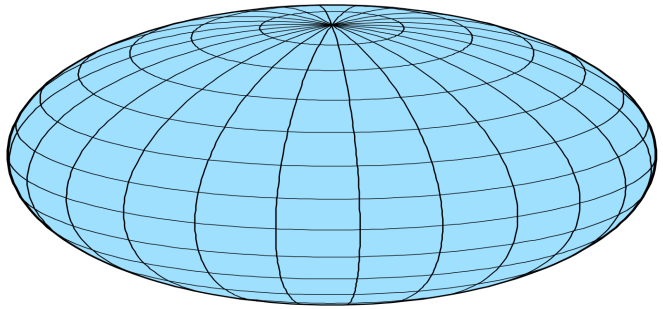
Shapes of Atomic Nuclei

Possible shapes of deformed nuclei



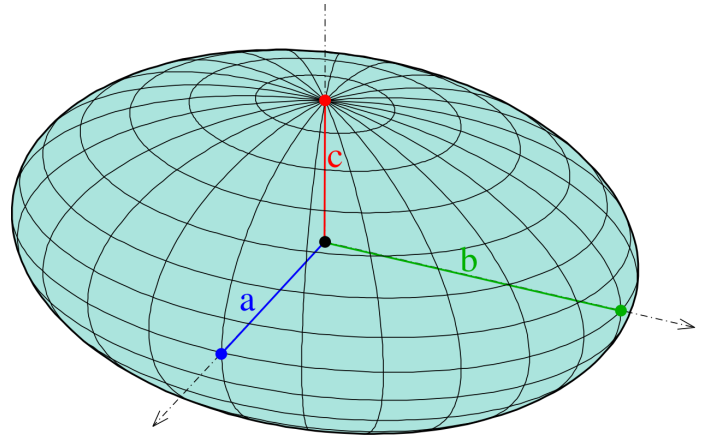
Prolate

$\gamma = 0^\circ$



Oblate

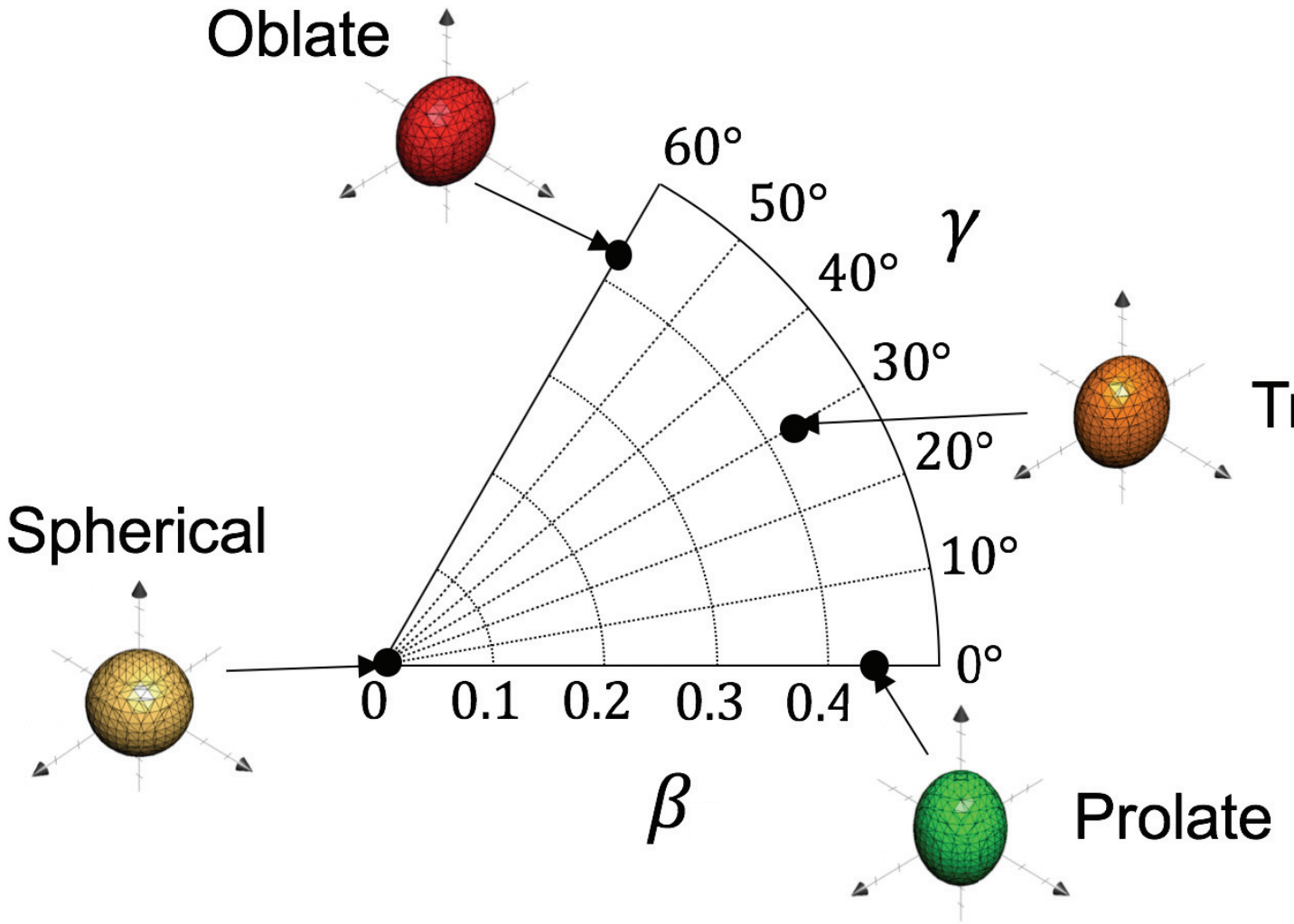
$\gamma = 60^\circ$



Triaxial

Degree of deformation: β, degree of asymmetry: γ

Shapes of Atomic Nuclei



Degree of deformation: β

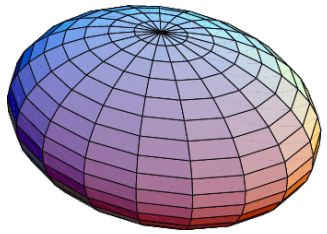
Degree of asymmetry: γ

$$R = R_0(1 + a_{2m}Y_{2m}(\theta, \phi))$$

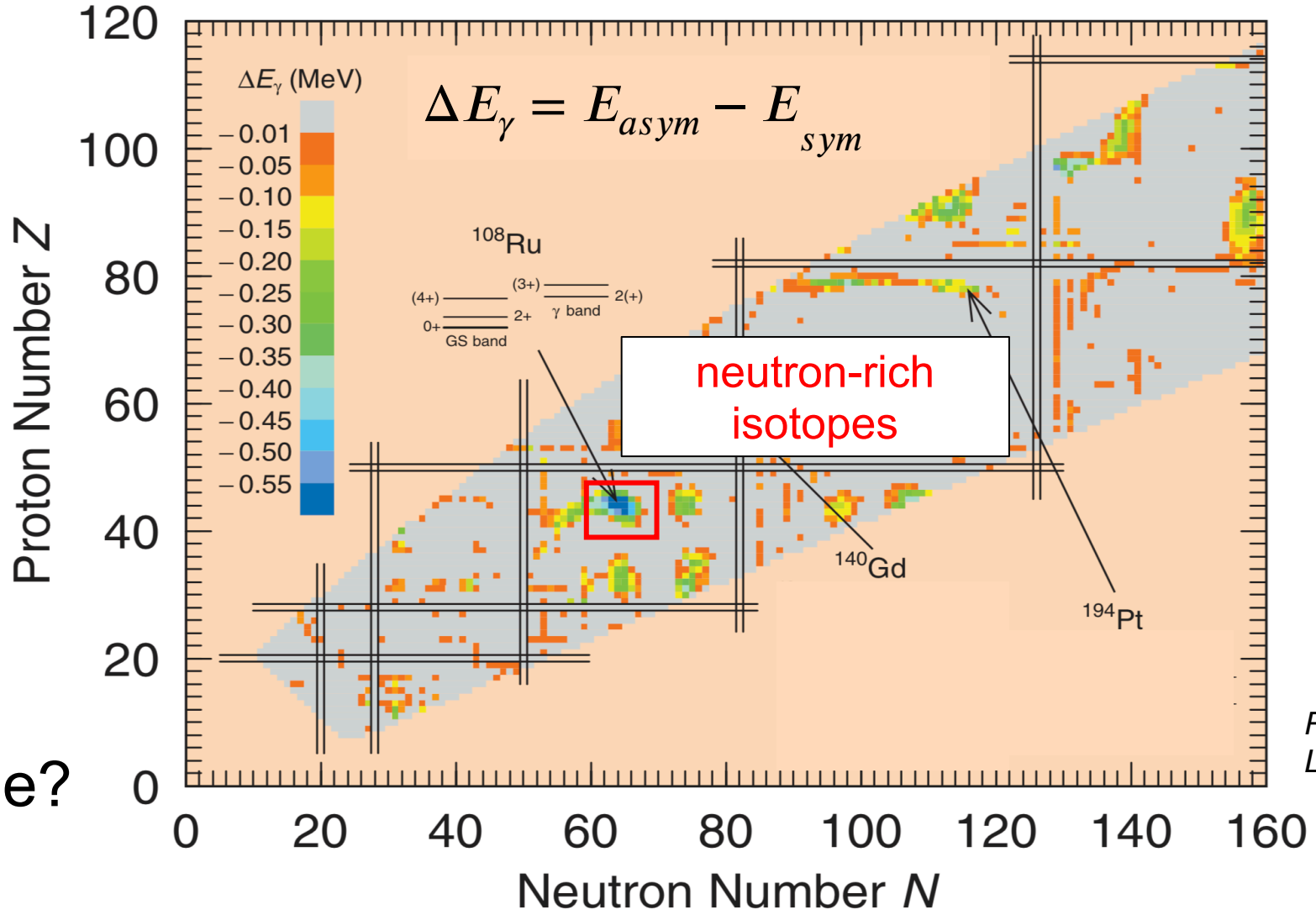
$$a_{20} = \beta \cos\gamma, \qquad a_{22} = \frac{1}{\sqrt{2}}\beta \sin\gamma$$

Shapes of Atomic Nuclei

Candidates of the triaxial ground-state shape



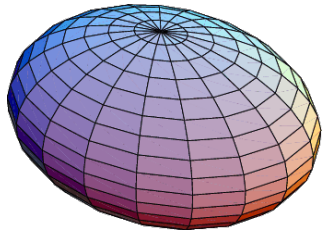
Triaxial shape?



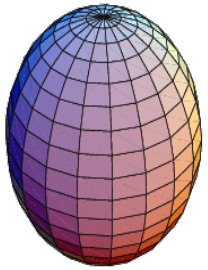
P. Moller et al., Phys. Rev. Lett. ***97****, 162502 (2006)*

Shapes of Atomic Nuclei

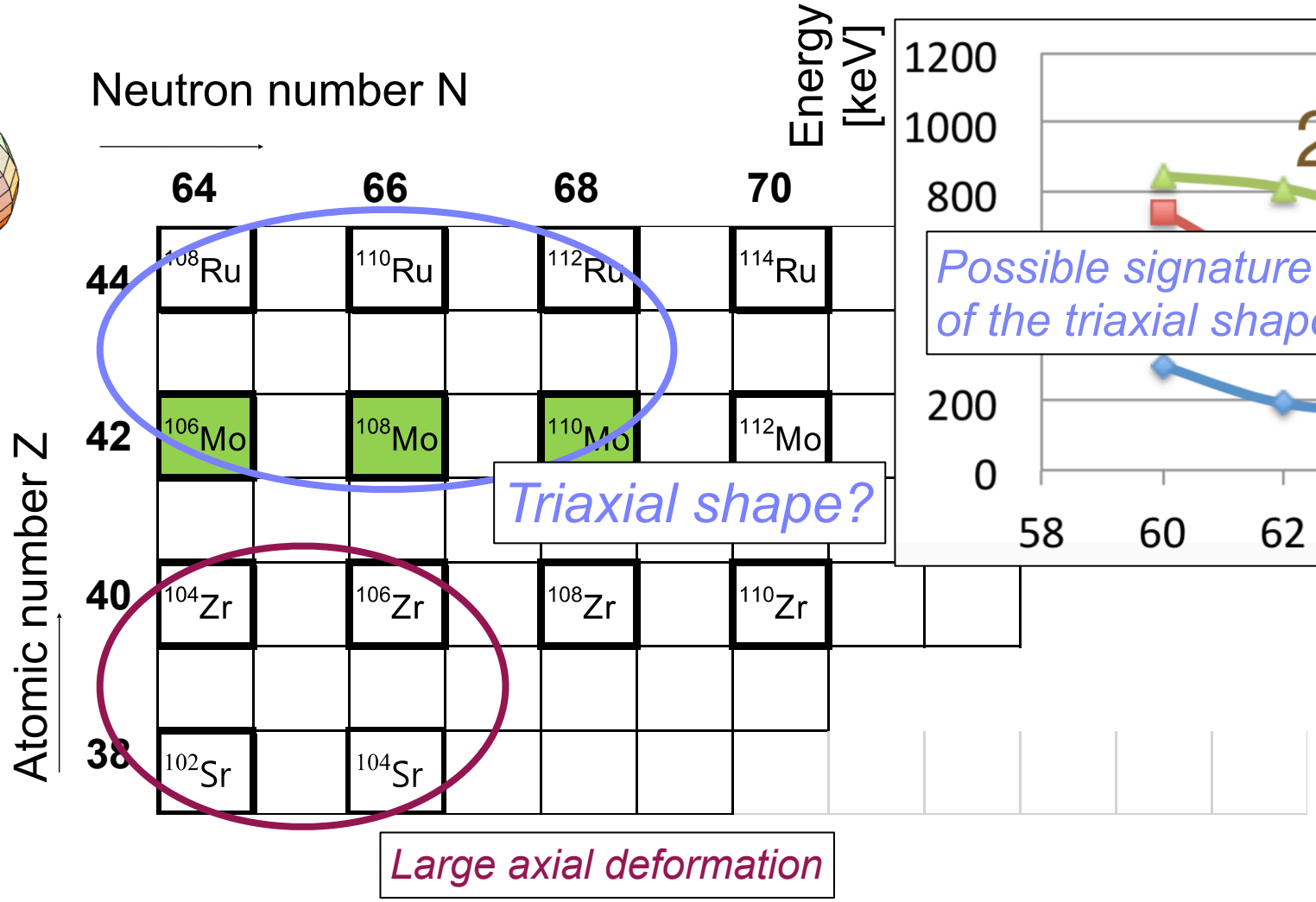
Nuclear chart around $A = 110$

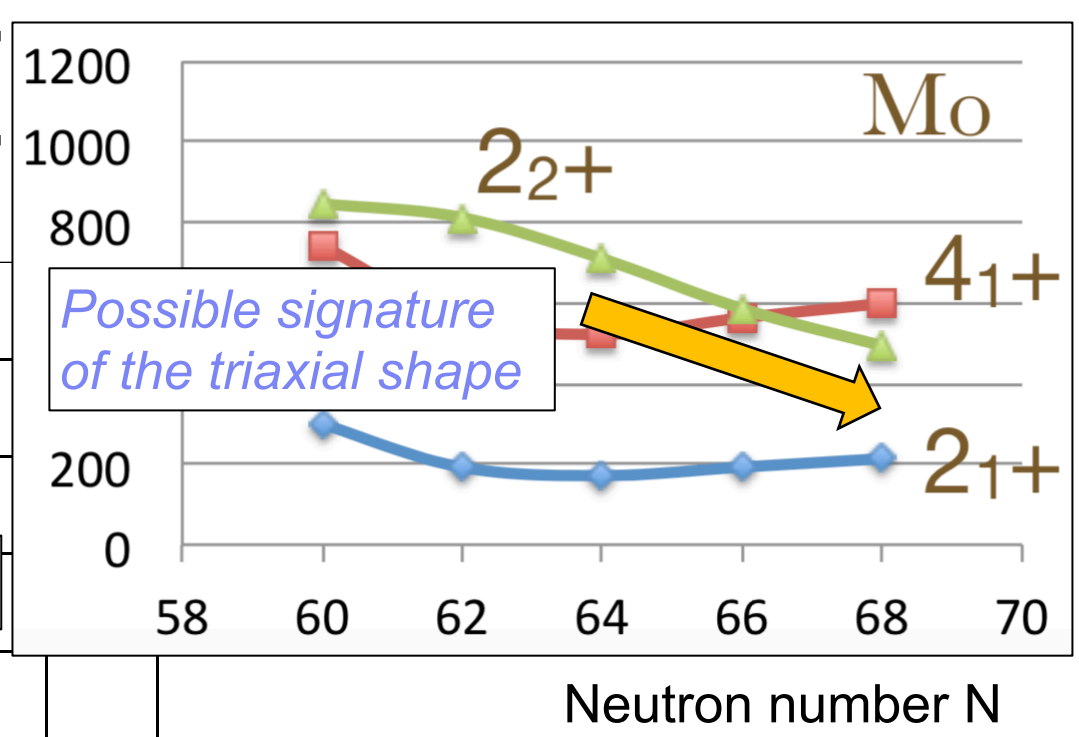


Triaxial shape?



