Exploring the low Z-shore of the Island of Deformation at N=60 using AGATA and VAMOS

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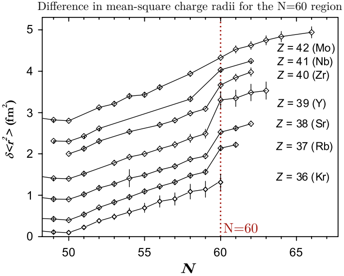
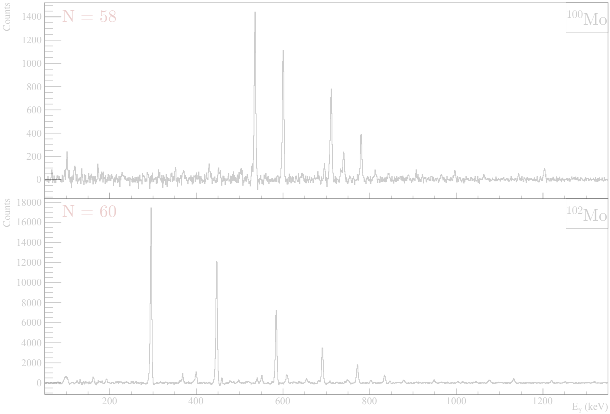
What are the limits of this N=60 island of deformation

- The Z=40 and N=60 region gives a remarkable example of sudden nuclear shape transition:
  - This effect seems to start at Z=42 (Mo) and ↗ with ↘ Z
  - N=58 : quasi-spherical shape ⇒ N=60 : rigid rotors with large deformation ($\beta_2 \sim 0.4$)



S. Naimi *et al.*, Phys. Rev. L **105**, 032502 (2010)



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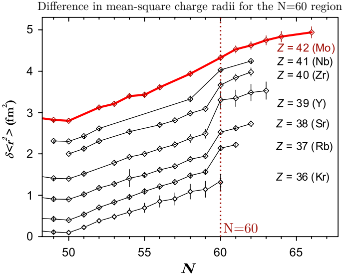

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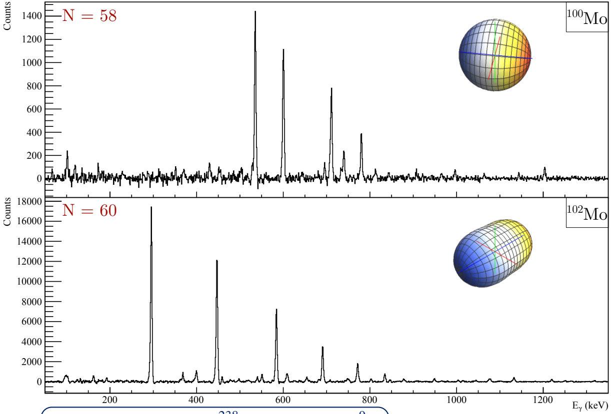

data from this experiment: ^{238}U@6.2 MeV/u on ^{9}Be

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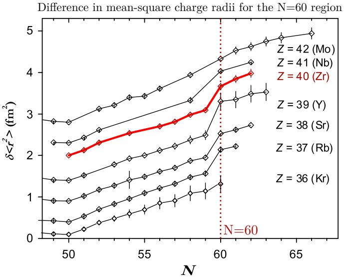

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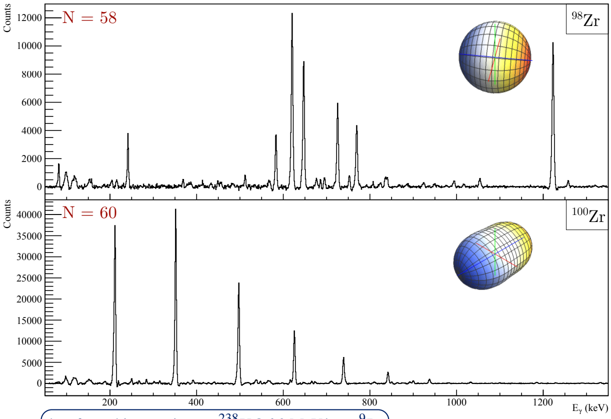

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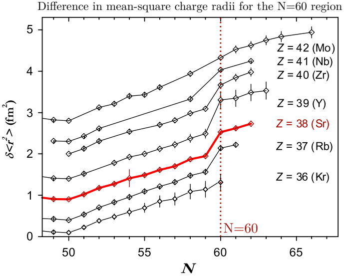

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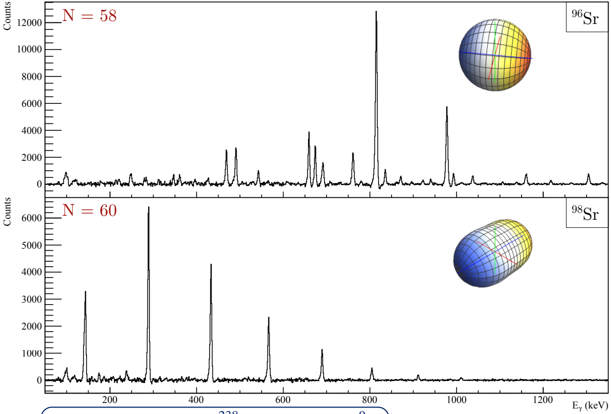

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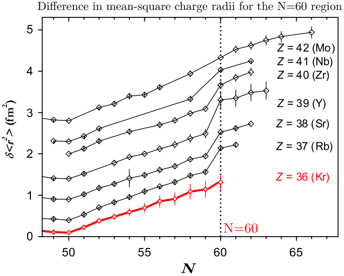

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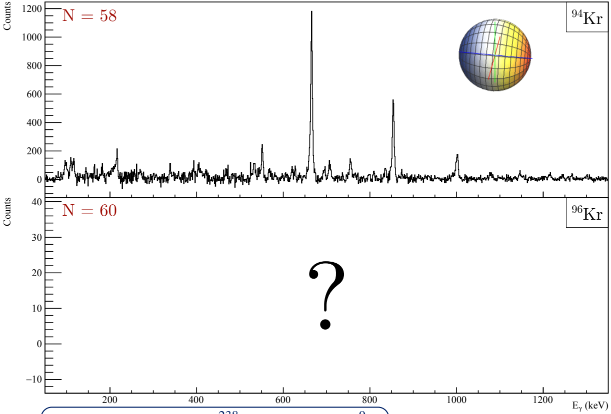
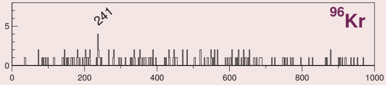


data from this experiment: ^{238}U@6.2 MeV/u on ^{9}Be

$^{96}_{36}Kr_{60}$ in the literature

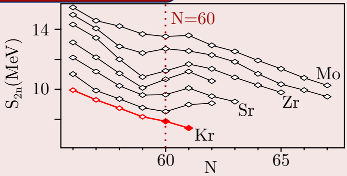
N. Marginean *et al.*, Phys. Rev. C 80, 021301 (R) (2009)

- Energy of the 2_1^+ excited state measured at 241 keV:
  - ⇒ Sudden drop of the $E(2_1^+)$ from ^{94}Kr to ^{96}Kr
  - ⇒ Possible rapid change in the ground state deformation as for Mo, Zr and Sr isotopic chains



