Search for Shape Coexistence Signatures in ^{100}Ru using Thermal Neutron Capture

NSERC CRSNG

UNIVERSITY OF GUELPH

NEUTRONS FOR SOCIETY

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CAP 2026 Ottawa

Historical Context of Ru Isotopes

Ruthenium
Z=44

^{98}Ru	^{99}Ru	^{100}Ru	^{101}Ru	^{102}Ru	^{103}Ru	^{104}Ru

Image: ANU Chart of Nuclides.

Spherical Vibrators

$$\frac{E(4_1^+)}{E(2_1^+)} =$$

2.14	2.27	2.32
[8] Van Voorthuysen *et al. (1981).*	[4] L. Genilloud *et al.* *(2000)*	[7] H. Duckwitz *et al.* *(2013)*

2nd phonon structure was nearly degenerate.

Multitude of Structural interpretations:

1. **Near Spherical Vibrators**
2. Transitional nucleus between spherical to γ-soft rotor
3. Shape coexistent chain.

Image: ANU Chart of Nuclides.

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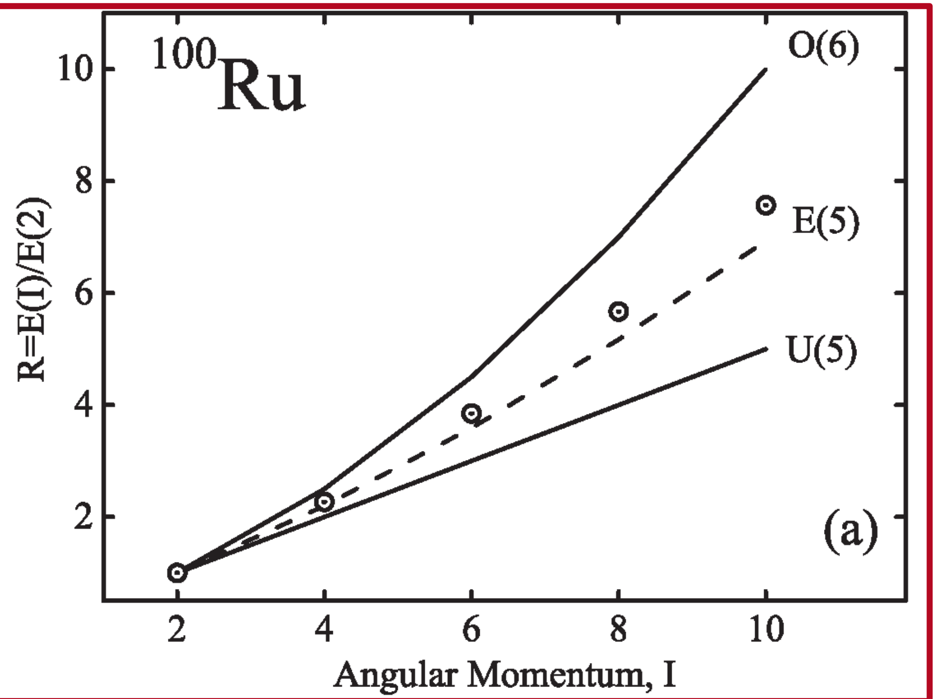
^{98}Ru	^{99}Ru	^{100}Ru	^{101}Ru	^{102}Ru	^{103}Ru	^{104}Ru

Image: ANU Chart of Nuclides.

γ-soft rotor O(6)

Spherical Vibrators
U(5)



Multitude of Structural interpretations:

1. Near Spherical Vibrators
2. **Transitional nucleus between spherical to γ-soft rotor**
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T. Konstantinopoulos et al., PRC 95, 014309 (2017).

Historical Context of Ru Isotopes

Ruthenium
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^{98}Ru | ^{99}Ru | ^{100}Ru | ^{101}Ru | ^{102}Ru | ^{103}Ru | ^{104}Ru

Image: ANU Chart of Nuclides.

Signatures of Shape coexistence **FOUND**

Shape coexistence signatures **AMBIGOUS!**

Unique **deformations** of low-lying 0+ States**.**

$\beta(0_1^+)=0.24$

$\beta(0_2^+)= 0.18$

Garrett, P. E, *et al.* (2022). *Physical Review. C*, *106*(6).

$\beta(0_1^+)=0.28$

$\gamma \sim 25^\circ$

$\beta(0_2^+)=0.21$

$\gamma \sim 30^\circ$

Srebrny, J., *et al. Nuclear Physics. A*, *766*, 25–51

Multitude of Structural interpretations:

1. Near Spherical Vibrators
2. Transitional nucleus between spherical to γ-soft rotor
3. ***Shape coexistent chain?***

Shapes and Configuration Co-existence

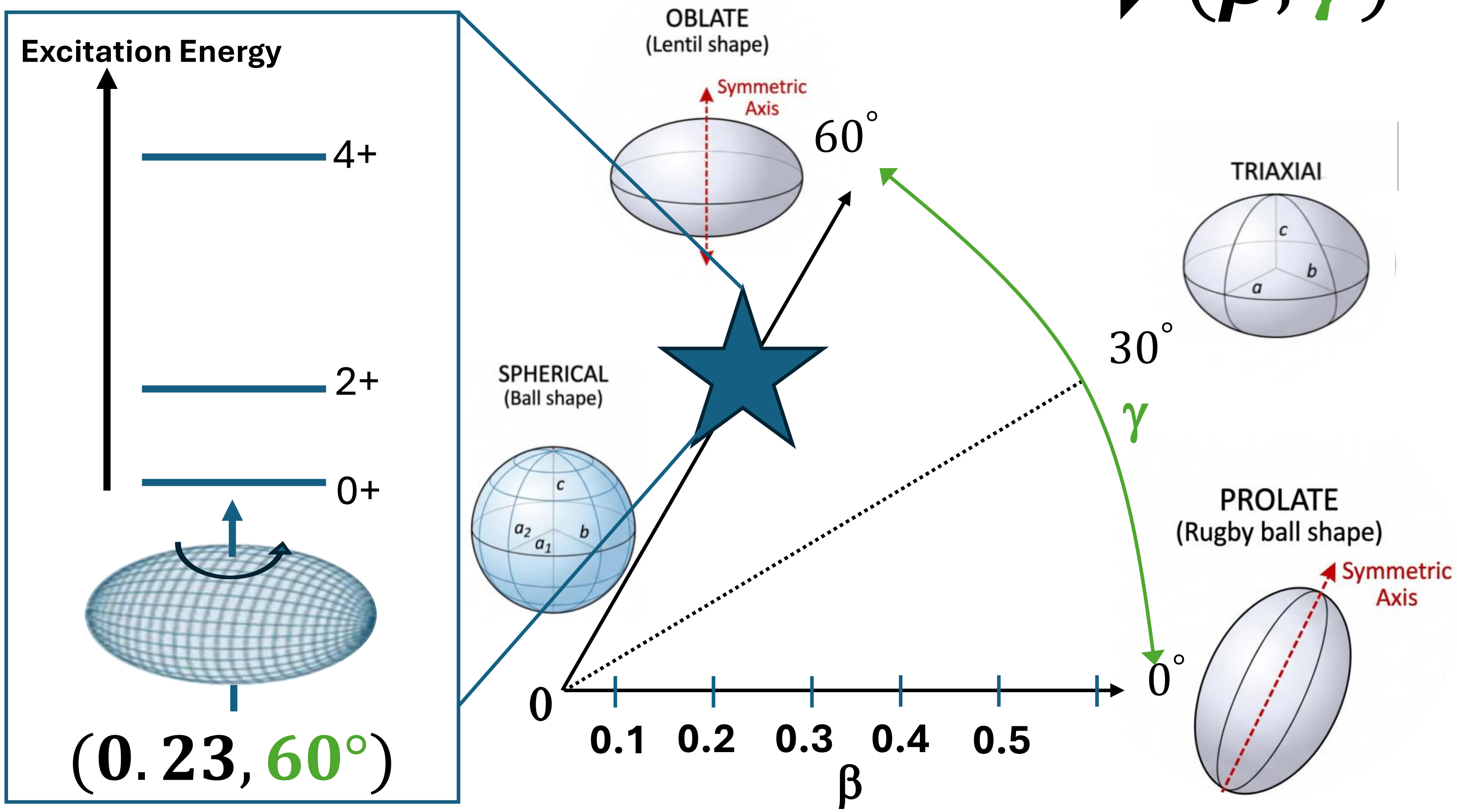
Shapes can be quantified by deformations parameters. → (β, γ)

"***Normal***" structures of nuclei conform to a ***single*** **intrinsic** shape.

The **COLLECTIVE** excitation characteristics "***revolve***" around this ***single*** shape.

$\boldsymbol{\beta}$ characterizes the **extent** of deformation.

γ denotes the **degree** of *axial* symmetry.



Shapes and Configuration Co-existence

Shapes can be quantified by deformations parameters. → (β, γ)

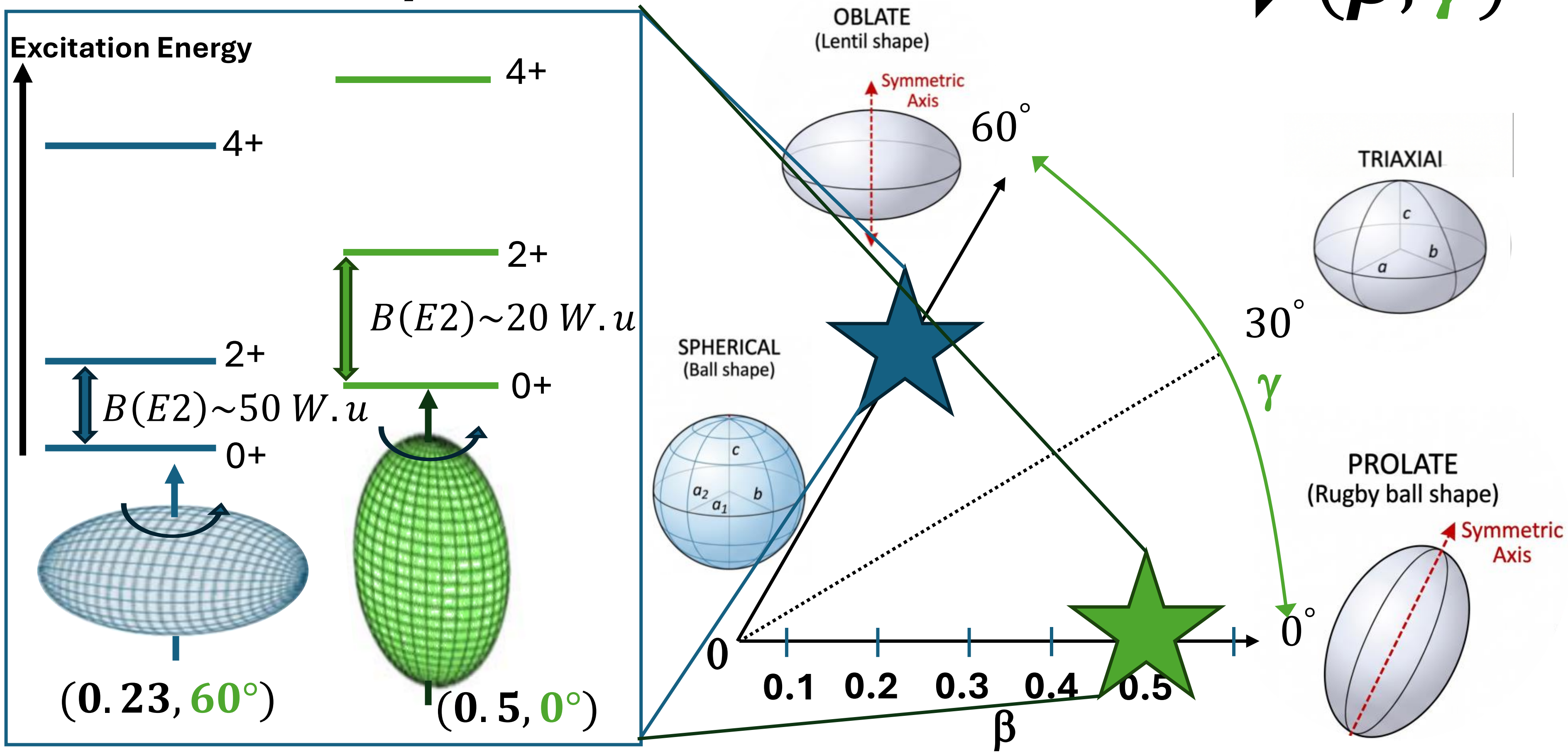
Configuration Coexistence

Signatures of Shape Coexistence:

1. **Unique energy spacing** of levels in bands
2. ***Different*** B(E2;2→0) in the bands.

Shape Coexistence: A critical benchmark for theoretical models.
Chains of Coexistence: The ultimate stress test for tracking structural evolution.

$B(E2) \propto \beta$



Spectroscopy of Ru isotopes

Image: ANU Chart of Nuclides.