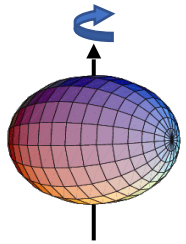
Axially symmetric shape



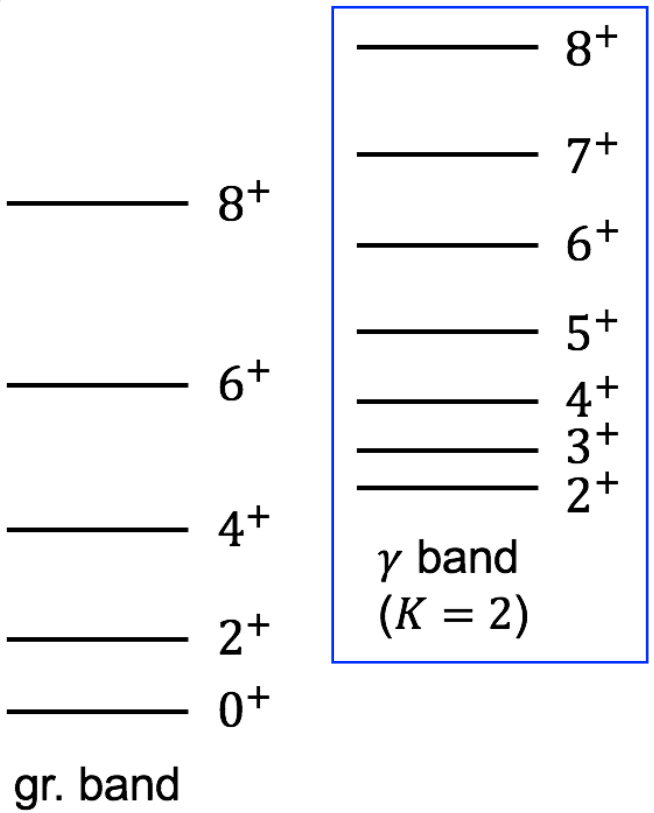


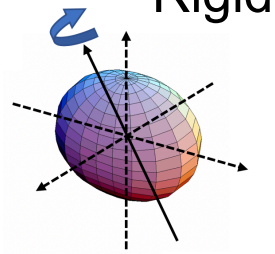
More Information → Better Understanding

Rotor models for $A \sim 110$ nuclei

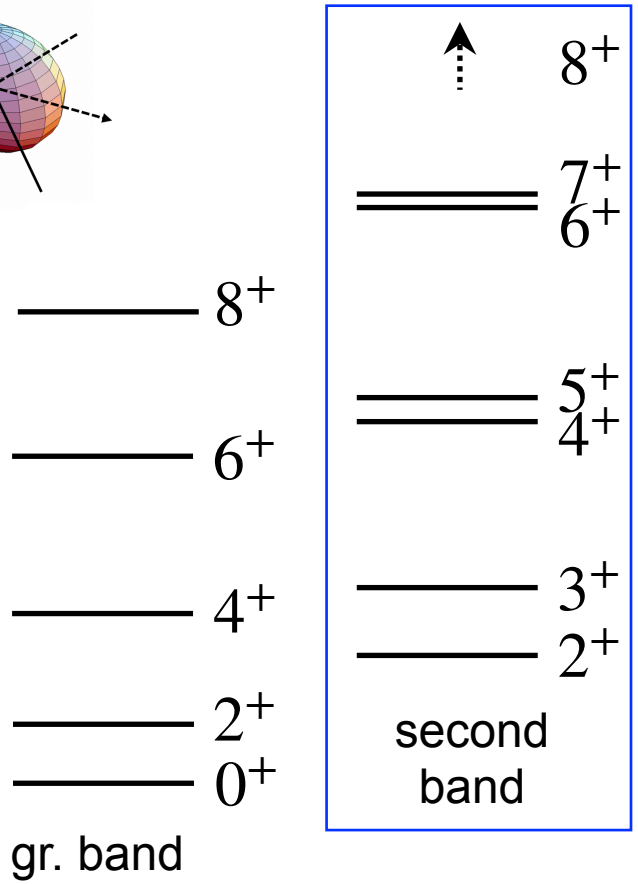


Axially symmetric rotor with γ-vibration

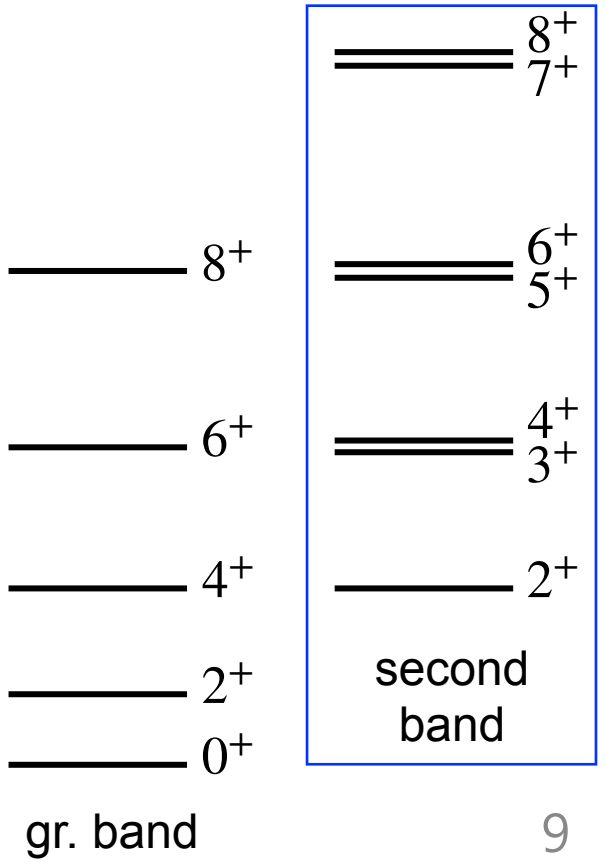


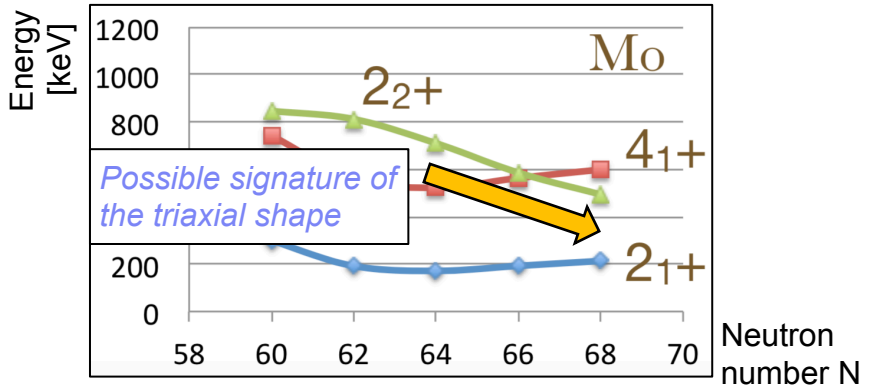


Rigid triaxial rotor model

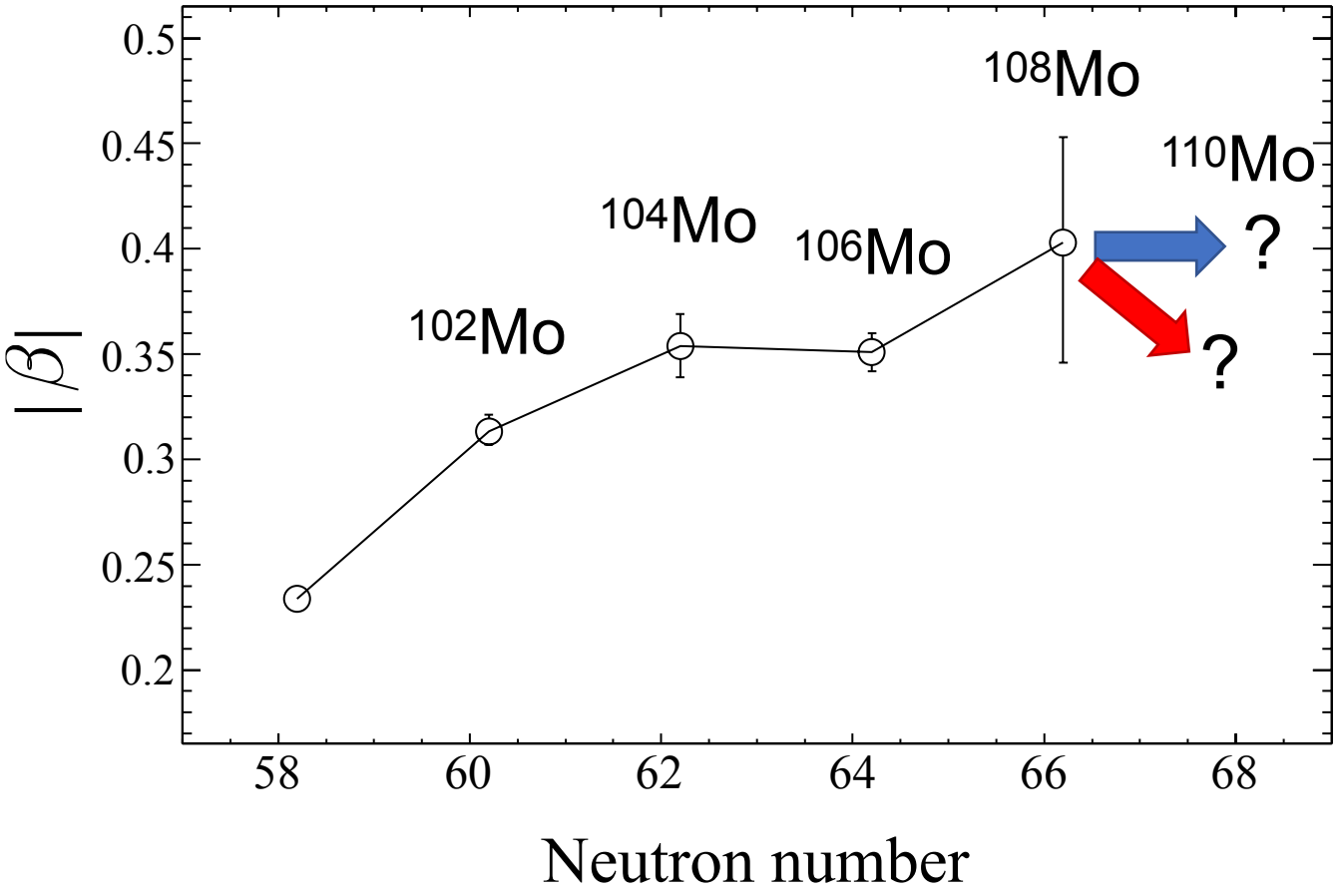


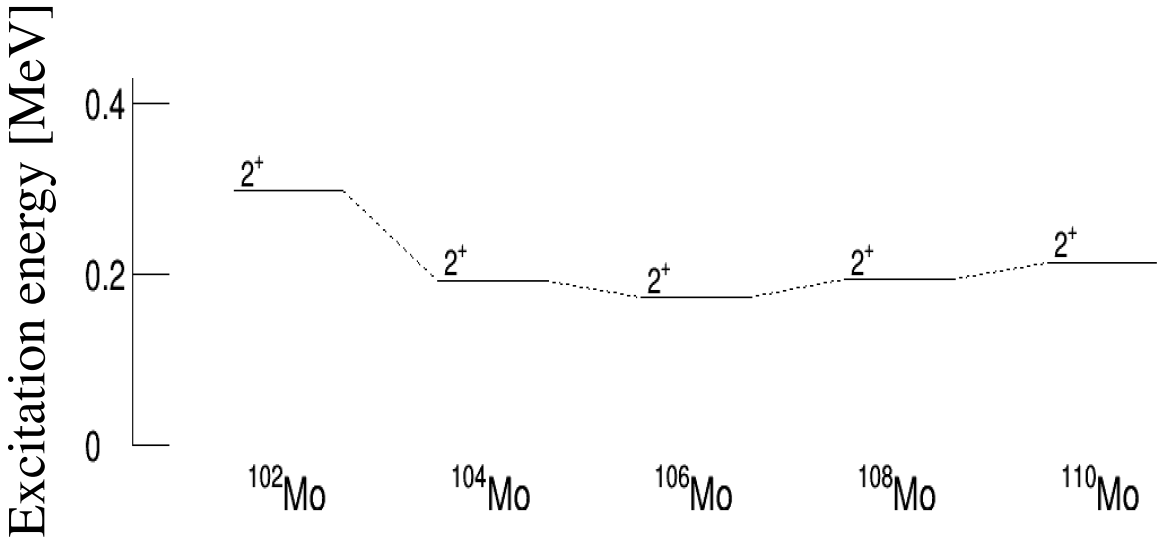
γ-unstable rotor model





Evolution of β and $E(2_1^+)$



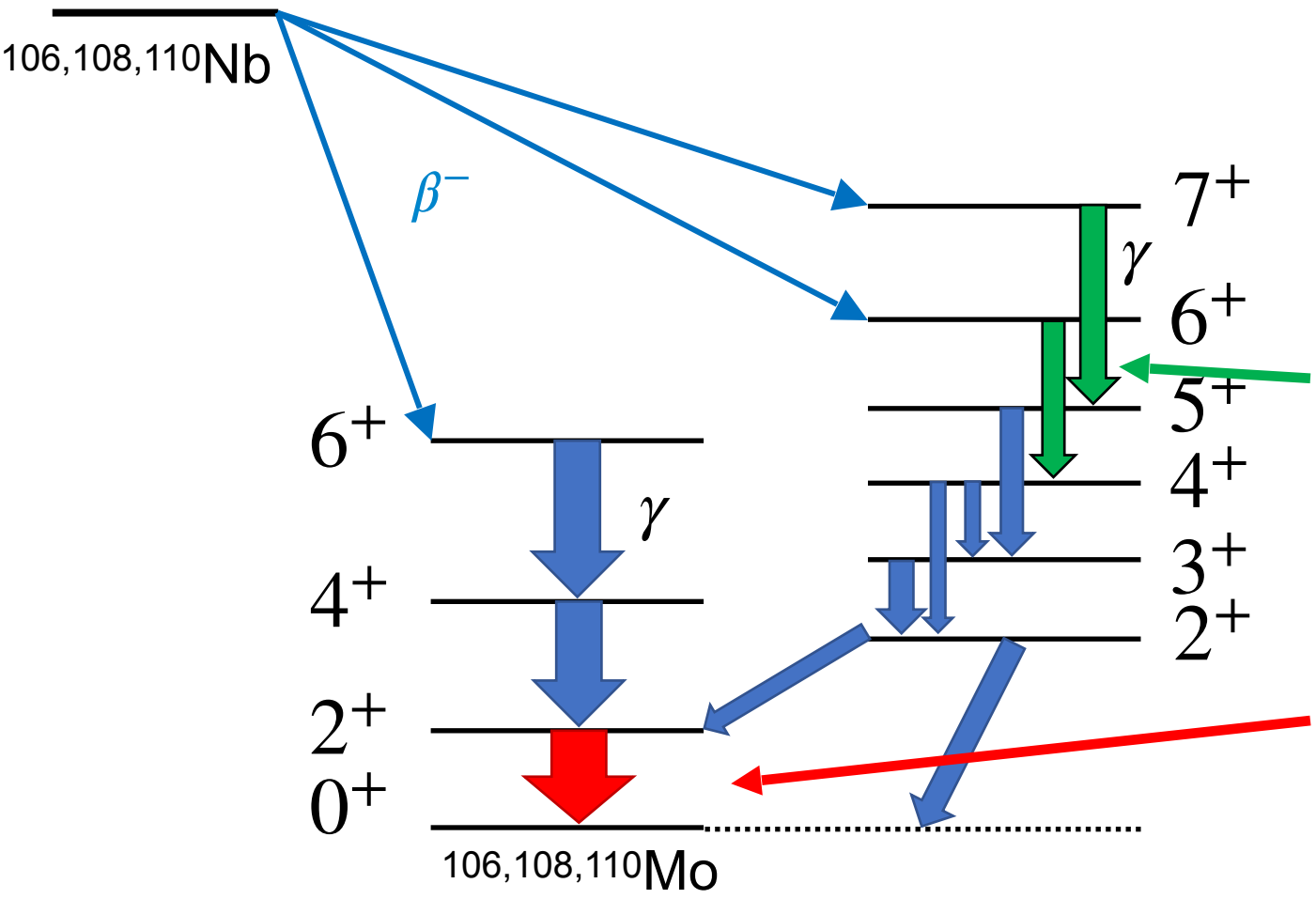


$$\beta \propto \sqrt{\frac{1}{E_\gamma^5}}$$

E_γ: γ-ray Energy ($2_1^+ \rightarrow 0_1^+$)

β : deformation parameter

β-γ Decay Spectroscopy



: identified in the previous study

: identified in the new results

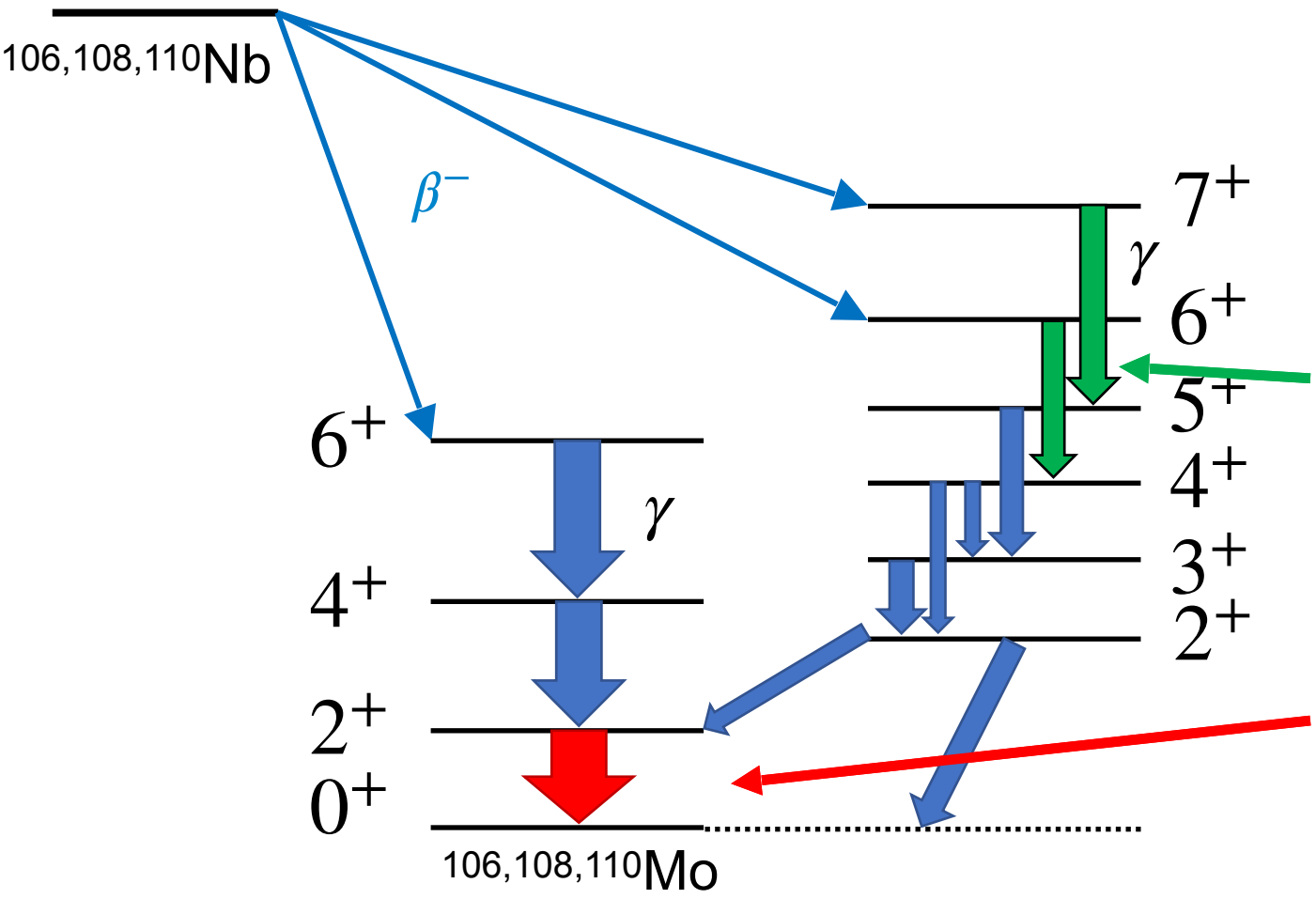
① Higher excited states

: energy spacing related to γ (^{110}Mo).

② Lifetime measurement of 2_1^+ state

:the deformation parameter β of ground state (^{106,108,110}Mo).