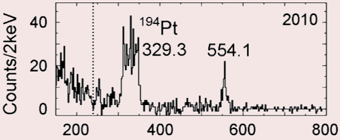
S. Naimi *et al.*, Phys. Rev. L 105, 032502 (2010)

- Mass measurement of ^{96,97}Kr:
  - ⇒ Contrary to the heavier isotopic chains, S_{2n} still decrease after N=58
  - ⇒ Result in contradiction with Marginean *et al.*

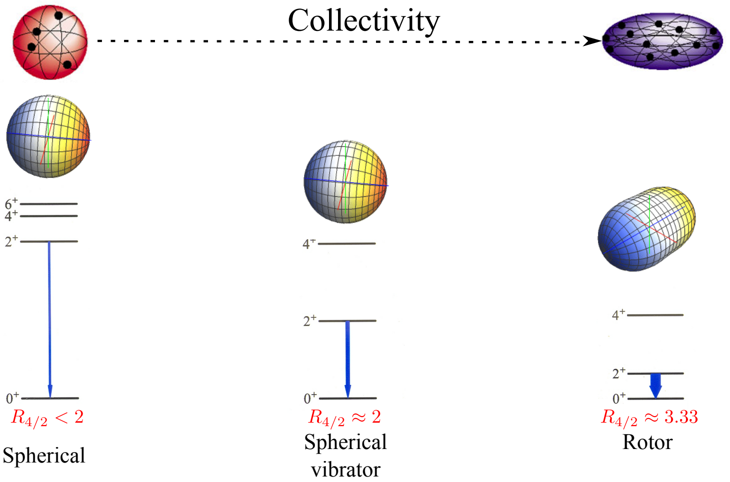


S. Albers *et al.*, Phys. Rev. L 108, 062701 (2012)

- Energy of the 2_1^+ excited state measured at 554.1 keV (no γ at 241 keV):
  - ⇒ This γ spectroscopic result imply a smooth onset of deformation in neutron-rich Kr isotopes around N=60
  - ⇒ Result in contradiction with Marginean *et al.* but validating Naimi *et al.* results



$B(E2), R_{4/2}$: main indicators of collectivity



→ $B(E2; 2_1^+ \rightarrow 0_1^+)$: reduced electric quadrupole transition probability

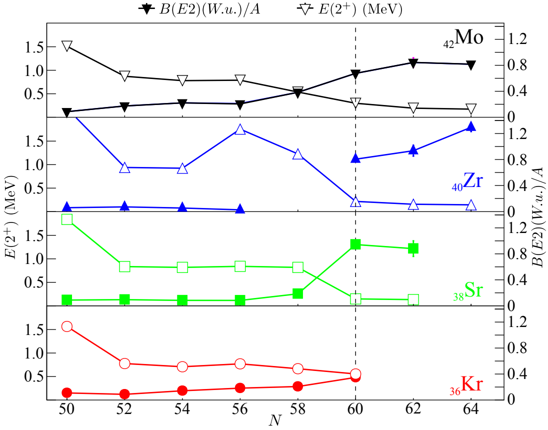
$R_{4/2} = E(4^+)/E(2^+)$

Systematic in the region

Standard increasing of collectivity

- ⇒ $E(2_1^+)$ vs $B(E2:2^+\rightarrow 0^+)$: $E(2_1^+)\searrow$, $B(E2)\nearrow$
- ⇒ $R_{4/2}=E(4^+)/E(2^+)$ vs $B(E2:2^+\rightarrow 0^+)$: $R_{4/2}\nearrow$, $B(E2)\nearrow$

↪ Kr follows a standard smooth increase of collectivity



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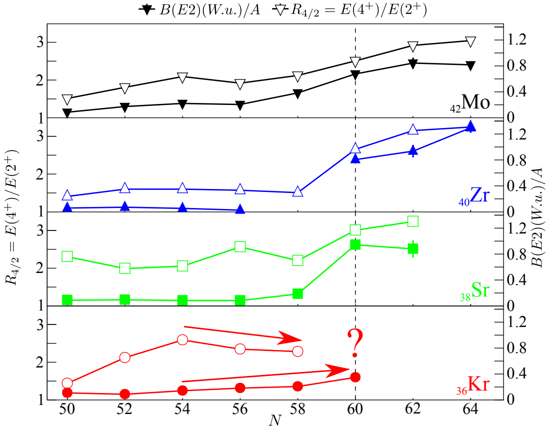
↪ Kr follows a standard smooth increase of collectivity... or not



Systematic in the region

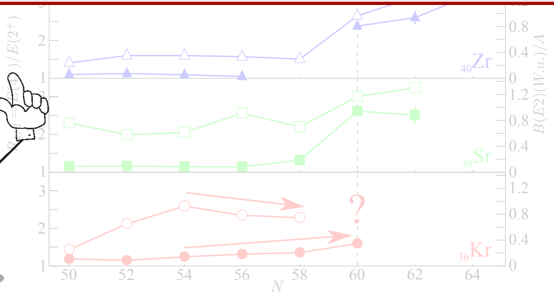
Standard increasing of collectivity

$\Rightarrow$ $E(2_1^+)$ vs $B(E2: 2^+ \rightarrow 0^+)$: $E(2_1^+) \searrow$, $B(E2) \nearrow$

$\Rightarrow$ $R_{4/2} = E(4^+)/E(2^+)$ vs $B(E2:$ … : … $_{/2} \nearrow$, $B(E2) \nearrow$

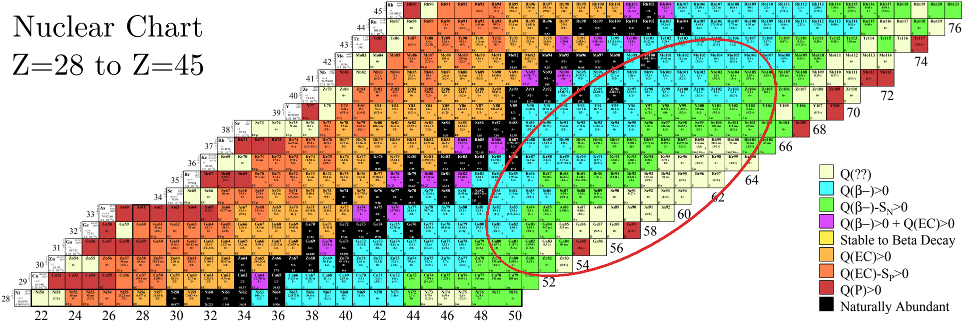
Quid of ^{96}Kr

- How can we resolve this contradiction on the 2_1^+ state energy ?
  - $\Rightarrow$ New high resolution γ-ray spectroscopy with isotopic identification
- Does this unexpected trend between $R_{4/2}$ and $B(E2)$ persists at N=60 ?
- What are the consequences on the nuclear ^{96}Kr structure?
  - $\Rightarrow$ Need spectroscopic measurements beyond the 2_1^+ state



How to populate Z=40 and N=60 region ?