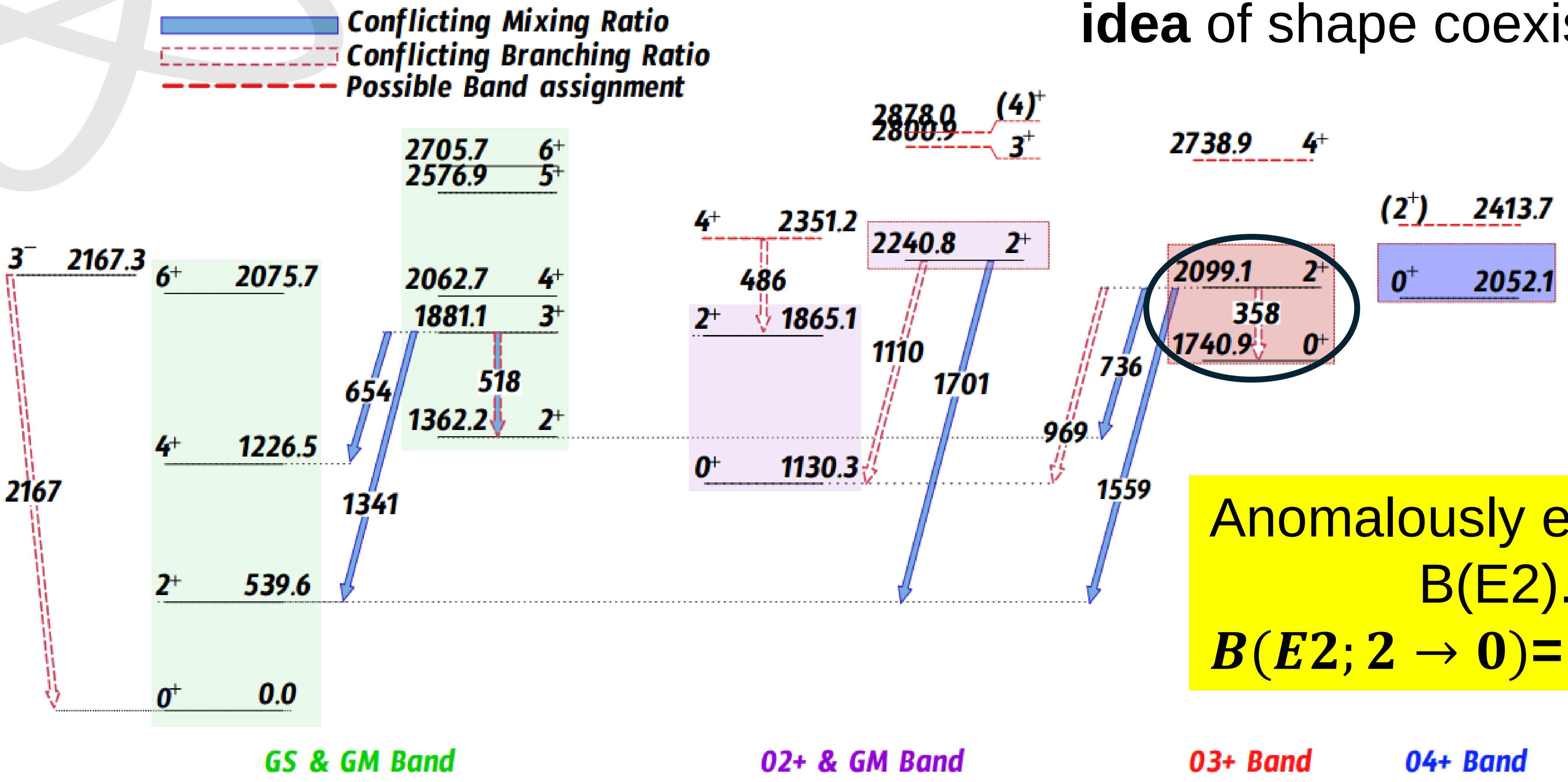
^{98}Ru, ^{102}Ru, ^{104}Ru have diverse spectroscopic datasets with ***firm*** **band assignments.**

^{100}Ru last spectroscopy over **20 years ago;** which has **various *conflicting* results** with previous experiments.

- Beta-decay of 98Rh to **98Ru (2020)**
- Coulomb excitation of **102Ru (2022)**
- Coulomb excitation of **104Ru (2005)**

Spectroscopy of 100 Ru

Missing/uncertain spectroscopy data ***limiting* idea** of shape coexistence.

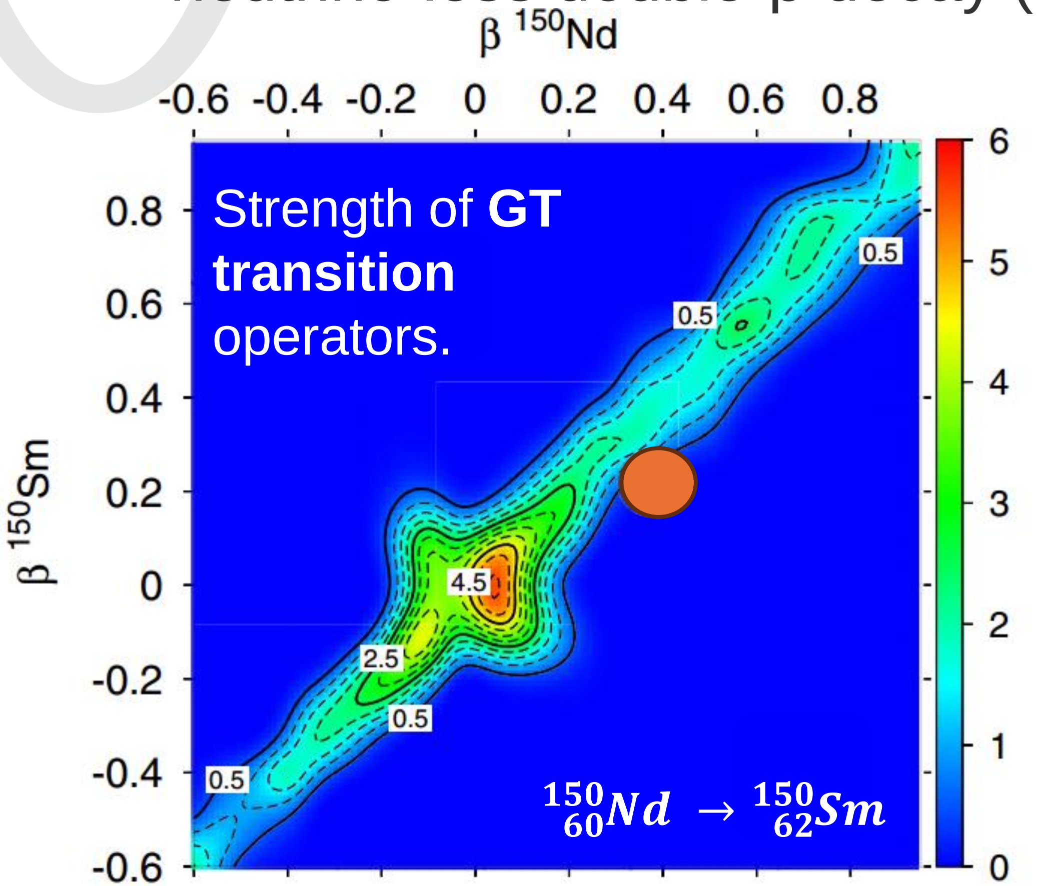


Anomalously enhanced B(E2).

$B(E2; 2 \rightarrow 0)$= **270 W.u**

Implications for clarifying Ru structure.

1. **Fundamental Symmetries & Standard Model Physics**: Better constraints on neutrino-less double-β decay (0νββ) candidate : $^{100}_{42}Mo \rightarrow ^{100}_{44}Ru$.



T. R. Rodríguez & G. Martínez-Pinedo, *Phys. Rev. Lett.* **105**, 252503 (2010).

$$m_{\beta\beta} \propto \frac{1}{|M^{0\nu}|}$$

Nuclear Matrix Element ($M^{0\nu}$) is the ***overlap*** of the **initial** and **final** wavefunctions between the **parent** and **daughter nucleus**.

→ **Deformation position** of **Parent** (150Nd) and **Daughter** (150Sm) nuclei. → **NME** is small.

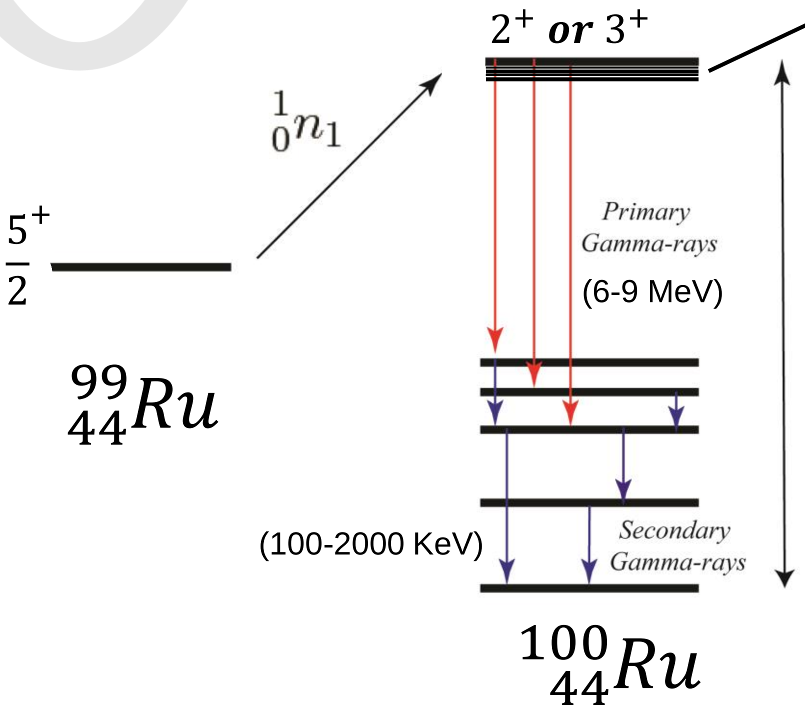
→ Decay between states with **different initial** and **final** deformations is **hindered**!

Neutron Capture: ${}^{100}_{44}Ru$ via ${}^{99}_{44}Ru(n,\gamma)$

Location:

ILL- (**I**nstitut **L**aue-**L**angevin)

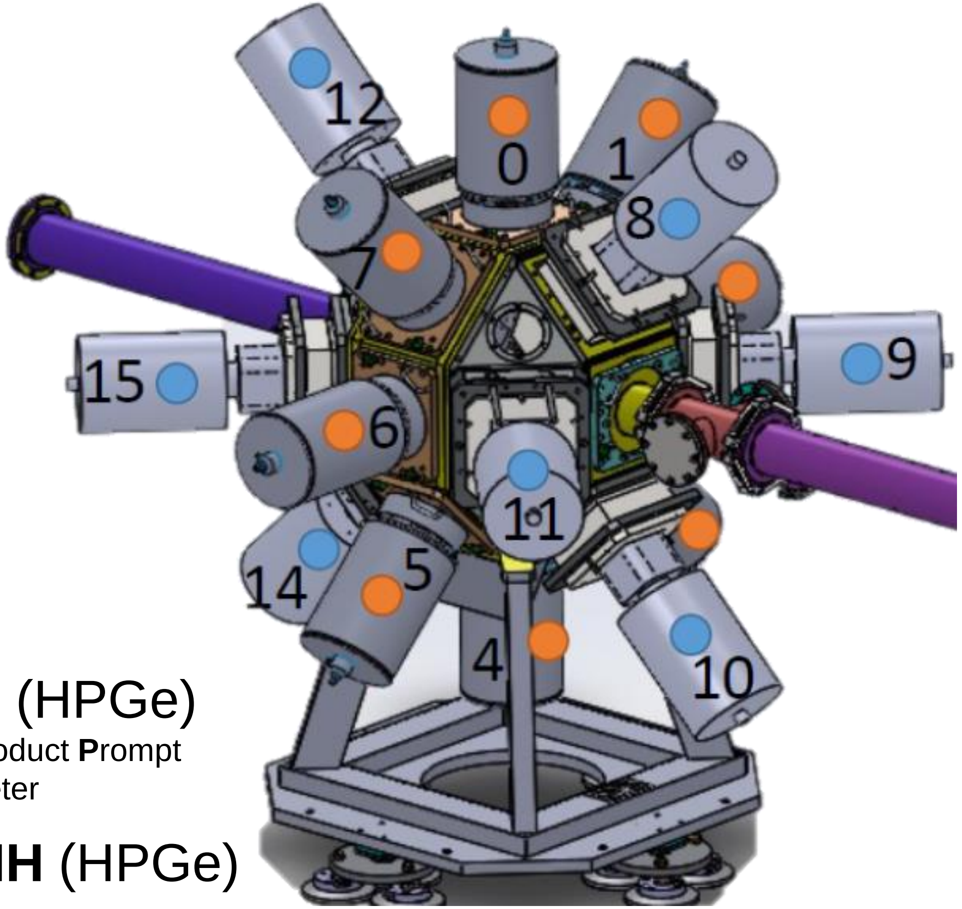
Grenoble, France



S-wave resonance spacing
D_0 = **0.025 keV**.
40 capture states per keV.

E1, M1, E2 Hierarchy
For primary decay.

