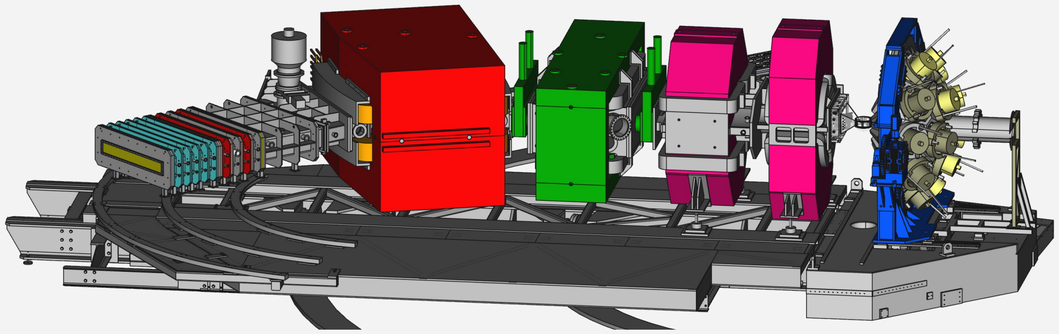
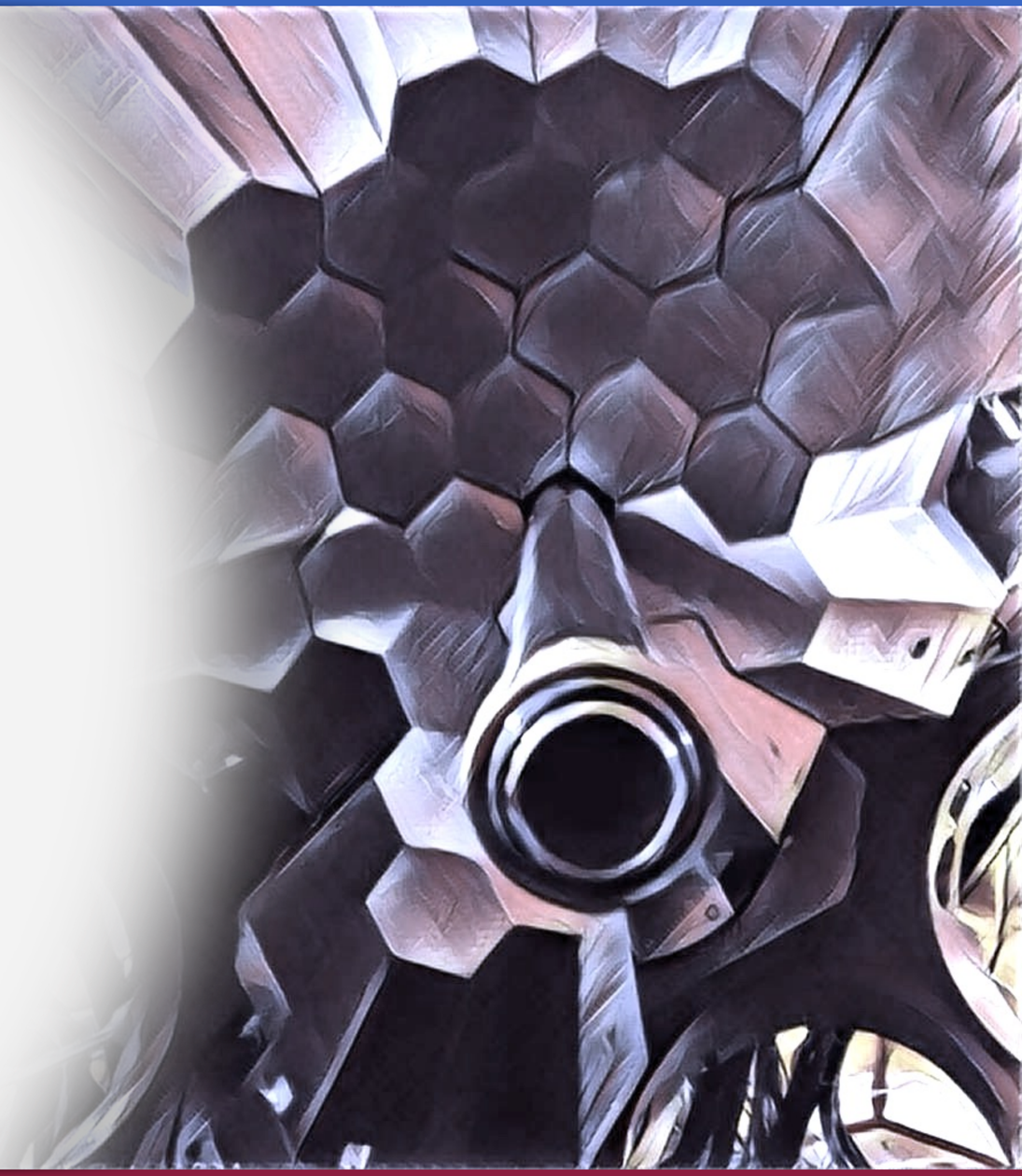
NUCLÉAIRE & PARTICULES

Shape evolution in the N≈60 region studied by fission-fragment γ-ray spectroscopy with AGATA

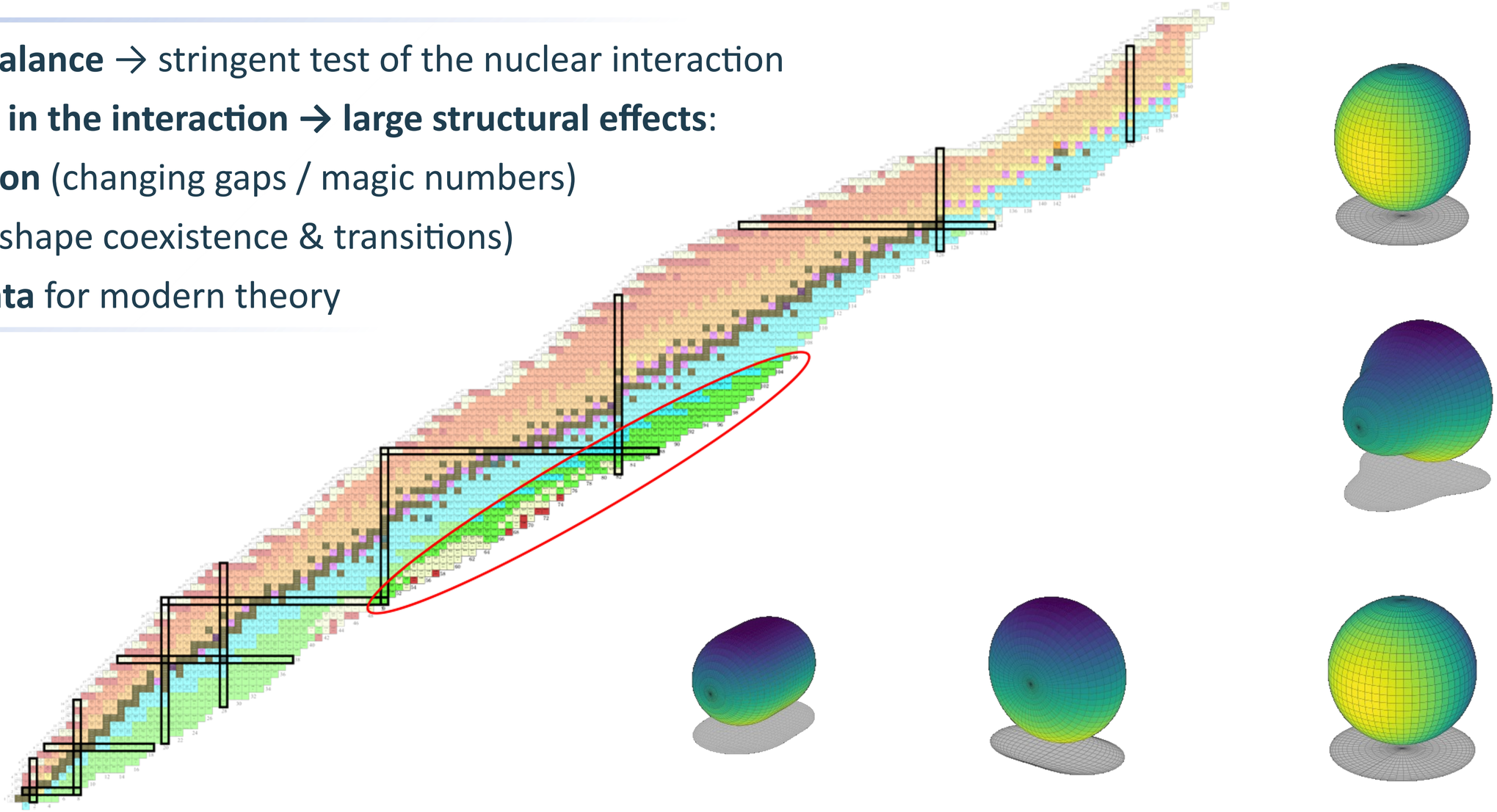
Jérémie Dudouet (IP2I Lyon, CNRS)





Neutron-rich nuclei as a laboratory for the nuclear interaction

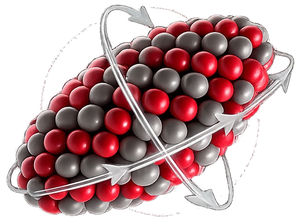
- **Large N/Z imbalance** → stringent test of the nuclear interaction
- **Small changes in the interaction → large structural effects**:
  - ➥ **shell evolution** (changing gaps / magic numbers)
  - ➥ **collectivity** (shape coexistence & transitions)
- **Benchmark data** for modern theory



Quadrupole collectivity and its experimental fingerprints

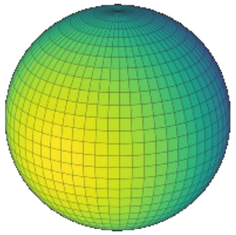
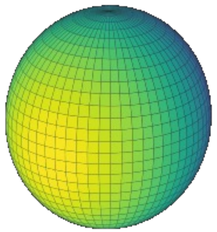
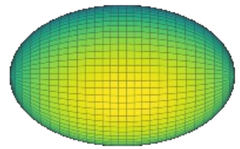
Collective motion of nucleons

- Coherent proton–neutron quadrupole interaction
- Enhanced E2 transition strength

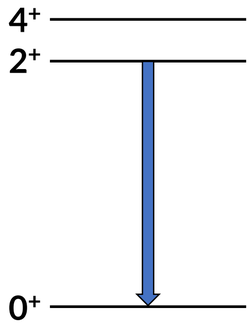
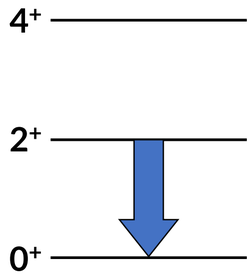
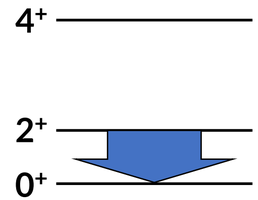


Collective quadrupole correlations drive nuclear deformation

Nuclear deformation

	Spherical	Spherical-vibrator	Rigid-rotor
			
$ß_2$	≈ 0	≈ 0.1	≈ 0.4

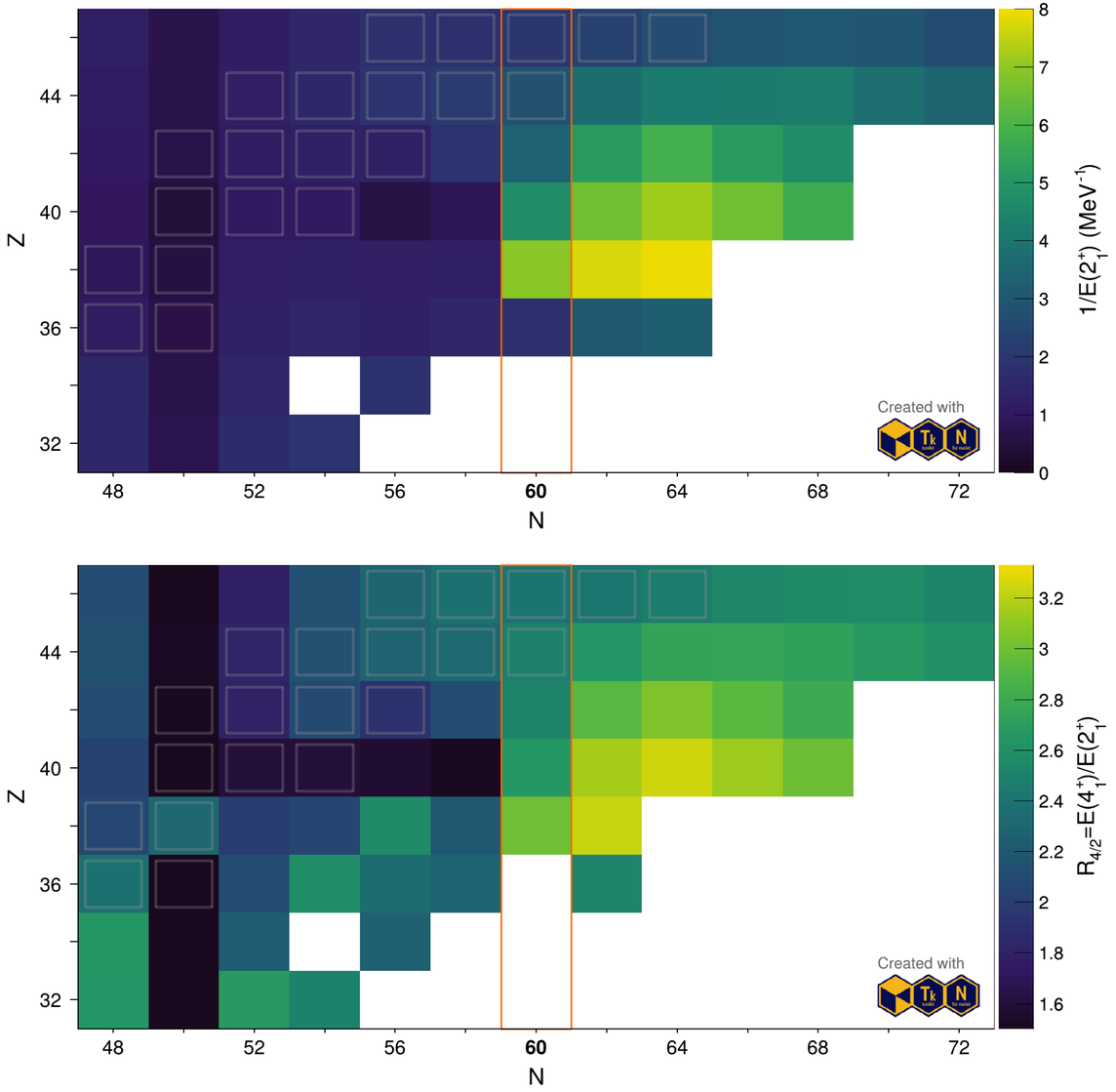
Experimental observables

			
$R_{4/2} = E_{4^+}/E_{2^+}$	< 2	≈ 2	≈ 3.33
B(E2) (W.u)	≈ 0	≈ 50	≈ 100

A sudden shape transition at N = 60

- **Spectroscopic reorganization at N = 60 (Z ≈ 38–40)**

  - Collapse of $E(2^+_1)$
    - ➥ Emergence of a new deformed minimum in the energy surface
  - $R_{4/2}$ approaching rigid-rotor limit
    - ➥ Onset of a rotational regime