Nuclear Chart
Z=28 to Z=45

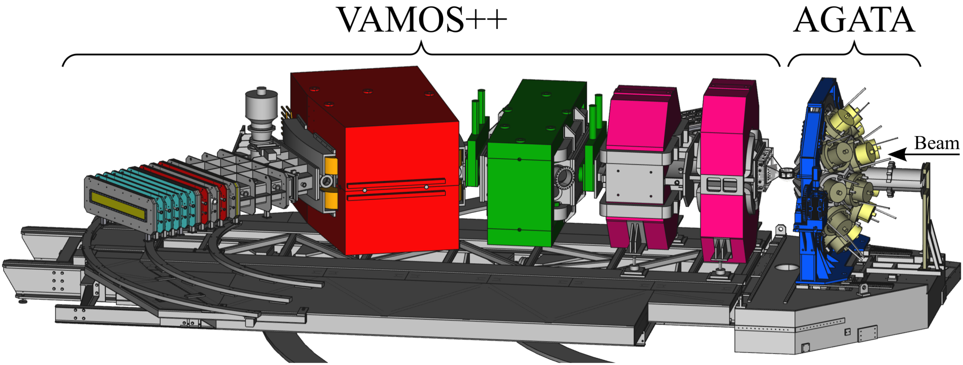


⇒ Transfer and fusion induced fission reactions in inverse kinematics:

Experimental setup

AGATA@GANIL: E680 experiment (May 2015)

- Spokesperson: Gilbert Duchêne (IPHC Strasbourg)
- Reaction : Transfer and fusion induced fission:
  $\hookrightarrow$ ^{238}U@6.2 MeV/u + ^{9}Be (1.85 mg/cm^2), I$\sim 6 \times 10^9$ pps
- Setup : VAMOS++ and AGATA spectrometers



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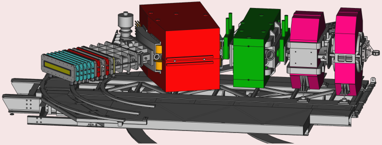
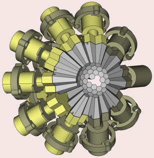
VAMOS++ setup



- VAMOS angle : 28°
- A, Z identified nuclei: 5×10^8
- Recoil velocity : $\beta \sim 0.11$
- Validation rate : $\sim$ 1.5 kHz

AGATA setup

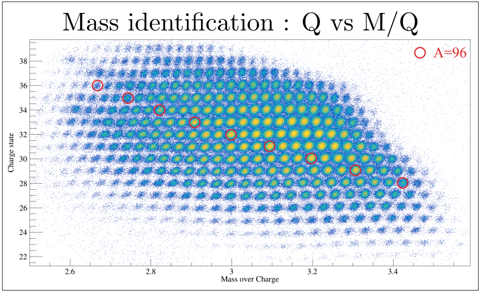


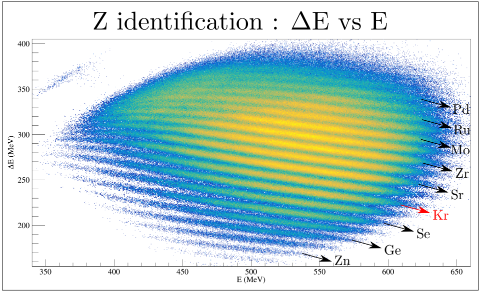
- Detectors : 24 crystals
- Geometry : compact ($\sim$ 14 cm)
- Tracked eff.: $\sim$ 10%@1 MeV
- Trigger : VAMOS++ & AGATA

Multi-parametric analysis of the VAMOS++ spectrometer

VAMOS++ spectrometer

- Mass identification
  - ↪ Nucleus trajectory reconstruction
  - ↪ Velocity measurement
  - ↪ Total energy measurement
- Z identification
  - ↪ Energy measurement (ΔE-E method)





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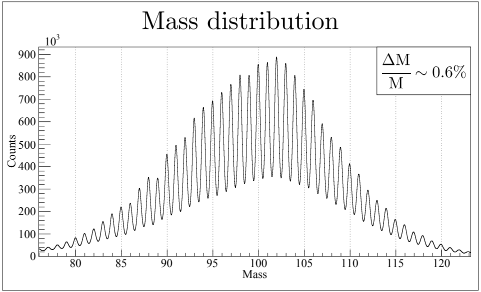
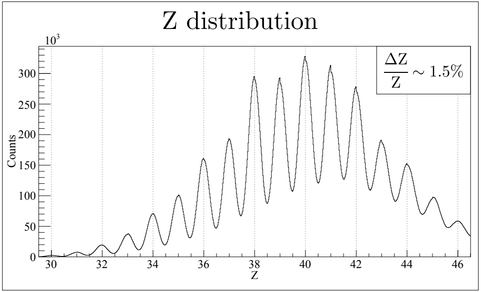
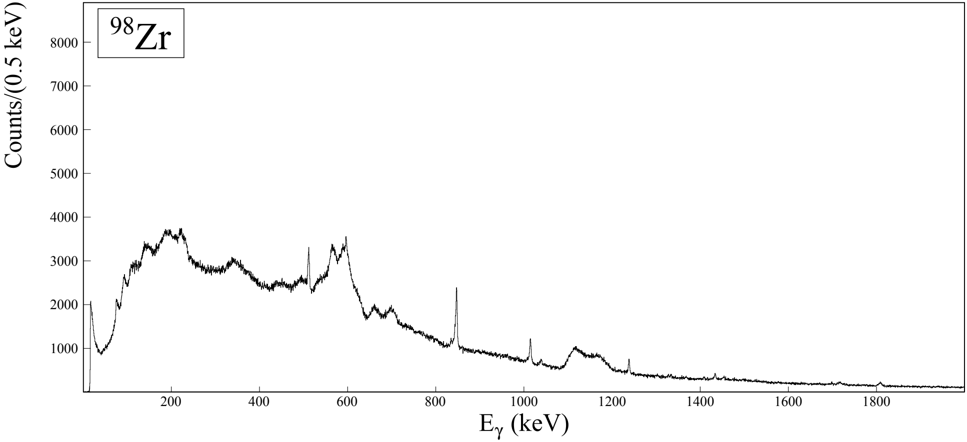




VAMOS++: Conclusions on VAMOS analysis

Results

- ⇒ Very precise Doppler correction → Agata FWHM = 5.0 keV@1.2 MeV (^{98}Zr, $\beta \sim 0.1$)
- ⇒ A set of 205 “well identified” nuclei has been obtained



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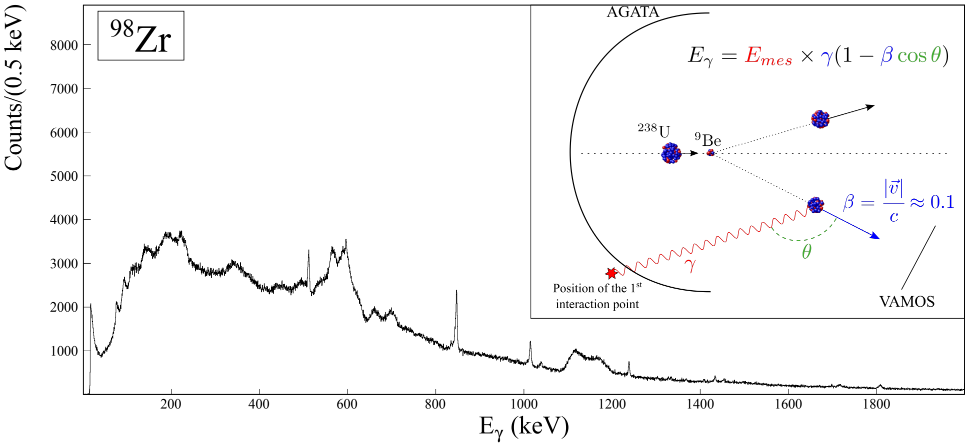