$\approx S_n$= **9.6** MeV

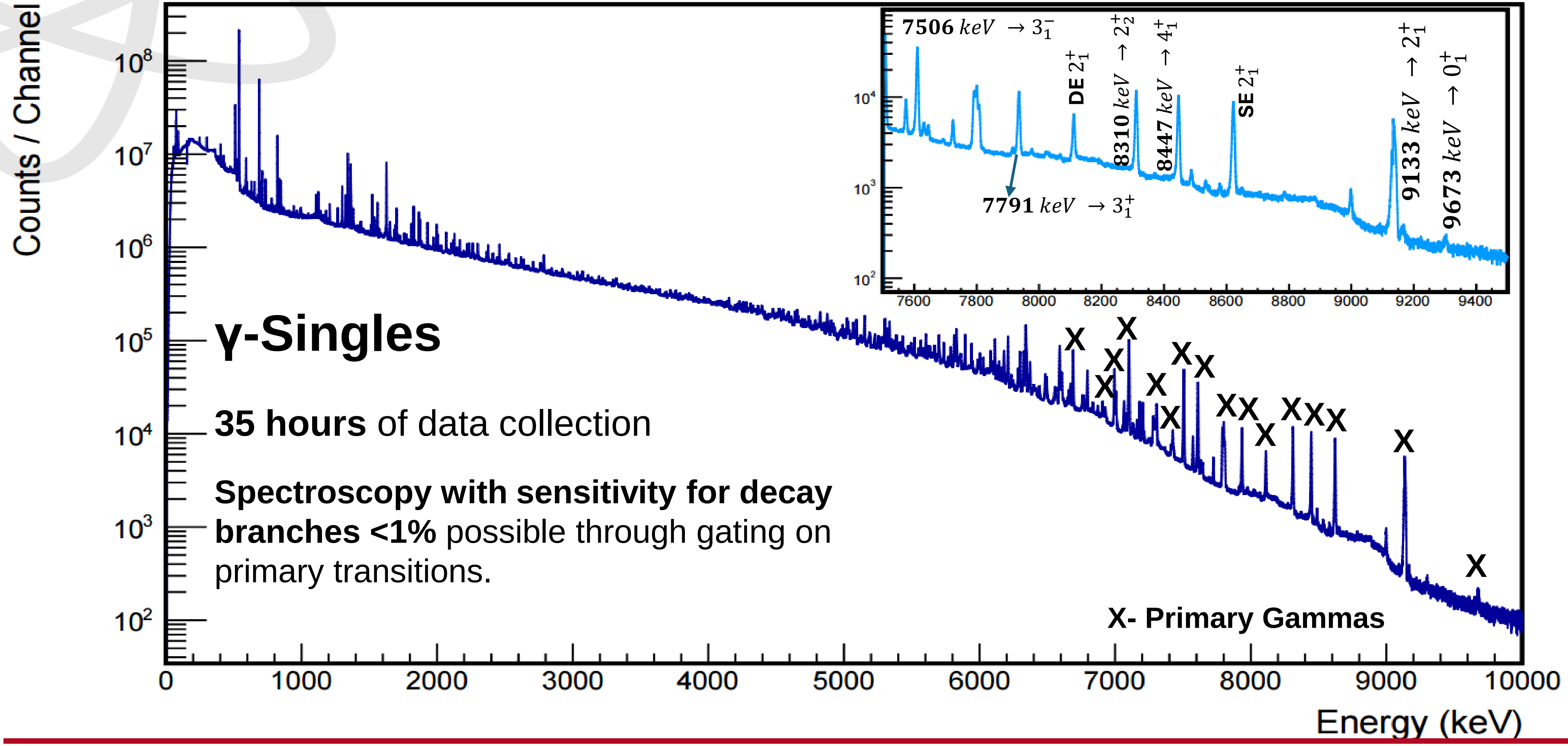


- **FIPPS** (HPGe)
  Fission **P**roduct **P**rompt **S**pectrometer
- **IFIN-HH** (HPGe)

High flux of **thermal neutrons** were **produced** by the onsite research **reactor** via **induced** fission of 235 U.

Total Array Efficiency: **4.8%** at **1MeV.**
FWHM: **2.5 keV** at **1MeV.**

Neutron Capture: Experimental Spectrum

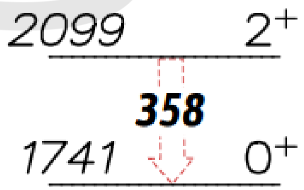


γ-Singles

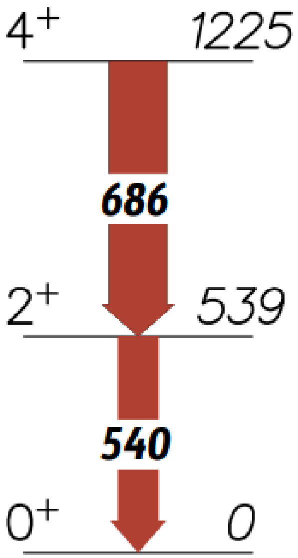
35 hours of data collection

Spectroscopy with sensitivity for decay branches <1% possible through gating on primary transitions.

Results: 0_3^+ Excited Band; 2_4^+ Large B(E2)



0_3^+ Band



Ground State Band

Table 2: Experimental data for the 2099 keV (2^+) level in ^{100}Ru

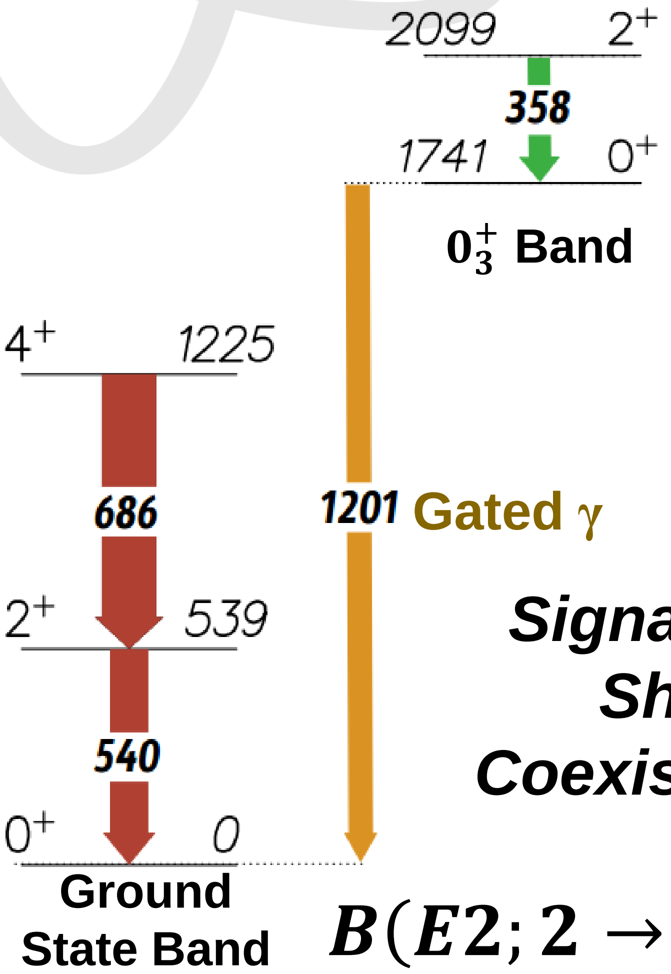
Level (keV)	J^π	E_γ (keV)	BR	B(E2)	Reaction	Year
2099	2^+	358	3.5(4)	267^{+50}_{-35}	(n,γ)	1988

Large B(E2) value **casts *doubt*** on the branch, and hence band assignment.

Results: 0_3^+ Excited Band; 2_4^+ Large B(E2)

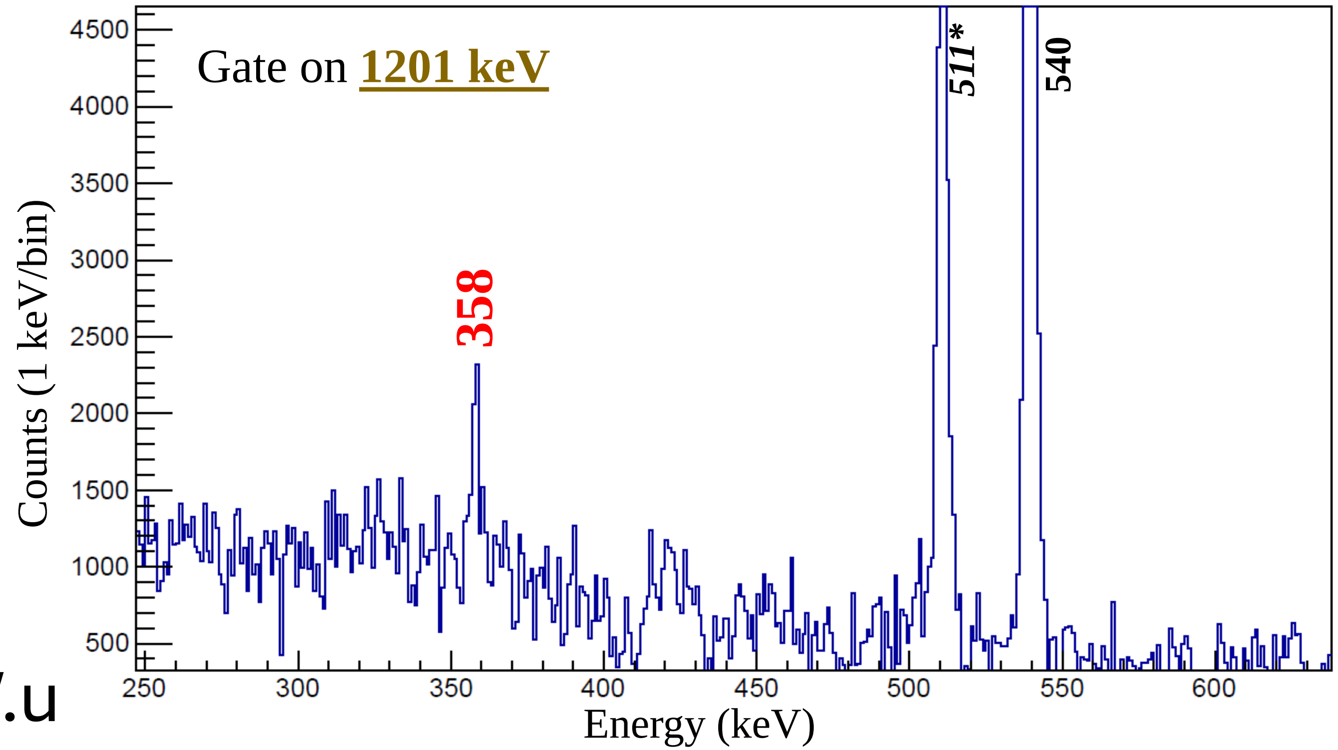
Table 2: Experimental data for the 2099 keV (2^+) level in ^{100}Ru

Level (keV)	J^π	E_γ (keV)	BR	B(E2)	Reaction	Year
2099	2^+	358	3.5(4)	267^{+50}_{-35}	(n,γ)	1988
Our Results →			0.8(2)	56^{+16}_{-14}	(n,γ)	2026



Signature of Shape Coexistence!!!

$B(E2; 2 \rightarrow 0) \sim 35$ W.u



Results: Overview of Spectroscopy

Transitions:

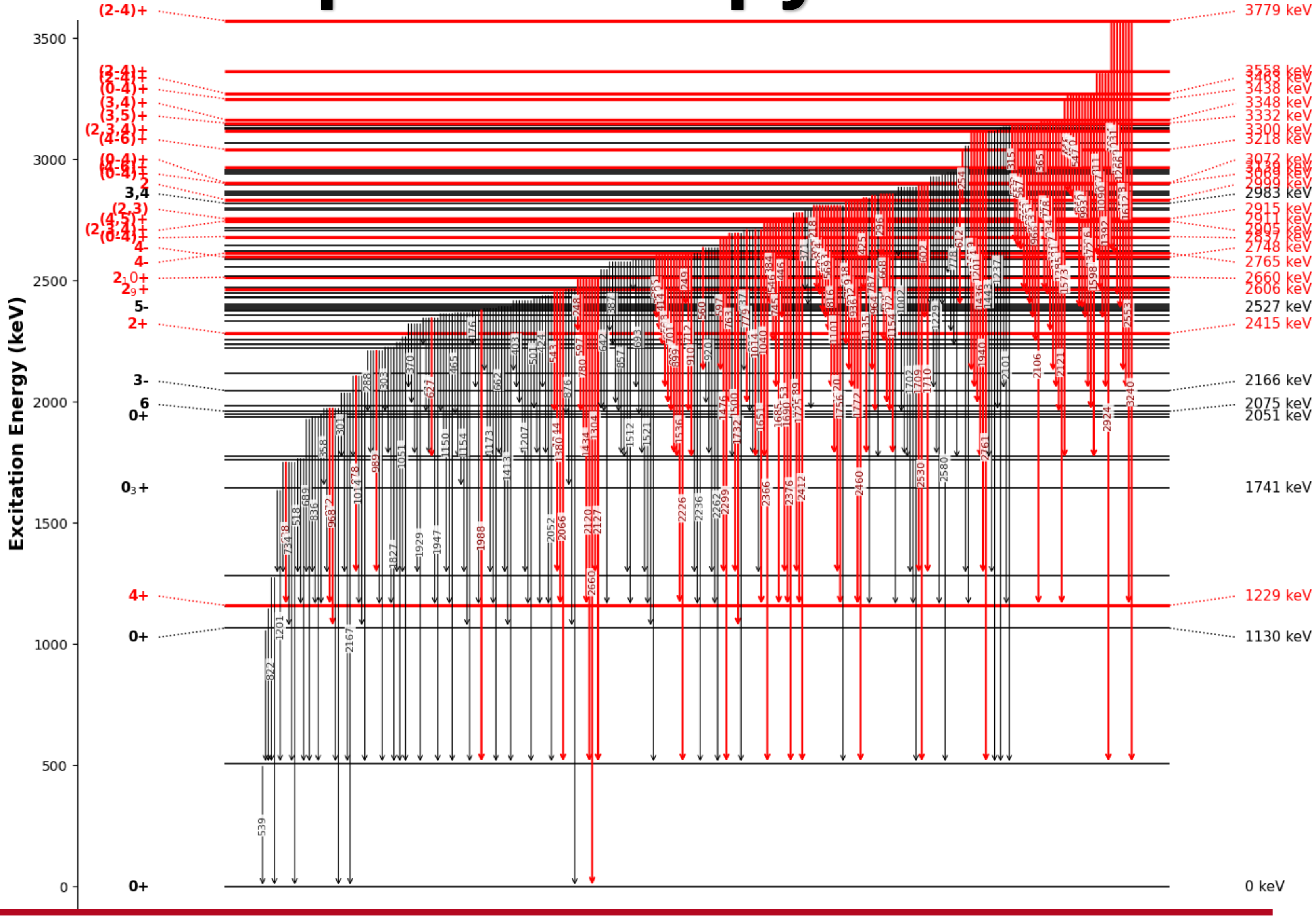
- **Total Identified**: **305** transitions found.
- **New Discoveries**: **105** newly discovered.