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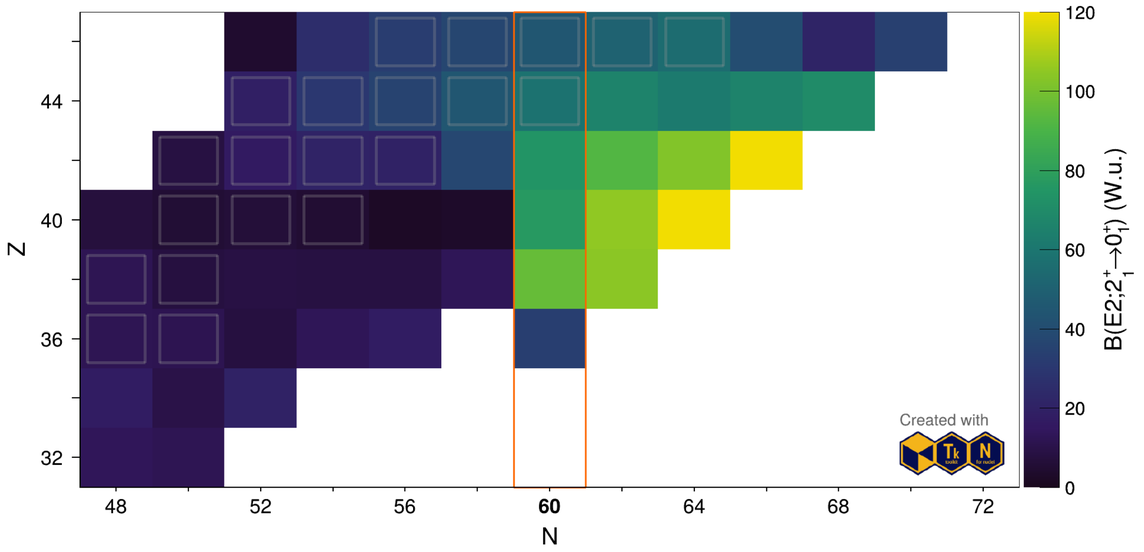
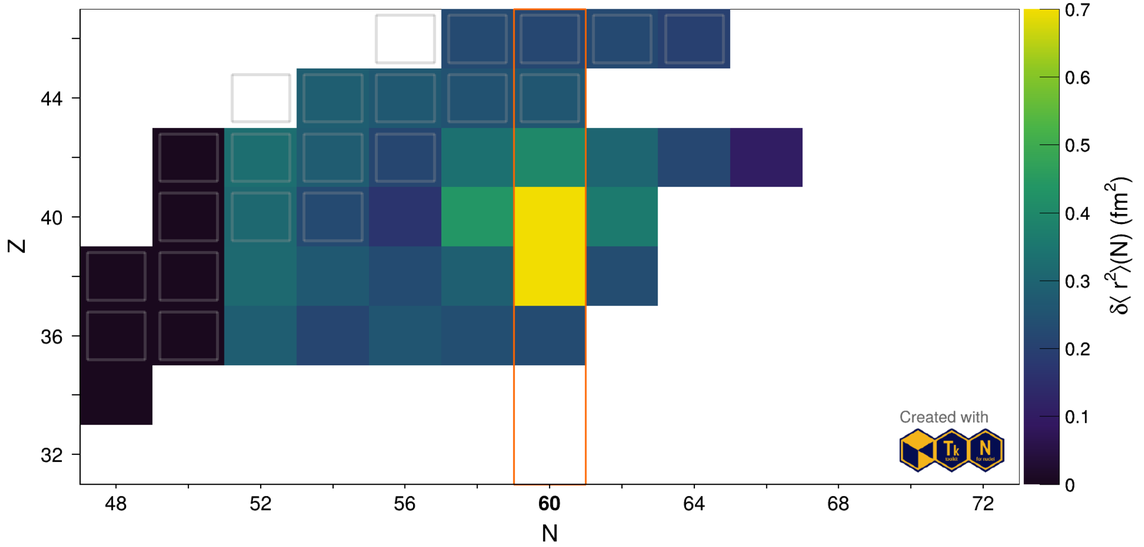
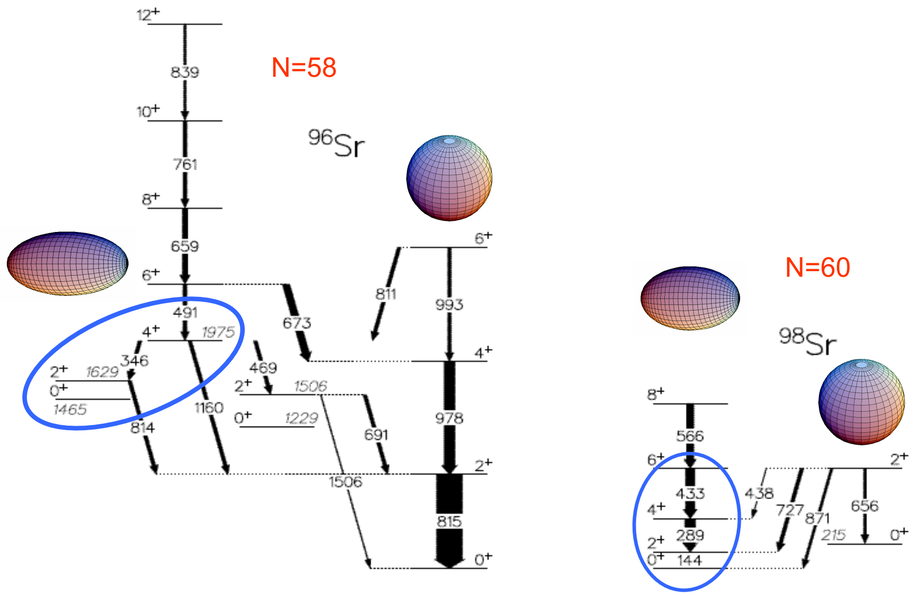
    - ➥ Emergence of a new deformed minimum in the energy surface
  - ➢ $R_{4/2}$ approaching rigid-rotor limit
    - ➥ Onset of a rotational regime
- **Intrinsic structural change**
  - ➢ Strong increase of B(E2)
    - ➥ Build-up of coherent quadrupole collectivity
  - ➢ Abrupt jump in charge radius
    - ➥ Stabilization of a new deformed equilibrium



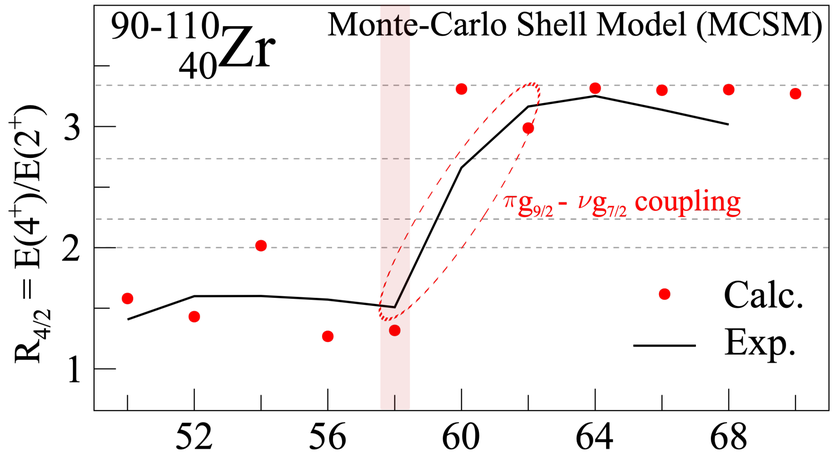


Caused by a shape coexistence phenomenon

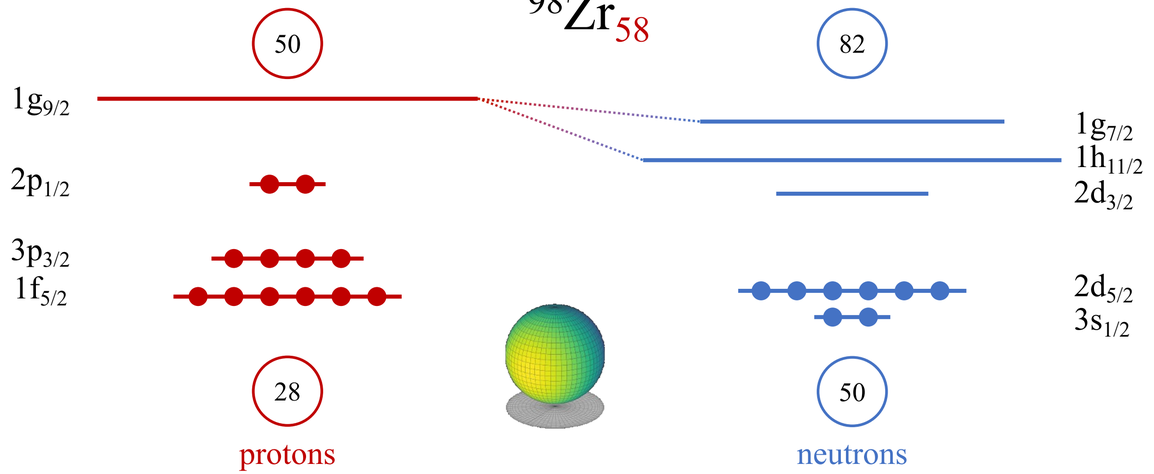
- Coexistence between a spherical and deformed band:
  - ➥ **Inversion of the two bands at N=60**
- Theoretically explained by Monte-Carlo Shell Model at Z=40
  - ➥ **Effect of $\pi g_{9/2}$ and $\nu g_{7/2}$ tensor force coupling**



E. Clement et al. PRL 116, 022701 (2016)



T. Togashi et al. PRL 117, 172502 (2016)



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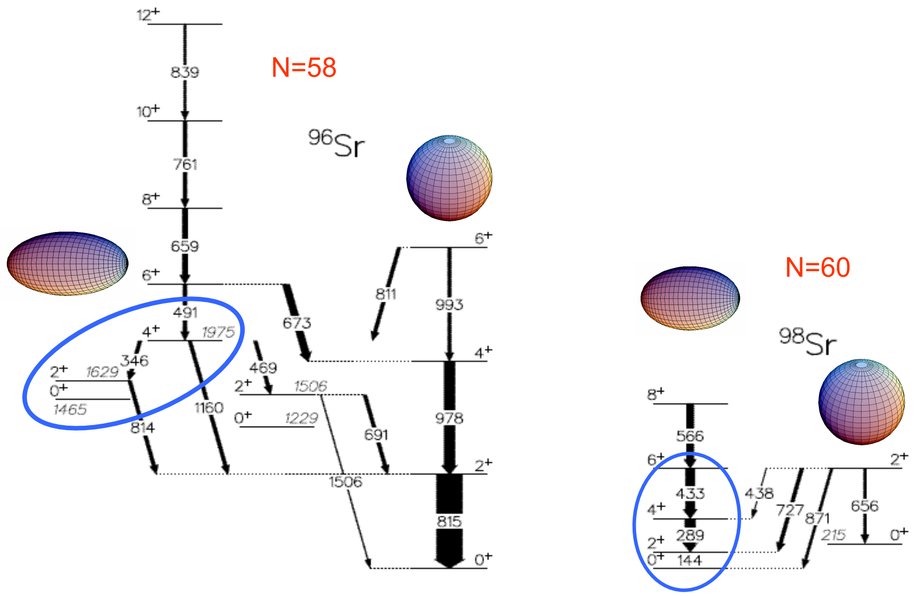

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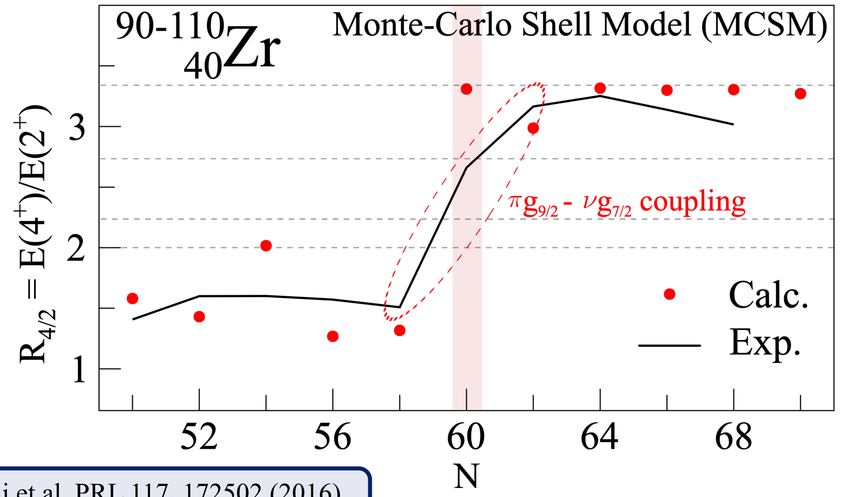

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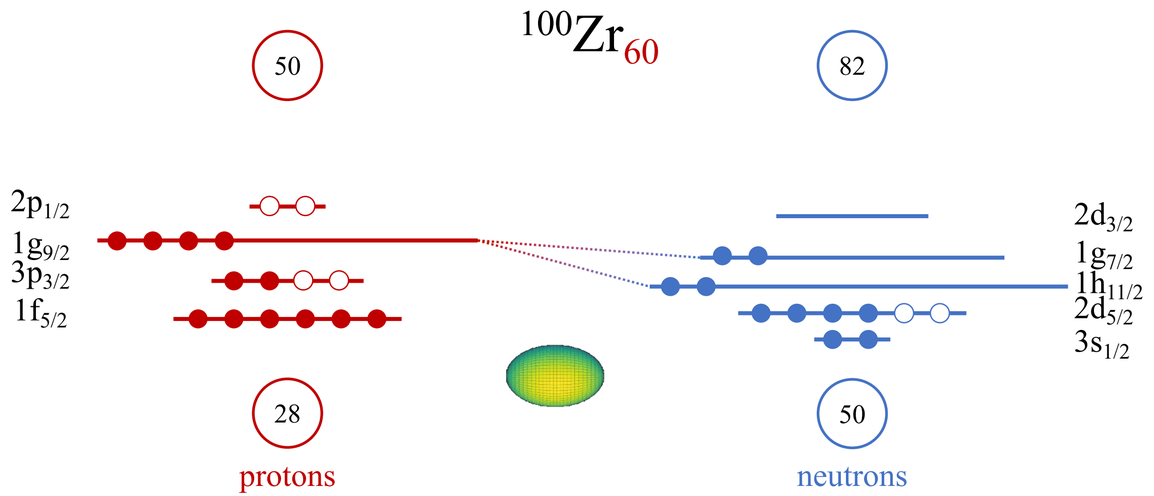

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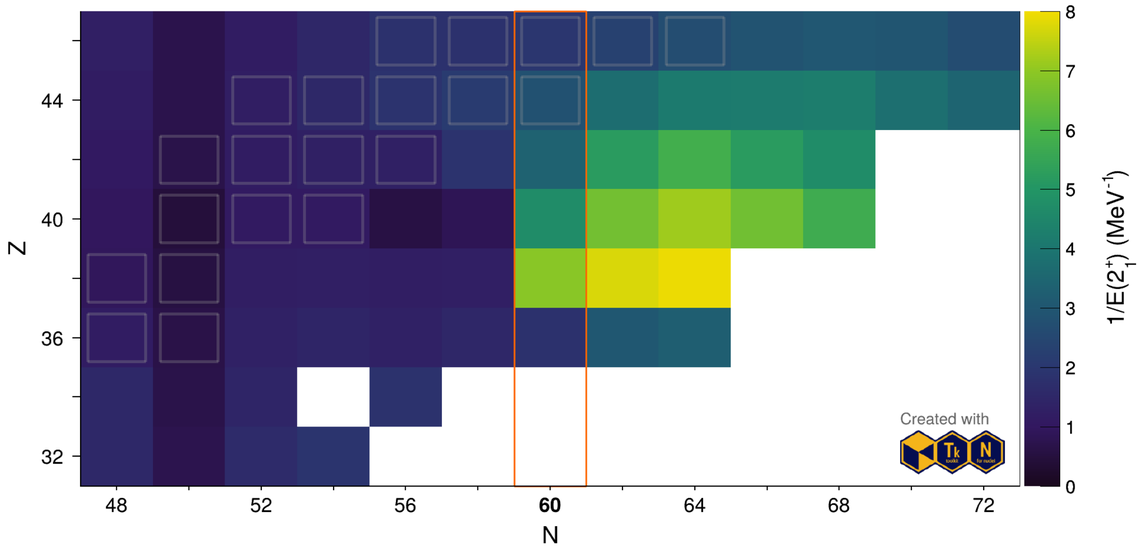
- But the limits of this island of deformation are still not clearly understood
  - **Sharp transition at N=60 for Z=38-40**
  - **Smooth triaxial shape evolution for Z>40**
  - **Sharp disapearance at Z=36**