β-γ Decay Spectroscopy



: identified in the previous study

: identified in the new results

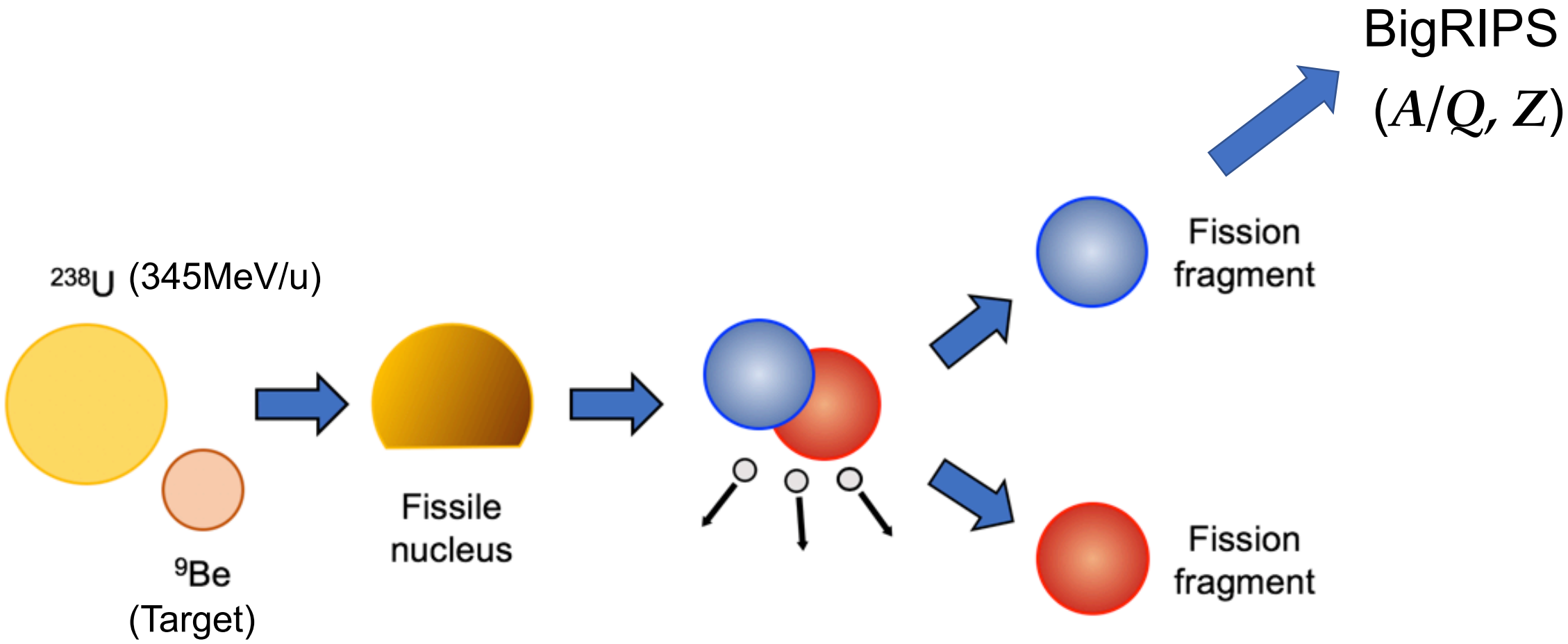
① Statistical improvement

② Clear γ-ray spectrum

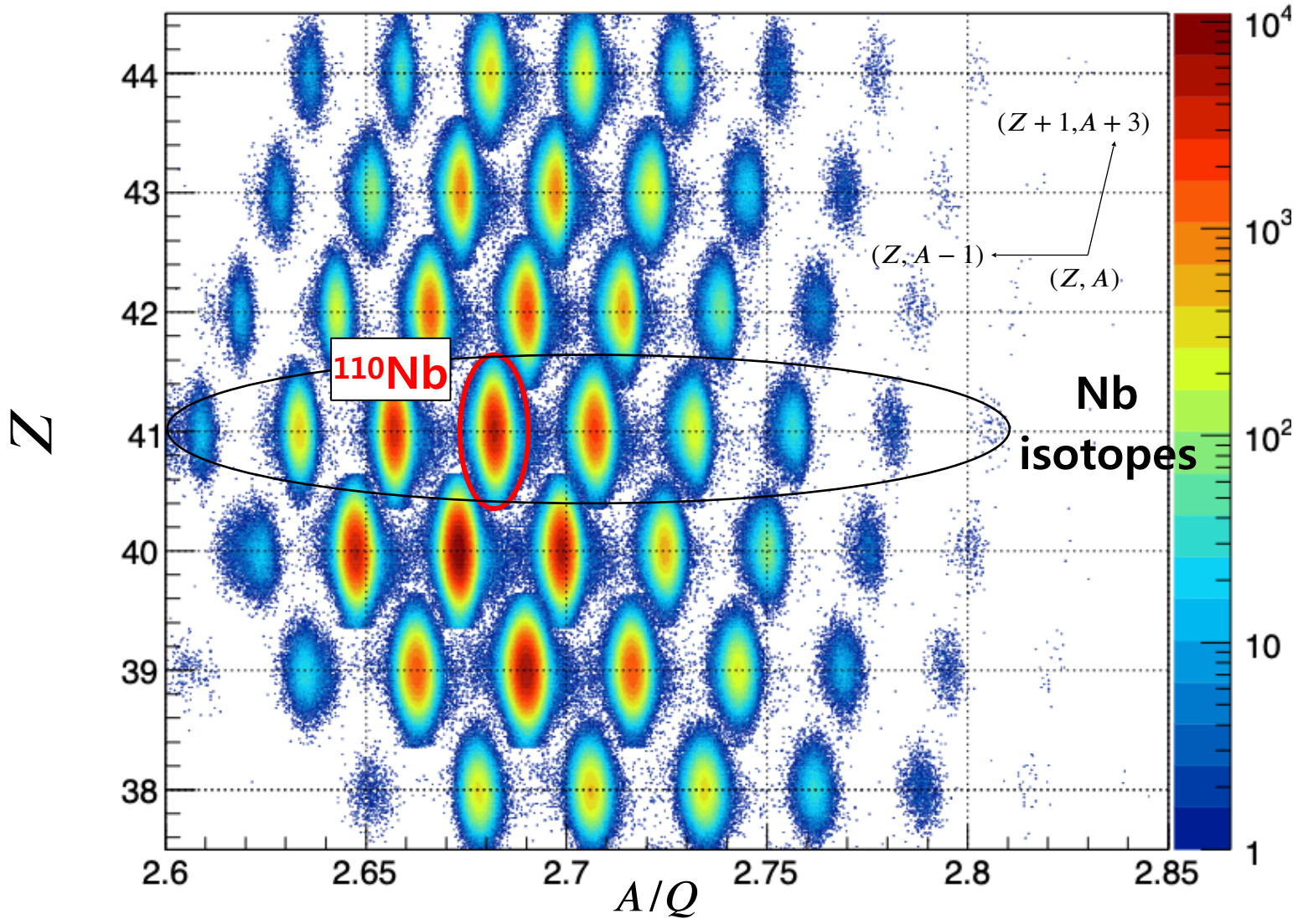
→ β-γ spectroscopy is useful

→ additional information on nuclear structure

Production of RIB at RIKEN



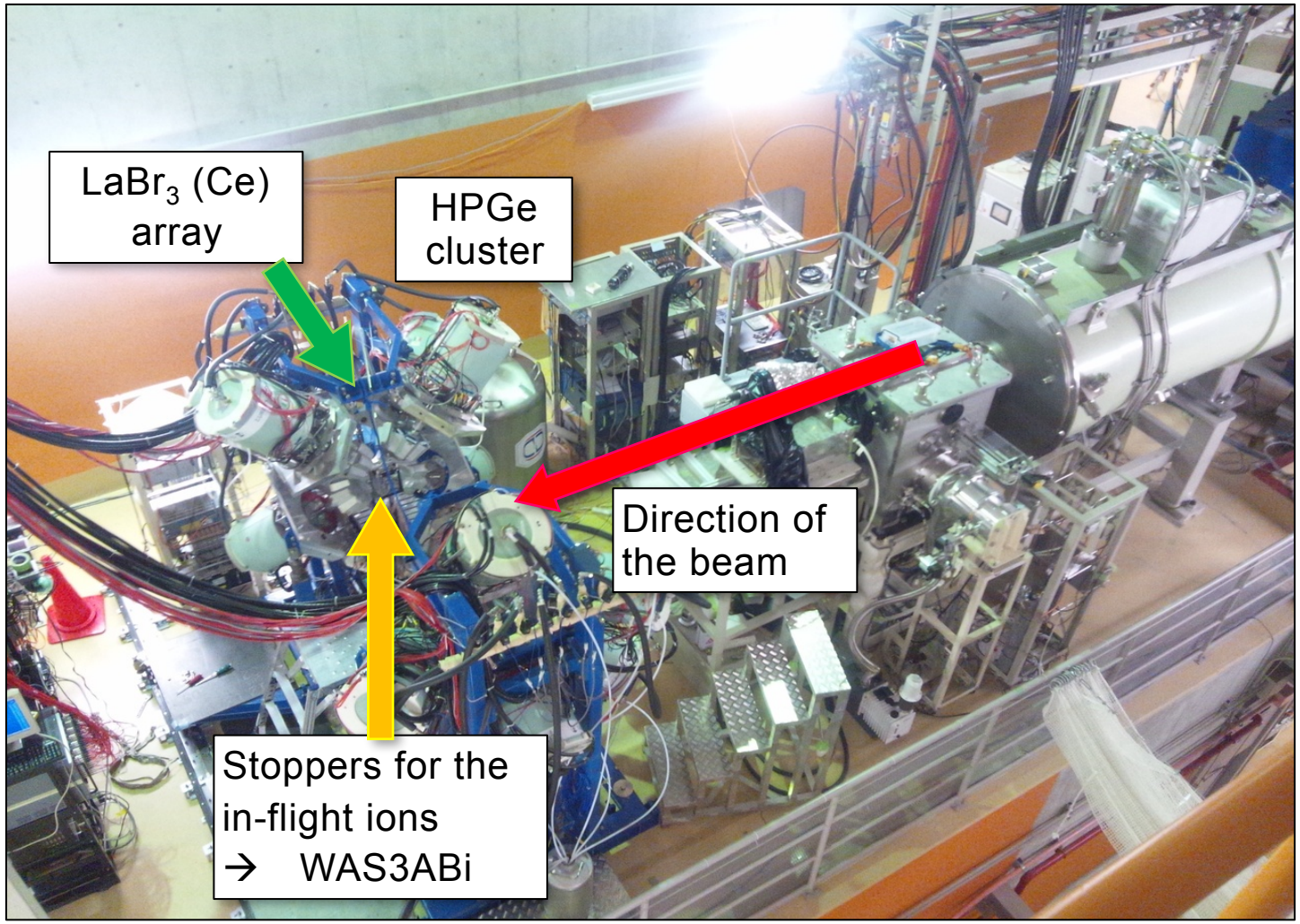
Identification of the Fragments



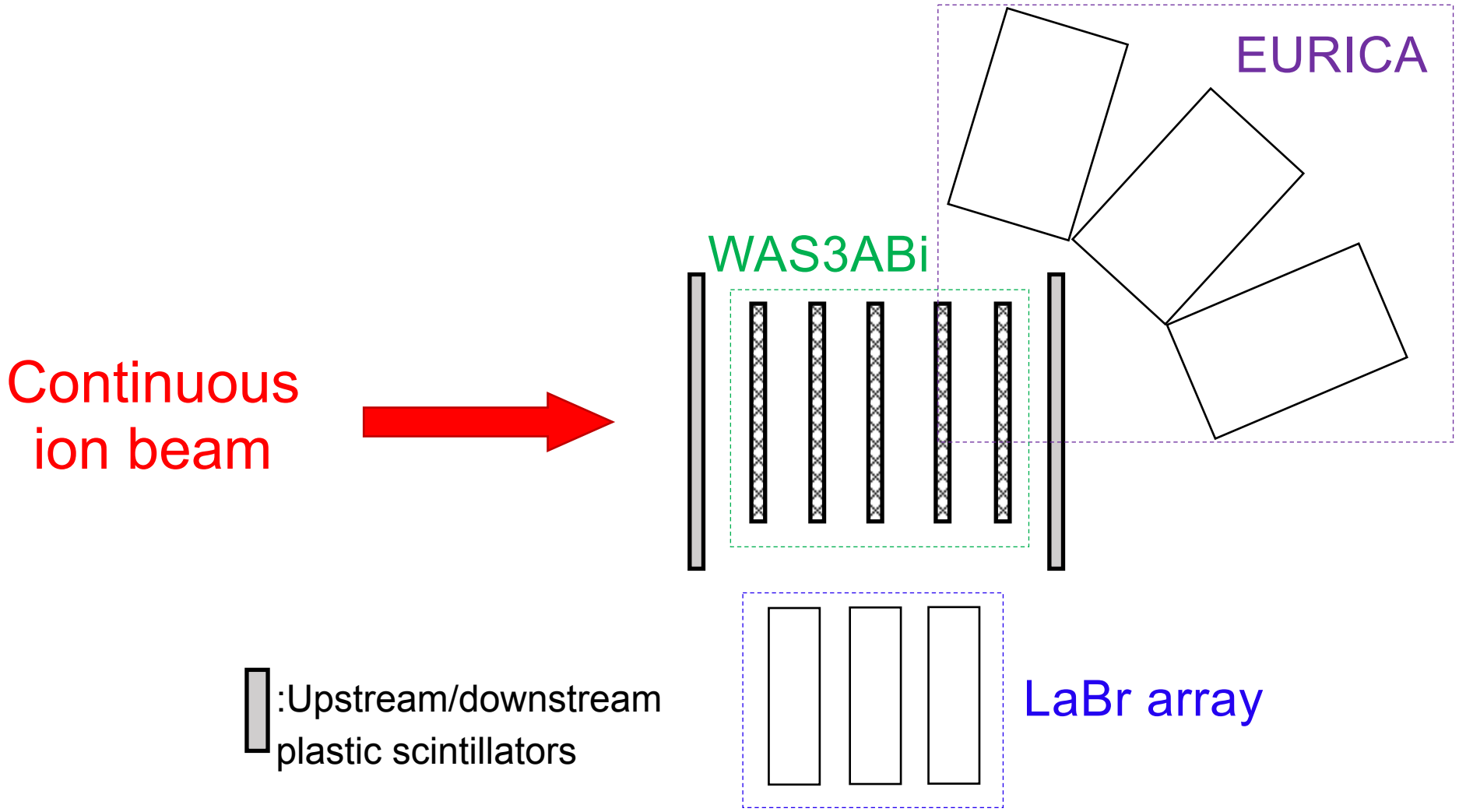
Isotope	The number of implanted ions
^{106}Nb	7.1×10^4
^{108}Nb	1.3×10^5
^{110}Nb	1.9×10^6

Detectors

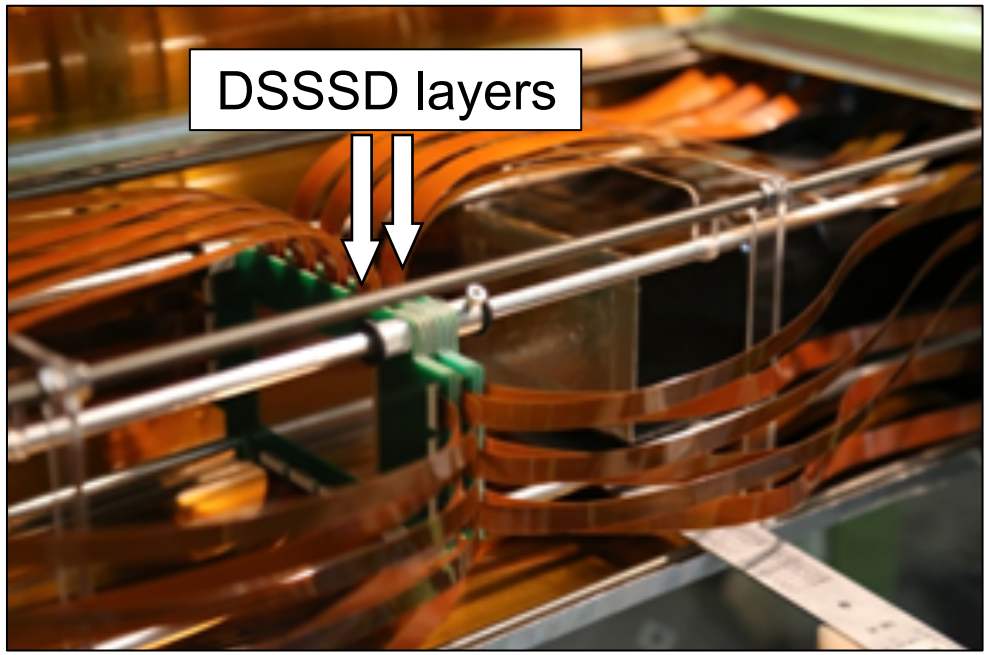
Overview of the experimental area



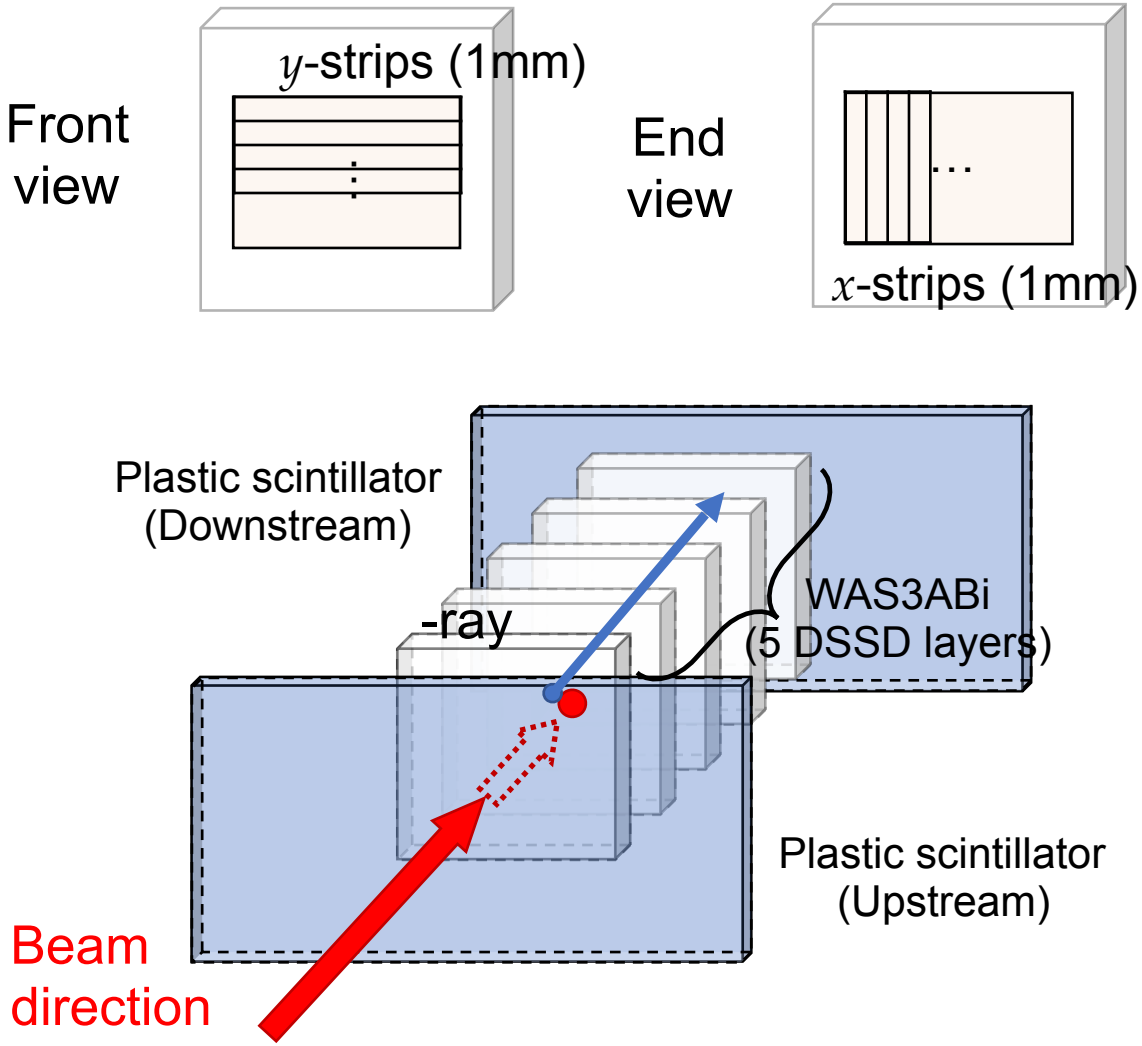
β-γ Decay Spectroscopy at RIBF



Ion Stopping at WAS3ABi

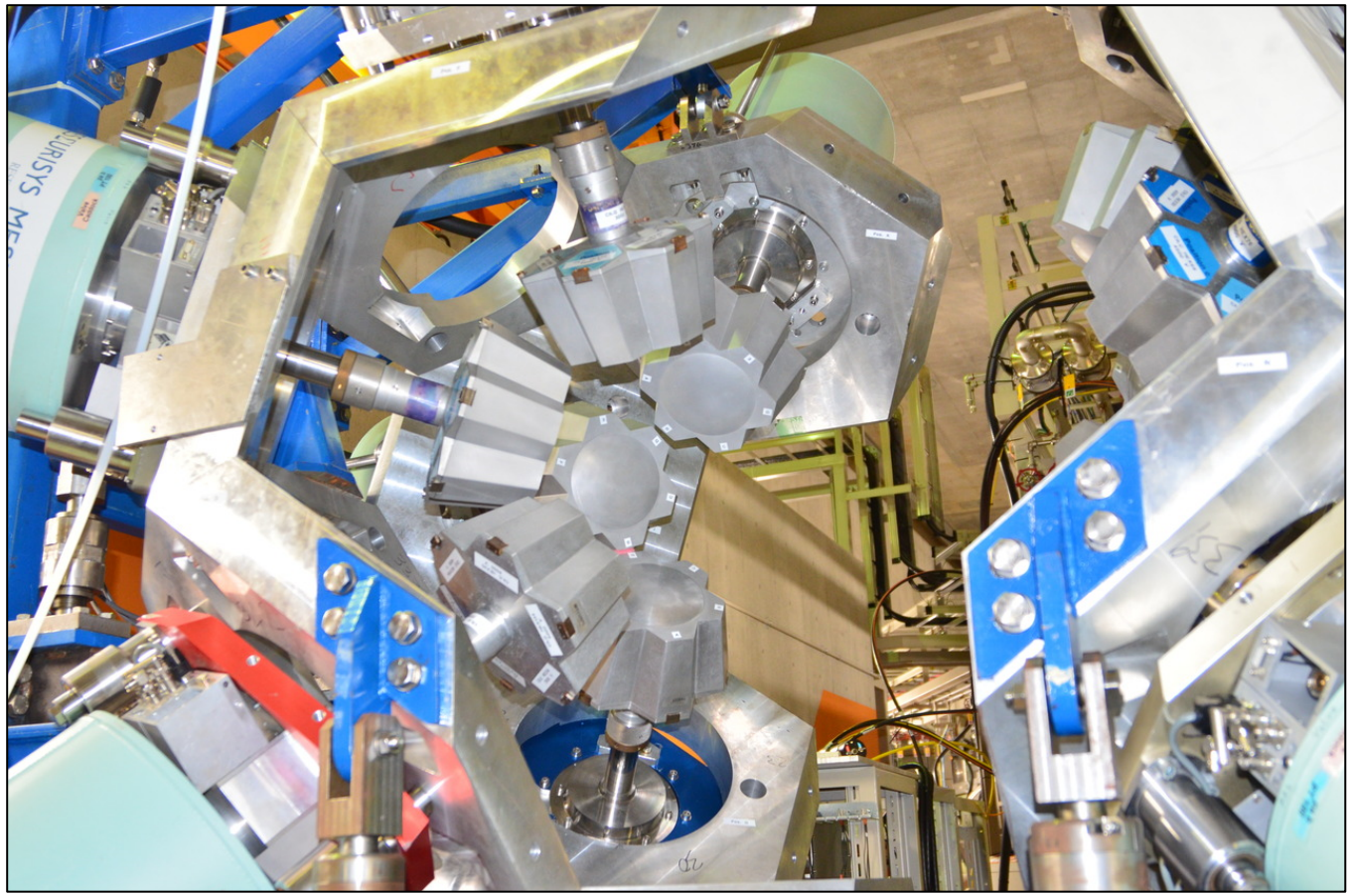


- Five DSSSDs (Double-Sided Silicon Strip Detectors) with 1-mm thickness
- 1-mm width x-strips and y-strips cover 6040 mm active area