Mixing Ratios:

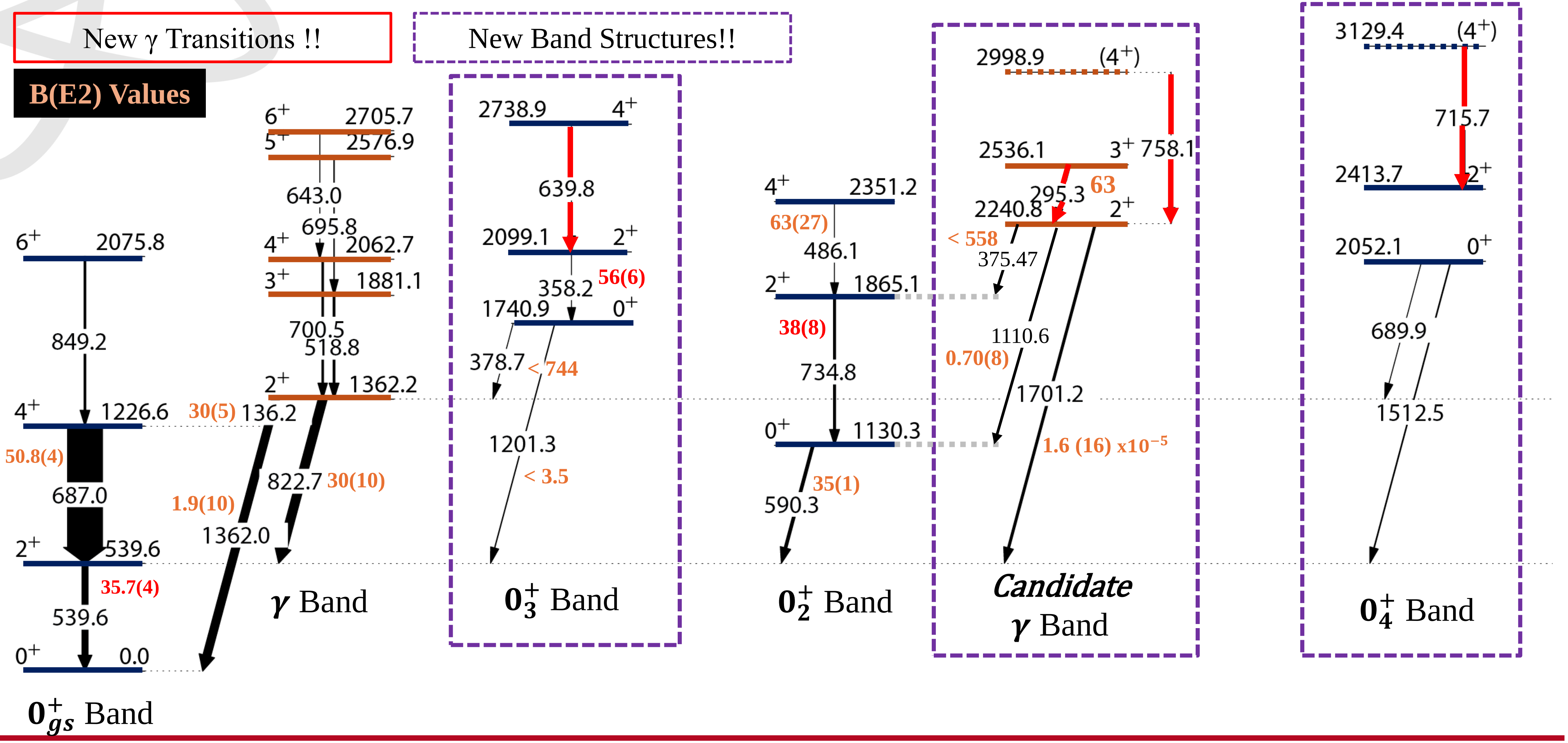
- **Total Extracted**: **30** unique mixing ratios.
- **Literature updates**: **7** re-measured values.

Band Structures:

- **02+ Band + γ Band structures.**
- **03+ Band + 04+ Band determined!**



Results: Built Structure within 100Ru



Summary/Next Steps

100Ru ***has signatures*** of **shape coexistence**, the assertion cannot be made based *Soley on level structure analysis.*

→ **We require a methodology of to extract the shape parameters!**

Solution: **Coulomb excitation studies** which can **extract β and γ parameters** in a **model-independent method!**

Next Steps are under progress:

Our group and **collaborators** from **HIL in Warsaw, Poland** are doing exactly that!

100Ru Coulomb excitation was successfully completed!

Our updated results from this analysis will allow the precise evaluations of the gamma and beta parameters!

Thank you

S. Pannu[1], P.E. Garrett[1], V. Bildstein[1], M. Rocchini[2] , J. Froats[1], K. Stoychev[1], D. Kalaydjieva[1] , M. Beuschlein[4], G. Colombi[1], K. Ide[4], C. Michelagnoli[3], J.R. Muria[6], K. Ortner[5], C. Petrache[7], N. Pietralla[4] , T. R. Rodríguez[8], K.H Yung[3]

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8. *Departamento de Física Teórica, Universidad Autónoma de Madrid, Spain*

Reference

[1] T. Konstantinopoulos *et al.*, Phys. Rev. C **95**, 014309 (2017).

[2] T. R. Rodríguez and G. Martínez-Pinedo, "Energy Density Functional Study of Nuclear Matrix Elements for Neutrinoless $\beta\beta$ Decay," Phys. Rev. Lett. **105**, 252503 (2010).

[3] T. R. Rodríguez, Departamento de Física Teórica, Universidad Autónoma de Madrid, Spain (theoretical calculations / private communication).

[4] P. E. Garrett, "Shape coexistence in the Sr – Ru isotopes," Presentation at the International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (CGS).

[5] National Nuclear Data Center (NNDC), Brookhaven National Laboratory. Data available at: https://www.nndc.bnl.gov/

[6] Australian National University, Interactive Chart of Nuclides. Available at: https://people.physics.anu.edu.au/~ecs103/chart/

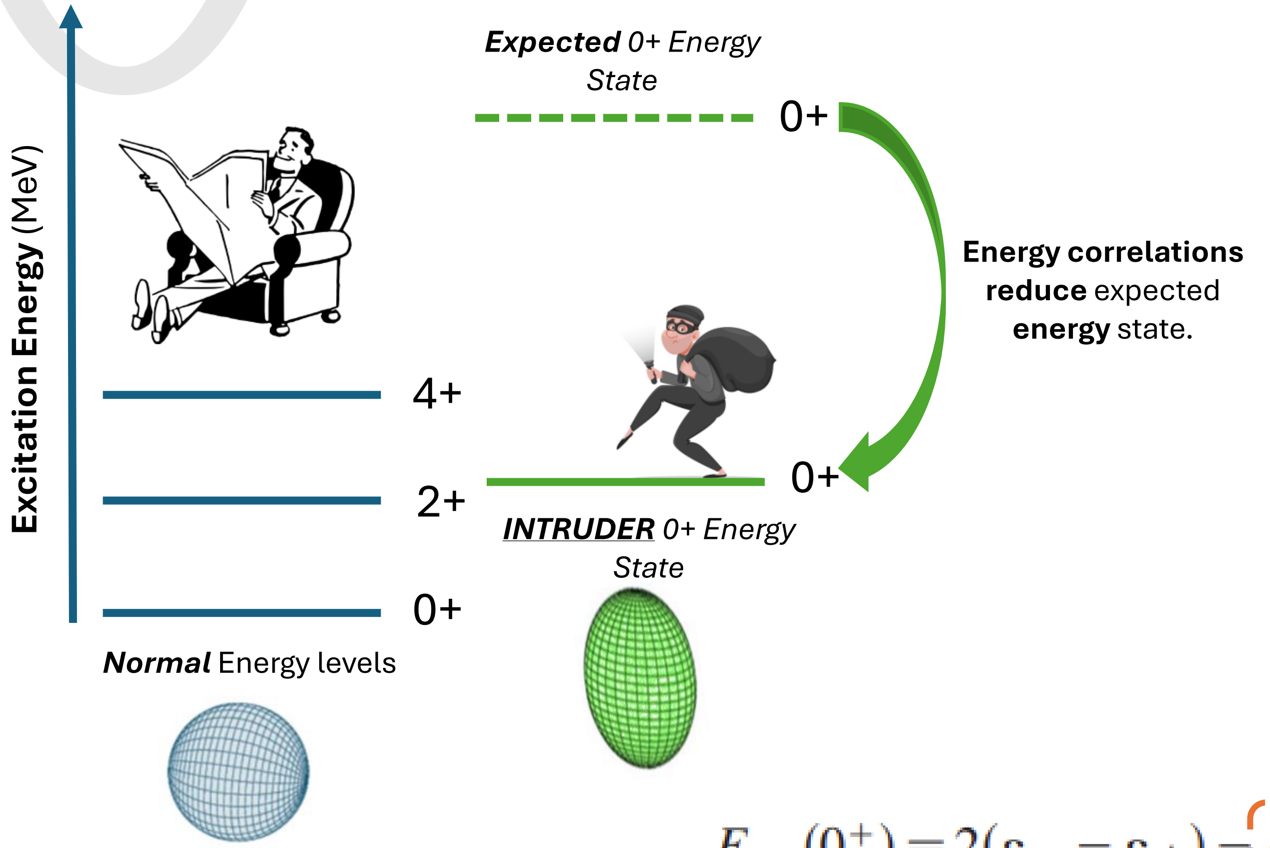
[7] Bonatsos *et al.*, "Triaxiality in Mo and Ru," Phys. Rev. C **133**, 054306 (2026).

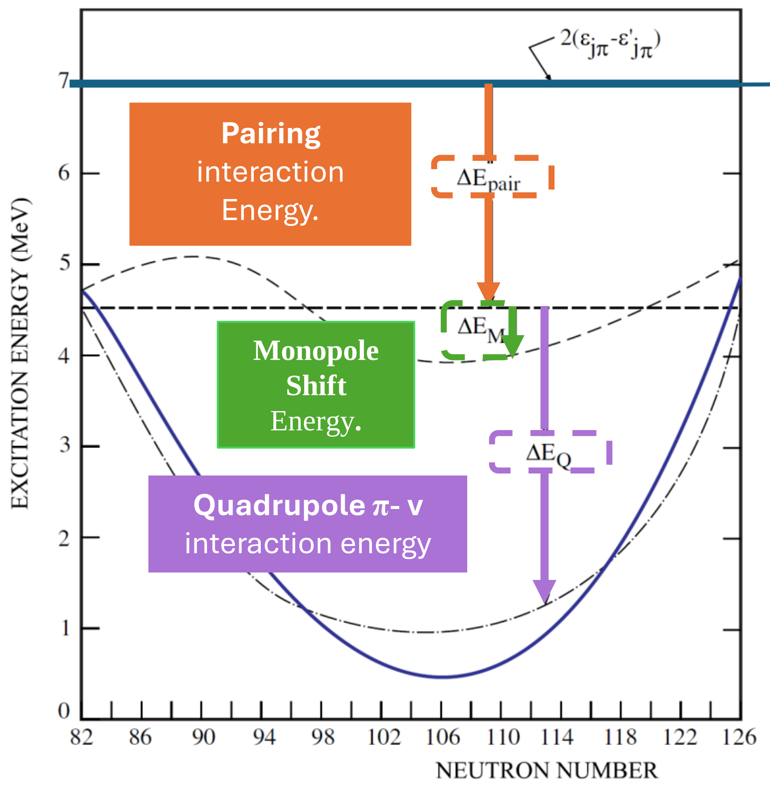
[8] Maass *et al.*, "Fingerprints of Triaxiality in Charge Radii of Neutron-Rich Ruthenium," Phys. Rev. C **135**, 202501 (2025).