Clear effect of p-n interaction:

perfect test-case for theory



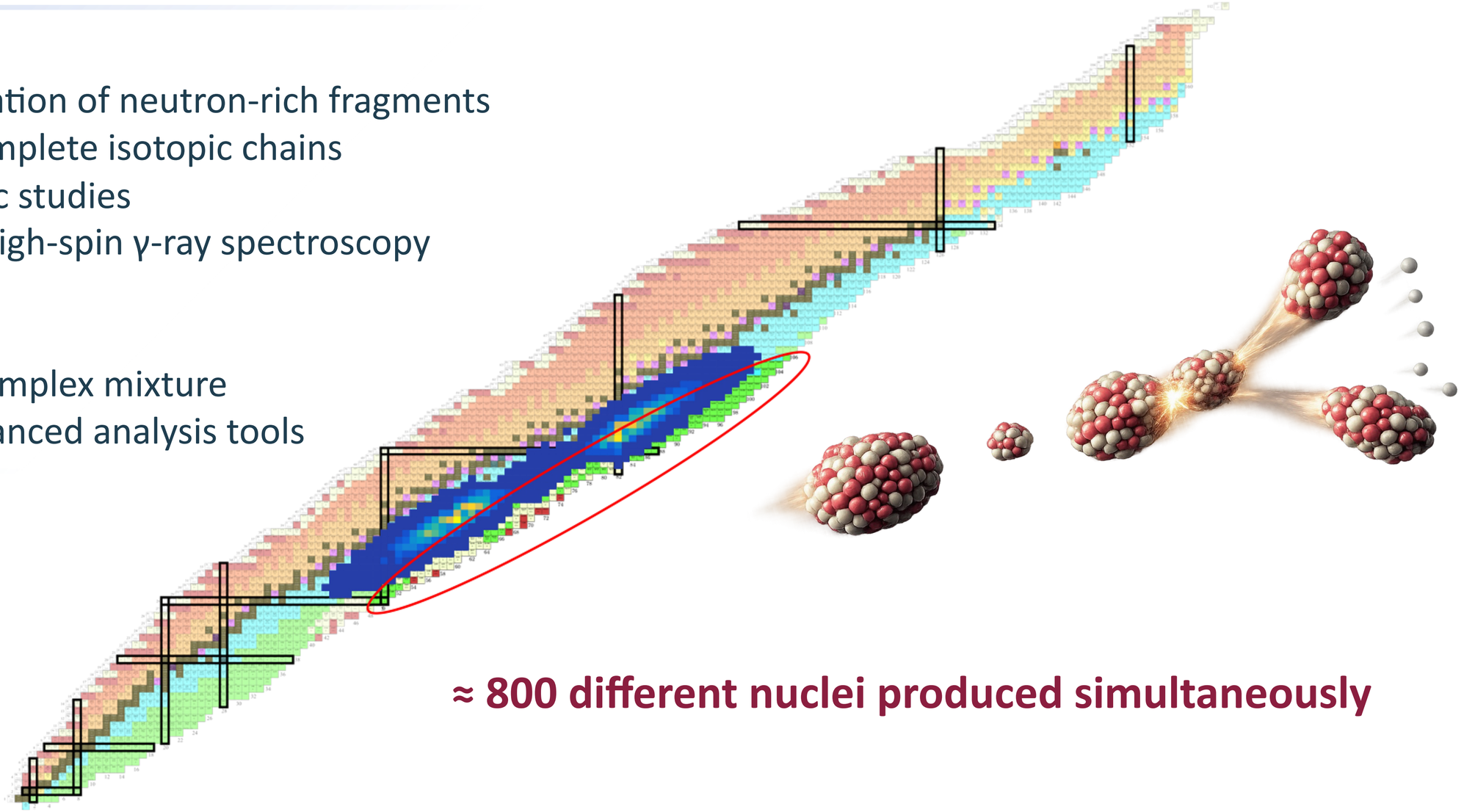
Fission: a gateway to neutron-rich nuclei

✅ **Advantage**

- Broad population of neutron-rich fragments
- Access to complete isotopic chains
  ➥ systematic studies
- Large-scale high-spin γ-ray spectroscopy

⚠️ **Challenge**

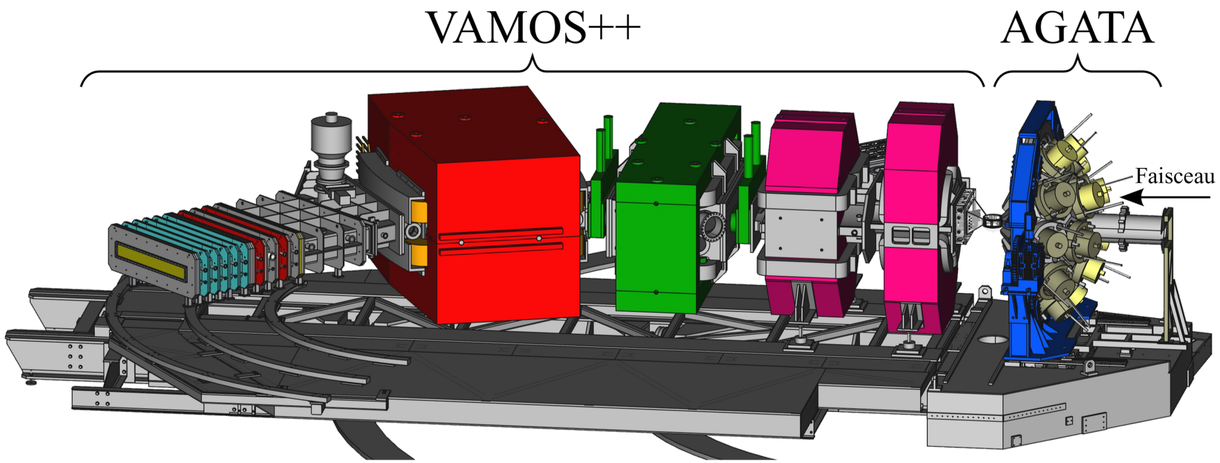
- Extremely complex mixture
- requires advanced analysis tools



≈ 800 different nuclei produced simultaneously

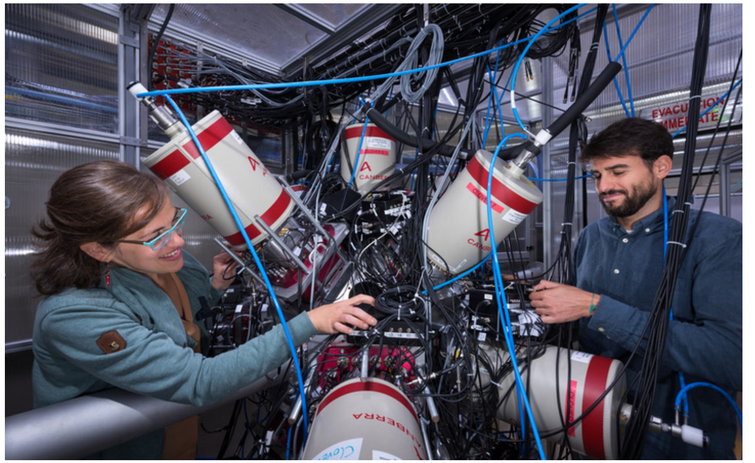
How to make γ-ray spectroscopy of fission fragments ?

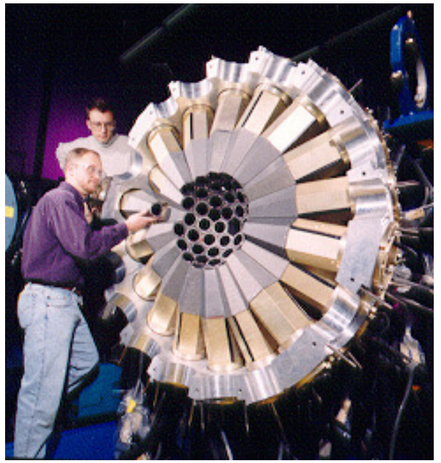
With fragment identification: AGATA + VAMOS



- ☑ Isotopic identification
  - ➥ very clean spectra, simple analysis
- ☒ Complicated detection system / pre-analysis
- ☒ Limited statistics / multiplicities

Without fragment identification: FIPPS/Gammasphere





- ☑ Datasets with huge statistics
- ☑ 4π solid angle → high multiplicities
- ☑ Simple detection system
- ☒ Complicated γ-ray analysis
- ☒ Cannot be applied on unknown nuclei

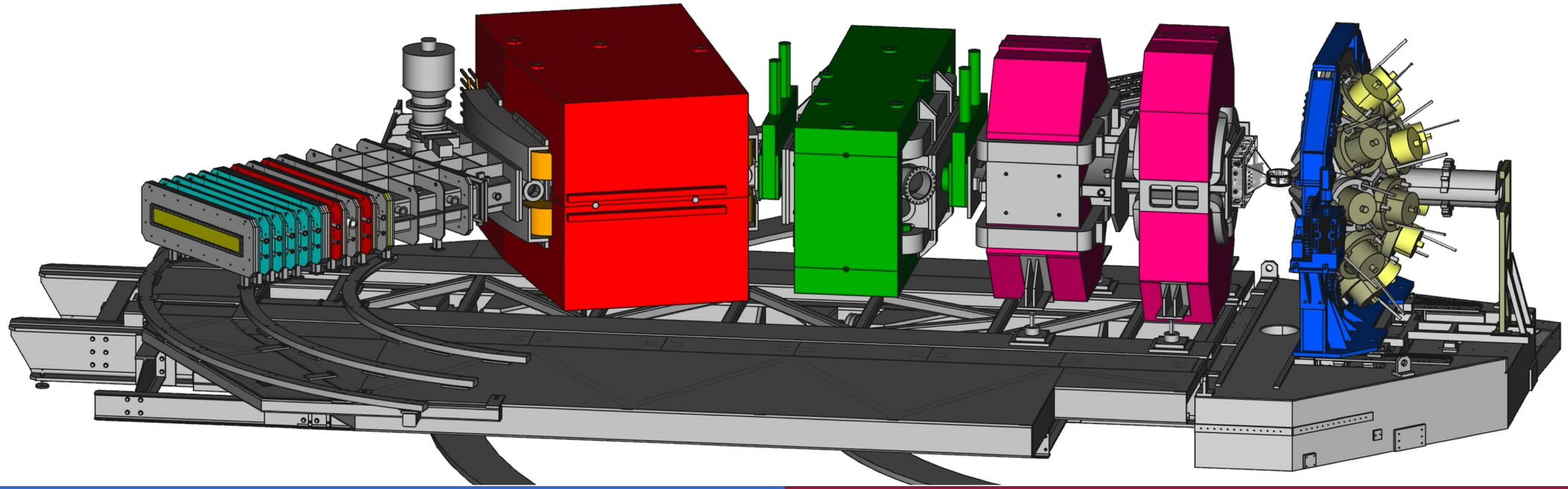
Jérémie Dudouet: j.dudouet@ip2i.in2p3.fr

The E680 Experiment: AGATA + VAMOS++ @ GANIL

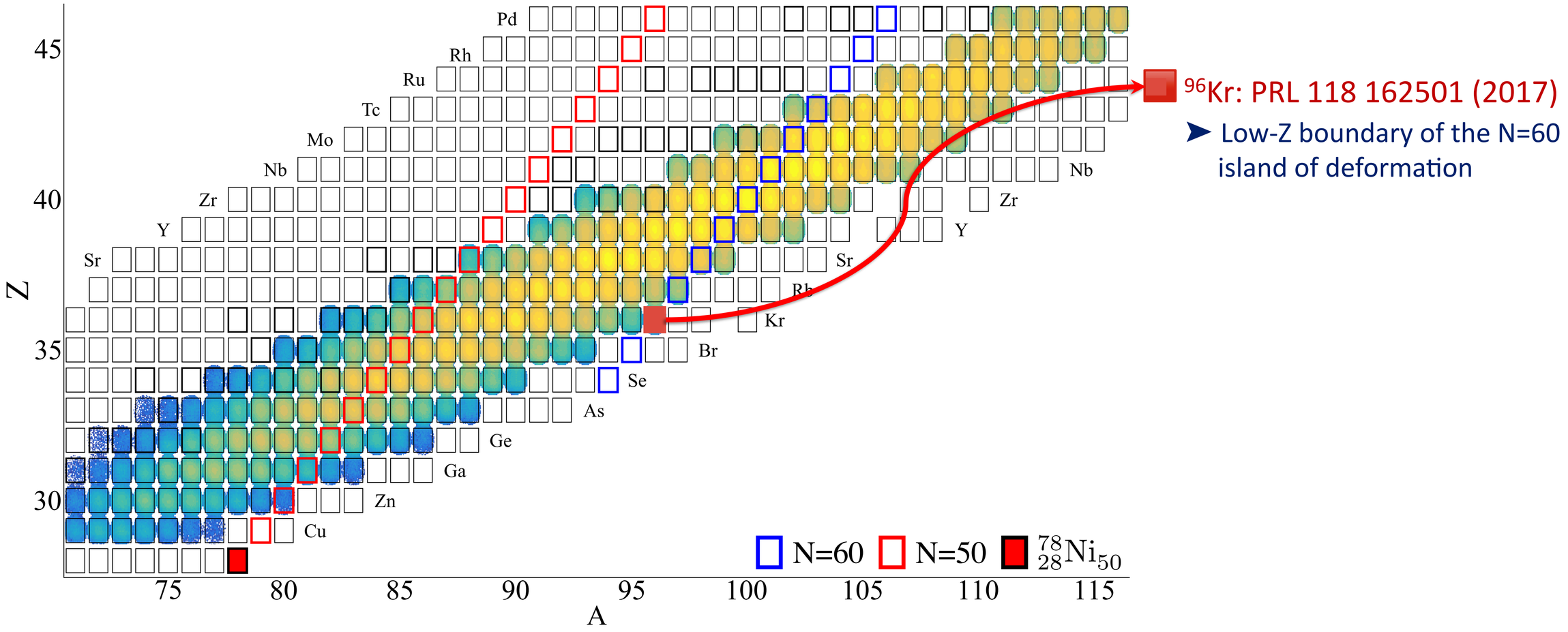
$\beta \sim 0.1$

^{9}Be

^{238}U at 6.2 MeV/u



^{96}Kr: low-Z shore of the island of deformation



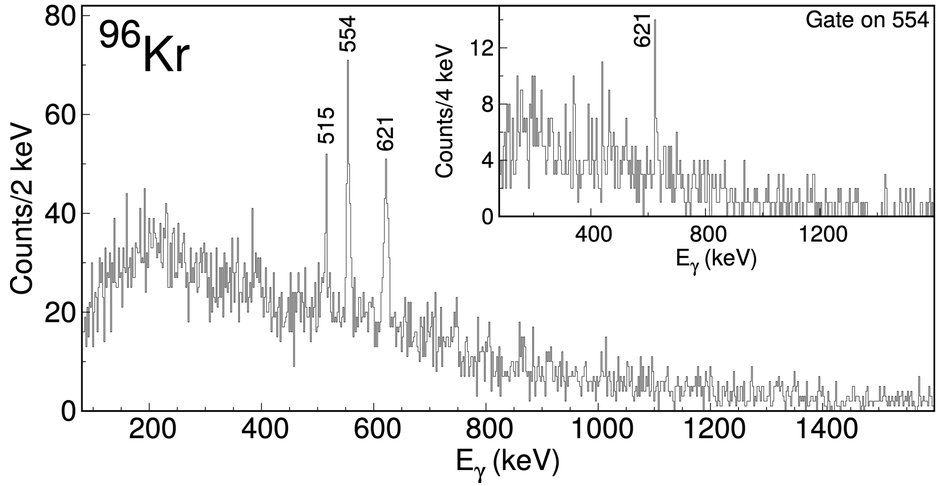
^{96}Kr: PRL 118 162501 (2017)