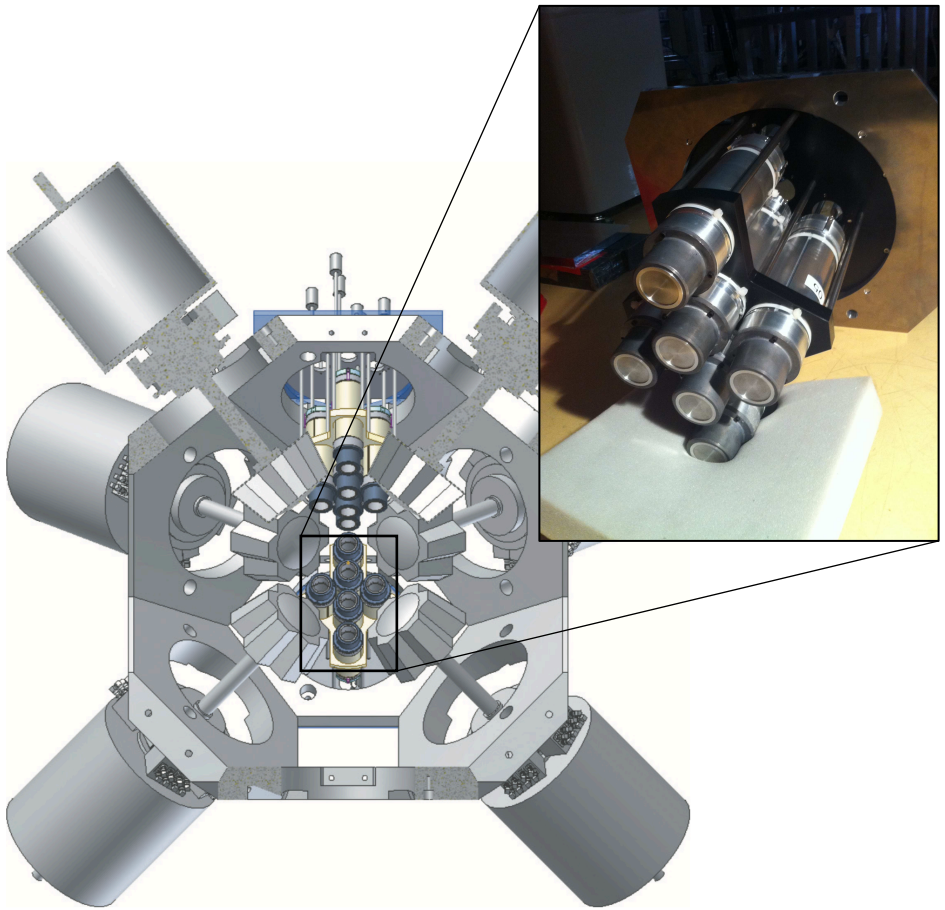
Gamma Ray Detection with EURICA*

* Euroball-RIKEN Cluster Array

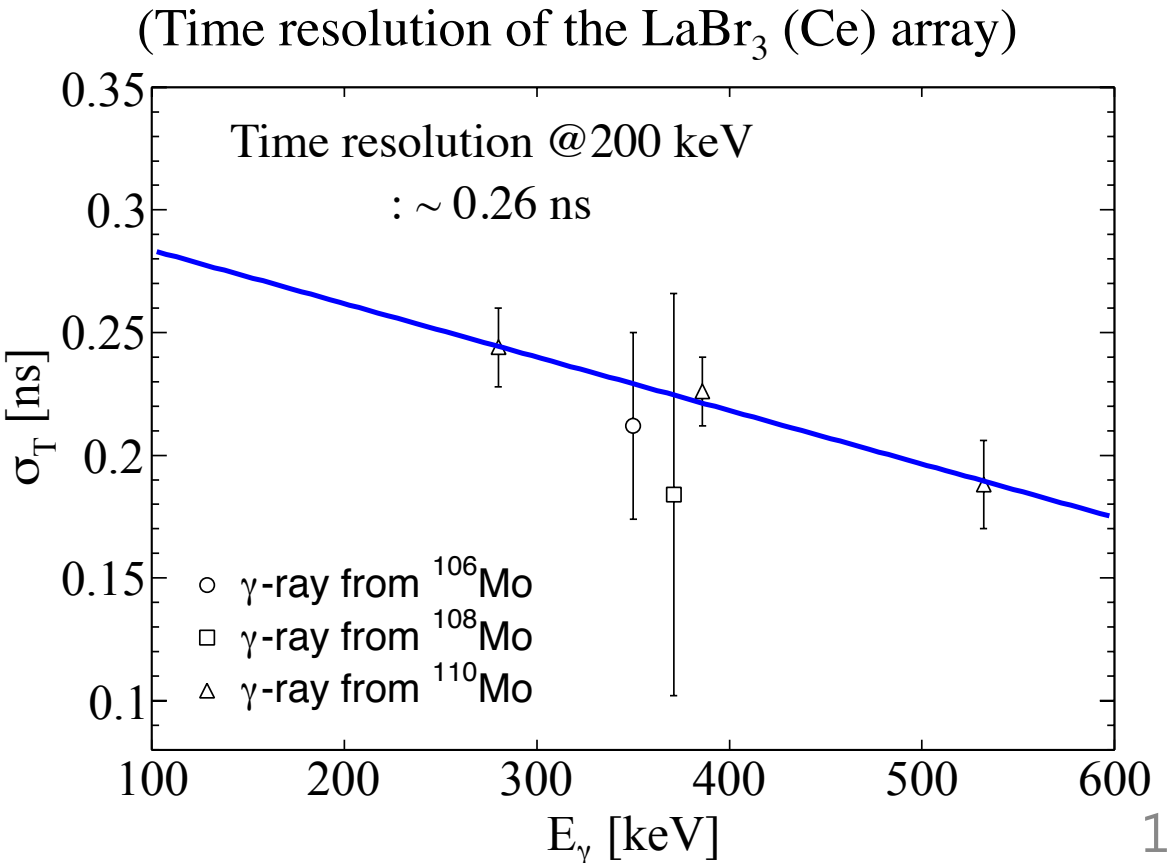


- 84 Ge crystals (7 crystals 12 clusters), designed for ~4π acceptance
- from Europe (GSI, Germany)

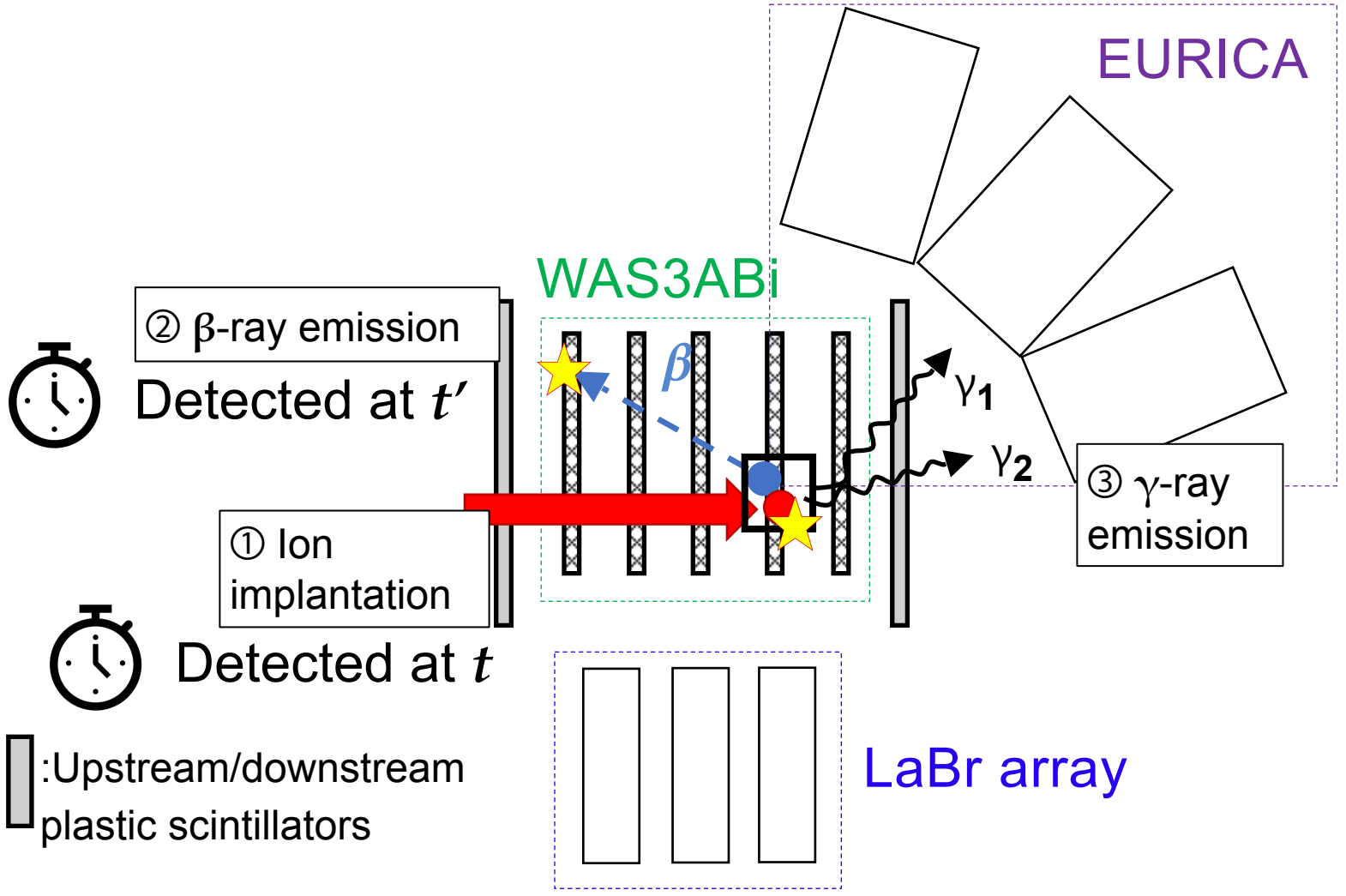
$LaBr_3$(Ce) Array - Gamma Ray Timing



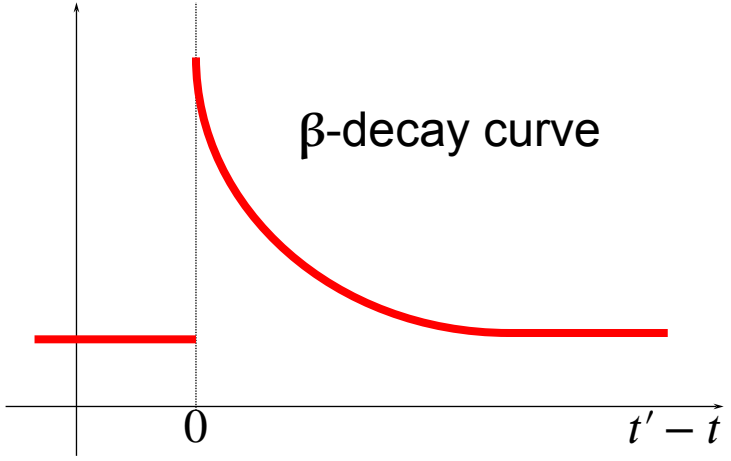
- 18 cerium-doped lanthanum tri-bromide crystals
- from United Kingdom
- **Fast response**



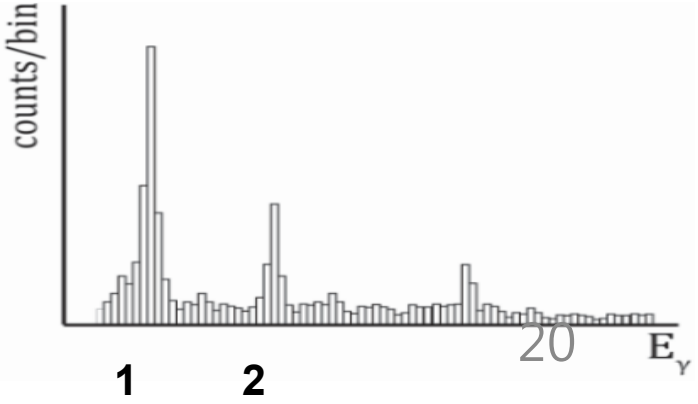
β-γ spectroscopy at RIBF



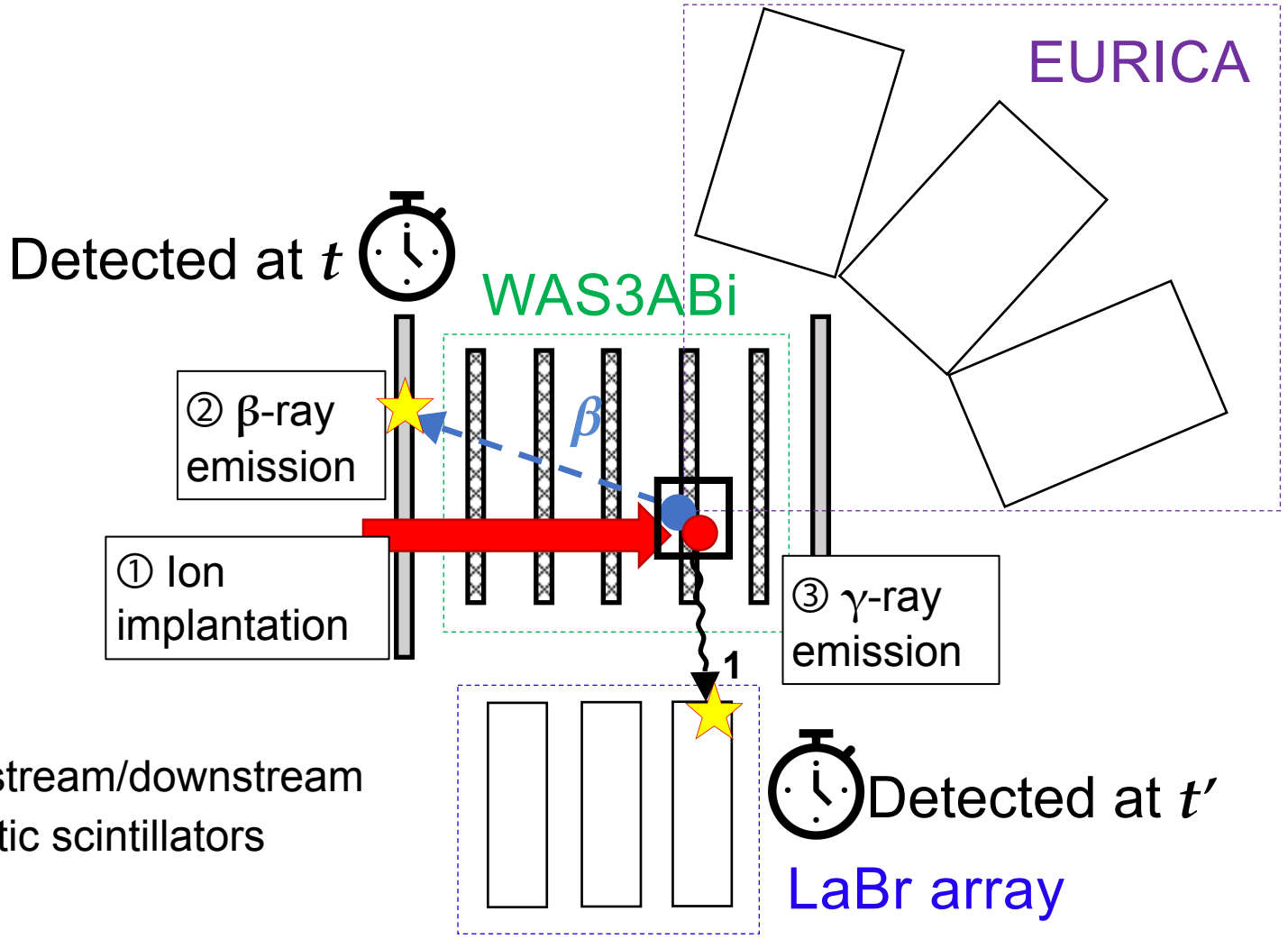
(Example) distribution of time difference