[9] D. T. Doherty *et al.*, "Triaxiality near the ^{110}Ru ground state from Coulomb excitation," Phys. Lett. B **766**, 334 (2017).

BACKUP SLIDES

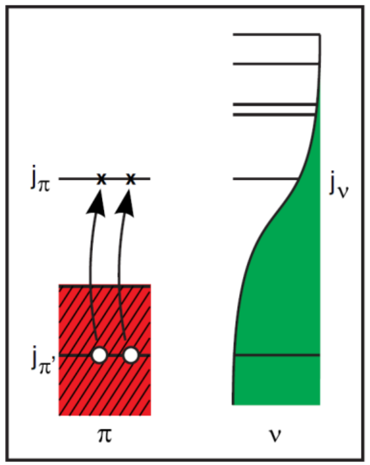
Backup: Phenomenon of Shape Coexistence.





Unperturbed Energy of Particle-Hole Excitation

Particle-Hole Excitation



2 Protons are excited out of the closed core.

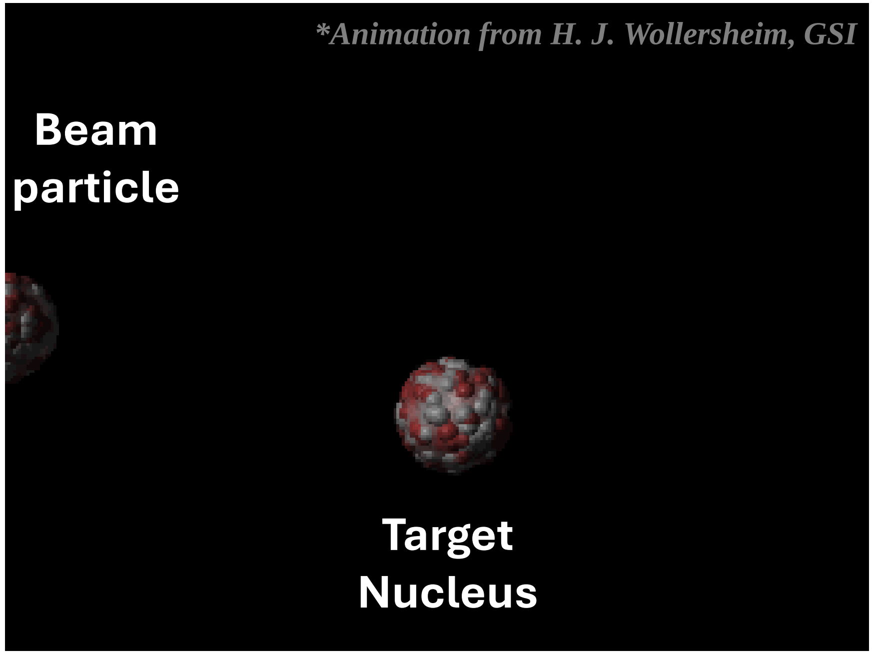
$$E_{\mathrm{intr}}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\mathrm{pair}} + \Delta E_M + \Delta E_Q$$

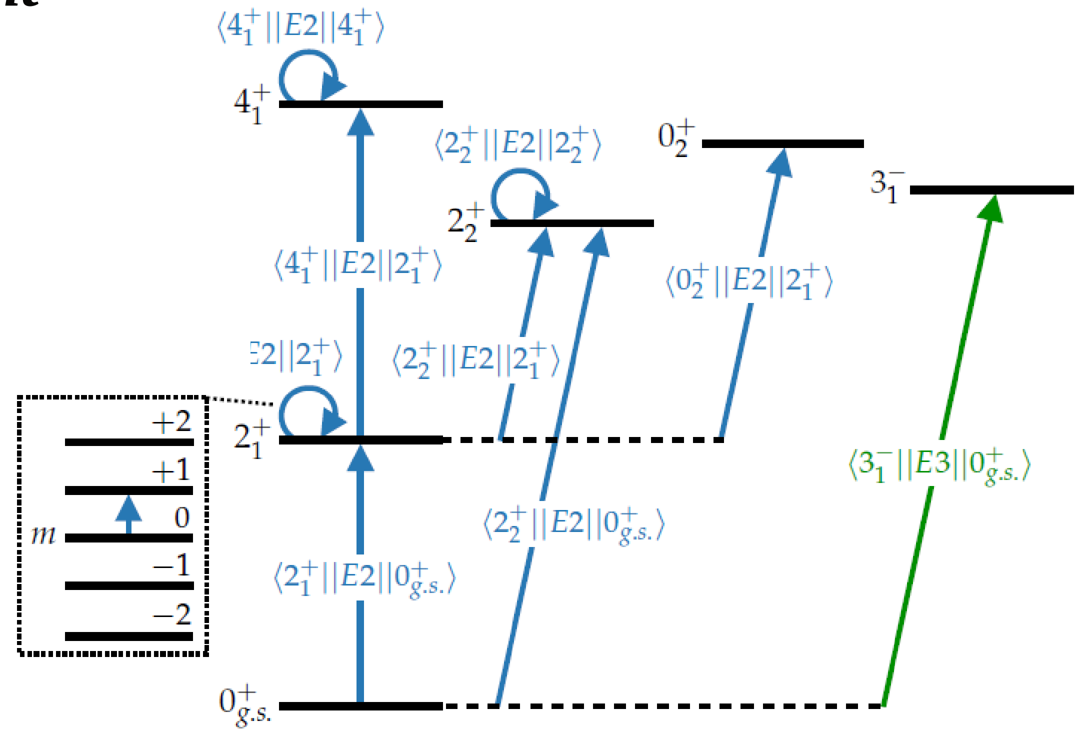
Heyde and Wood, RMP 83, 1467 (2011)

Backup: Coulomb Excitation, Probe for Shapes

- **Direct Reaction: Only** Electromagnetic interactions
- **Best** method for extracting ***shape invariant* parameters.**
  - *Model independent results!*

Excitation via EM Interactions / De-excitation via γ emissions.





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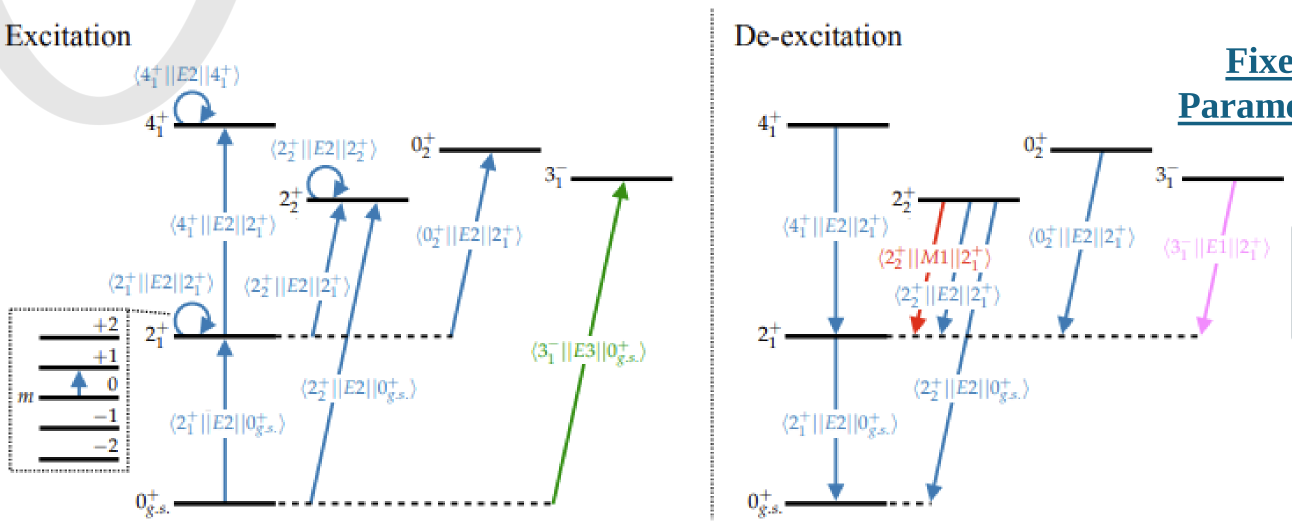
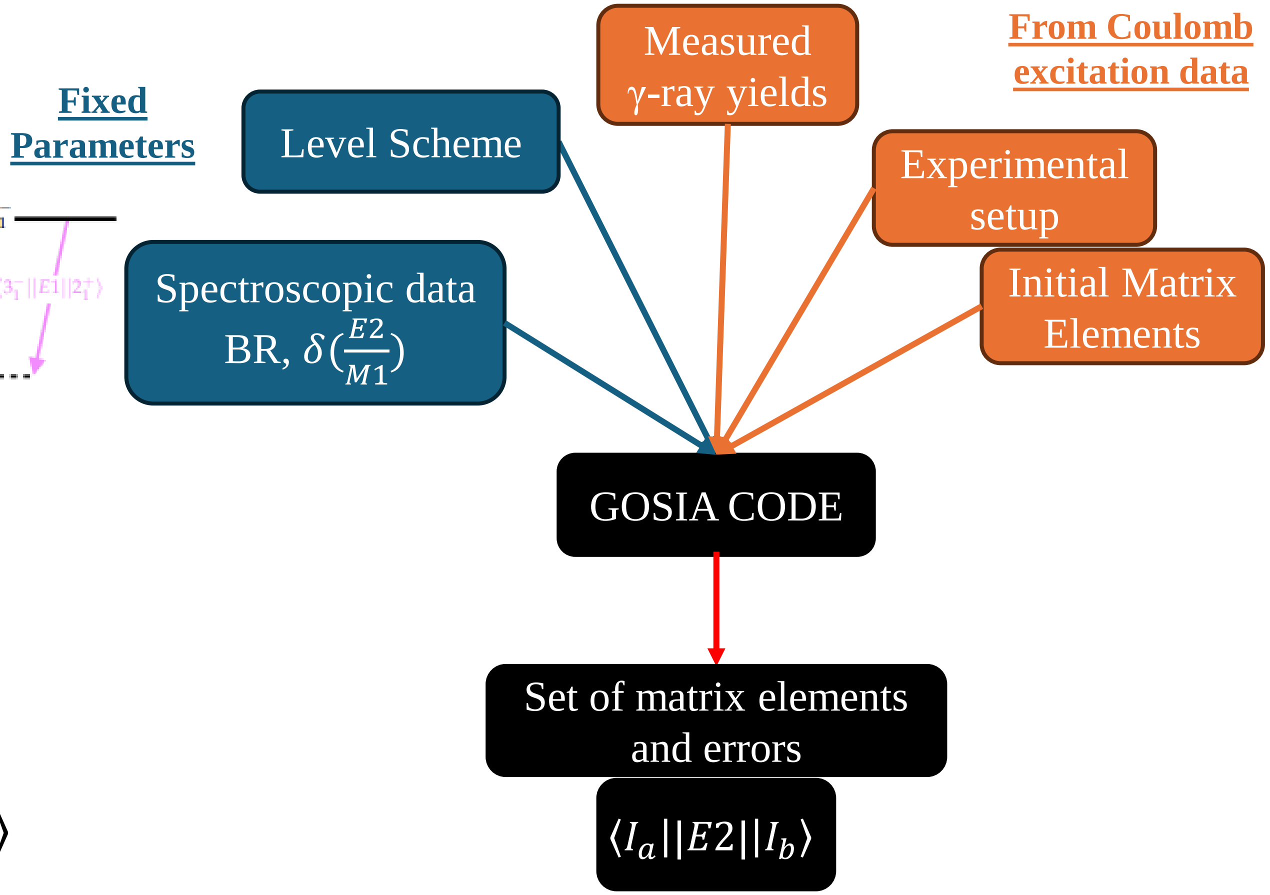
Backup: Coulomb Excitation, Probe for Shapes





$$\langle I_n|Q^2|I_n\rangle = \frac{\sqrt{5}(-1)^{2I_n}}{\sqrt{2I_n+1}}\sum_m M_{nm}M_{mn}\begin{Bmatrix} 2 & 2 & 0 \\ I_n & I_n & I_m \end{Bmatrix}, \sim\langle\beta^2\rangle$$

$$\langle I_n|Q^3\cos 3\delta|I_n\rangle = -\sqrt{\frac{35}{2}}\frac{(-1)^{2I_n}}{2I_n+1}\sum_{ml} M_{nl}M_{lm}M_{mn}\begin{Bmatrix} 2 & 2 & 2 \\ I_n & I_m & I_l \end{Bmatrix}\sim\langle\beta^3 cos3\gamma\rangle$$

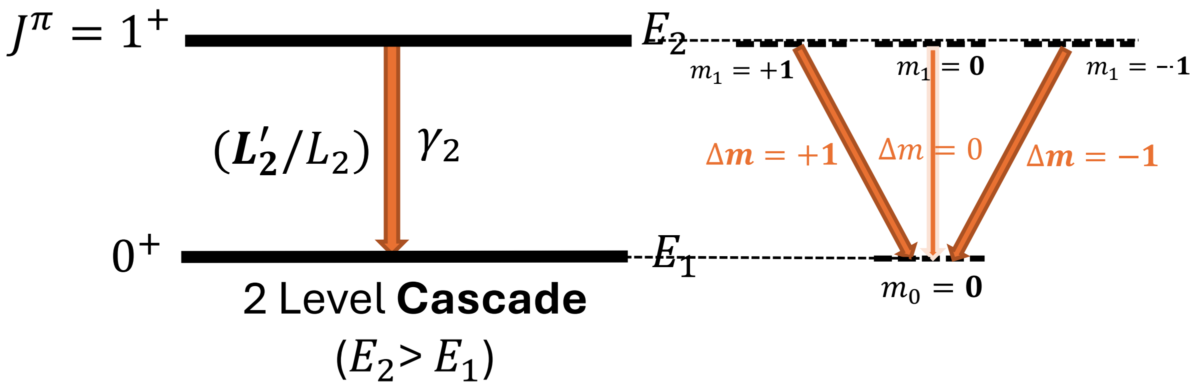
$$M_{ab} \equiv \langle I_a||E2||I_b\rangle$$