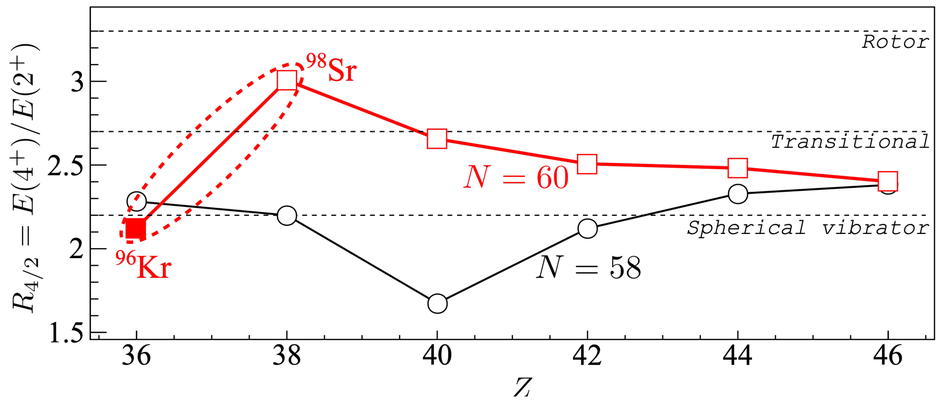
➤ Low-Z boundary of the N=60 island of deformation

^{96}Kr: low-Z shore of the island of deformation

First result from the fission campaigns at GANIL

- First measurement of the 4+ level in ^{96}Kr
- $R_{4/2}$ confirms the other observables (E_{2+}, Δr^2)
  - ➥ ^{96}Kr is not strongly deformed
  - ➥ $R_{4/2}$ value suggests a spherical vibrator nucleus





J. Dudouet et al. PRL 118, 162501 (2017)

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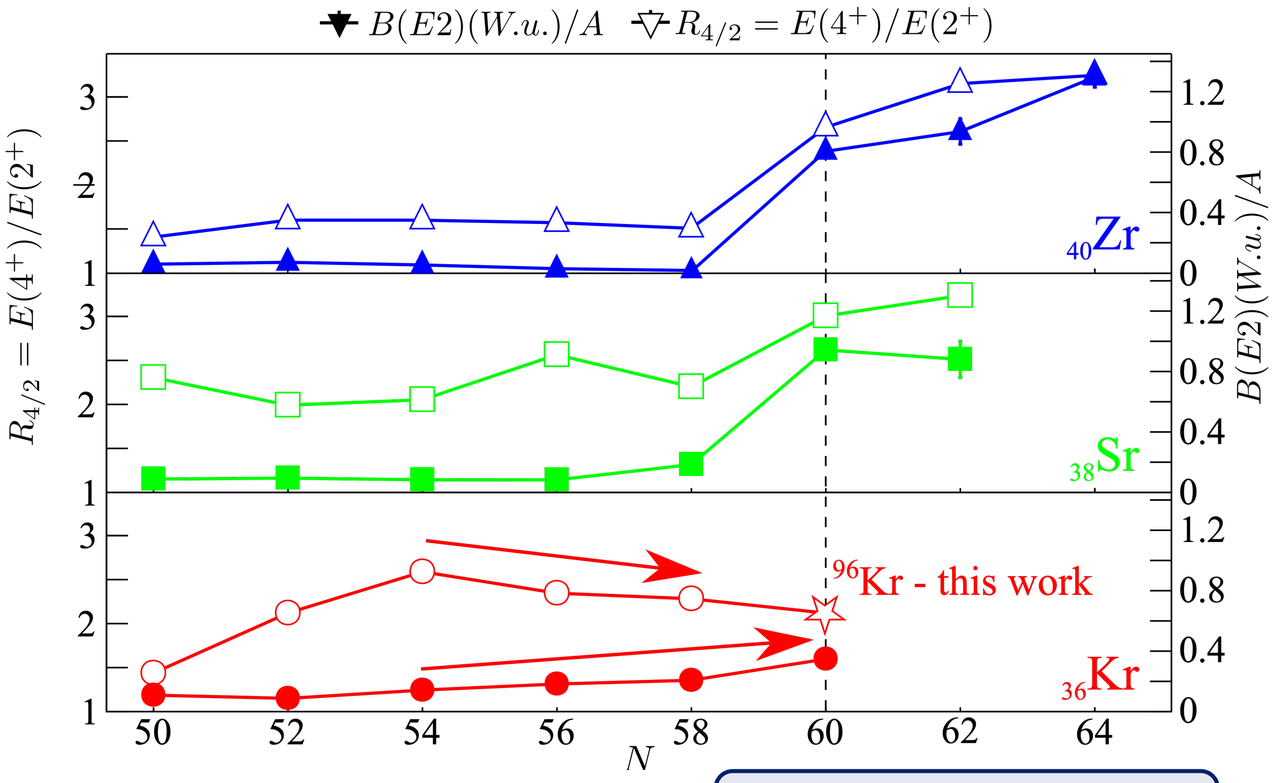
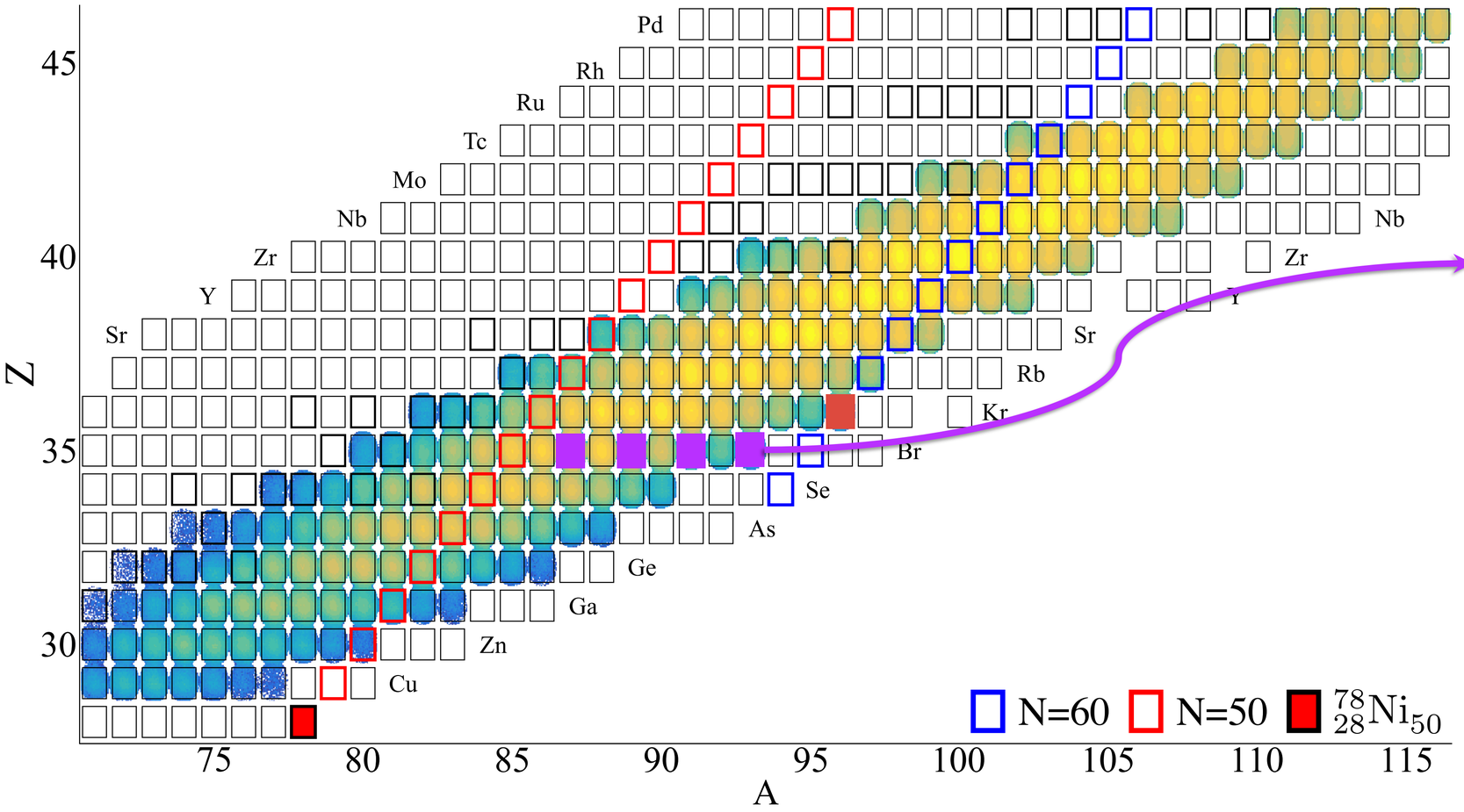
  - ➥ ^{96}Kr is not strongly deformed
  - ➥ $R_{4/2}$ value suggests a spherical vibrator nucleus
- Kr follows an unexpected trend between $R_{4/2}$ and B(E2)



J. Dudouet et al. PRL 118, 162501 (2017)

Br isotopic chain: prolate to oblate shape transition



^{96}Kr: PRL 118 162501 (2017)

➤ Low-Z boundary of the N=60 island of deformation

$^{87, 89, 91, 93}$Br: PRC 110, 034304 (2024)

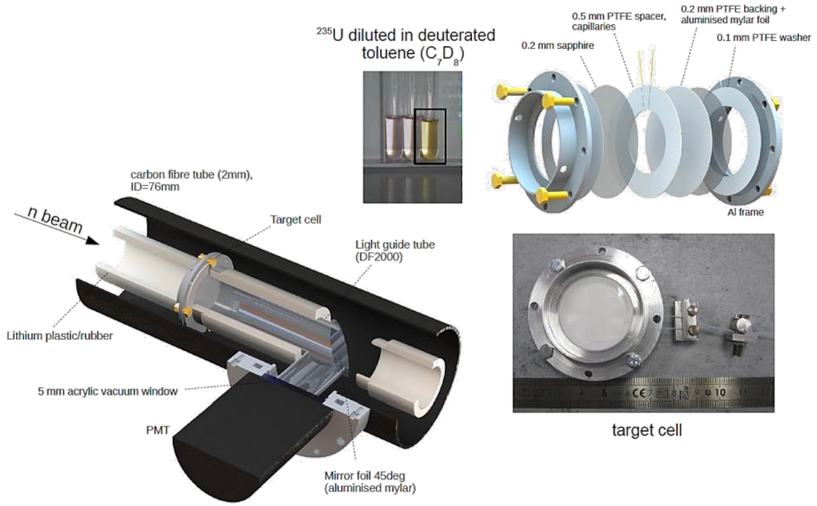
➤ Prolate-to-oblate shape transition close to N=60

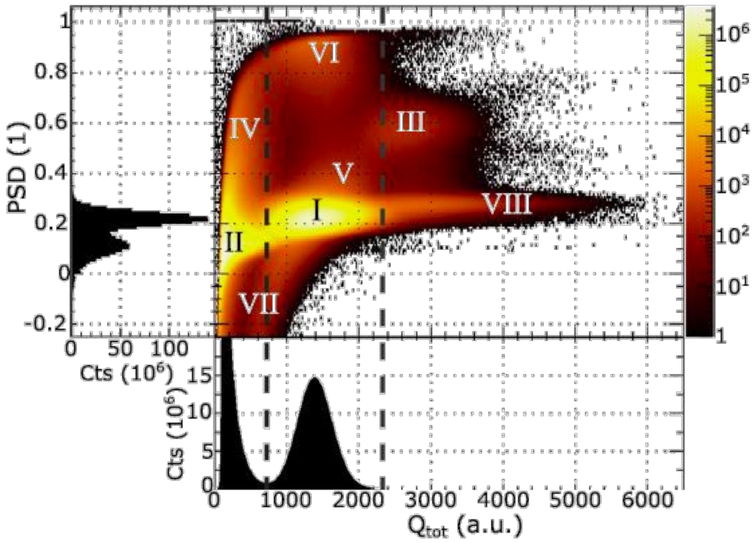
Fission data from FIPPS + Active target @ ILL

- 16 Compton suppressed HPGe clover detectors (8 from IFIN-HH)
- Pencil like thermal neutron beam, (10^8 neutrons/s/cm^2 at target position)
- Active ^{235}U fission target (dissolved in liquid scintillator)

C. Michelagnoli et al ., EPJ Web Conf ., 193 (2018) 04009

Giacomo Colombi and Daniela Reygadas PhD thesis

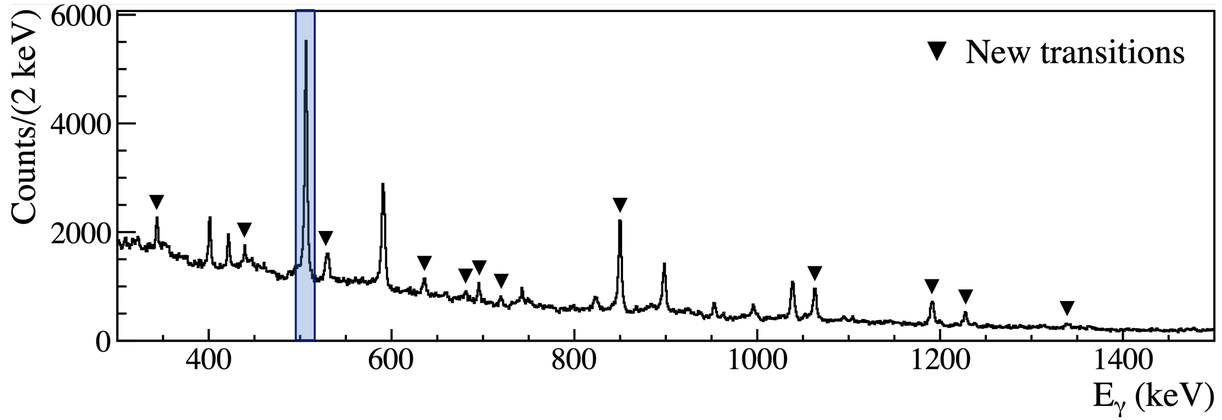




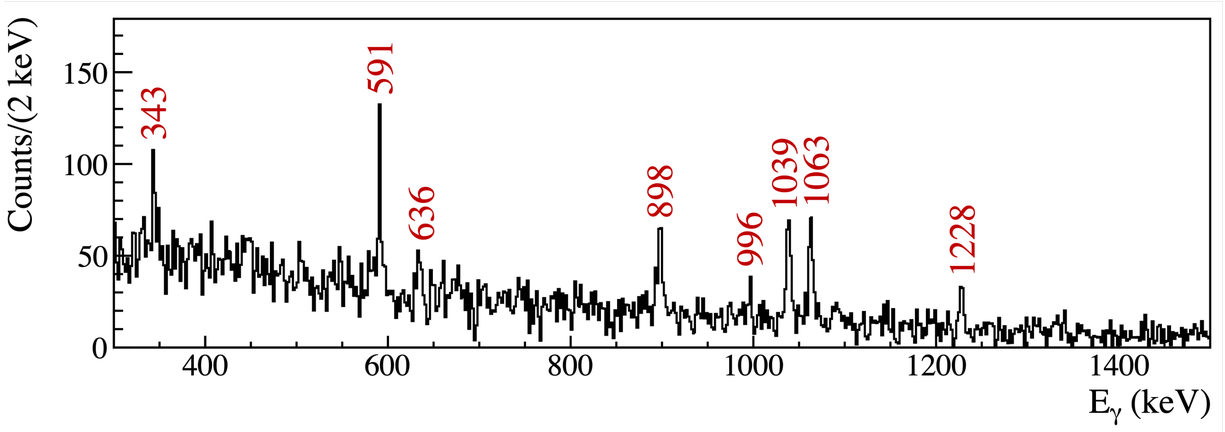
F. Kandzia et al ., Eur. Phys. J. A 56, 207 (2020)