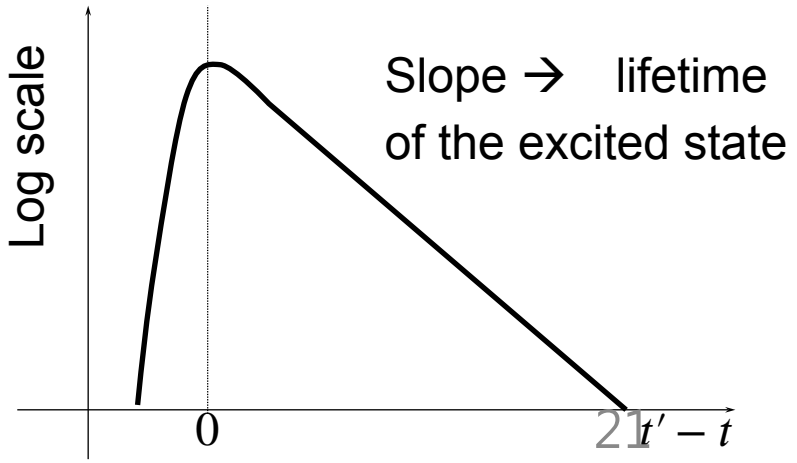
(Example) β-delayed γ-ray spectrum



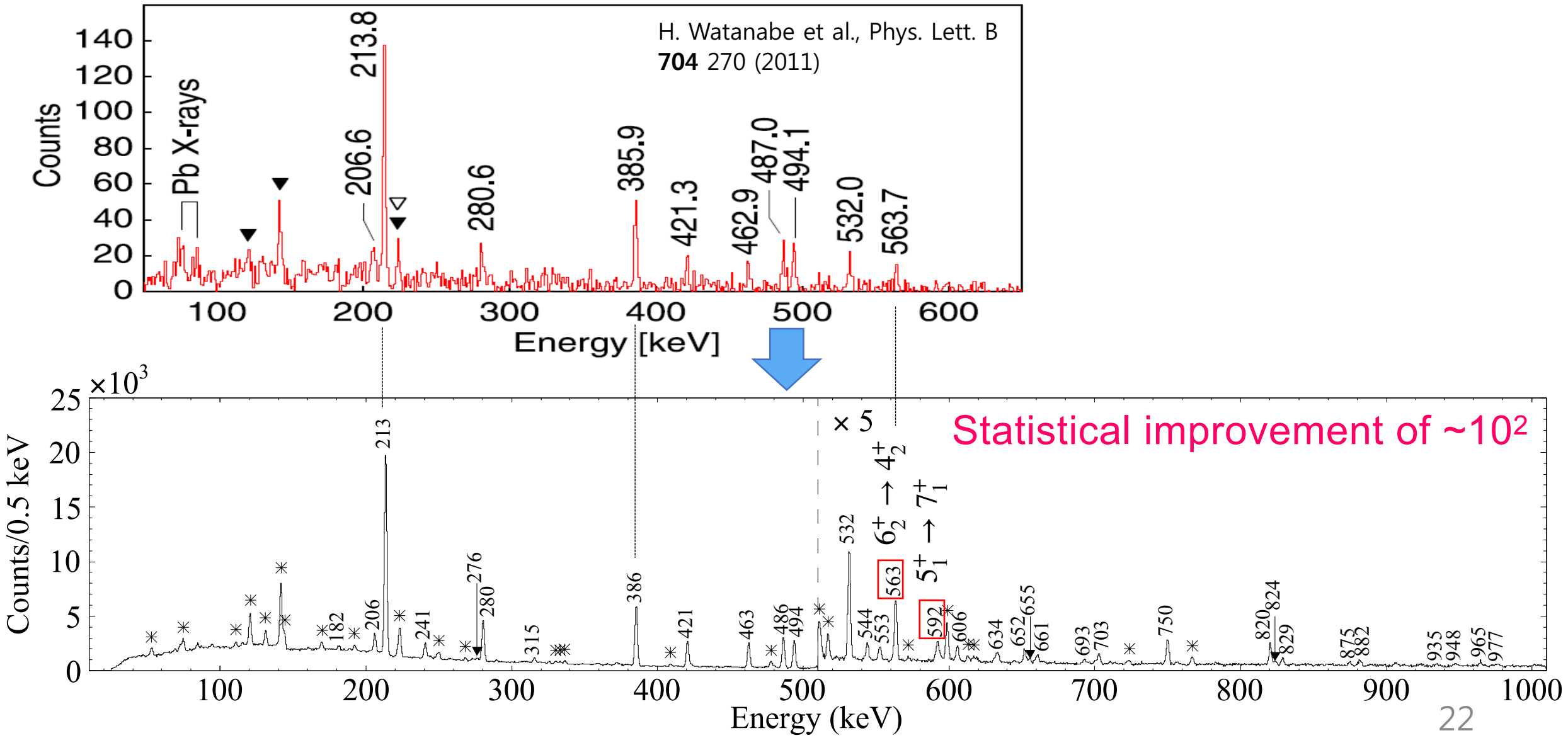
β-γ spectroscopy with LaBr Array



(Example) distribution of time difference $t-t'$



γ-ray spectrum of ^{110}Mo produced from β-decay

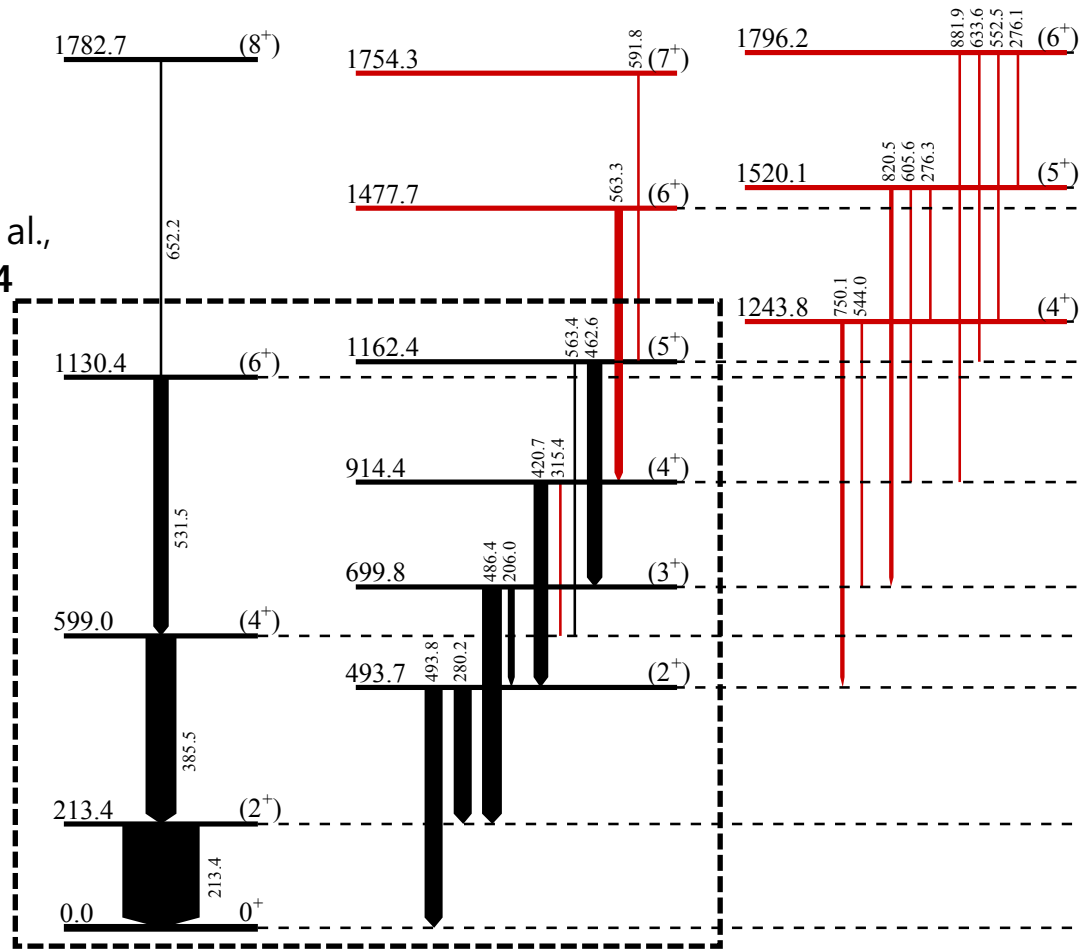


β-decay to ^{110}Mo

A partial level scheme of ^{110}Mo

β^-

^{110}Nb



H. Watanabe et al., Phys. Lett. B **704** 270 (2011)

New results

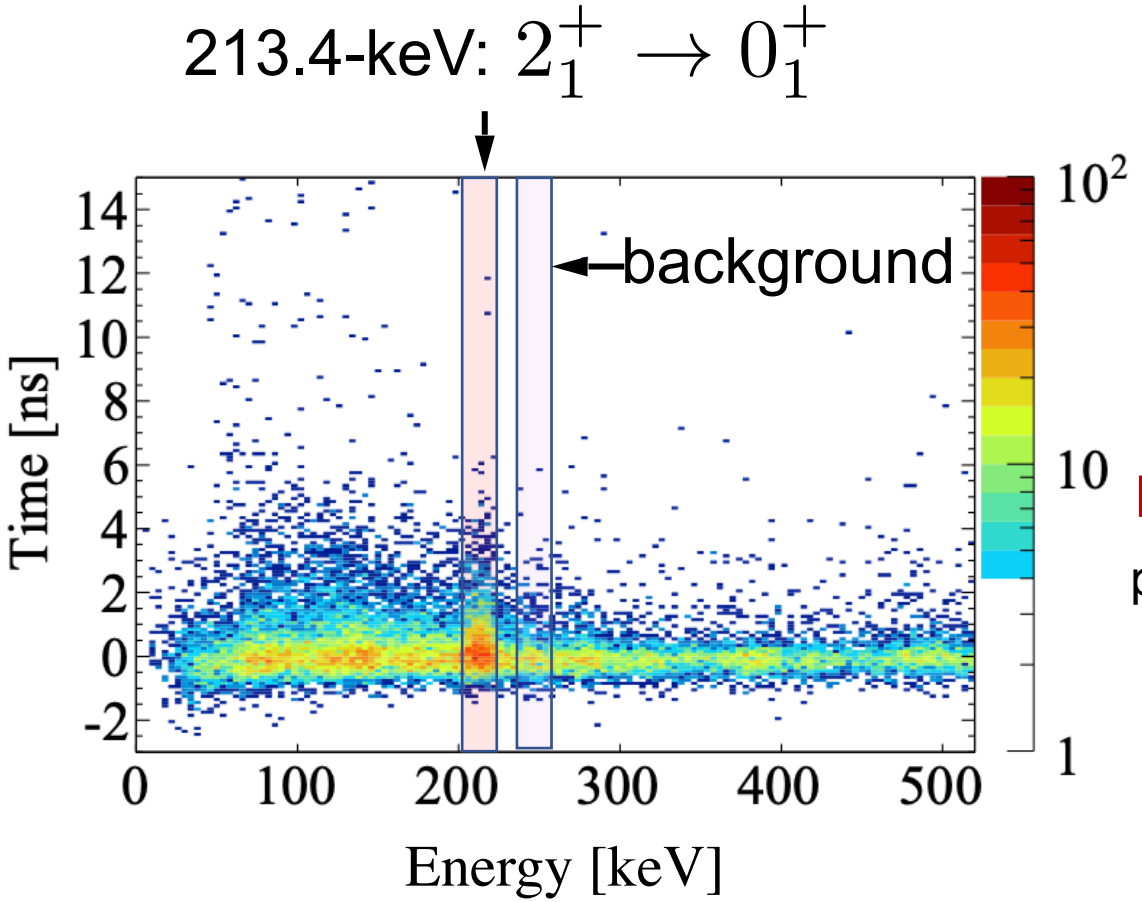
- Observation of the 6^+, 7^+ states in the second band
- Observation of the third band ($\gamma\gamma$-vibration?)

→Kinematic moment of inertia

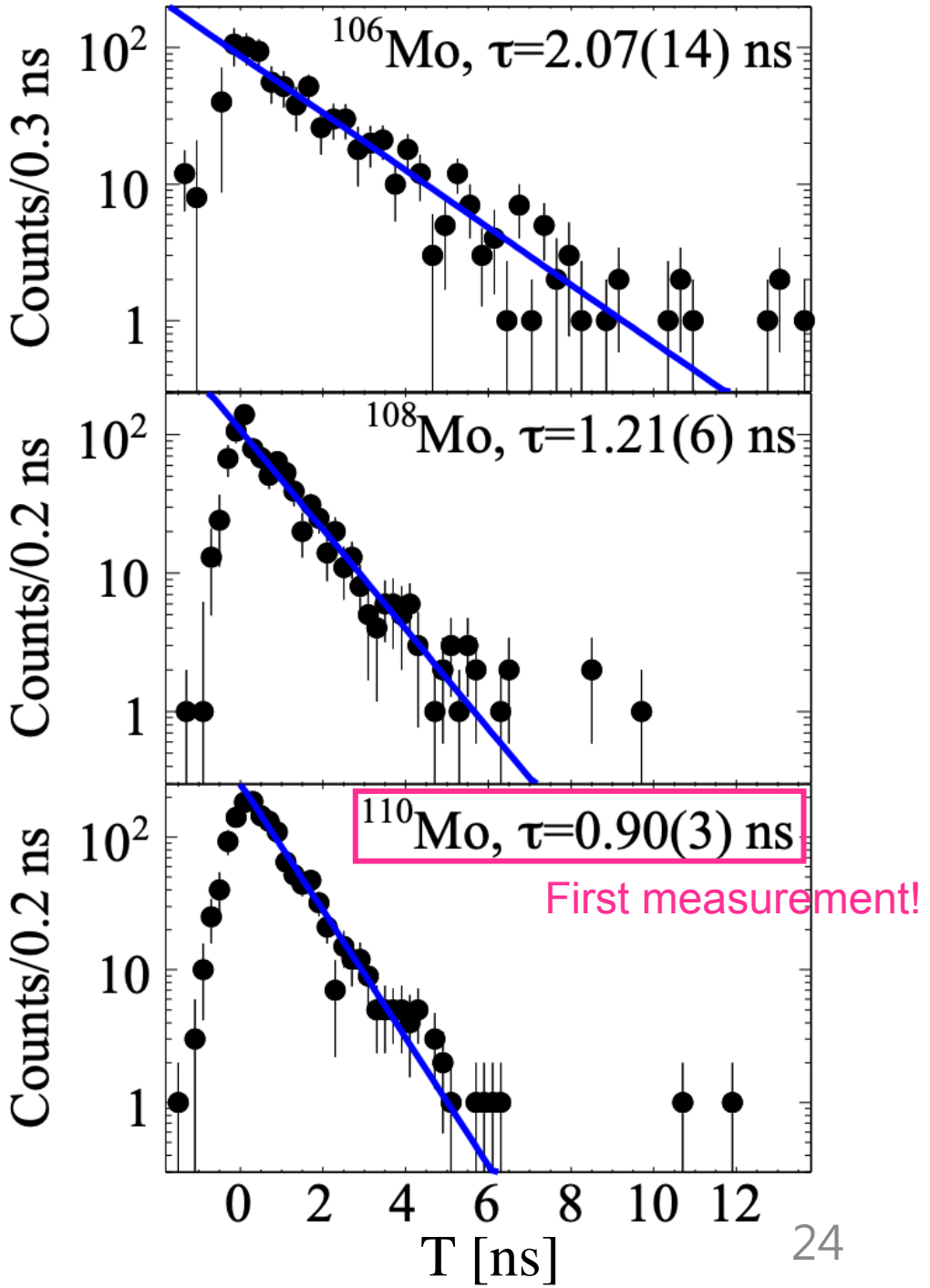
Red lines: new levels and transitions

Lifetime measurement of 2_1^+ states

(The energy-time plot of ^{110}Mo)



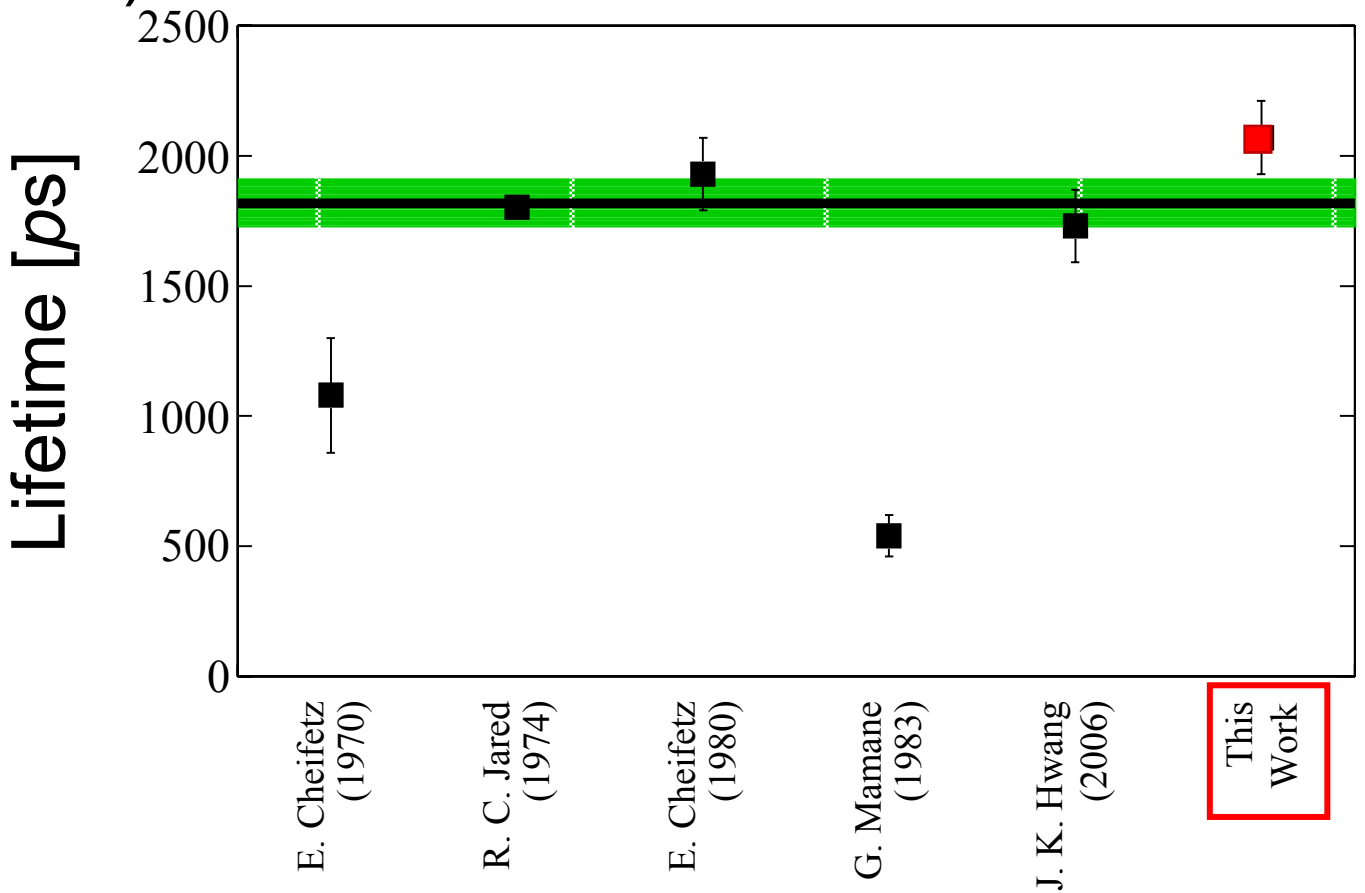
projection



First measurement!

Lifetime measurement of 2_1^+ states

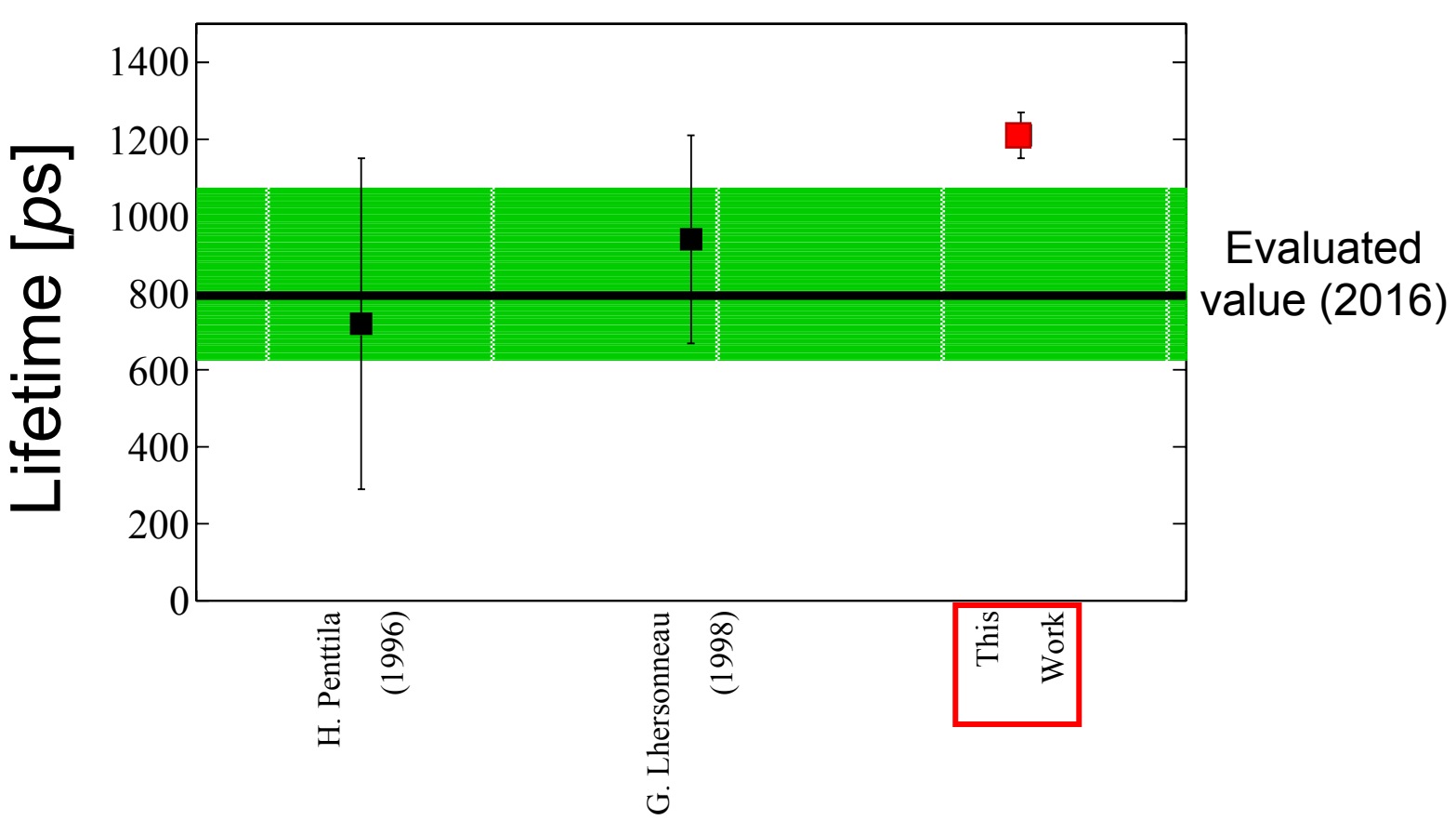
* ^{106}Mo (N = 64)



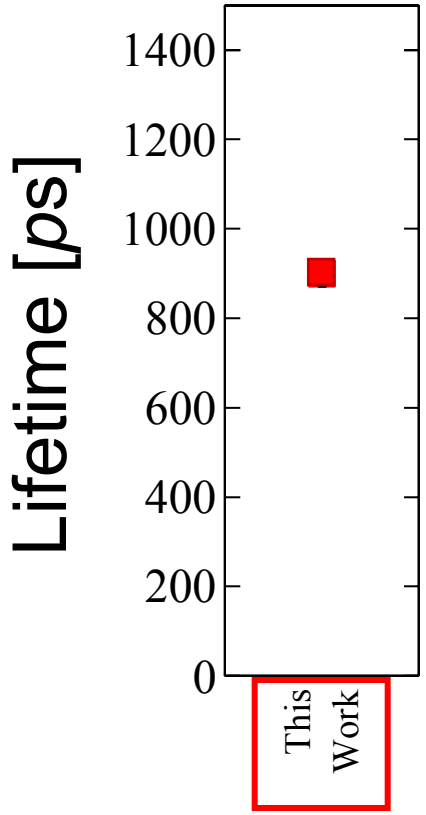
→ First results using $LaBr_3$ (Ce) detector!