Backup: Coulomb Excitation, Probe for Shapes

Angular Correlations

Behind the scenes

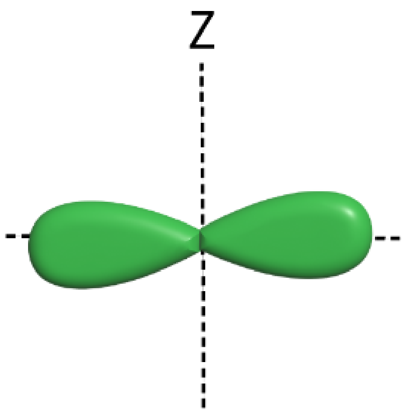
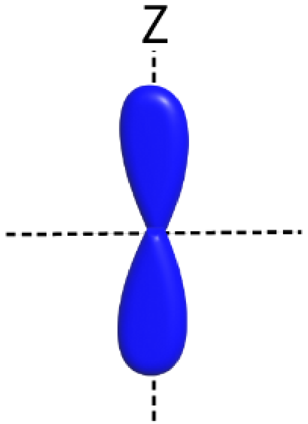
Degenerate
Magnetic Sub-states



Multipole character has an **angular emission probability.**

$$(L = 1)\ (\Delta m = 0)\ \propto \sin^2\theta$$

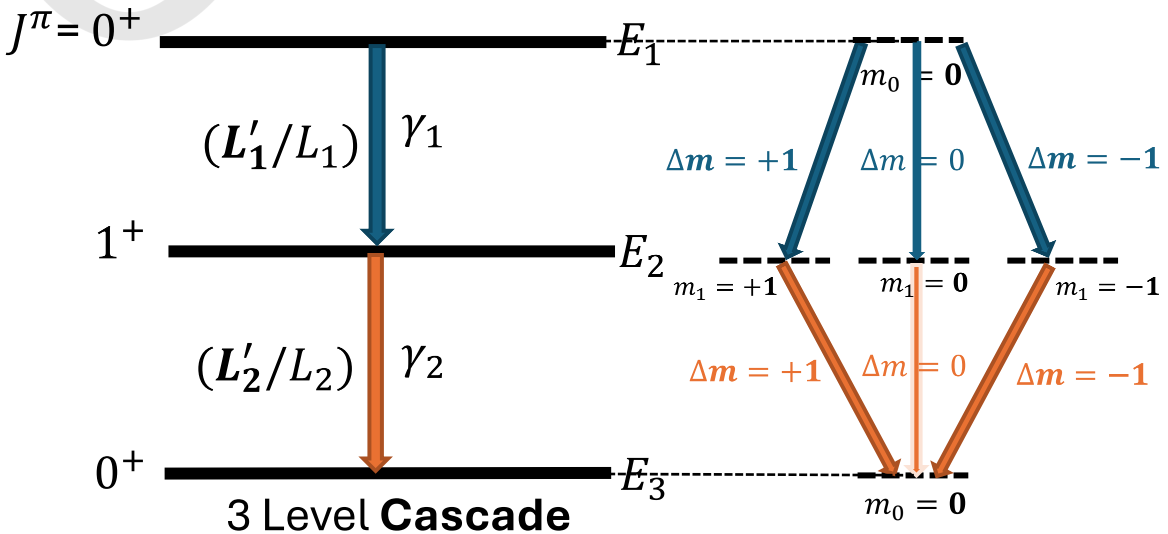
$$(L = 1)\ (\Delta m = \pm 1)\ \propto \frac{1}{2}(1 + \cos^2\theta)$$

Δm = +/- 1	Δm = 0
$W(\theta) = \frac{1}{2}(1 + cos^2(\theta))$	$W(\theta) = sin^2(\theta)$
	

Backup: Coulomb Excitation, Probe for Shapes

Angular Correlations

Behind the scenes



3 Level **Cascade**

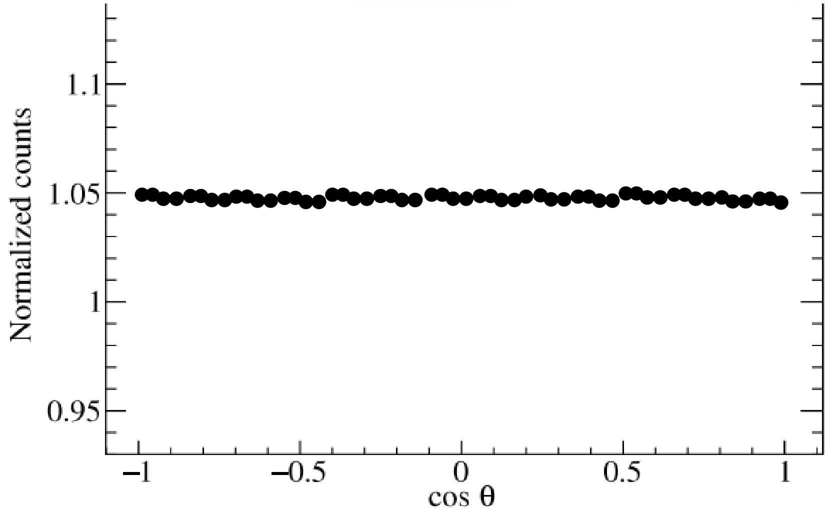
$(E_1 > E_2 > E_3)$

Multipole character has an **angular emission probability.**

$$(\boldsymbol{L} = \mathbf{1})\ (\Delta\boldsymbol{m} = 0)\ \propto \sin^2\theta$$

$$(\boldsymbol{L} = \mathbf{1})\ (\Delta\boldsymbol{m} = \pm 1)\ \propto \frac{1}{2}(1 + \cos^2\theta)$$

$$\boldsymbol{W_{exp}(\theta)} \propto \frac{1}{2}(1 + \cos^2\theta) + \frac{1}{2}(1 + \cos^2\theta) + \sin^2\theta \propto \mathbf{1}$$

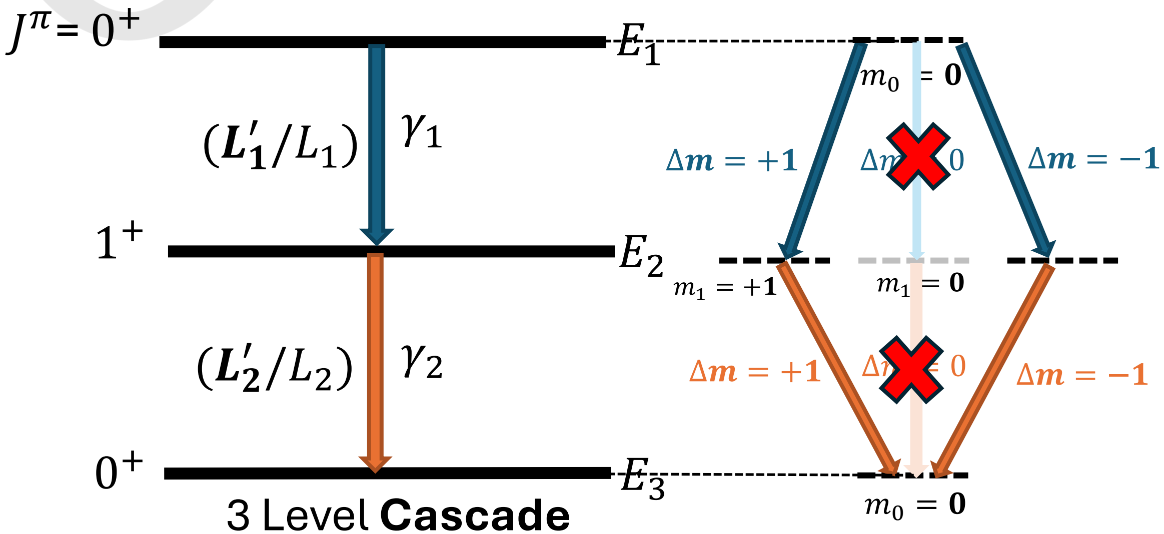


Backup: Coulomb Excitation, Probe for Shapes

Angular Correlations

Behind the scenes

Measure angular emission **probability** $\left(W_{exp}(\theta) \right)$ with respect to $\hat{z}$ direction of $\boldsymbol{\gamma_2}$.

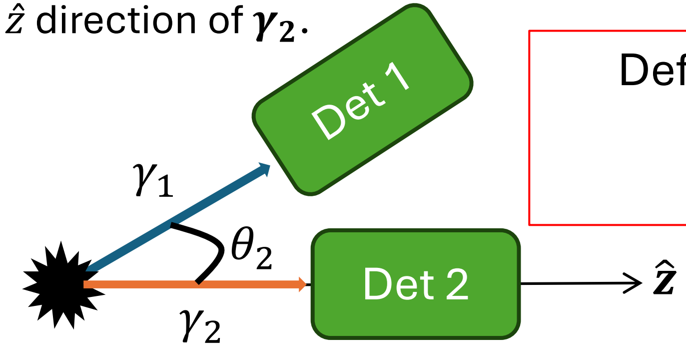


3 Level **Cascade**

$(E_1 > E_2 > E_3)$

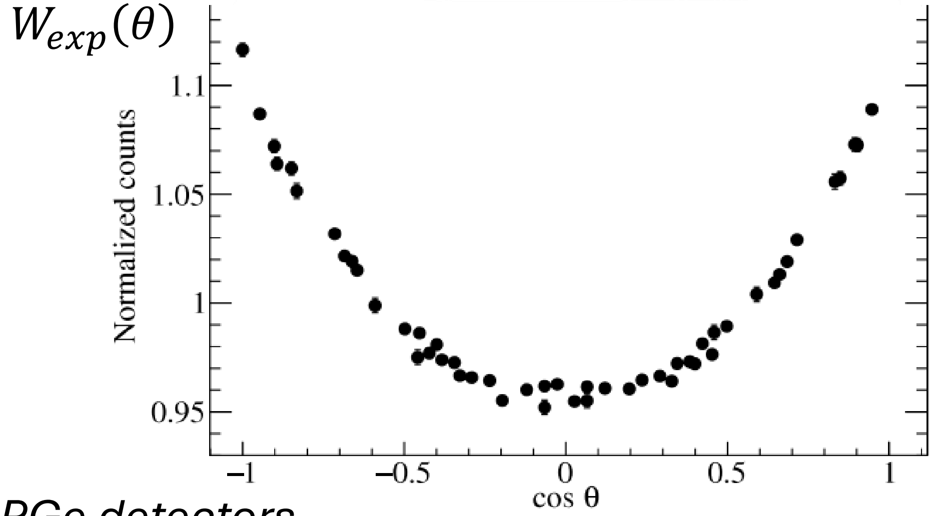
✗ $(\boldsymbol{L = 1})\ (\Delta \boldsymbol{m} = 0) \propto \sin^2\theta$

$$(\boldsymbol{L = 1})\ (\Delta \boldsymbol{m} = \pm 1) \propto \frac{1}{2}(1 + \cos^2\theta)$$



Define $\boldsymbol{\gamma_2}$ **as** the fixed $\hat{\boldsymbol{z}}$ direction.