The power of combined analysis AGATA-VAMOS + FIPPS

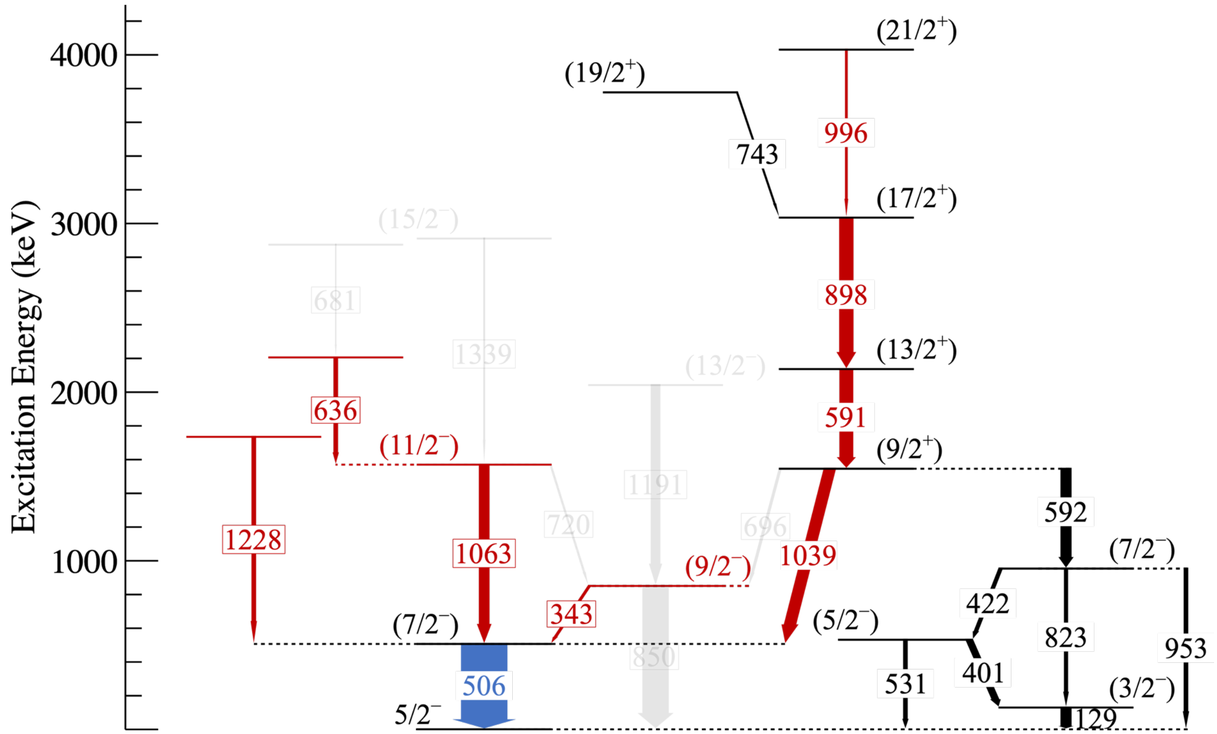
^{89}Br AGATA single spectrum



AGATA Gate at 506 keV



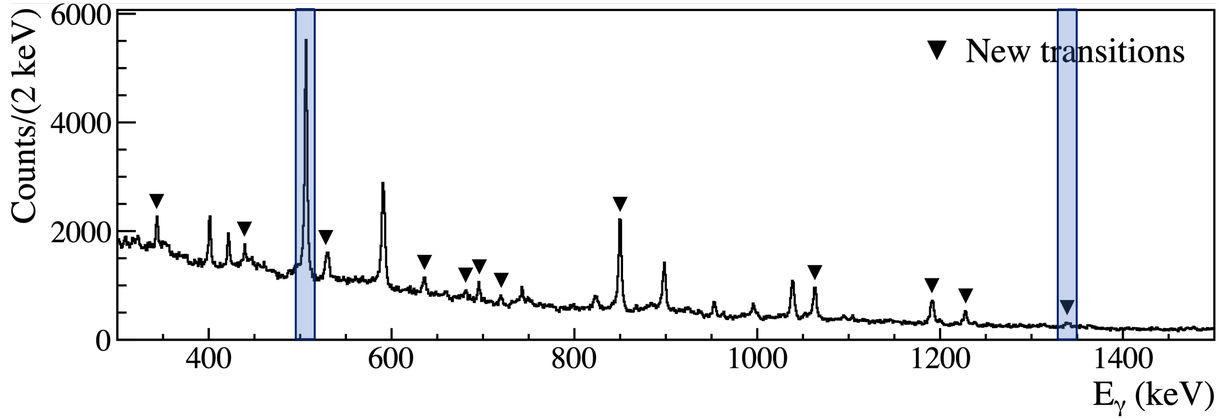
^{89}Br level scheme



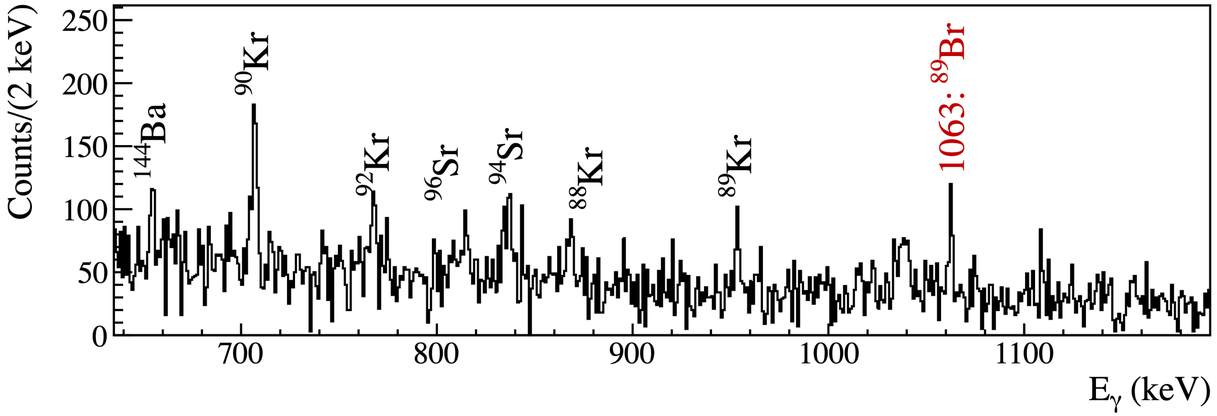
J. Dudouet et al. PRC 110, 034304 (2024)

The power of combined analysis AGATA-VAMOS + FIPPS

^{89}Br AGATA single spectrum



FIPPS Gate at 506 and 1339 keV



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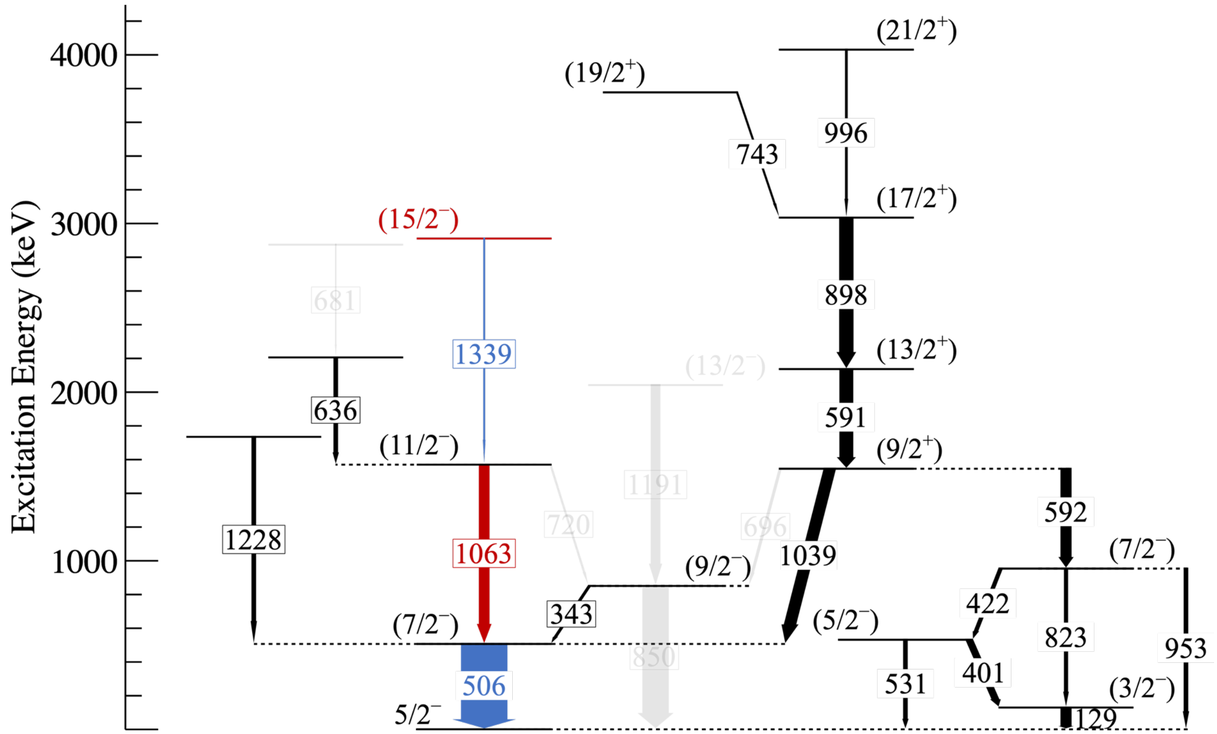
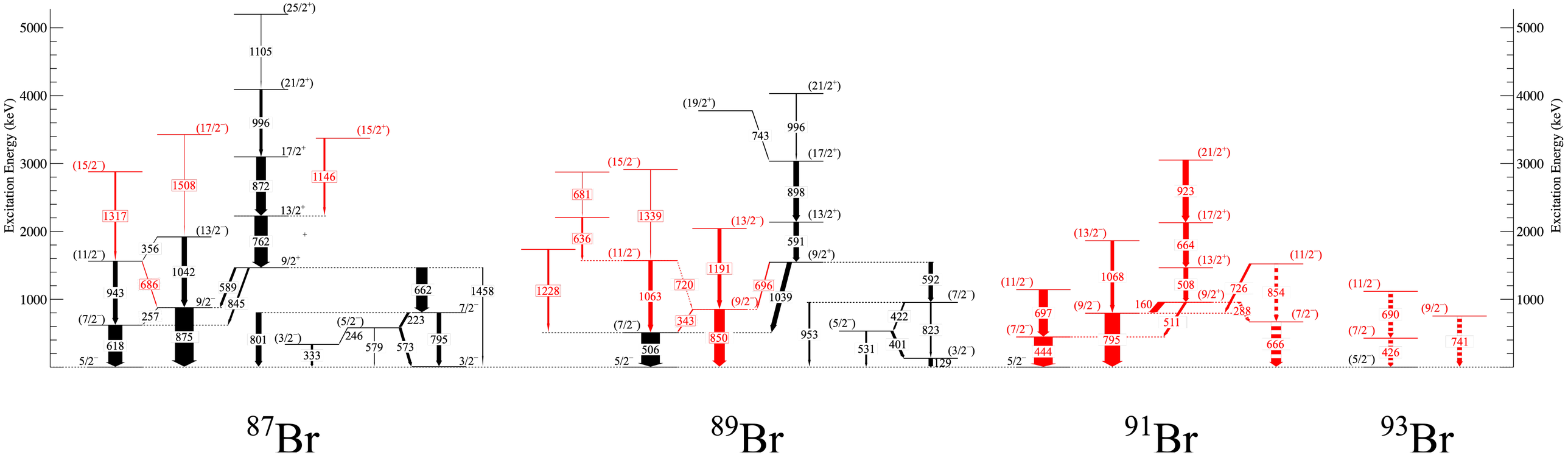


J. Dudouet et al. PRC 110, 034304 (2024)

New spectroscopic results in the Br isotopic chain

- New spectroscopic data for 4 Br isotopes: $^{87, 89, 91, 93}$Br
- **First spectroscopy of ^{91}Br and ^{93}Br**

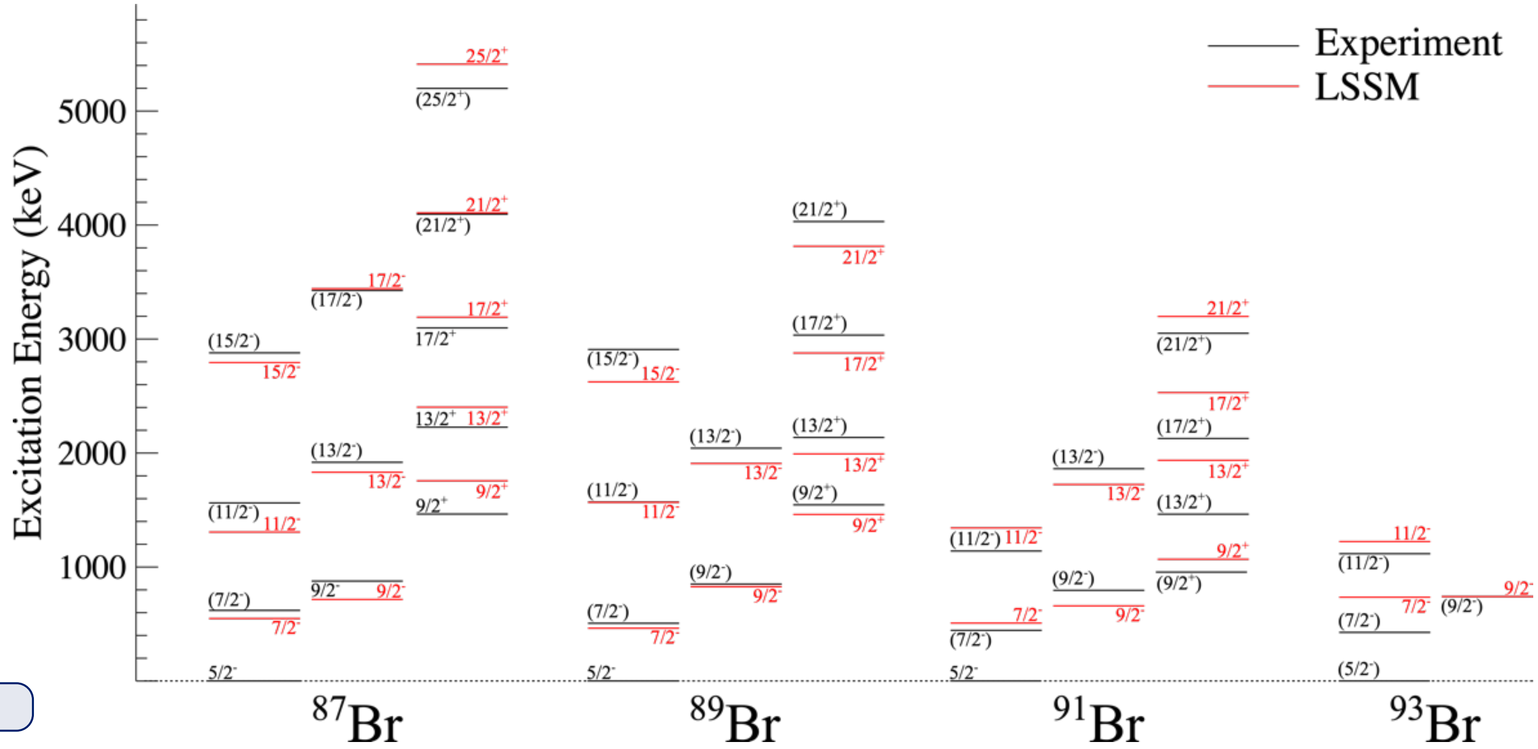


^{87}Br ^{89}Br ^{91}Br ^{93}Br

J. Dudouet et al. PRC 110, 034304 (2024)

New spectroscopic results in the Br isotopic chain

- State of the art Large Scale Shell Model calculations produced by F. Nowacki
  - ➥ very good overall reproduction of the level energies