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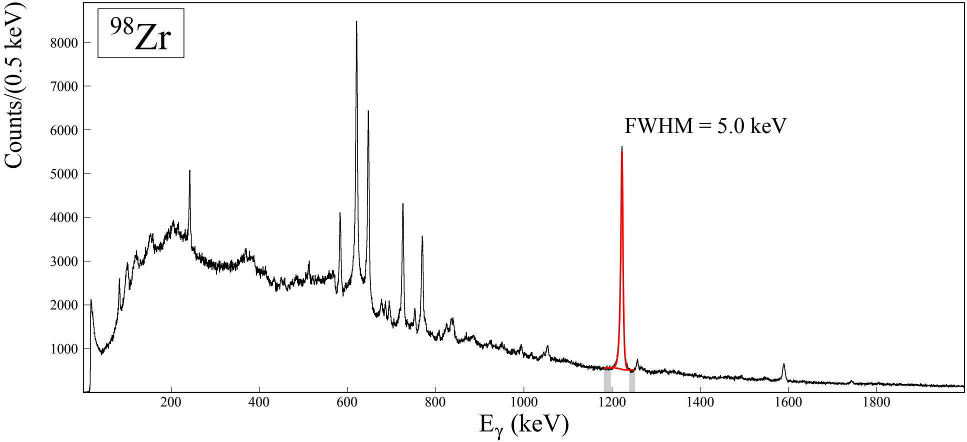

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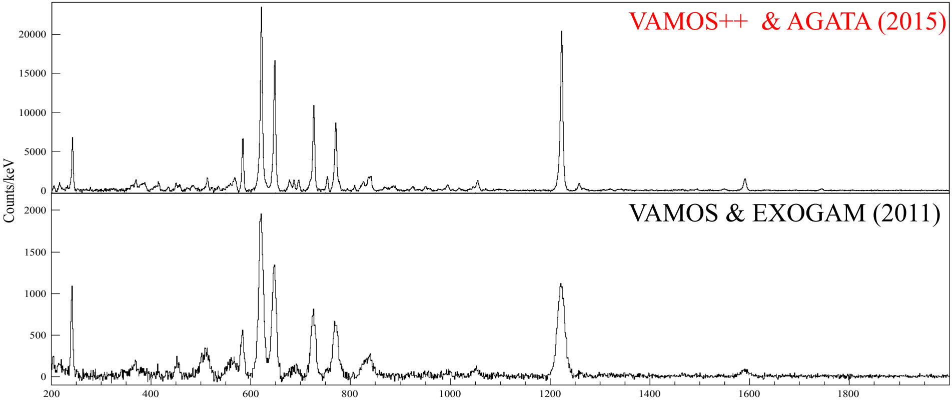

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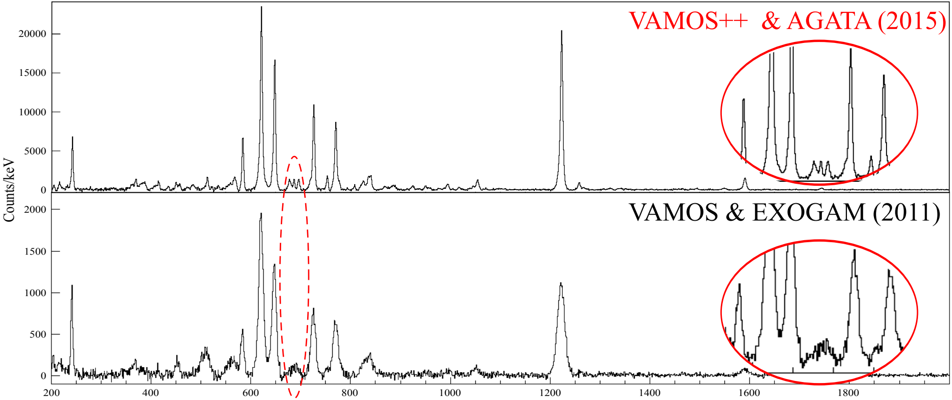

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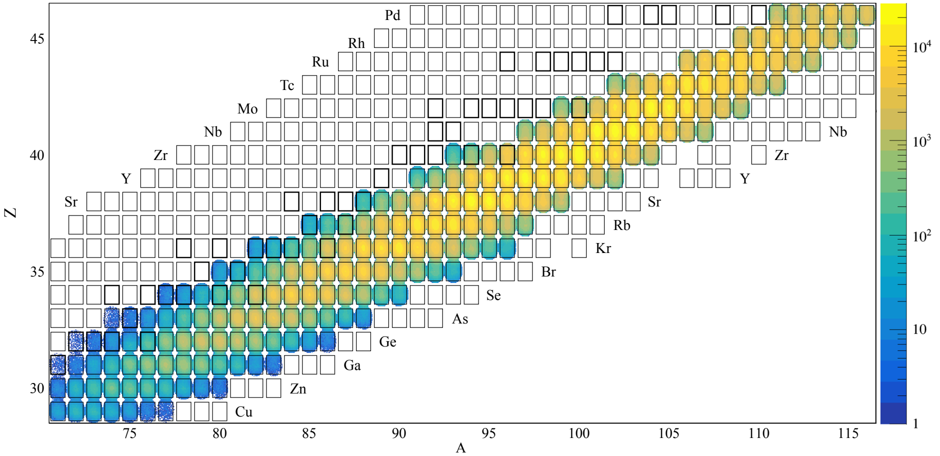

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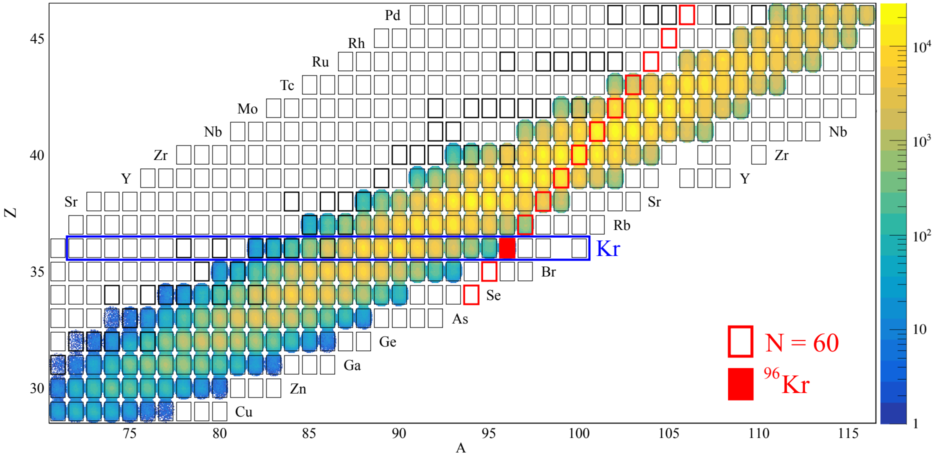
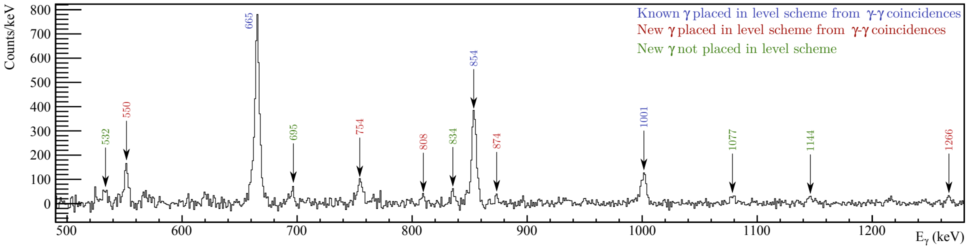
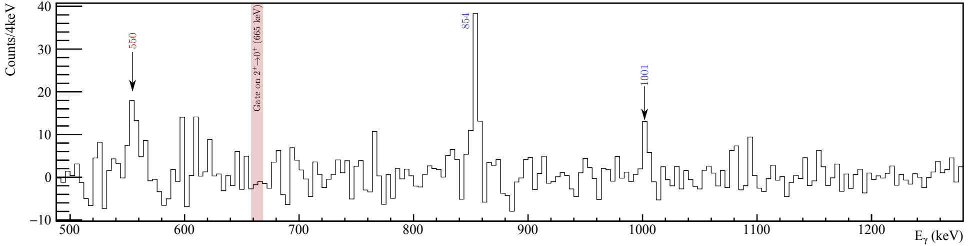