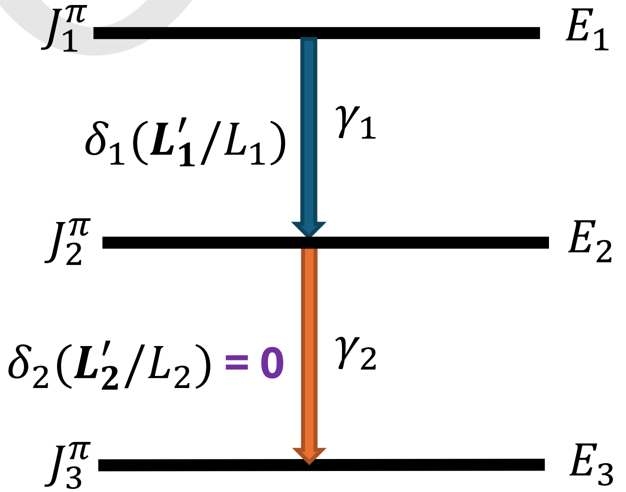
$\theta_1 = 0$



*Note: Det **1** and **2** are **equivalent** HPGe detectors.*

Backup: Angular Correlations Methodology

Angular Correlations



3 Level **Cascade**
(E_1>E_2> E_3)

$$\boldsymbol{L'_i} = L_i + 1$$

Where L_i is the multipole.

$$W_{theo}(\theta_i) = 1 + \boldsymbol{a_2} P_2(cos\theta_i) + \boldsymbol{a_4} P_4(cos\theta_i)$$

$$a_k = B_k(J_1 J_2)\, D_k(J_2 J_3)$$

Constant terms **tabulated** in [5]

Mixing Ratio dependence

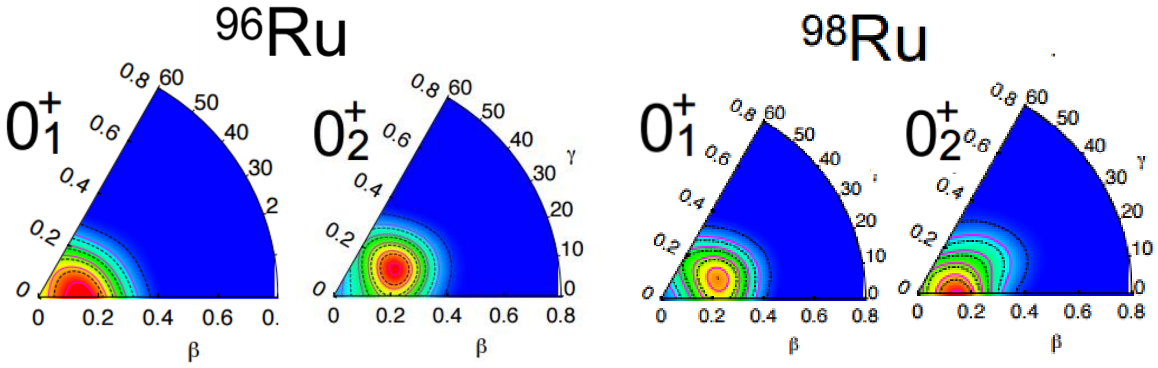
$$B_k(J_1 J_2) = \frac{R_k(L'_1 L'_1\, J_2 J_1) + (-)^{L'_1 - L_1} 2\delta_1 R_k(L'_1 L_1\, J_2 J_1) + \delta_1^2 R_k(L_1 L_1\, J_2 J_1)}{1 + \delta_1^2}$$

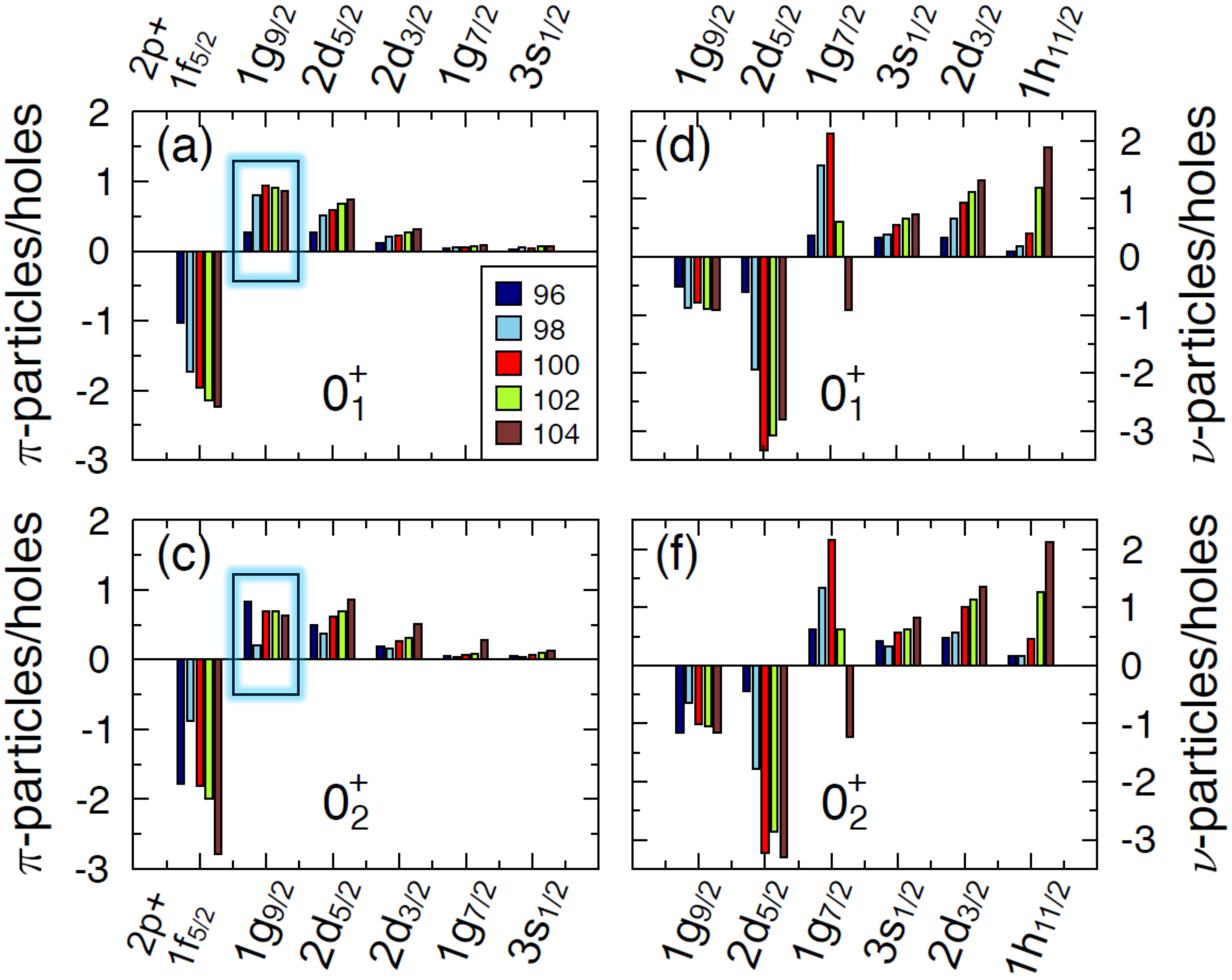
$$D_k(J_2 J_3) = \frac{R_k(L'_2 L'_2\, J_2 J_3) + 2\delta_2 R_k(L'_2 L_2\, J_2 J_3) + \delta_2^2 R_k(L_2 L_2\, J_2 J_3)}{1 + \delta_2^2} = R_k(L'_2 L'_2\, J_2 J_3)$$

$\boldsymbol{\delta_2 = 0}$, as $\boldsymbol{\gamma_2}$ is usually a pure **Multipole** ($L'_i = L_i$) transition and has no mixing.

Backup: Inversion @ 96-98 Ru

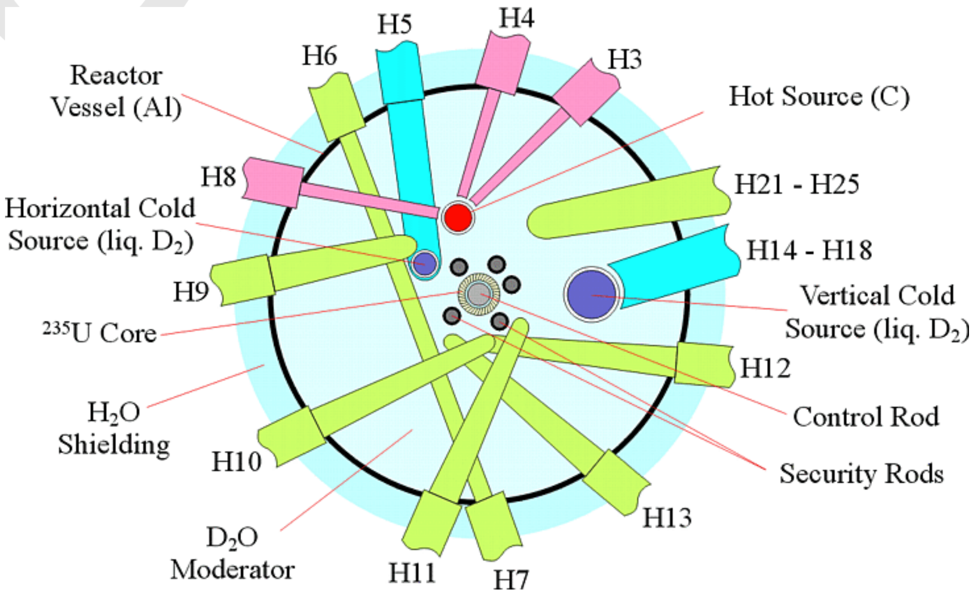
- Occupancies of orbitals with respect to spherical HF states extracted
- Generally, *p-h* content increases as *N*, reflecting higher deformation in both gs and 0_2^+ state
- Change in proton *p-h* content for 0_1^+ and 0_2^+ states from ^{96}Ru to ^{98}Ru – crossing of configurations in calculations
- Large increase in neutron *p-h* content occurring from ^{96}Ru to ^{100}Ru





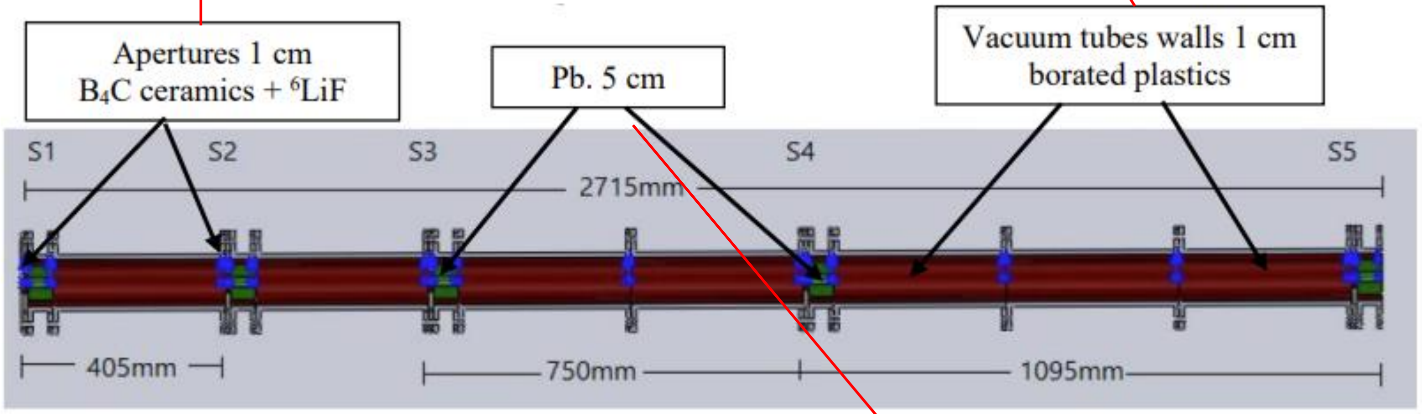
PG *et al.*, PLB 809, 135762 (2020)

Backup: Beamline information



Both have a high neutron capture cross section

Absorb the neutrons backscattered from the apertures.



Avoids the γ ray background from boron being carried through beamline

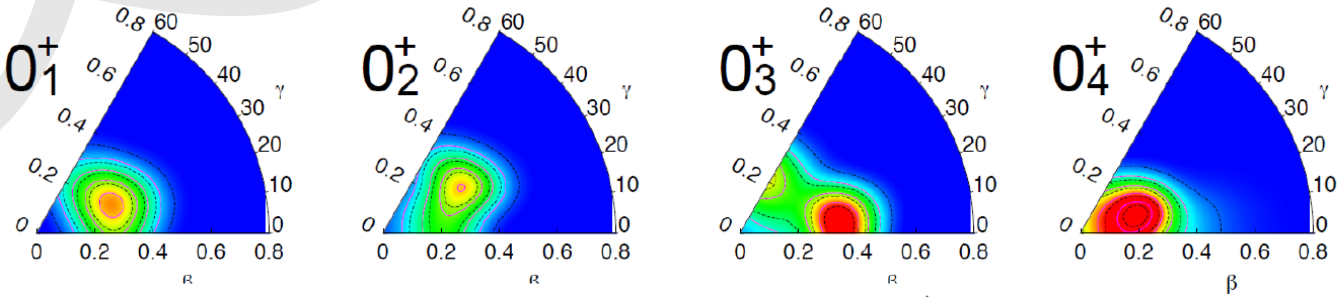
The beam tubes are made of thin-walled aluminum metal, which is virtually transparent to neutrons.

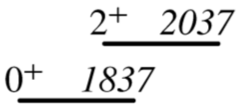
The neutron beams are ***guided*** in nickel-coated glass.

High reflectivity, which contain the neutrons in the guides.