J. Dudouet et al. PRC 110, 034304 (2024)

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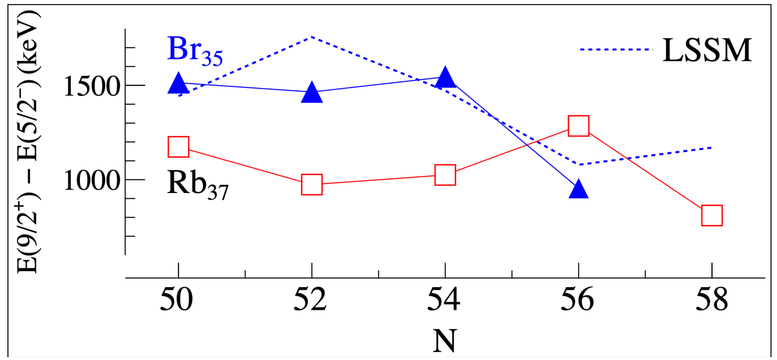
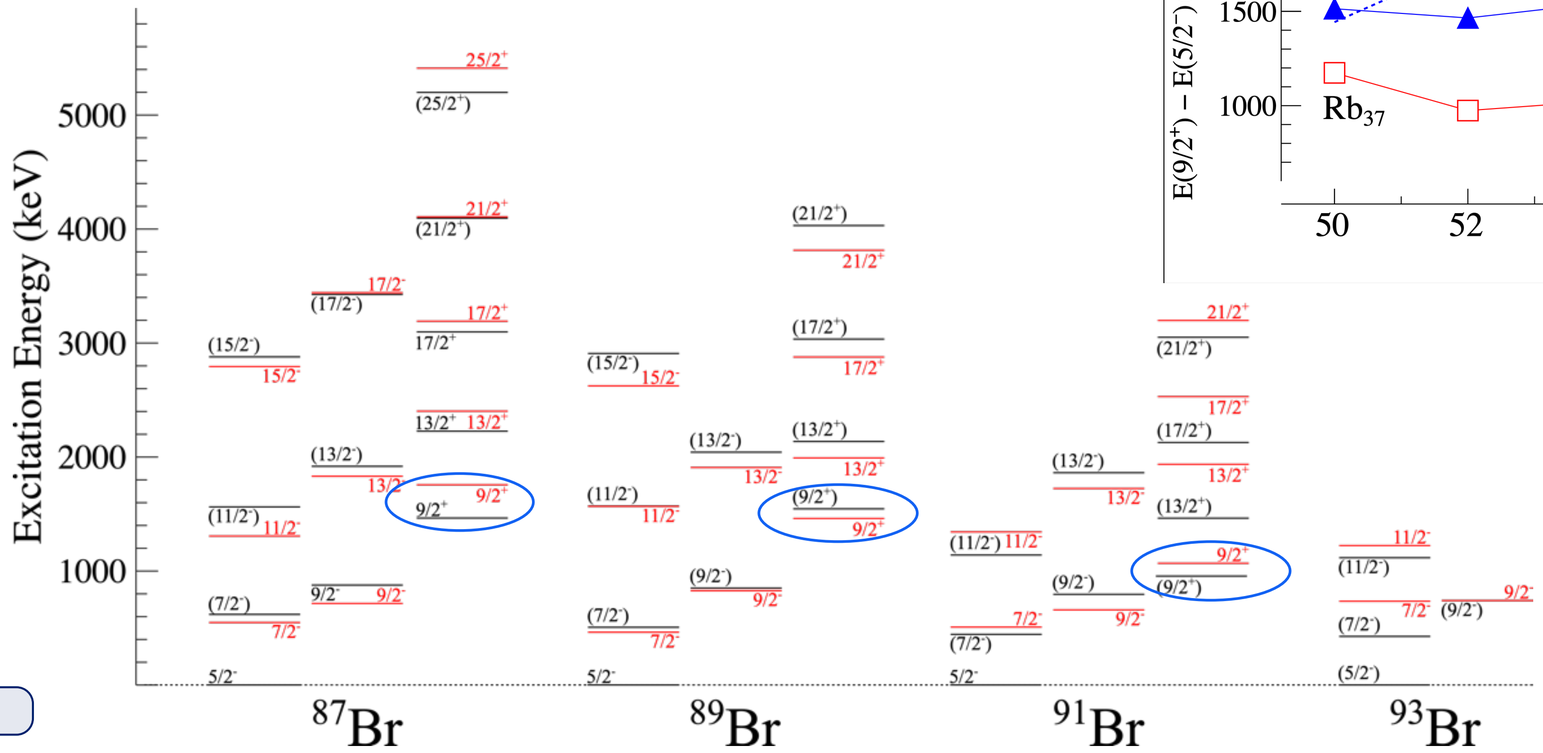
- Unexpected drop of the $9/2^+$ at N=56 ($d_{5/2}$ shell-closure) reproduced by theory





J. Dudouet et al. PRC 110, 034304 (2024)

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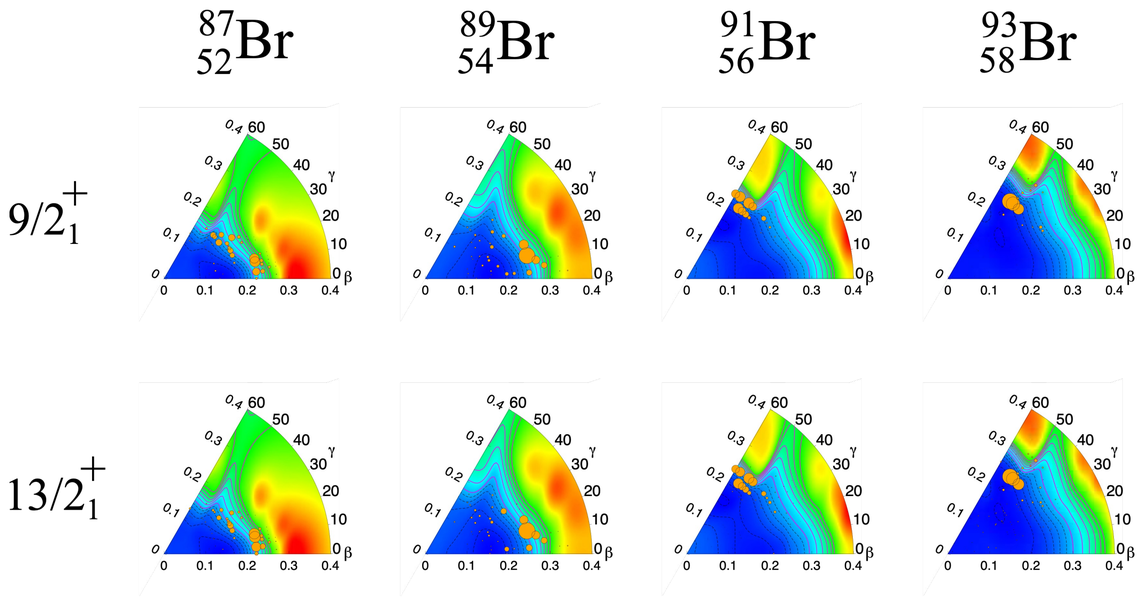
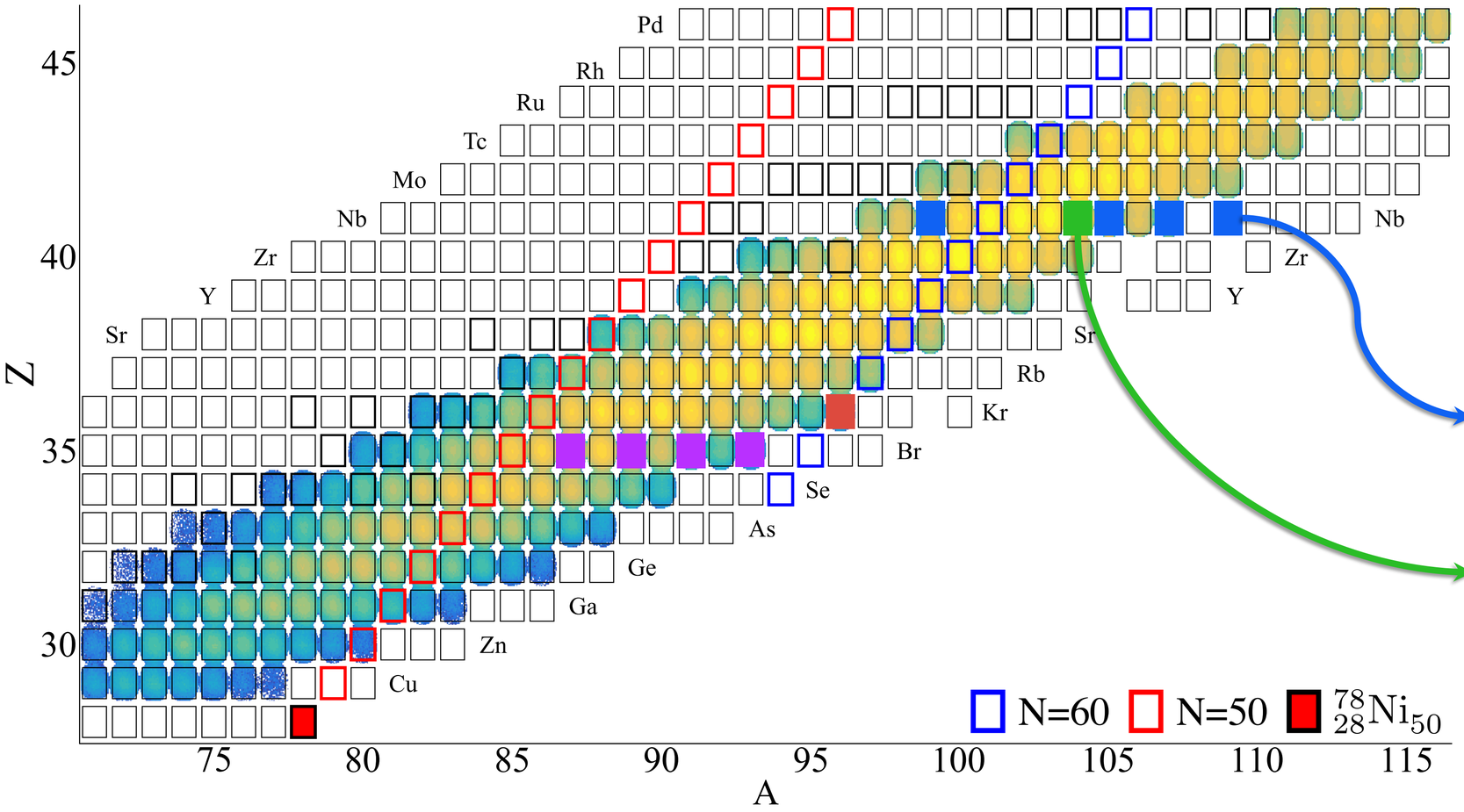
- DNO calculations performed by D. Dao (IPHC) predicts an oblate transition at N=56



J. Dudouet et al. PRC 110, 034304 (2024)

Nb isotopic chain: emergence of triaxiality



^{96}Kr: PRL 118 162501 (2017)

➤ Low-Z boundary of the N=60 island of deformation

$^{87, 89, 91, 93}$Br: PRC 110, 034304 (2024)

➤ Prolate-to-oblate shape transition close to N=60

$^{99, 105, 107, 109}$Nb: PRC 113, 014308 (2026)

➤ Signature splitting and shape coexistence

^{104}Nb: PRL 136 072501 (2026)

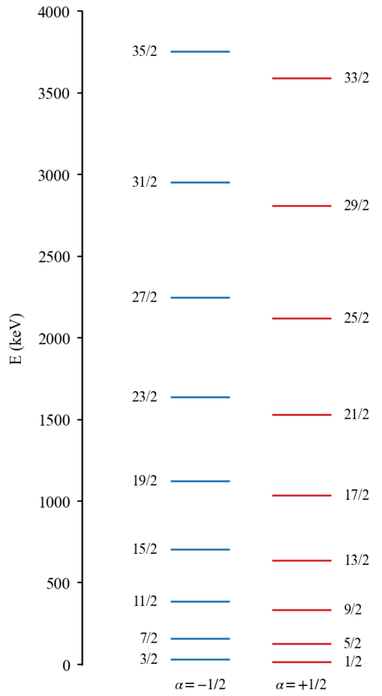
➤ multi-phonon gamma-vibrations bands

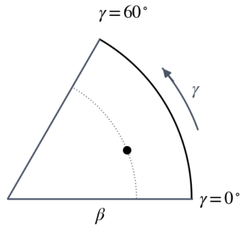
See Enhong's talk this afternoon

What about triaxiality ?

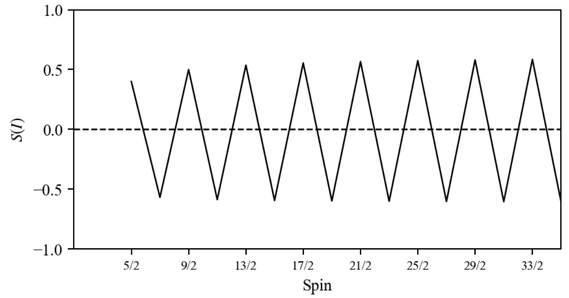
- In odd-A nuclei, the unpaired particle generates two signature-partner rotational sequences (ΔI = 2).
- In a triaxial shape, the three principal moments of inertia differ ($\mathcal{I}_1 \neq \mathcal{I}_2 \neq \mathcal{I}_3$),
- The projection quantum number K is no longer conserved

  ➥ production a ΔI = 1 staggering: **signature splitting**





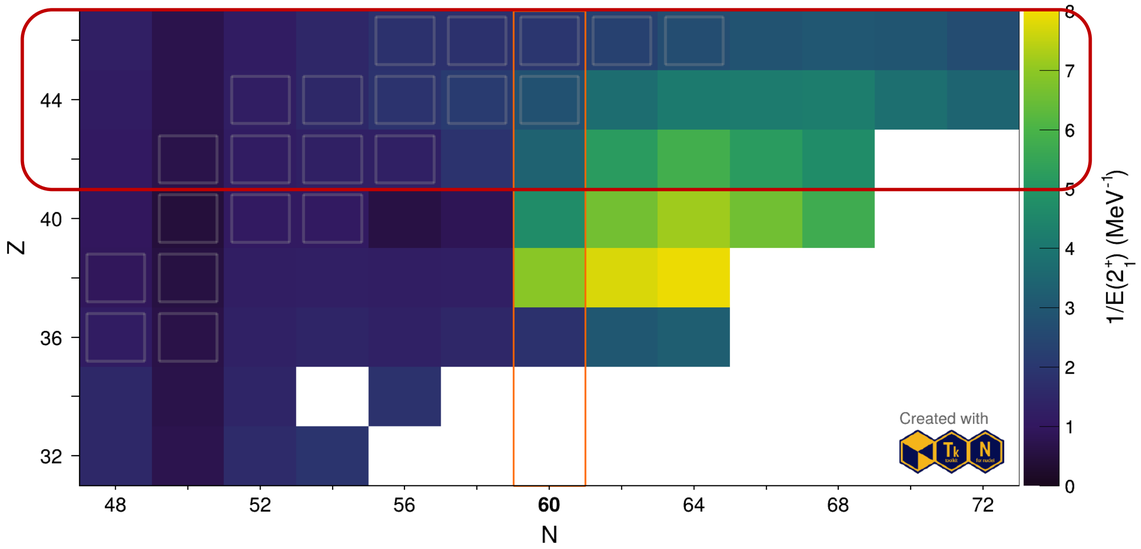
$$S(I) = \frac{E_I - E_{I-1}}{E_I - E_{I-2}} \frac{I(I+1) - (I-2)(I-1)}{I(I+1) - (I-1)I} - 1.$$