Lifetime measurement of 2_1^+ states

* ^{108}Mo (N = 66)

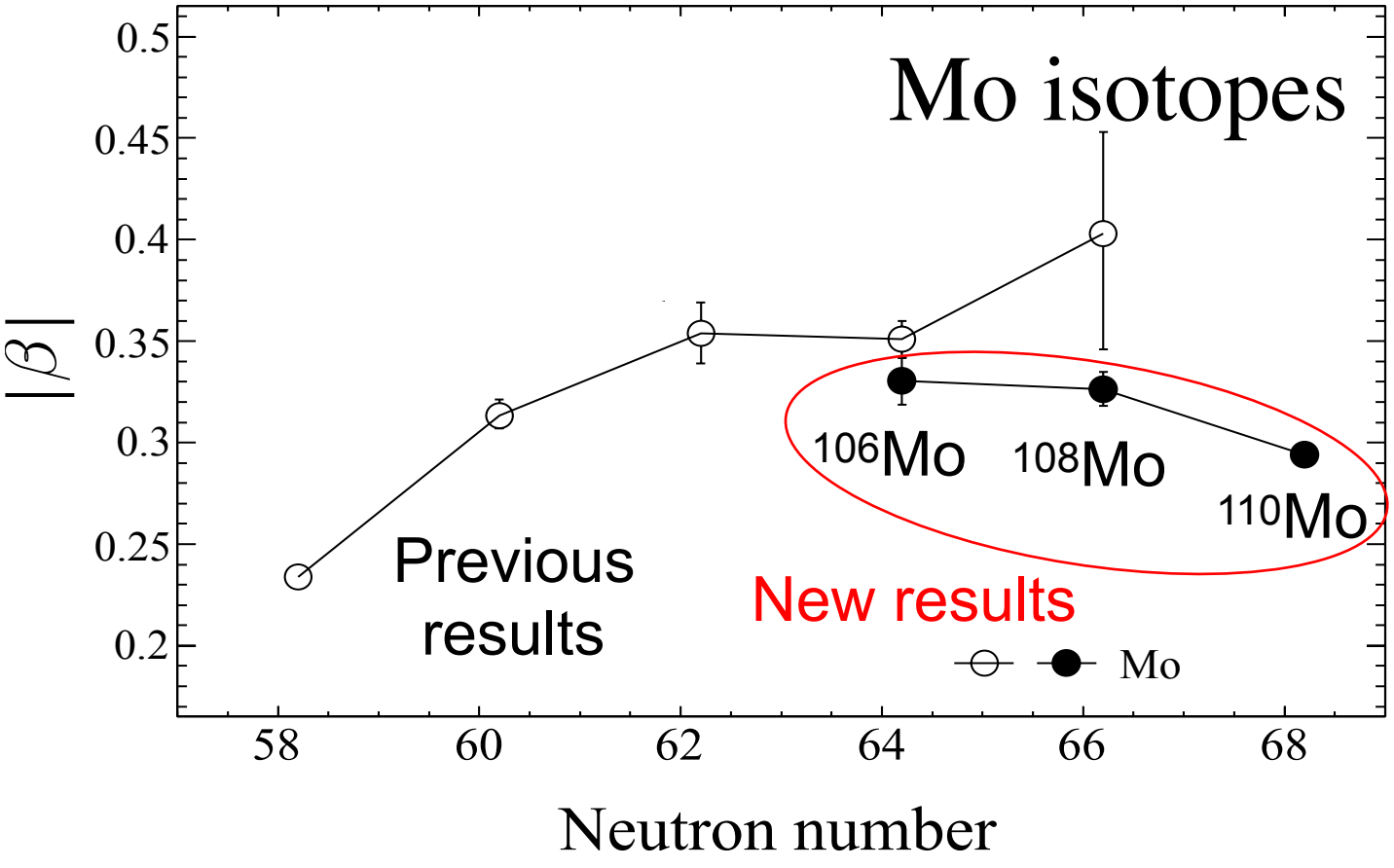


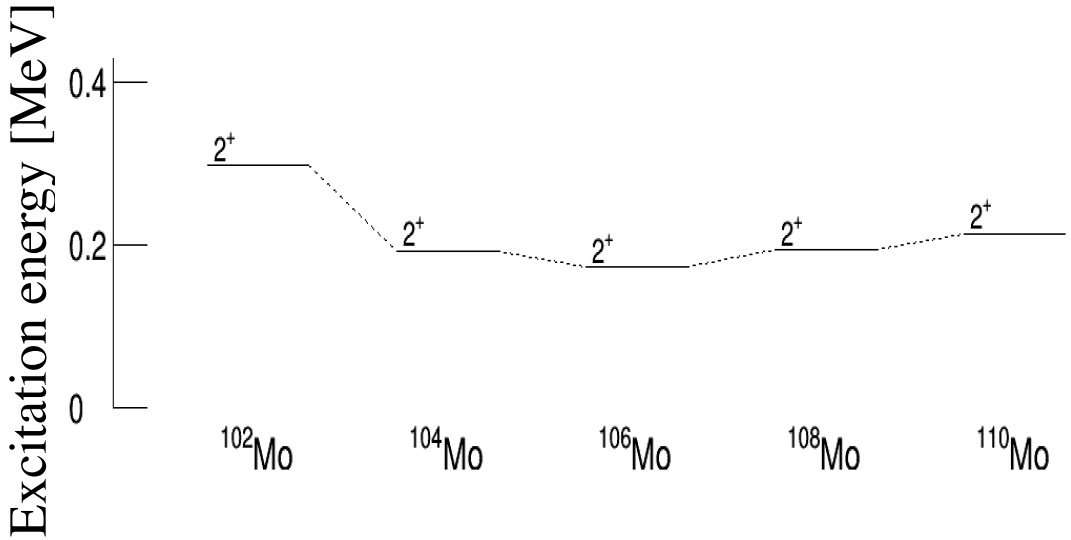
* ^{110}Mo (N = 68)



→ First results using $LaBr_3$ (Ce) detector!

Quadrupole deformation of the ground state





$$\beta = \frac{4\pi}{3ZR_0^2}\frac{1}{\sqrt{\tau(1+\alpha)}}\sqrt{40.81\times10^{13}\frac{1}{E_\gamma^5}}$$

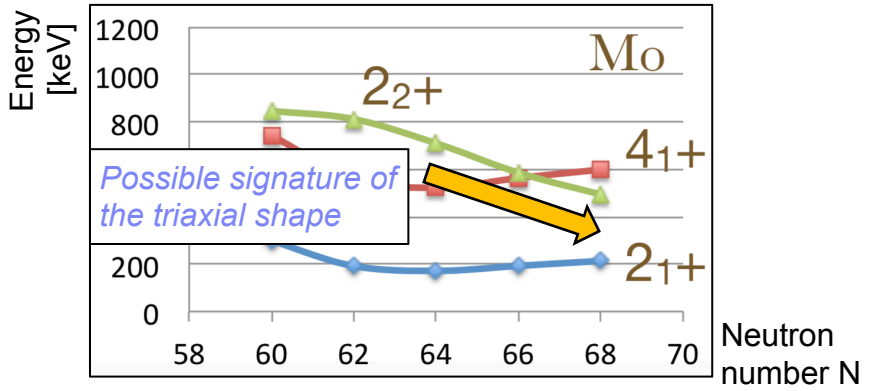
τ : lifetime

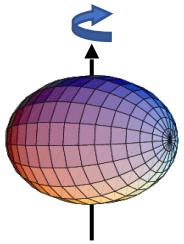
α : internal conversion coeff.

R_0: (fm)

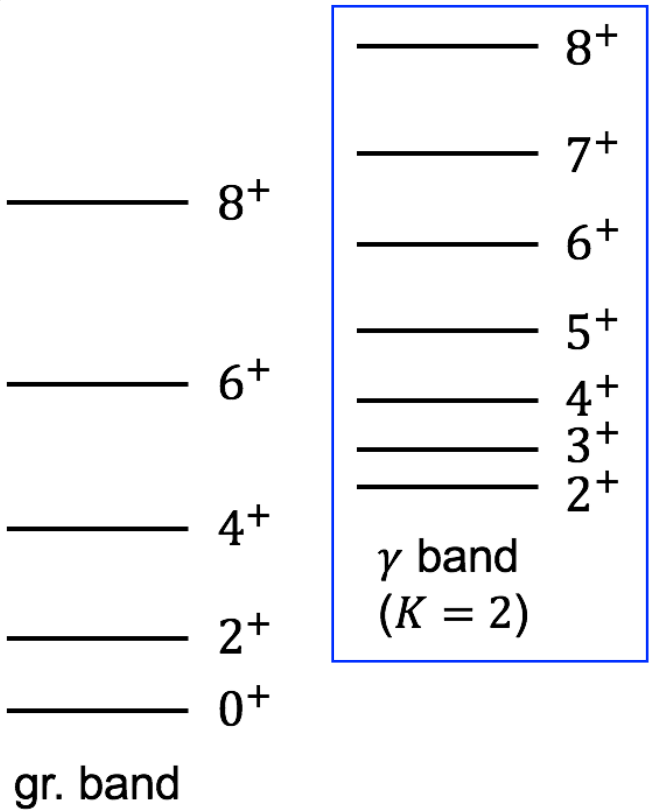
Triaxiality in the second band

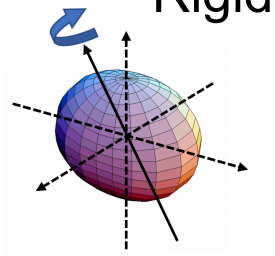
Rotor models for $A \sim 110$ nuclei



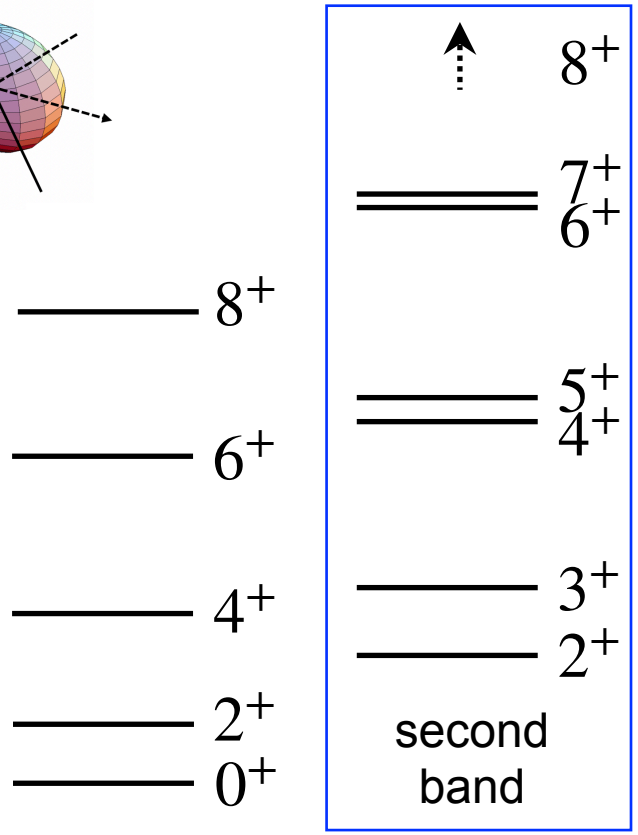


Axially symmetric rotor with γ-vibration

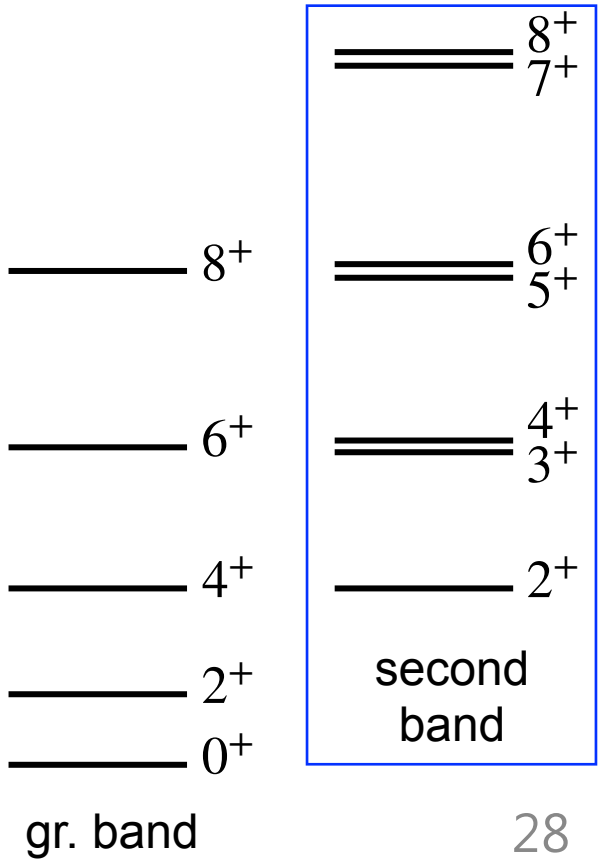




Rigid triaxial rotor model

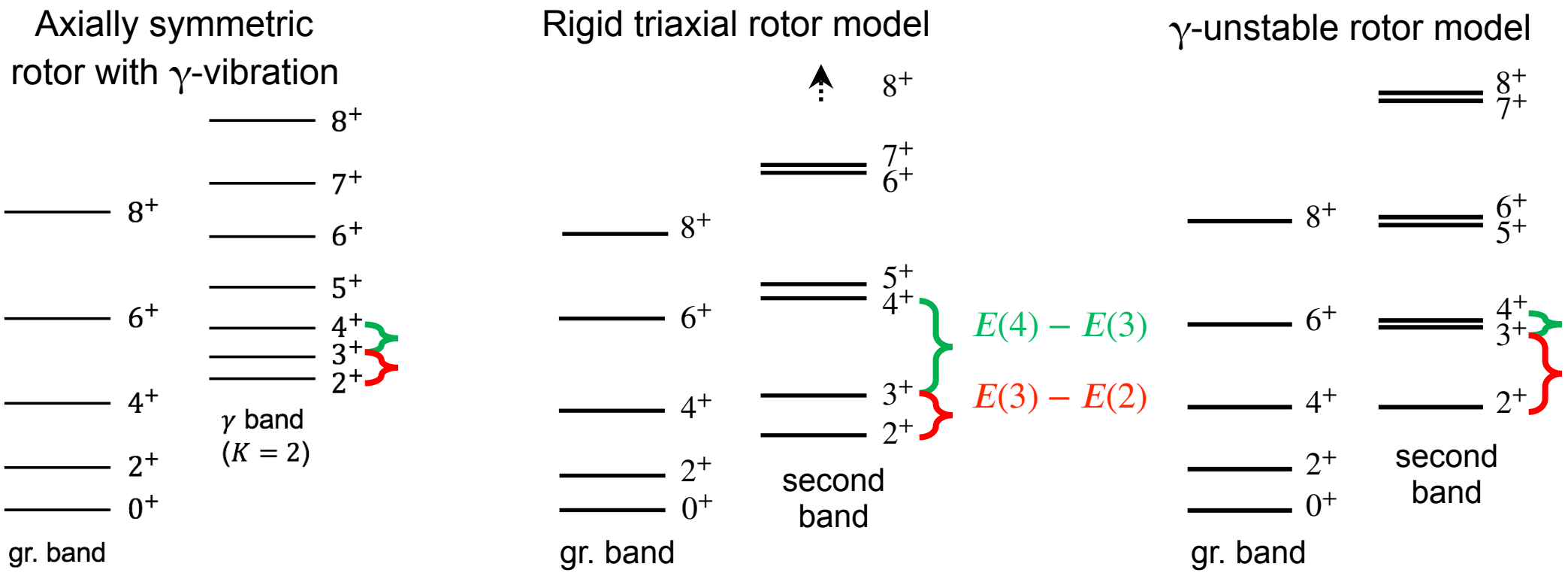


γ-unstable rotor model



Triaxiality in the second band

Rotor models for $A \sim 110$ nuclei



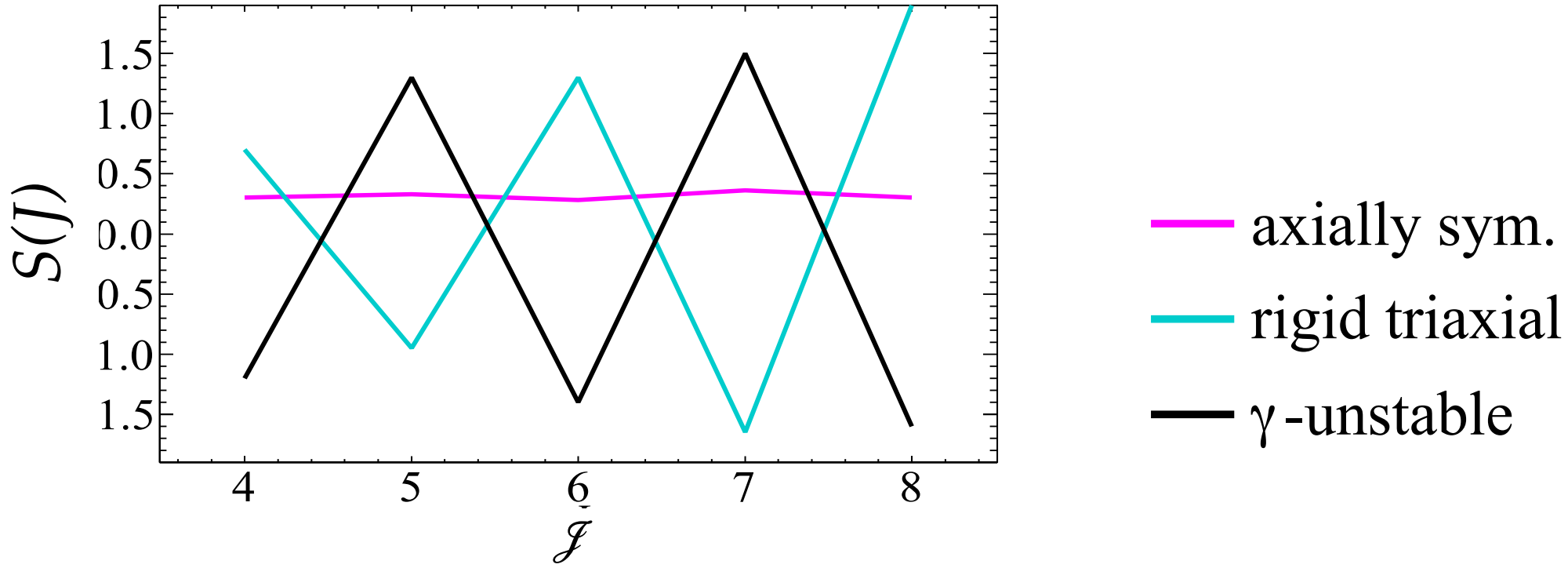
Level spacing in side band is different for each model

One useful indicator $S(\mathcal{J}) \equiv \frac{E_s(J)}{E(2_1^+)} = \frac{[E(J) - E(J-1)] - [E(J-1) - E(J-2)]}{E(2_1^+)}$