Backup: Overestimation of Collectivity in 102Ru

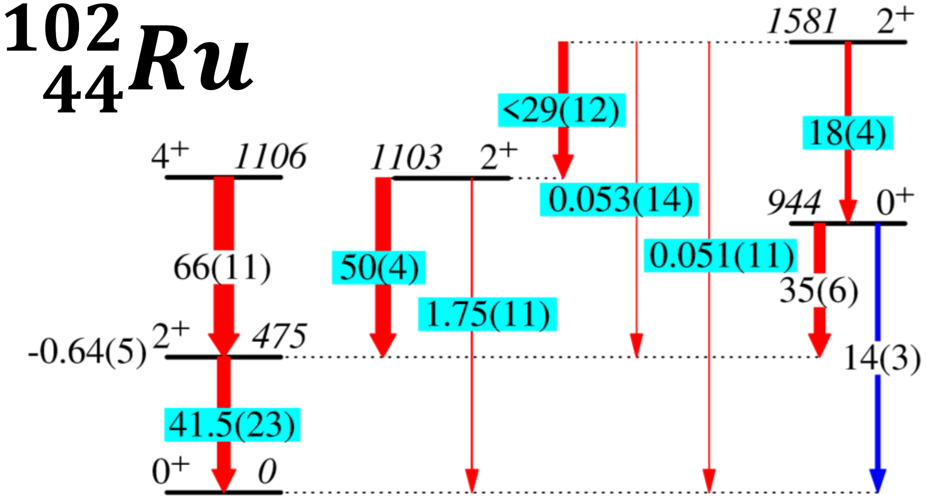
Predictions overestimate the degree of deformation of all states



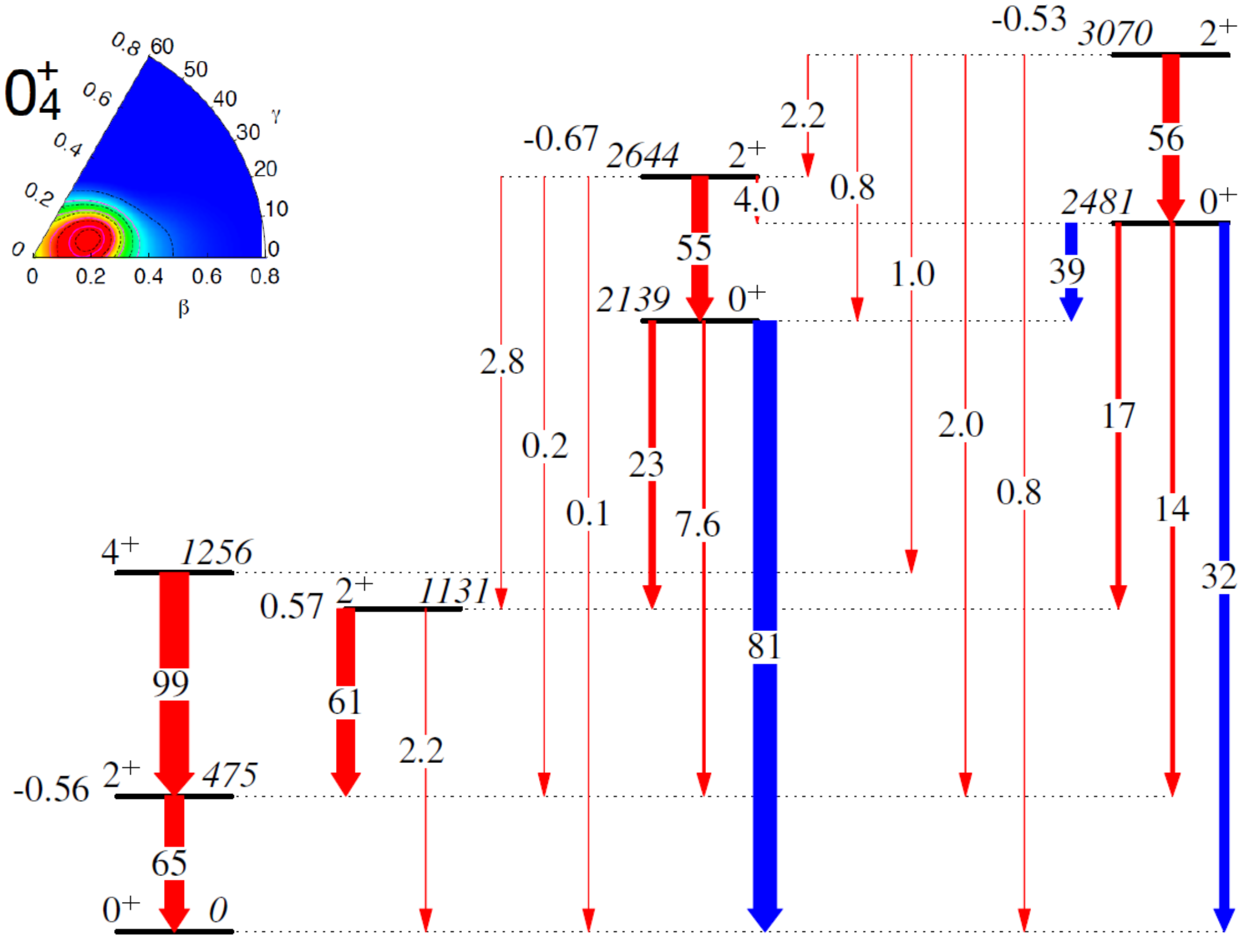


Garrett, P. E, *et al.* (2022). *Physical Review. C*, *106*(6).

$^{102}_{44}Ru$



Experimental results from Coulomb excitation.



Beyond Mean Field Calculations

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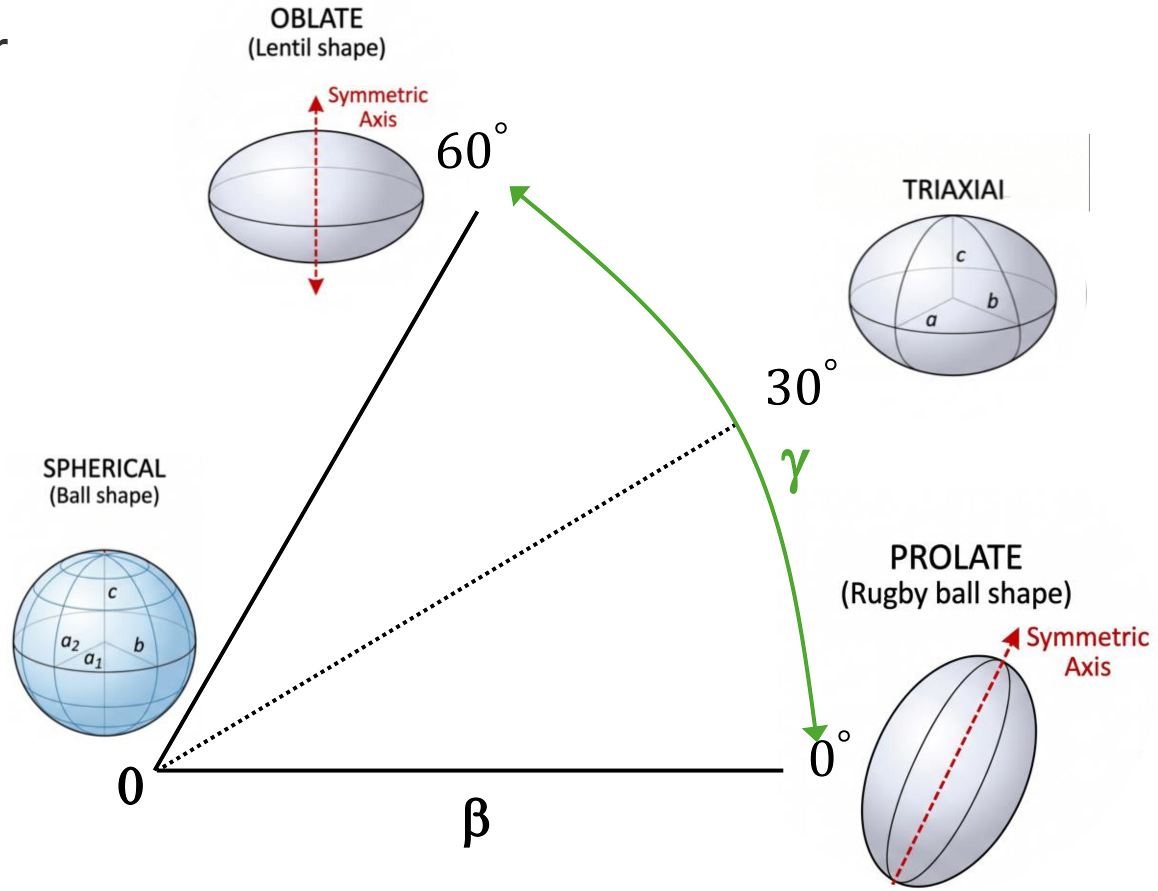
Backup: BMF Wavefunction Plots

<u>Model Complexity</u>: Facilitates deeper insights into **structural evolution** and **configuration mixing**.

Wavefunction distributions in **(β,γ)** plots.

Allows **<u>access to</u>** state **deformation properties**.



Backup: Configuration interactions Calculations

$^{102}_{44}Ru$ (n, γ) **results:**

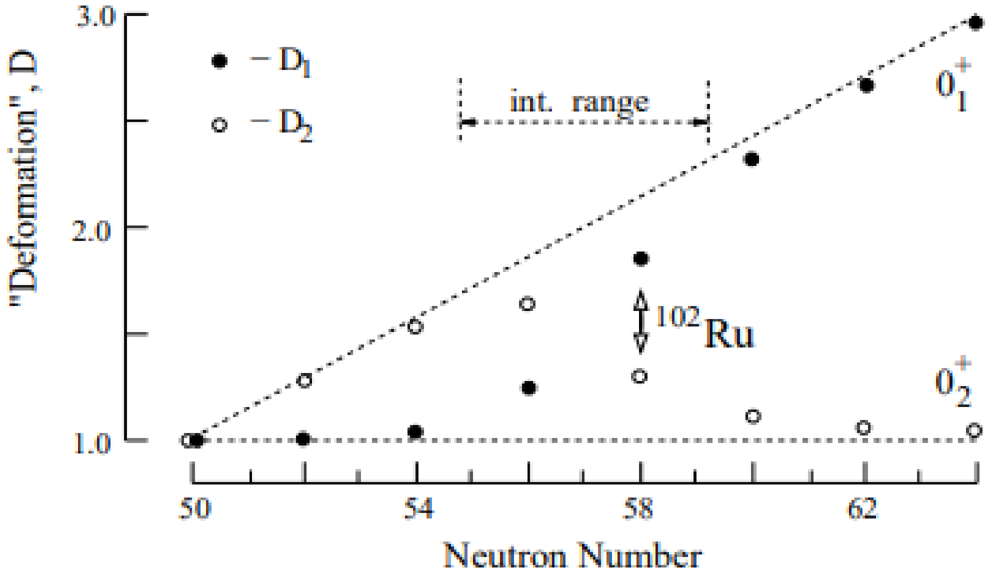
Mixing amplitudes

$$D_1 = \langle 0_1^+|D|0_1^+\rangle = \alpha D_{1u} + \beta D_{2u}$$

$$D_2 = \langle 0_2^+|D|0_2^+\rangle = -\beta D_{1u} + \alpha D_{2u}$$

0_1^+ → Past crossing point **collectivity increases.**

0_2^+ → Past crossing point **collectivity decreases.**



Exchange of properties between the **0+ configurations**, as simulated in **two-level mixing**.

0_3^+ experimental results were **scarce** and **unable** to **explore** its **effect on lower 0+ configurations**

Backup: Configuration interactions Calculations

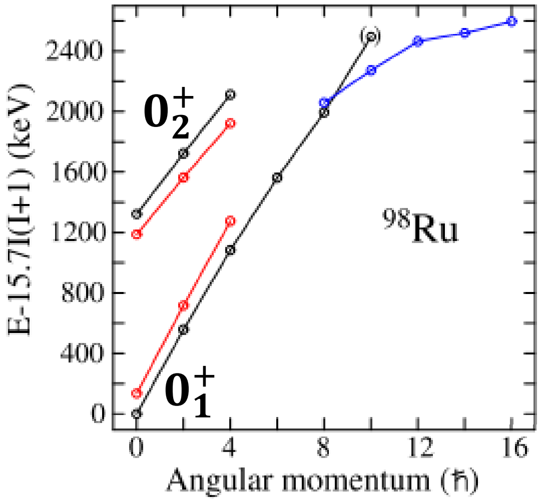
$^{98}_{44}\boldsymbol{Ru}$ results:

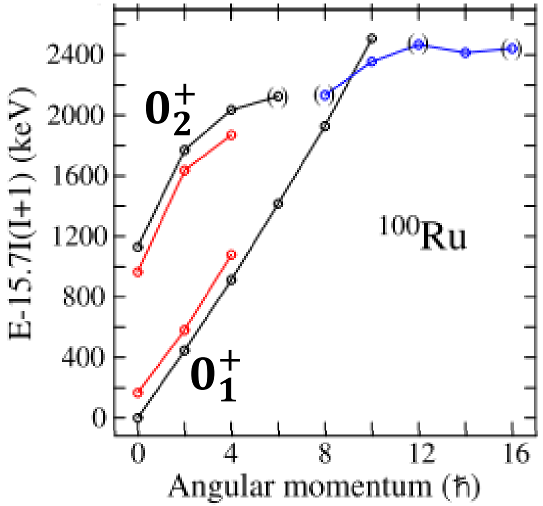
Slope of lines has inverse relation to moment of Inertia.

$^{98}_{44}\boldsymbol{Ru}$: $\mathbf{0_1^+}$ Moment of inertia is Small.
$\mathbf{0_2^+}$ Moment of inertia is **Large**

$^{100}_{44}\boldsymbol{Ru}$: $\mathbf{0_1^+}$ Moment of inertia is **Large**.
$\mathbf{0_2^+}$ Moment of inertia is Small

$^{102}_{44}\boldsymbol{Ru}$: $\mathbf{0_1^+}$ Moment of inertia is Large.
$\mathbf{0_2^+}$ Moment of inertia is Small





$$\boldsymbol{E_{rot}} = \frac{\hbar}{\mathbf{2T}}\boldsymbol{I(I+1)}$$

Moment of Inertia