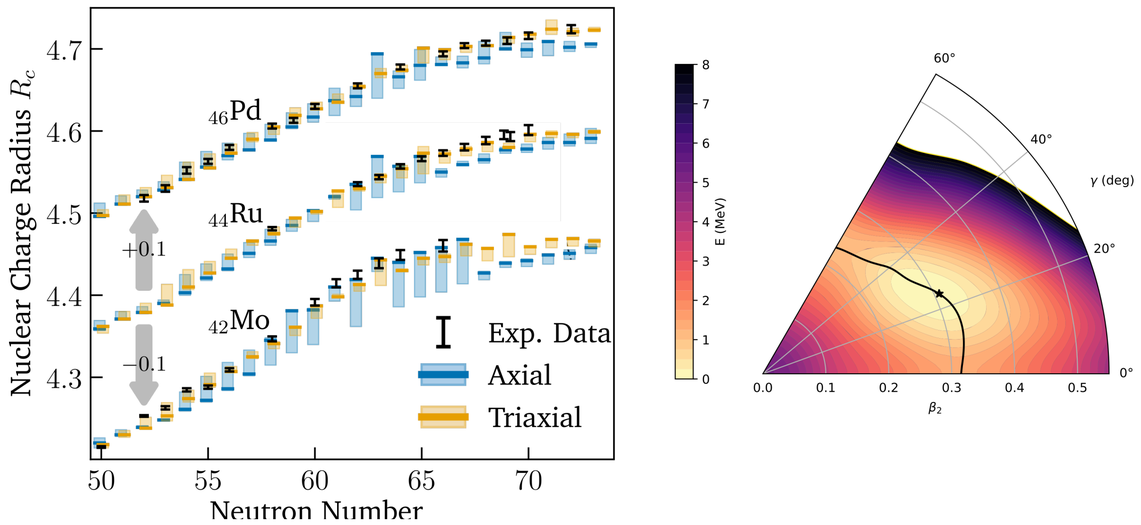


Signature splitting therefore provides a sensitive probe of triaxial deformation in odd-A nuclei.

What about triaxiality ?

- This region is already known to exibit large degree of triaxiality
  - ➥ This is explaining the smoother onset of deformation for Z>40 compared to Sr and Zr
- Validated on charge radii by recent calculations using Brussels-Skyrme-on-a-Grid model

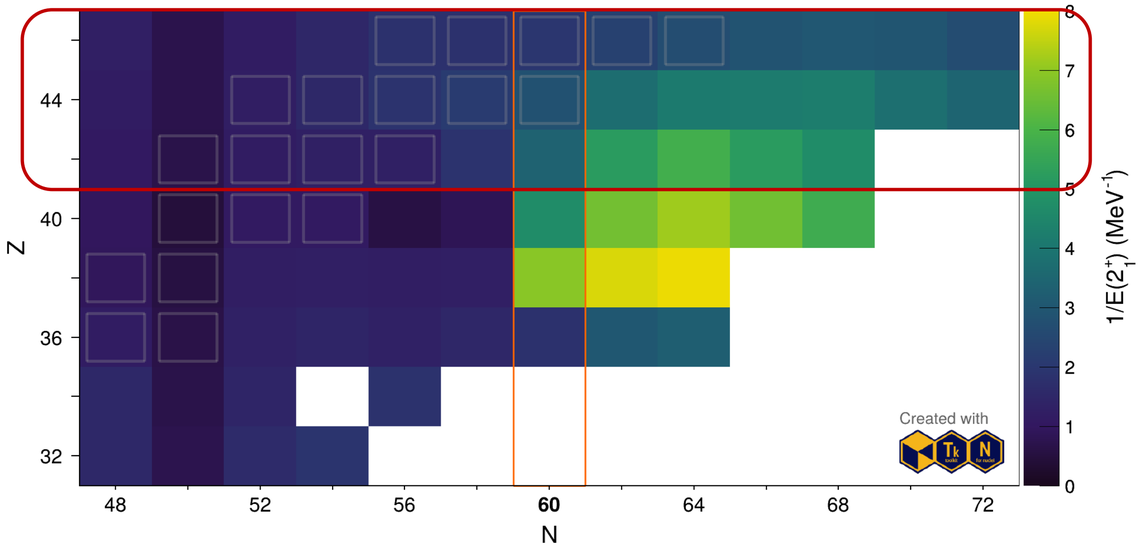


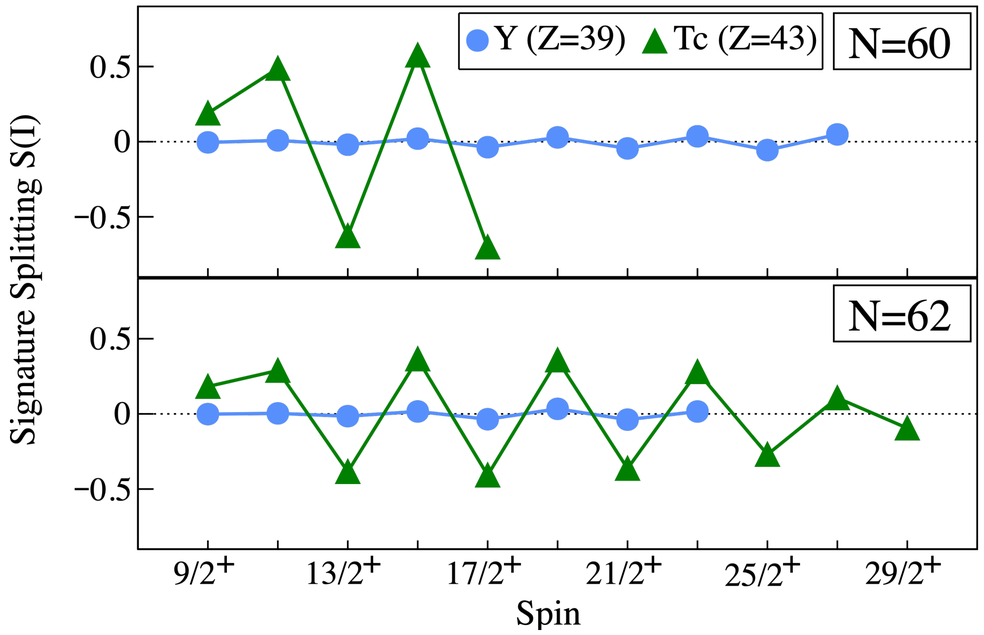


B. Maas et al. PRL 135, 202501 (2025)

What about triaxiality ?

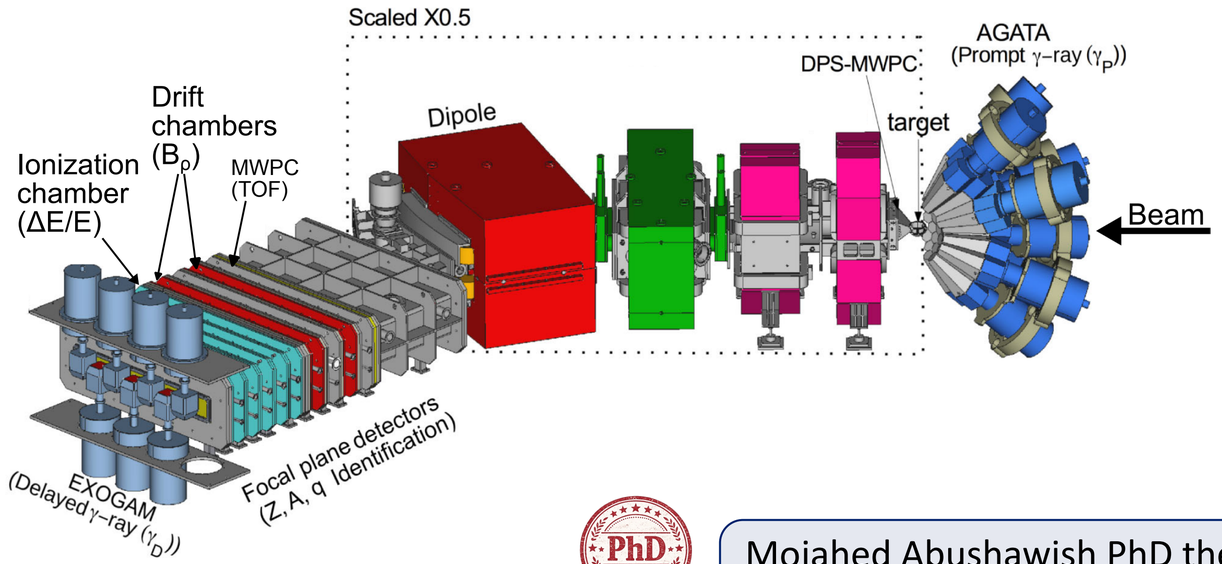
- This region is already known to exibit large degree of triaxiality
  - ➥ This is explaining the smoother onset of deformation for Z>40 compared to Sr and Zr
- Validated on charge radii by recent calculations using Brussels-Skyrme-on-a-Grid model
- Spin-splitting on odd-even nuclei gives clear indications on the triaxiality onset

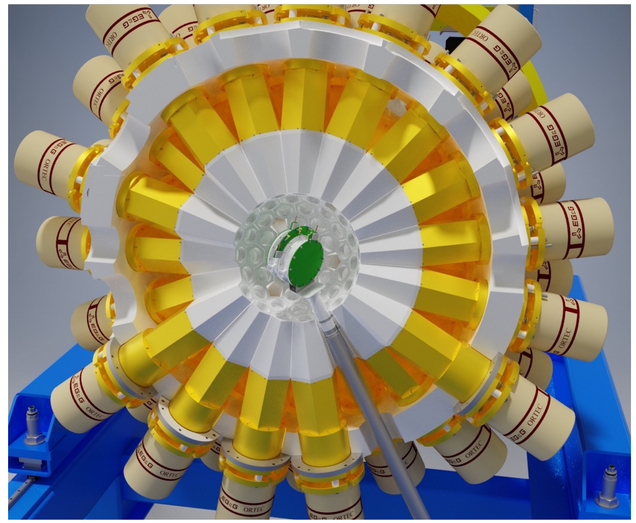




New results on the Nb isotopic chain: AGATA-VAMOS / GAMMASPHERE

- Sum of two AGATA-VAMOS fission experiments: **E680+E661**
- New high-fold data from collaboration with **Enhong Wang** on **Gammasphere data**
  - ➥ sum of multiple runs of spontaneous fission of a 62 µCi ^{252}Cf
  - ➥ access to triple energy gates and lifetime measurements (2-100ns)



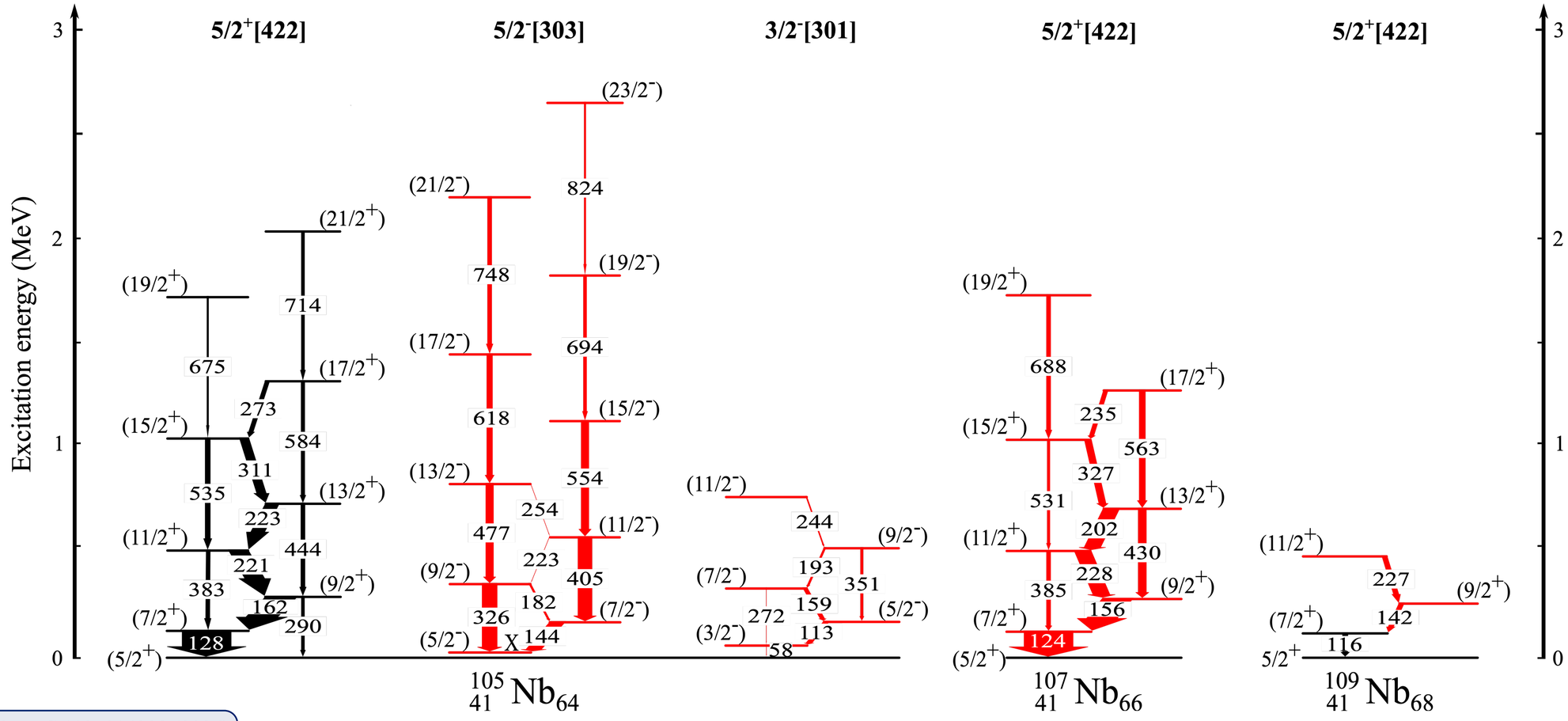


PhD

Mojahed Abushawish PhD thesis

New results on the Nb isotopic chain: AGATA-VAMOS / GAMMASPHERE

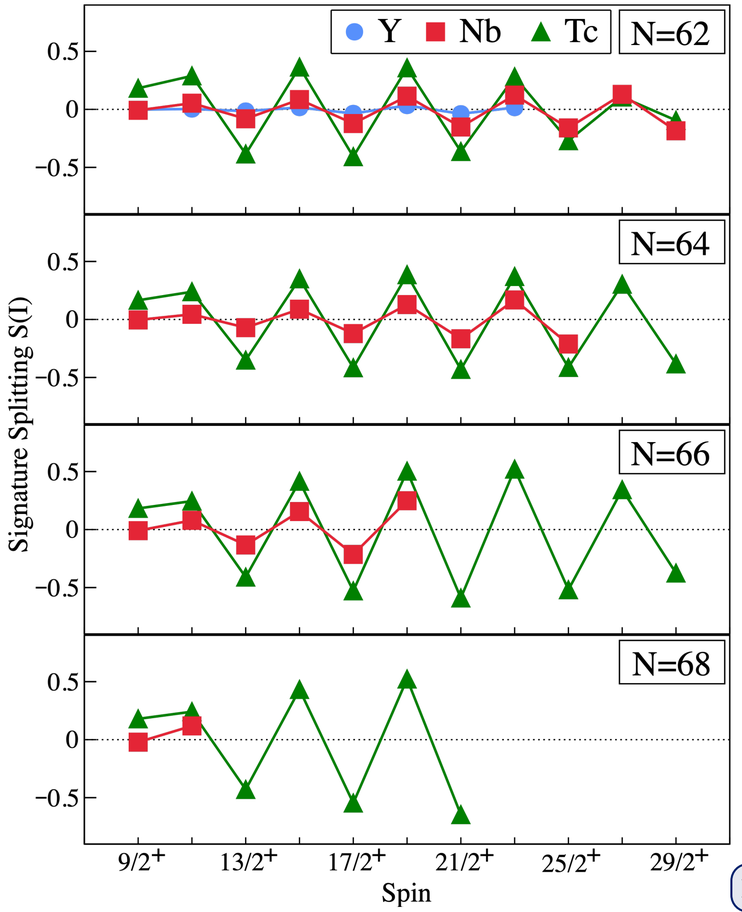
New spectroscopic data for $^{105, 107, 109}$Nb