Spectroscopic results for Kr isotopes: ^{94}Kr

^{94}Kr spectrum

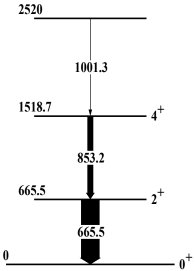


^{94}Kr spectrum gated on the $2_1^+ \rightarrow 0_1^+$ transition (665 keV)



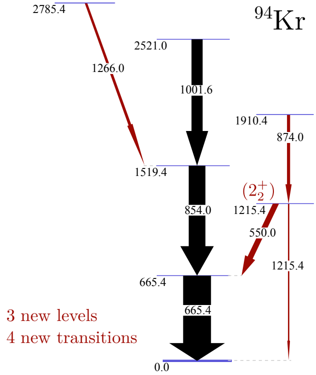
Spectroscopic results for Kr isotopes: ^{94}Kr Level Scheme

Urban et. al. 2000



- Spontaneous fission of ^{248}Cm
  - ⇒ EUROGAM 2 array
  - ⇒ 2.5×10^9 γ coincidences of fold ≥ 3

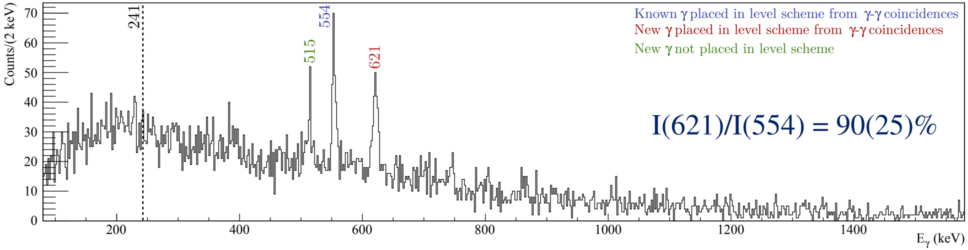
This work
(preliminary results)



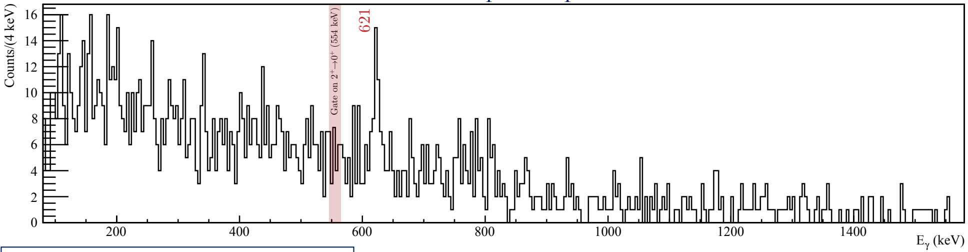
- ^{238}U + Be @ GANIL
  - ⇒ 24 AGATA crystals
  - ⇒ 5×10^8 A, Z identified fission fragments

Spectroscopic results for Kr isotopes: $^{96}Kr_{60}$

^{96}Kr spectrum



^{96}Kr spectrum gated on the $2_1^+ \rightarrow 0_1^+$ transition (554 keV)



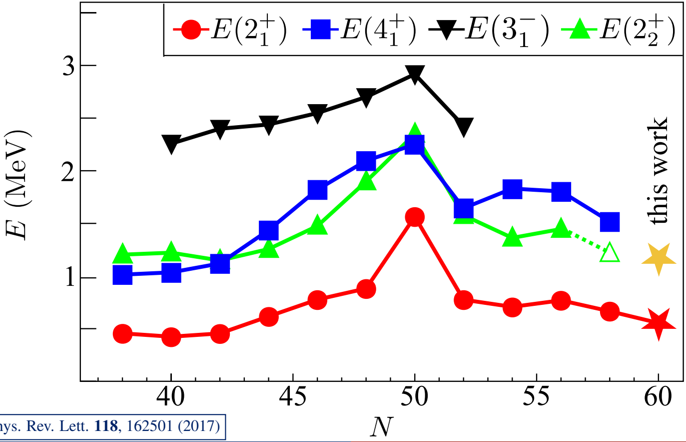
J. Dudouet *et al.*, Phys. Rev. Lett **118**, 162501 (2017)

Spectroscopic analysis

Possible attributions: systematic on Kr isotopes

- 3_1^- : Energy ? – Intensity ($\sim$ 0 $\rightarrow$ 30%) ?
- 2_2^+ : Energy ? – Intensity ($\sim$ 0 $\rightarrow$ 20%) ?
- 4_1^+ : Energy ? – Intensity ($\sim$ 50 $\rightarrow$ 100%) ?

I(621)/I(554) = 90(25)%



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Spectroscopic analysis

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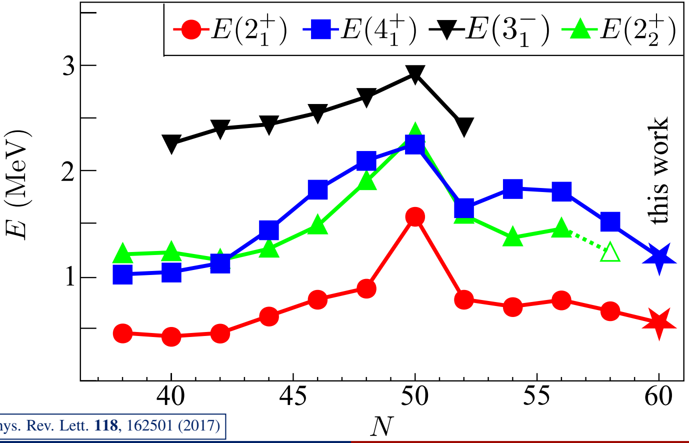
- 3^-_1 : Energy ✗ – Intensity ($\sim$ 0 $\rightarrow$ 30%) ✗
- 2^+_2 : Energy ✓ – Intensity ($\sim$ 0 $\rightarrow$ 20%) ✗
- 4^+_1 : Energy ✓ – Intensity ($\sim$ 50 $\rightarrow$ 100%) ✓