Triaxiality in the second band

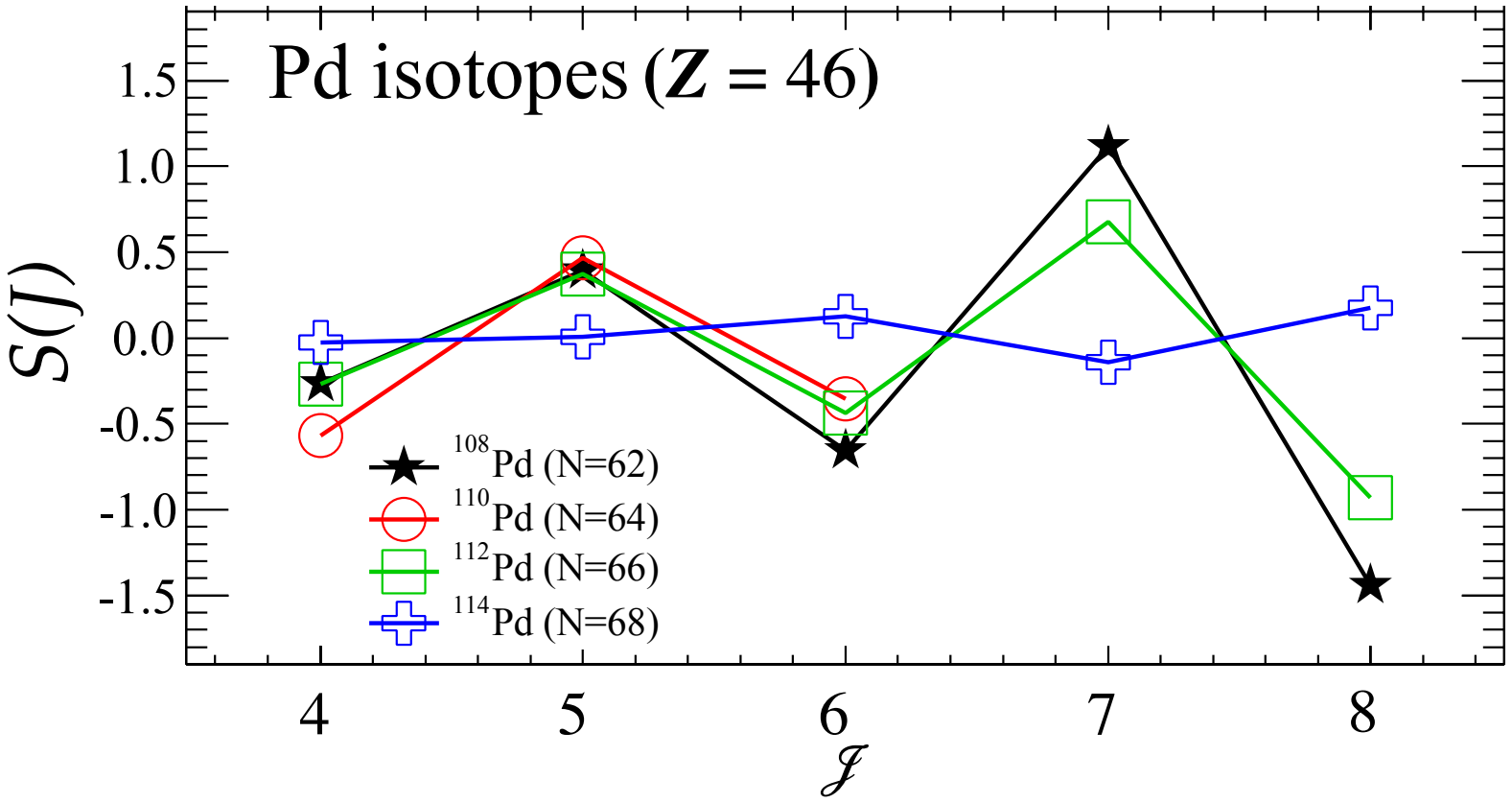
Energy staggering of γ-band

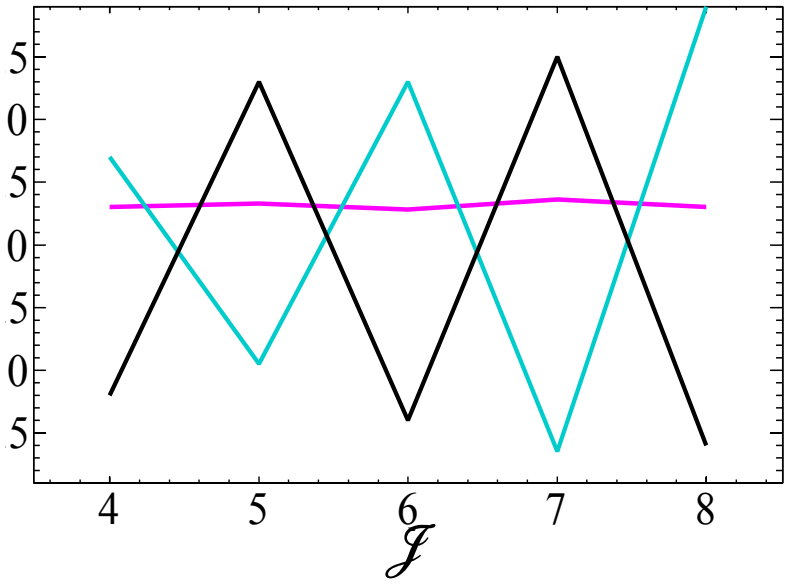
$$S(J) \equiv \frac{E_s(J)}{E(2_1^+)} = \frac{[E(J) - E(J-1)] - [E(J-1) - E(J-2)]}{E(2_1^+)}$$



Triaxiality in the second band

$S(J)$ of neutron-rich Mo, Ru, and Pd isotopes

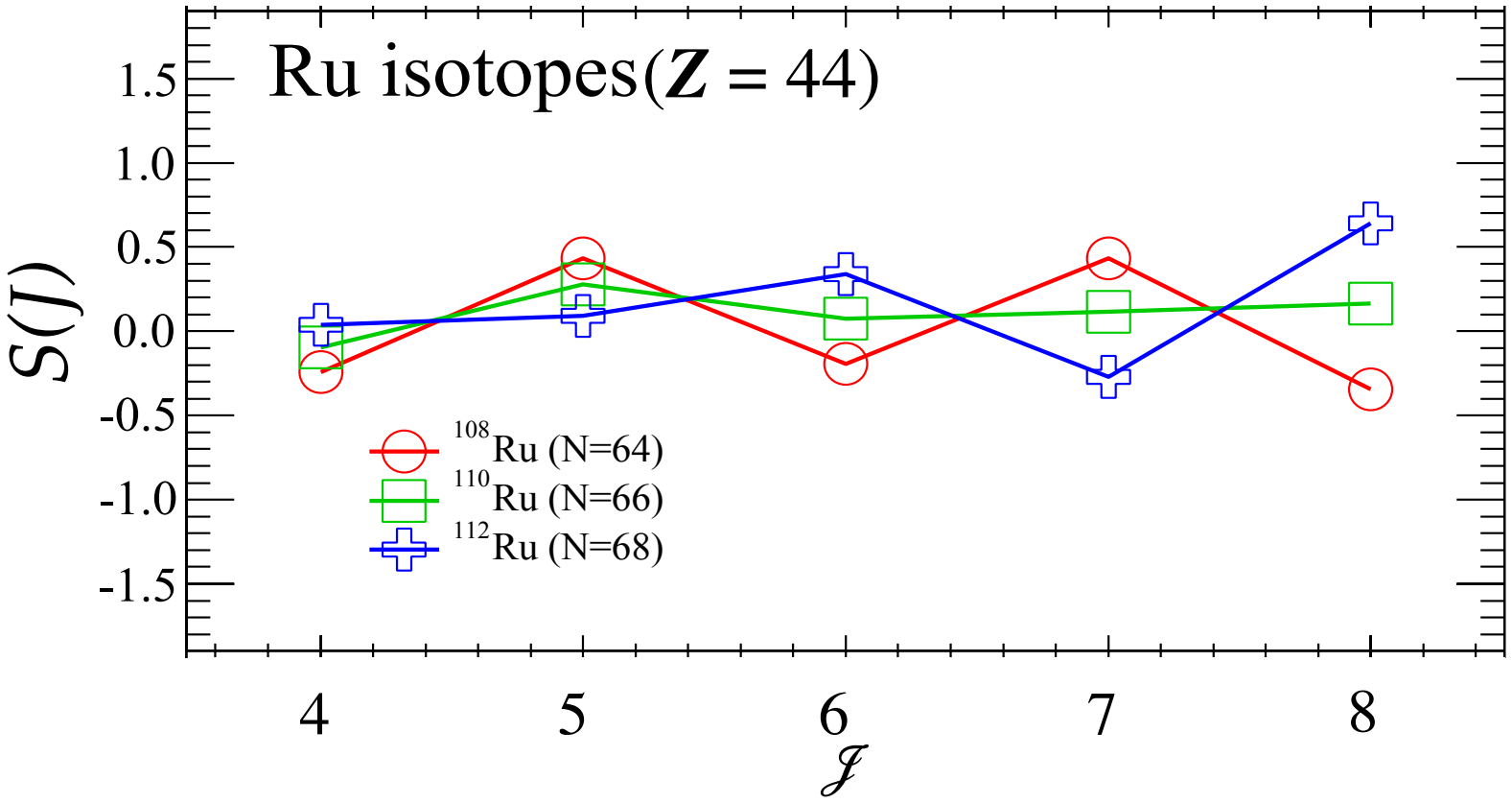




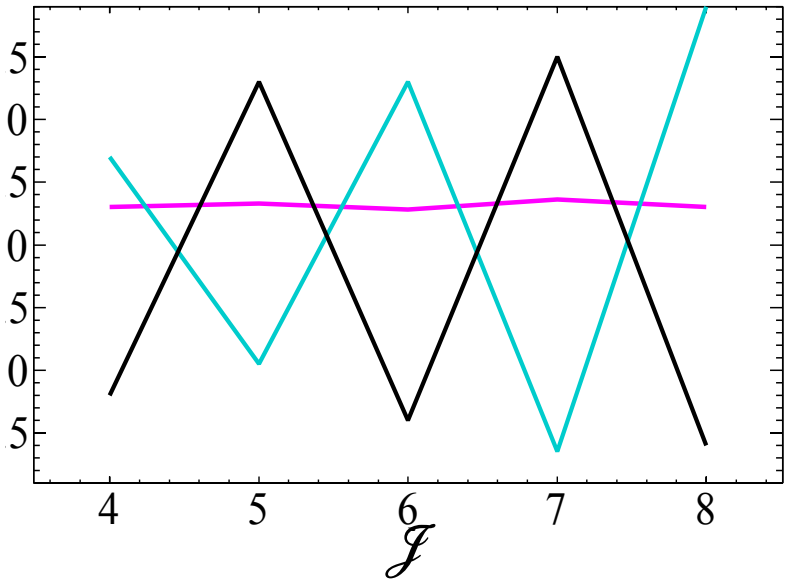
M.A. Caprio, PRC83(2011)064309

Triaxiality in the second band

$S(J)$ of neutron-rich Mo, Ru, and Pd isotopes



M.A. Caprio, PRC83(2011)064309



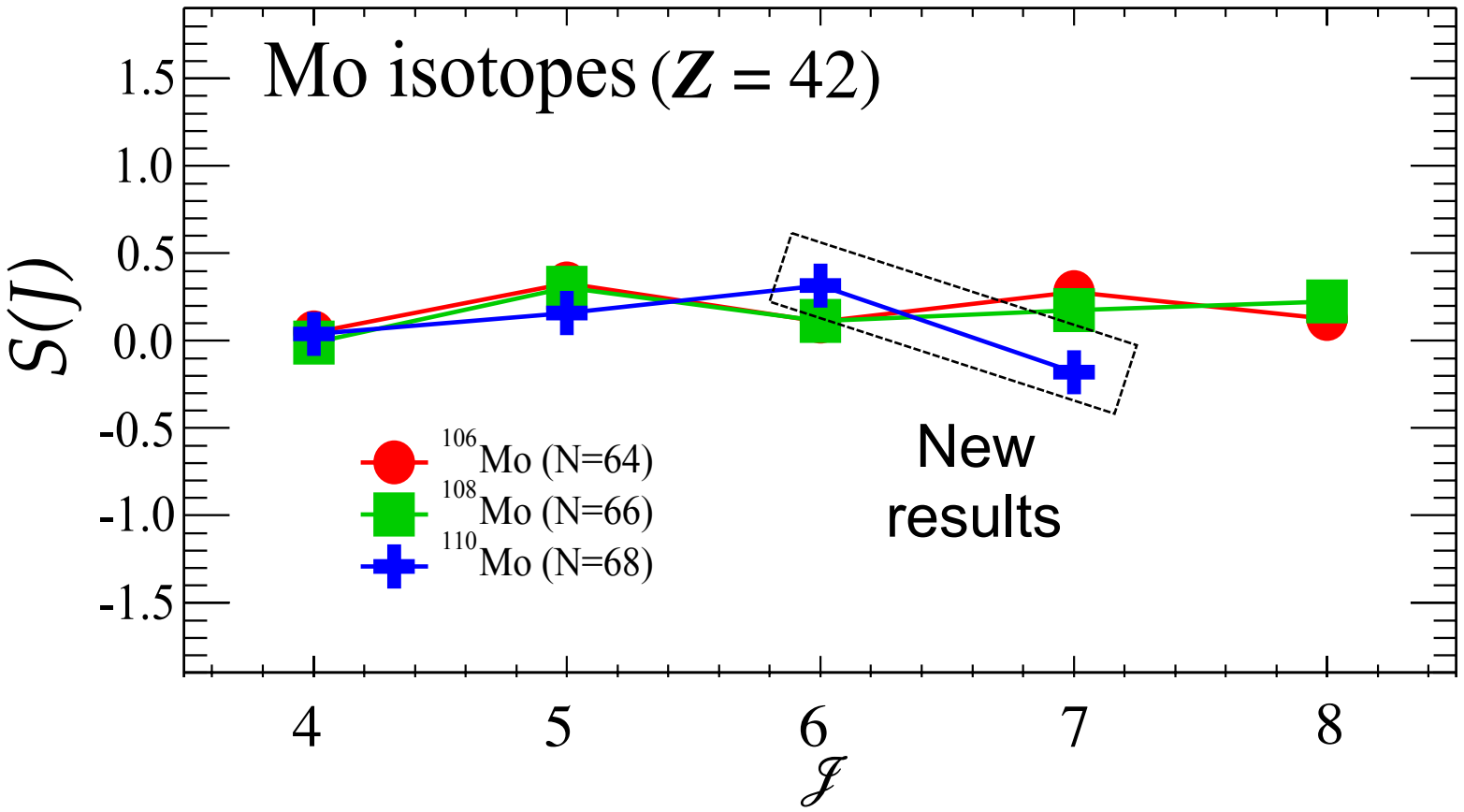
axially sym.

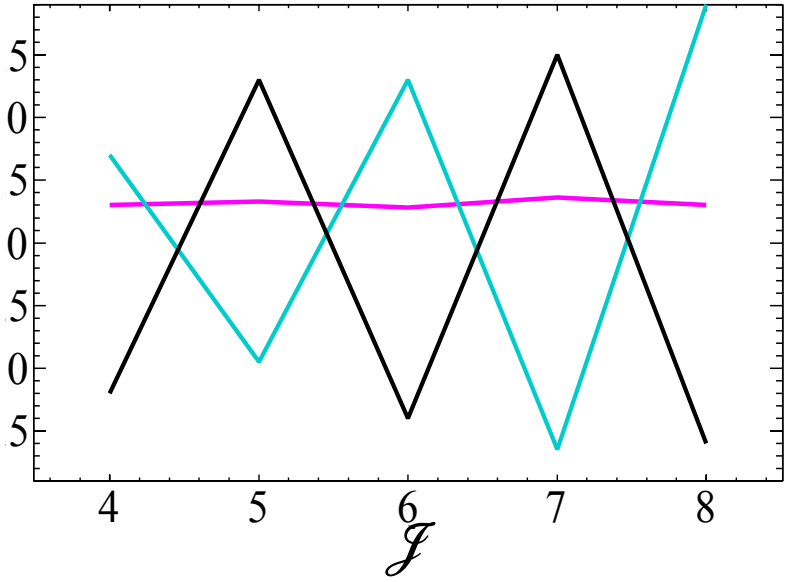
rigid triaxial

γ-unstable

Triaxiality in the Second Band

S(J) of neutron-rich Mo, Ru, and Pd isotopes



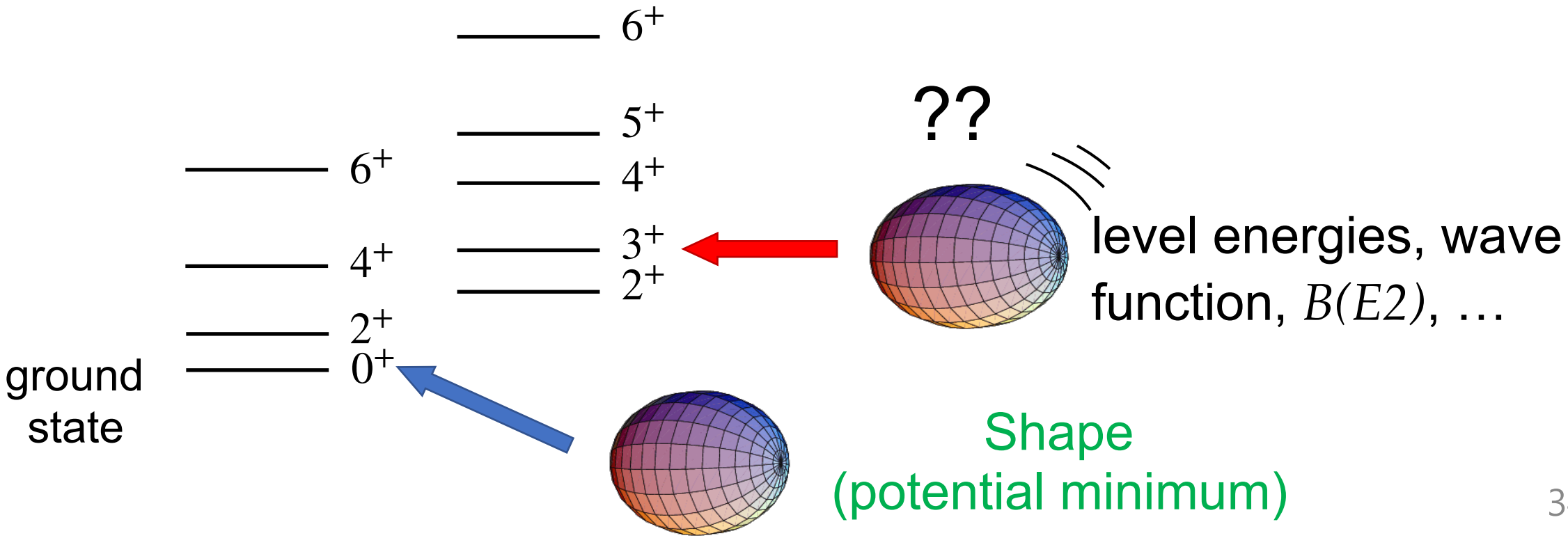


^{106,108,110}Mo: close to the <u>axially symmetric shape</u>

Microscopic 5D Collective Hamiltonian Calculation

Mean field theory is suitable to predict the shape (in body-fixed frame).

Prediction of the observables → Go beyond



Microscopic 5D Collective Hamiltonian Calculation

Beyond mean field (BMF) theory can give information on the observables.