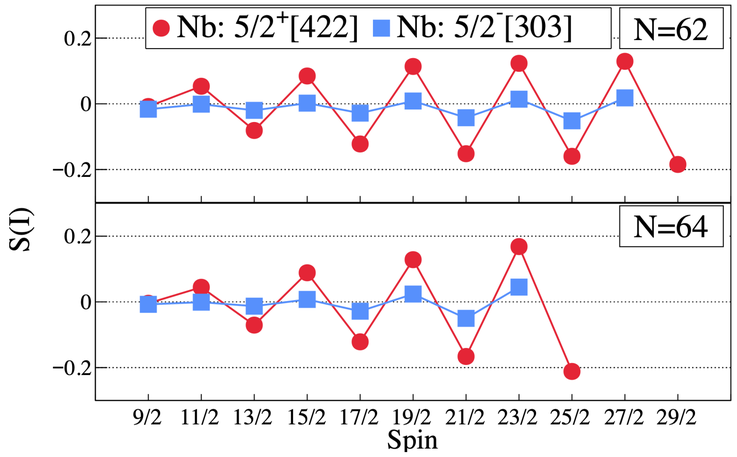
M. Abushawish et al. PRC 113, 014308 (2026)

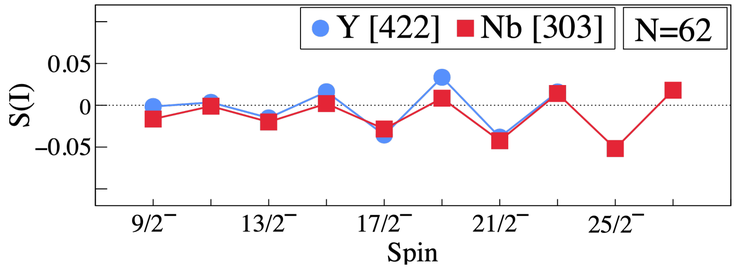
New results on the Nb isotopic chain: AGATA-VAMOS / GAMMASPHERE

- **Ground state positive parity band**
  - ➥intermediate SS values compared to Z=39 and Z=43



- **Excited negative parity band**
  - ➥ small SS values compared to the GS band
  - ➥ very similar to the axial Y case

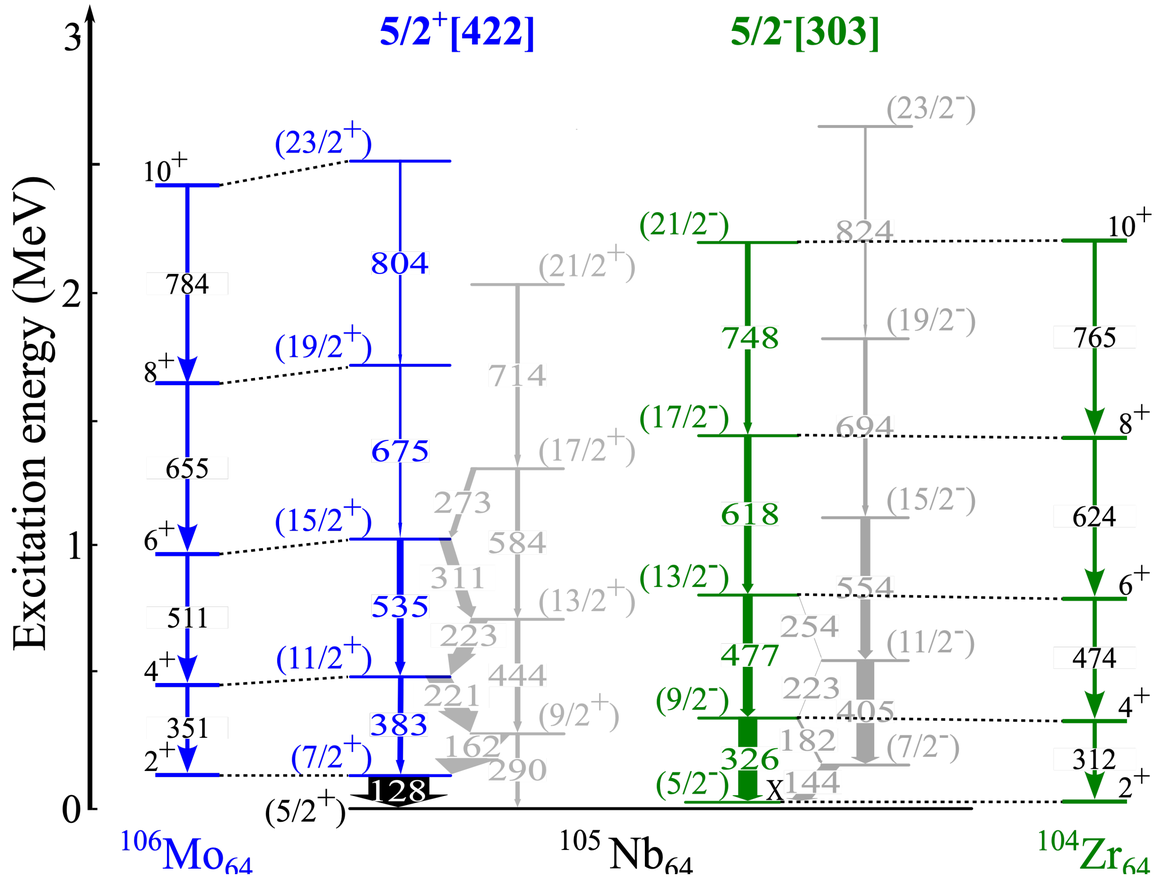




M. Abushawish et al. PRC 113, 014308 (2026)

New results on the Nb isotopic chain: AGATA-VAMOS / GAMMASPHERE

Nb (Z=41) in the context of Mo (Z=42) and Zr (Z=40)



M. Abushawish et al. PRC 113, 014308 (2026)

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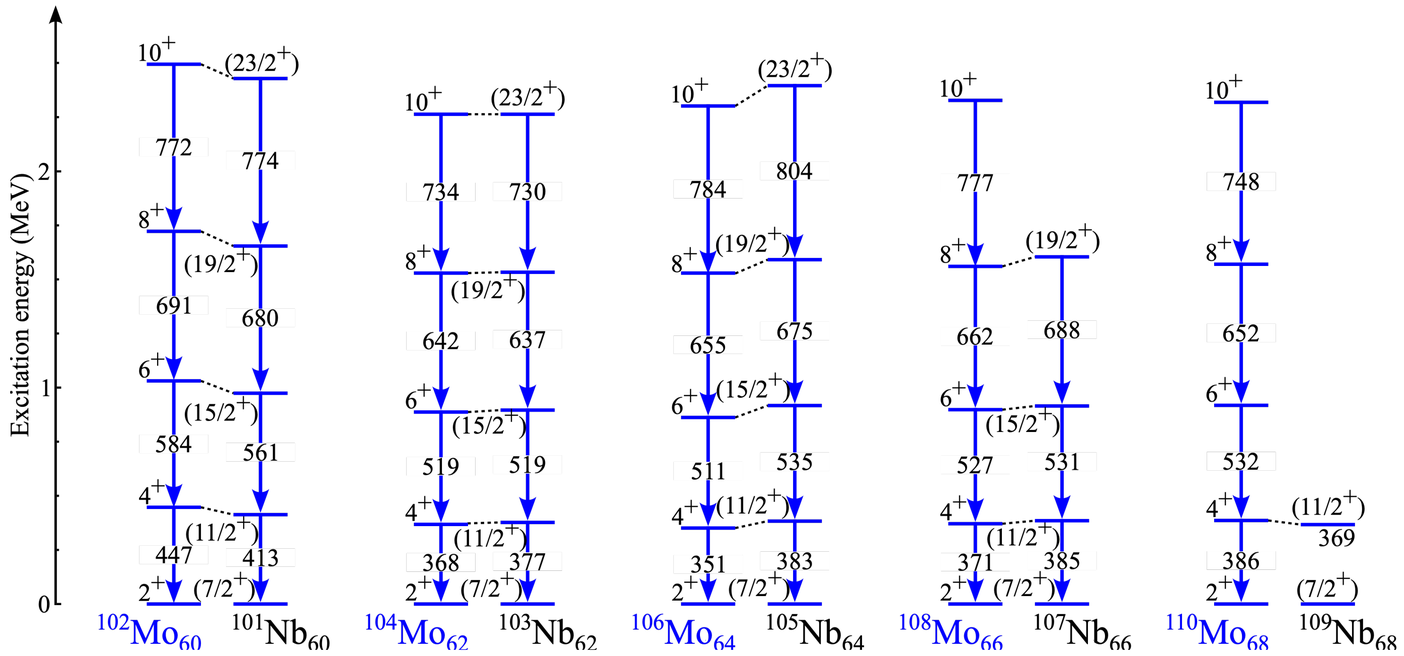
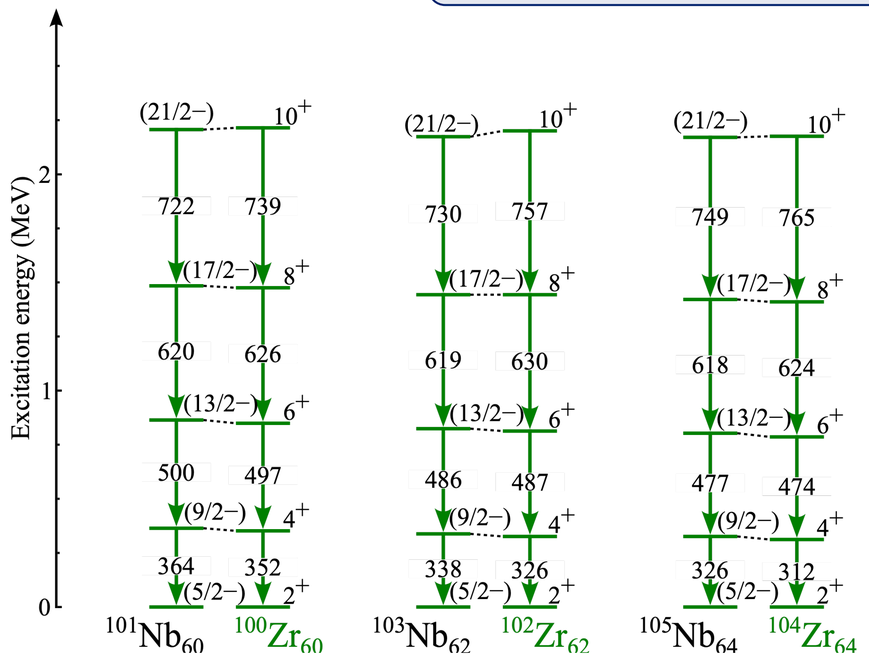
M. Abushawish et al. PRC 113, 014308 (2026)



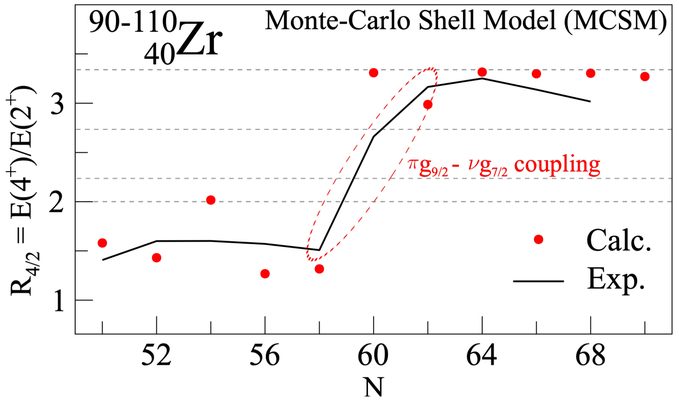


The Nb chain exhibits a **transitional character to triaxiality with a shape coexistence scenario**:

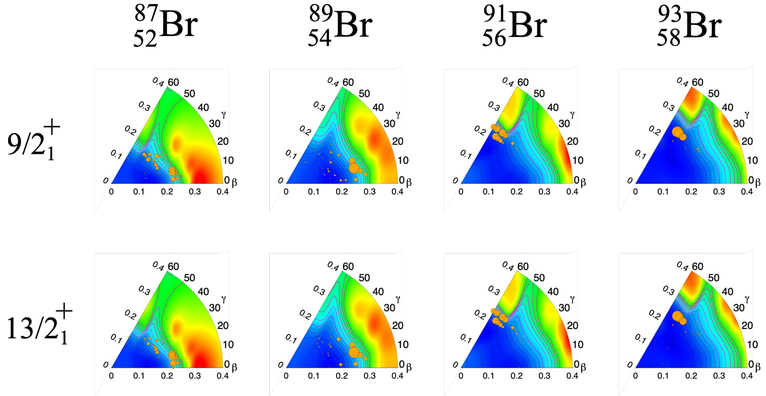
- The GS band shows triaxiality: **proton hole coupled to a triaxial Mo-like core**
- The excited band is axialy deformed: **proton particle coupled to an axially deformed Zr-like core**

What about theory ?

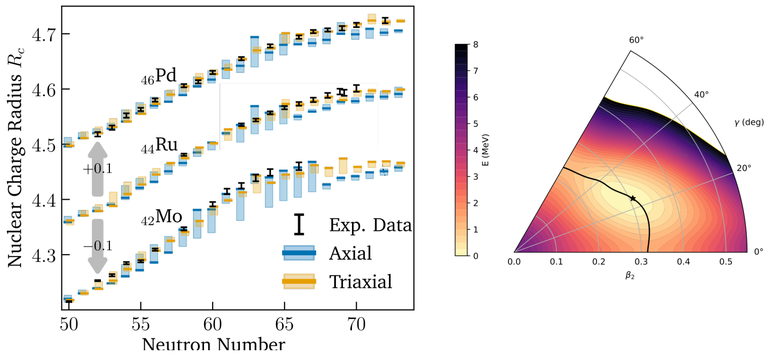
T. Togashi et al. PRL 117, 172502 (2016)



J. Dudouet et al. PRC 110, 034304 (2024)



B. Maas et al. PRL 135, 202501 (2025)



Calculations exists and are locally successful, but so far, no theory to predict simultaneously:

- **The sharp transition in Sr and Zr**
- **The absence of transition in Kr**
- **The triaxiality behaviour in Mo and Ru**

Conclusions and perspectives

What we have learn ?

- **Many very interesting results in key region for nuclear structure**
- **We have developed technical skills for standardized, powerful and efficient analysis**
- **The complementarity with other detectors/experiments is a game changer**

What's next ?

- **To go higher in exoticity, a factor 10 is needed !**

✓ **Long fission runs experiments with AGATA and fragment identification, but where ?**

➥ PRISMA@LNL: no more feasible

➥ VAMOS@GANIL: no fission campain planed

✓ **New long measurements with FIPPS**

➥ ^{245}Cm with fission fragment mass identification