I(621)/I(554) = 90(25)%

621 keV : 4^+_1(1175 keV)$\rightarrow$ 2^+_1(554 keV)



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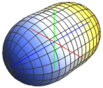
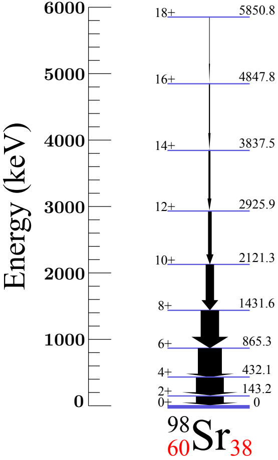
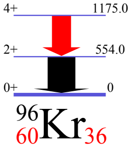
Level scheme of the N=60 GS band





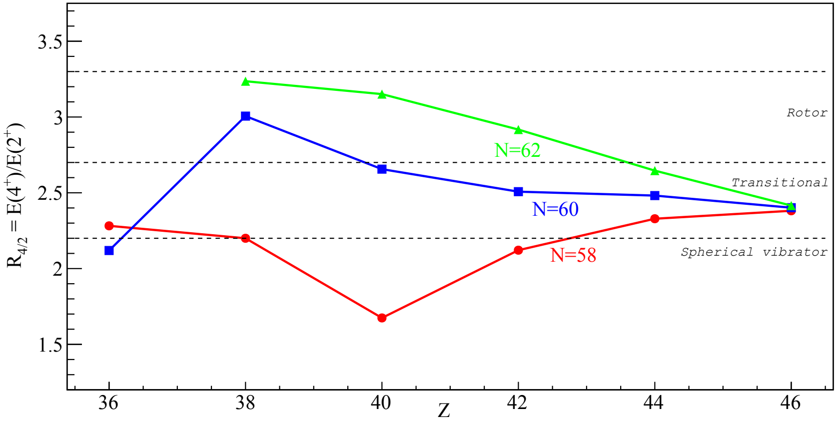
$R_{4/2} = E(4^+_1)/E(2^+_1) = 2.12(1)$



The ^{96}Kr case : low Z boundary of the A$\sim$ 100 island of deformation

Informations from the $R_{4/2} = E(4^+)/E(2^+)$ ratio

- ⇒ Sharp transition at N=60 when moving from Sr to Kr
- ⇒ $R_{4/2}$ value confirms previous observations: ^{96}Kr seems not highly deformed



-------- Horizontal lines : schematic view of the nuclear structure evolution (from R. F. Casten, 2001)

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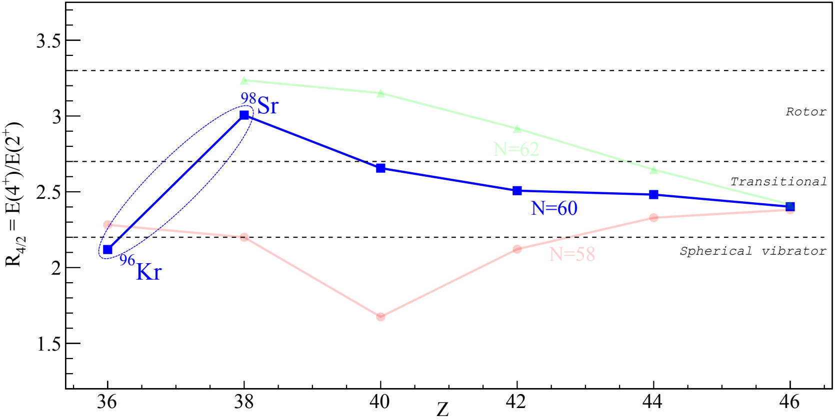


-------- Horizontal lines : schematic view of the nuclear structure evolution (from R. F. Casten, 2001)

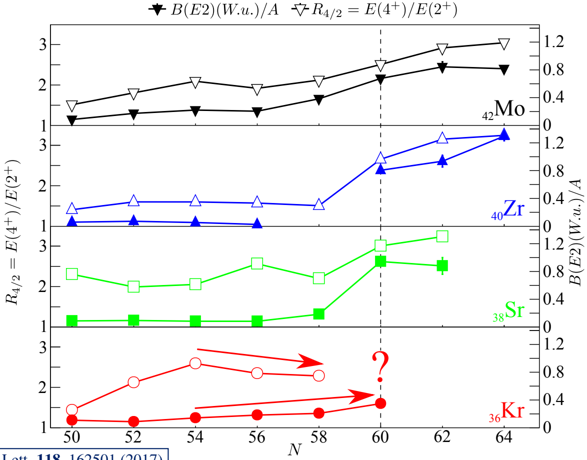
J. Dudouet *et al.*, Phys. Rev. Lett **118**, 162501 (2017)

The strange behaviour of Kr nuclei

Usual increasing of collectivity

⇒ $R_{4/2} = E(4^+)/E(2^+)$ vs $B(E2:2^+ \to 0^+)$: $R_{4/2} \nearrow$, $B(E2) \nearrow$

↪ Kr follows an unexpected trend between $R_{4/2}$ and $B(E2)$ up to $N = 58$



J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017)

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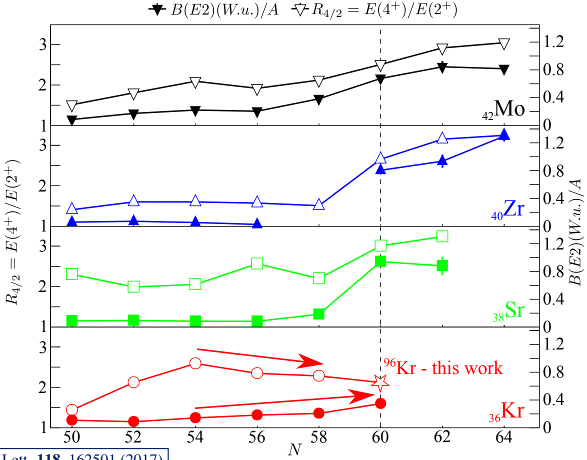

J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017)

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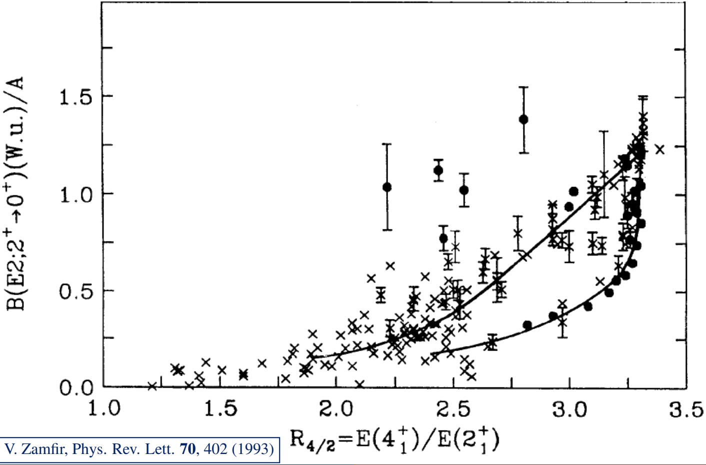