5D-Collective Hamiltonian

$$H = \frac{1}{2}\sum_{k=1}^{3} J_k \omega_k^2 + \frac{1}{2} B_{\beta\beta}(\beta,\gamma)\dot{\beta}^2 + B_{\beta\gamma}(\beta,\gamma)\beta\dot{\beta}\dot{\gamma} + \frac{1}{2} B_{\gamma\gamma}(\beta,\gamma)\beta^2\dot{\gamma}^2 + V(\beta,\gamma)$$

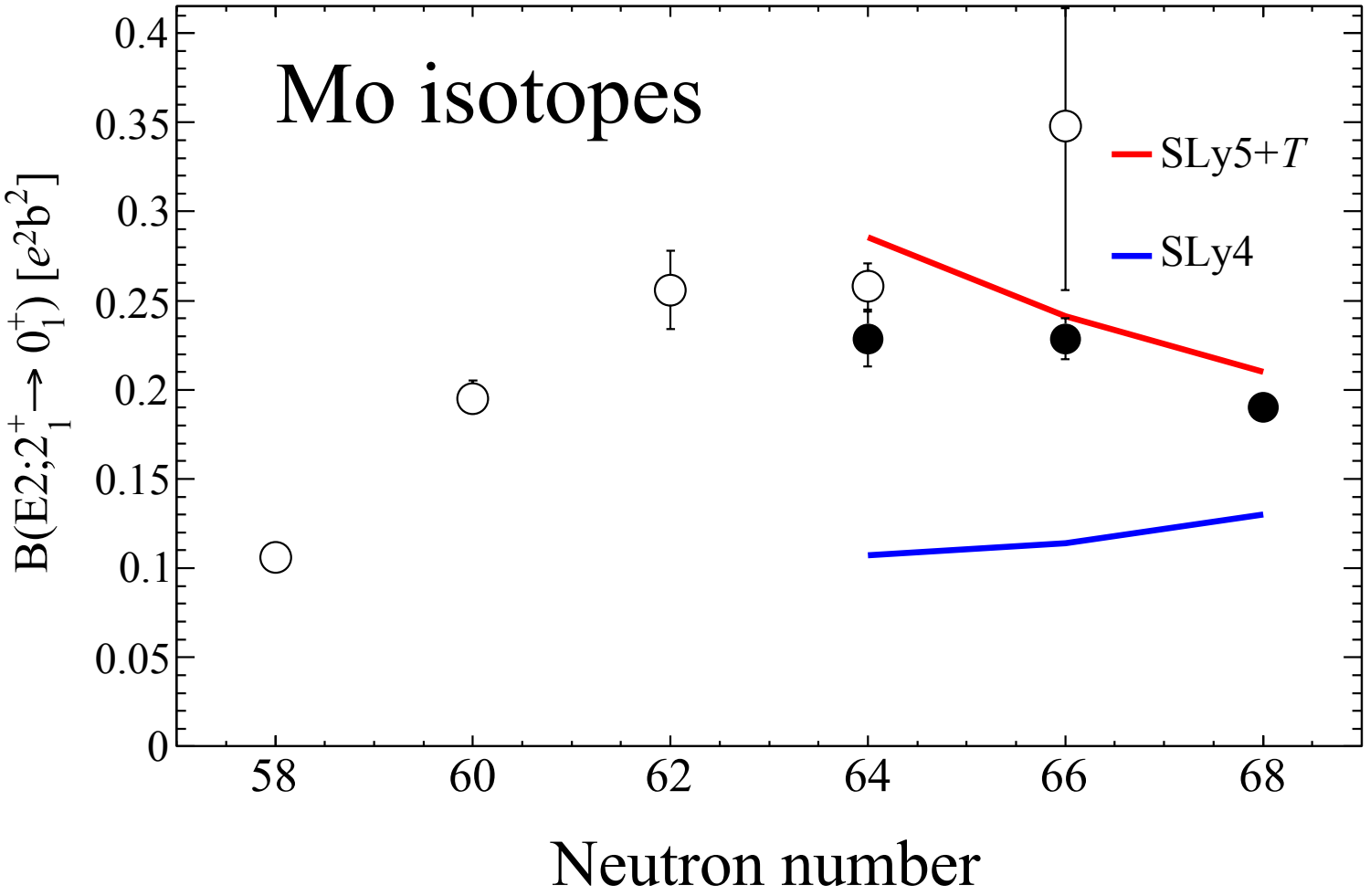
rotation vibration potential

J_k, $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$, and V: determined through the beyond mean-field approach

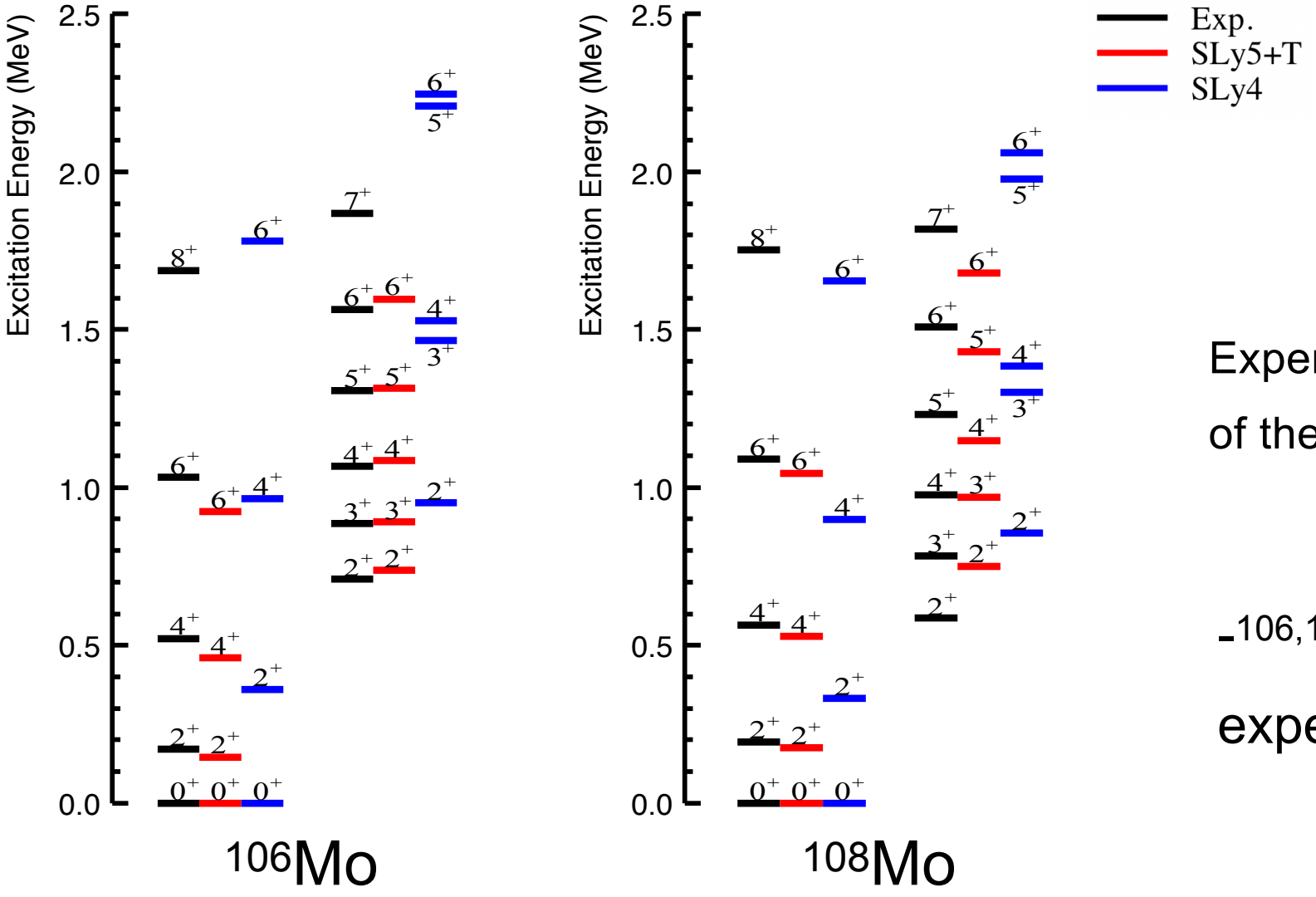
Skyrme type interaction SLy4 and SLy5+T are used and compared.

N. Hinohara *et al.*, PRC82(2010)064313, PRC84(2011)061302
K. Sato *et al.*, PRC86(2012)024316

Microscopic 5D Collective Hamiltonian Calculation



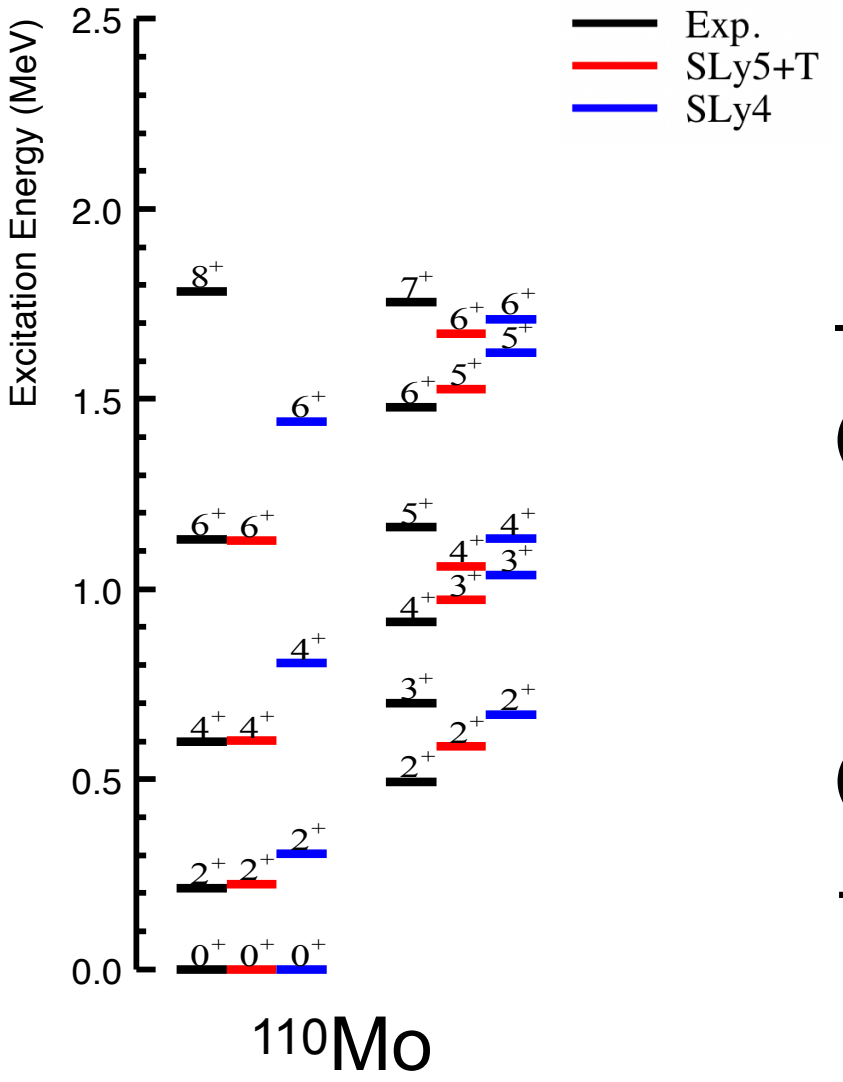
Microscopic 5D Collective Hamiltonian Calculation



Experimental and theoretical energies of the low-lying excited states

- ^{106,108}Mo: consistent with the experimental results

Microscopic 5D Collective Hamiltonian Calculation



- ^{110}Mo

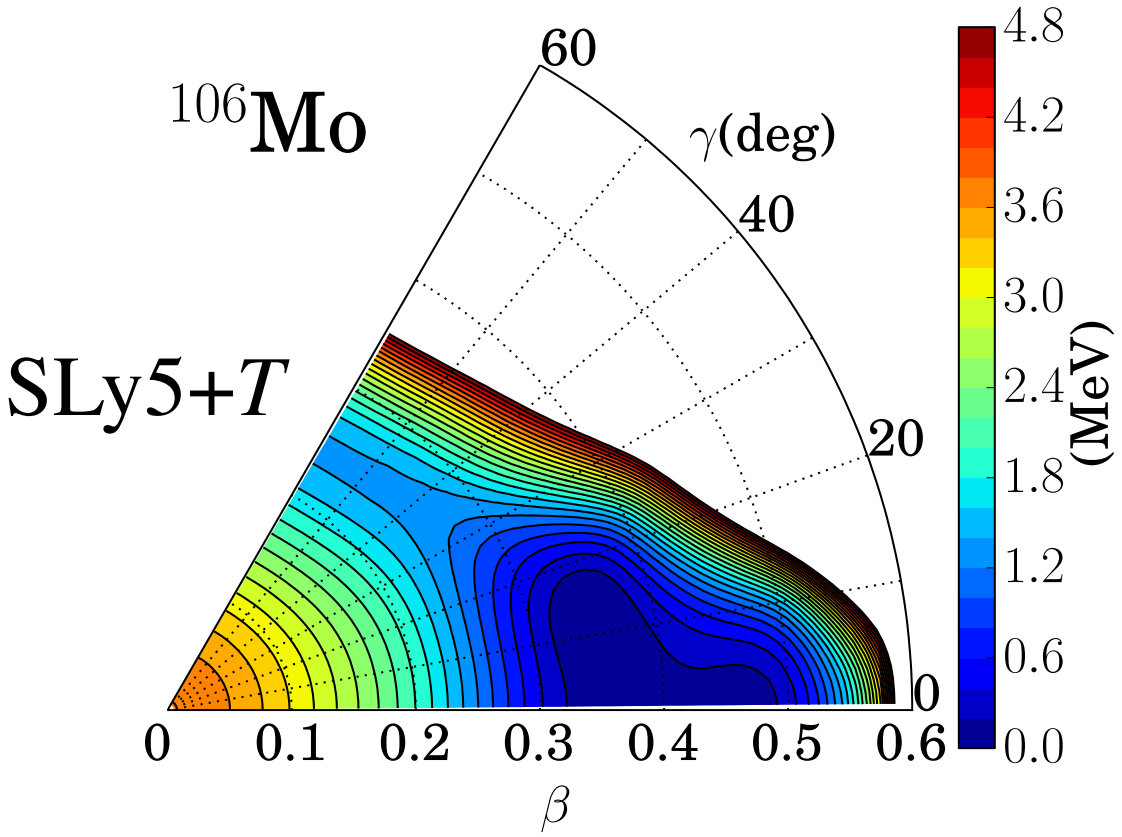
(1) Ground band: good agreement with the experimental results

(2) Side (K = 2) band: γ-soft character

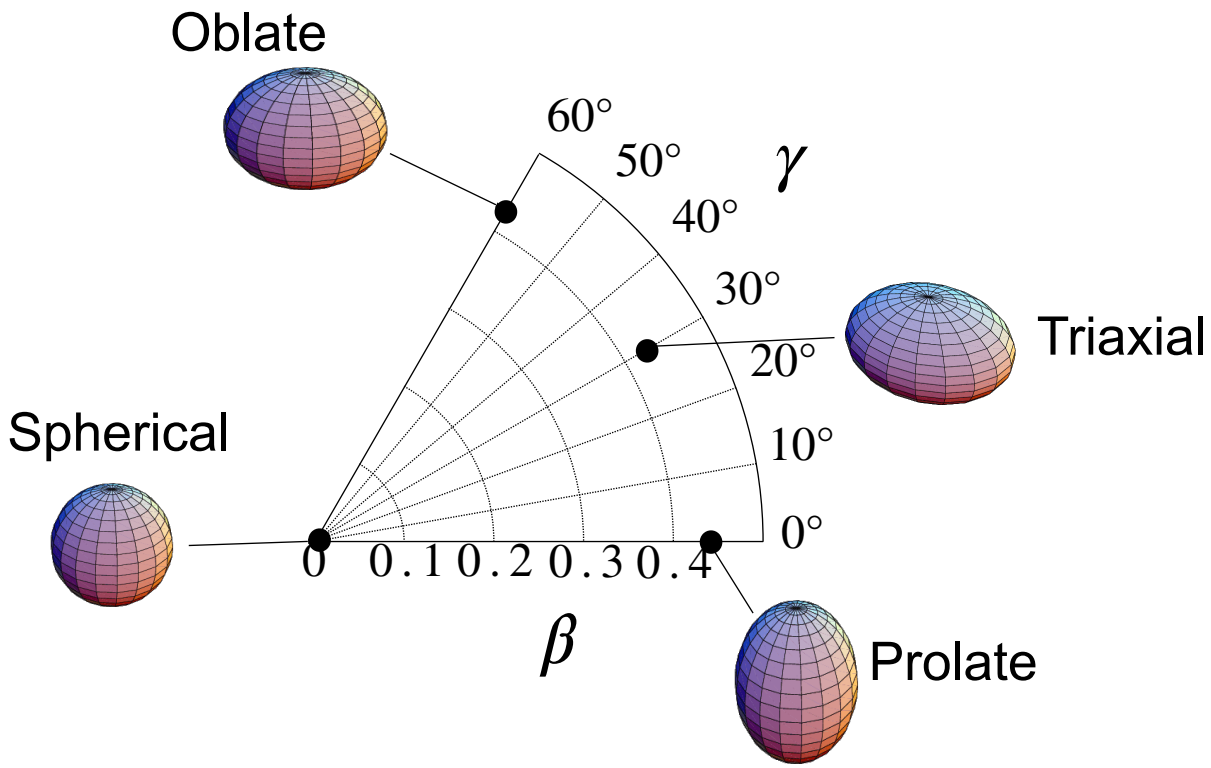
→ inconsistent with the experimental results

Microscopic 5D Collective Hamiltonian Calculation

Potential Energy Surface (PES)

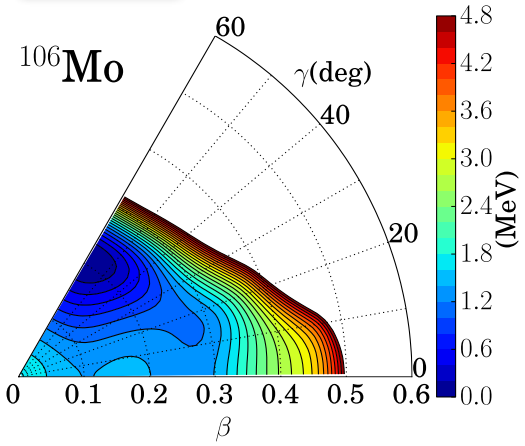


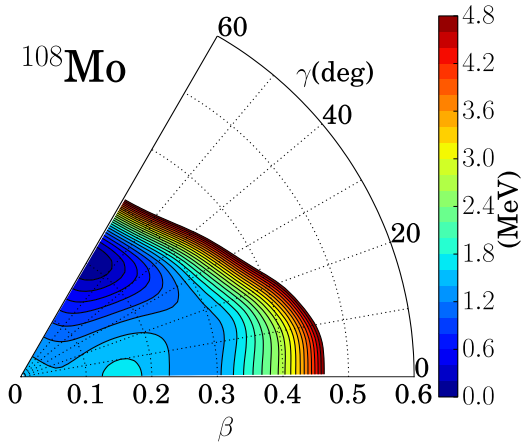
($\beta-\gamma$ plane)

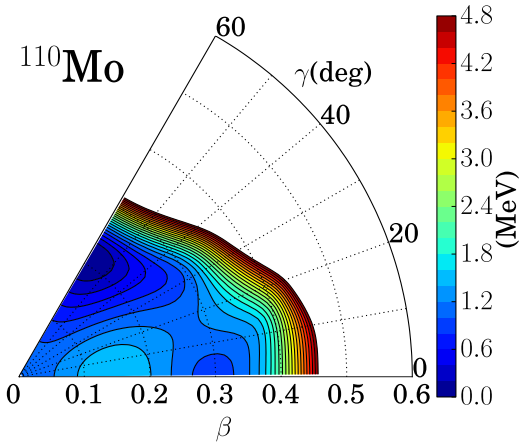


Microscopic 5D Collective Hamiltonian Calculation

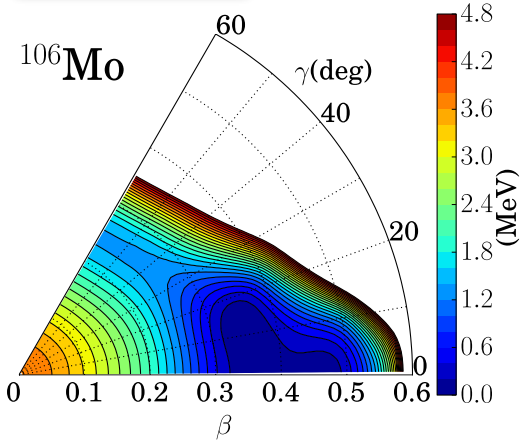
SLy4

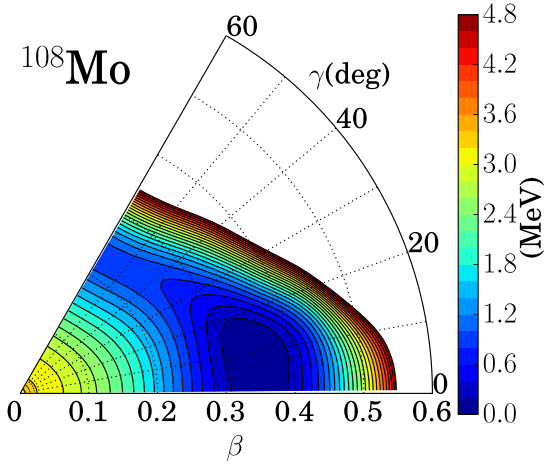


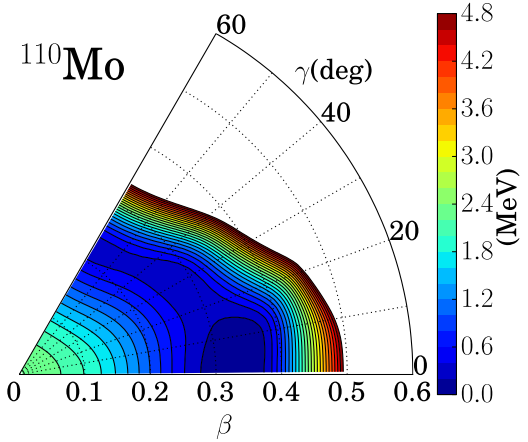




SLy5+*T* ✓







^{106,108}Mo: prolate

^{110}Mo: γ-soft, close to γ-unstable

Summary

The shapes of ^{106,108,110}Mo were studied via the β-γ spectroscopy

(1) The lifetime measurement of the $E(2_1^+)$ states: the degree of deformation decreases with increasing neutron number.

(2) The observation of 6^+, 7^+ states in ^{110}Mo: the energy staggering indicator $S(J)$ for newly observed levels suggests the axially symmetric shape.

(3) Comparison with BMF calculation: the experimental $B(E2)$ and energy of the low-lying states are consistent with SLy5+T, which indicates prolate ground-state shape.

Acknowledgement: Most of the slides were derived from those of Dr. Jeongsu Ha, who finished his PhD with this experiment.