R. F. Casten and N. V. Zamfir, Phys. Rev. Lett. **70**, 402 (1993)

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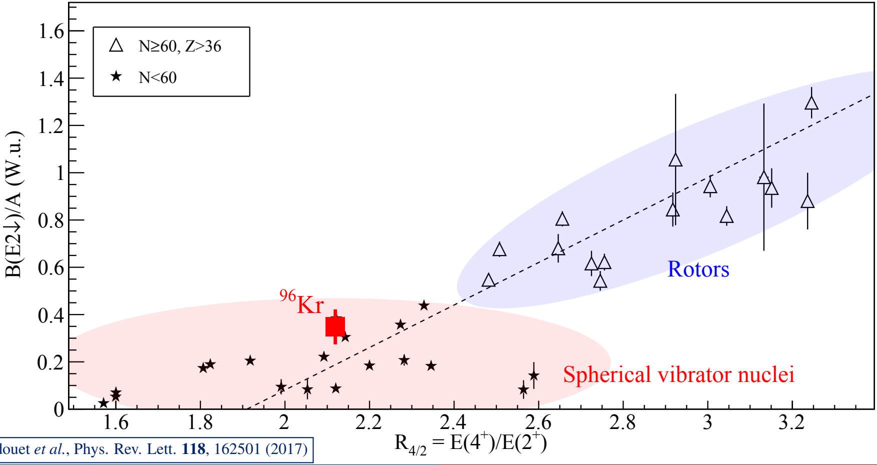

J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017)

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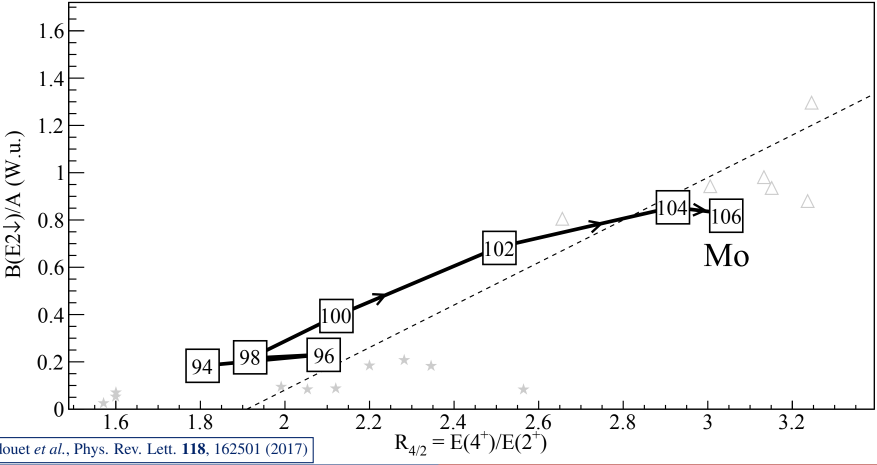

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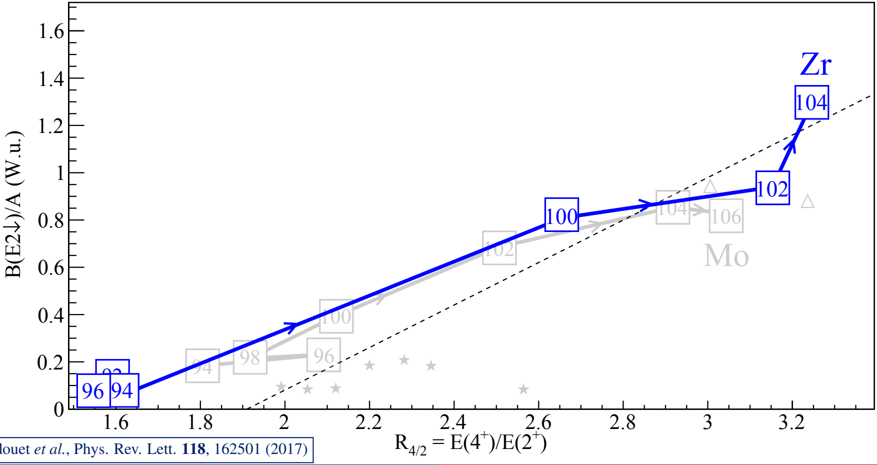

J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017)

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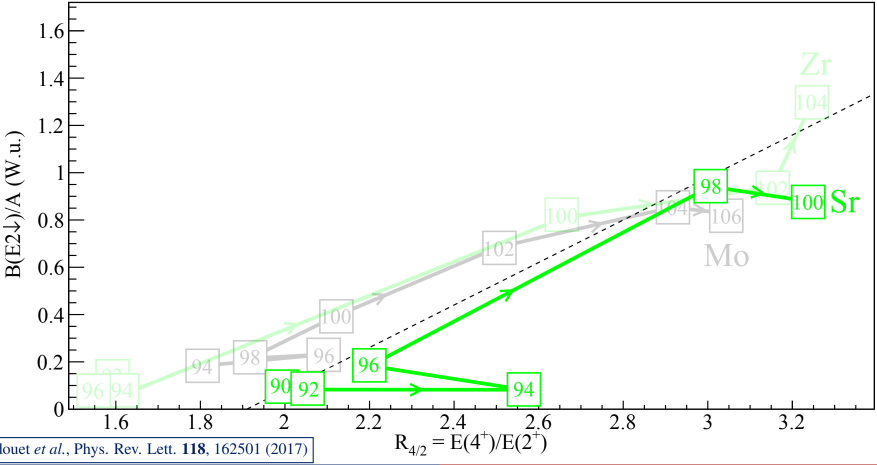

J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017)

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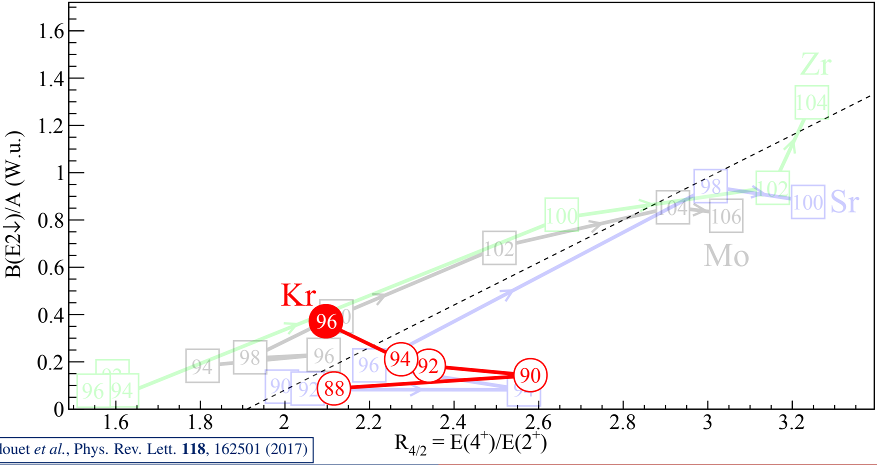
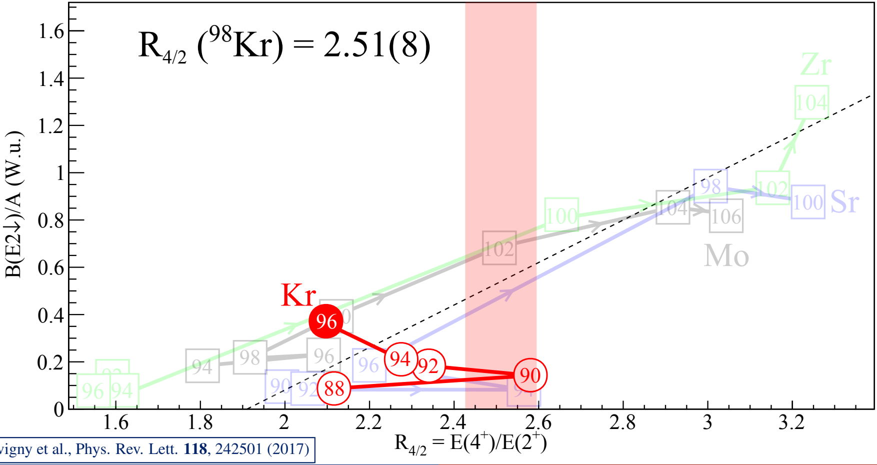


J. Dudouet *et al.*, Phys. Rev. Lett. **118**, 162501 (2017)

The strange behaviour of Kr nuclei

New measurements on very neutron rich $^{98-100}$Kr

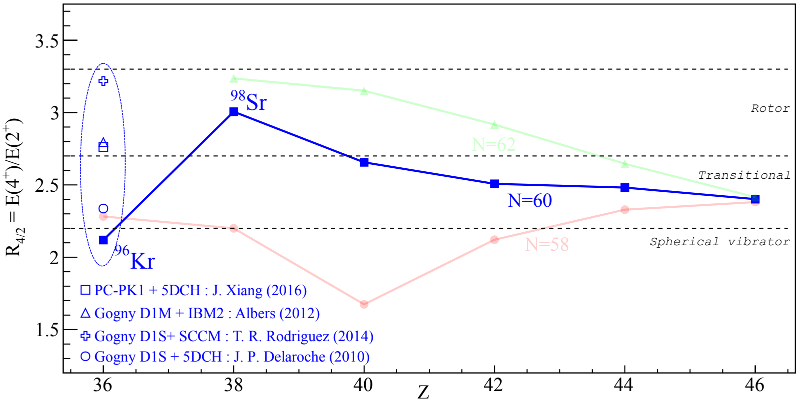
⇒ Recent results on $^{98-100}$Kr suggest a delayed onset of deformation at N=62
↪ $B(E2: 2^+ \rightarrow 0^+)$ not measured



F. Flavigny et al., Phys. Rev. Lett. **118**, 242501 (2017)

Comparisons to theoretical calculations

- To understand these phenomena, theoretical calculations needs to reproduce:
  - ⇒ The sharp transition at N=60 for Z>36,
  - ⇒ the absence of transition at Z=36,
  - ⇒ the decreasing trend of the $R_{4/2}$ ratio.



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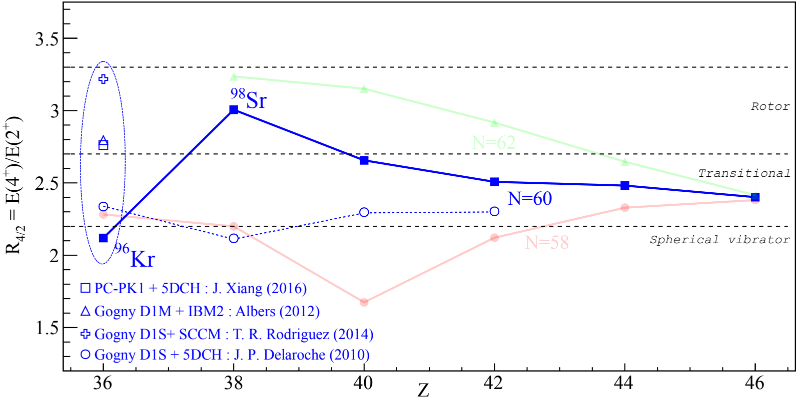

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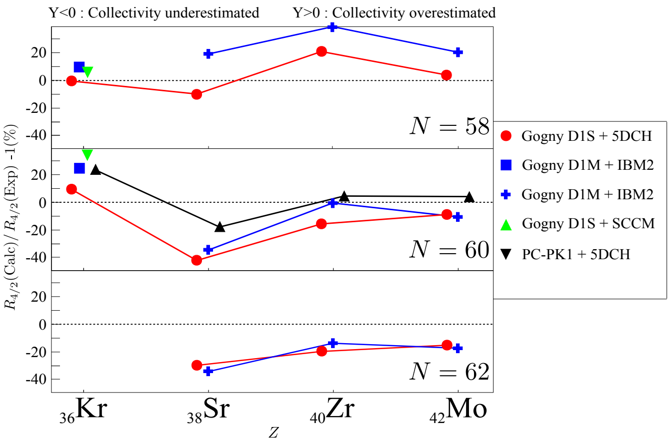

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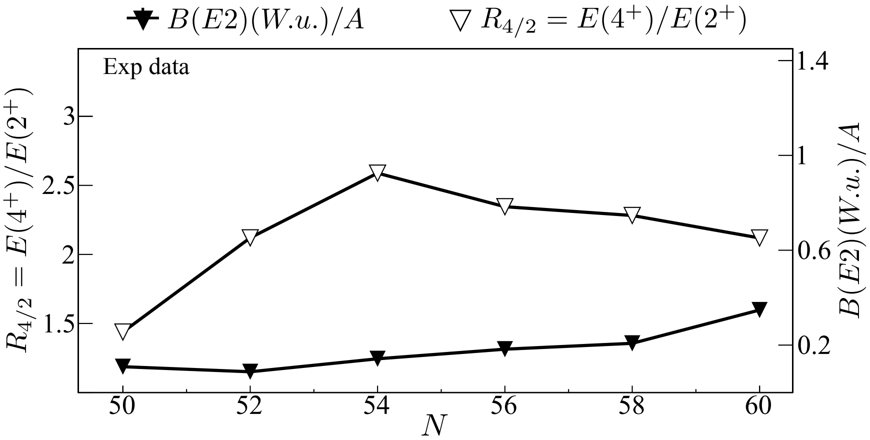

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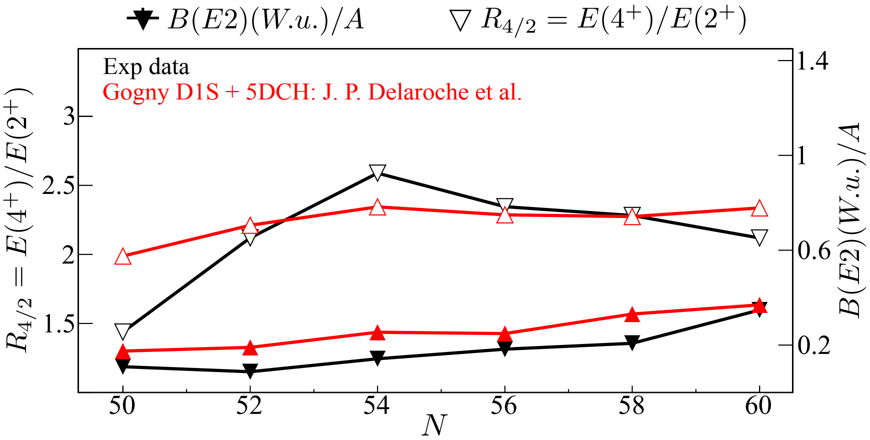

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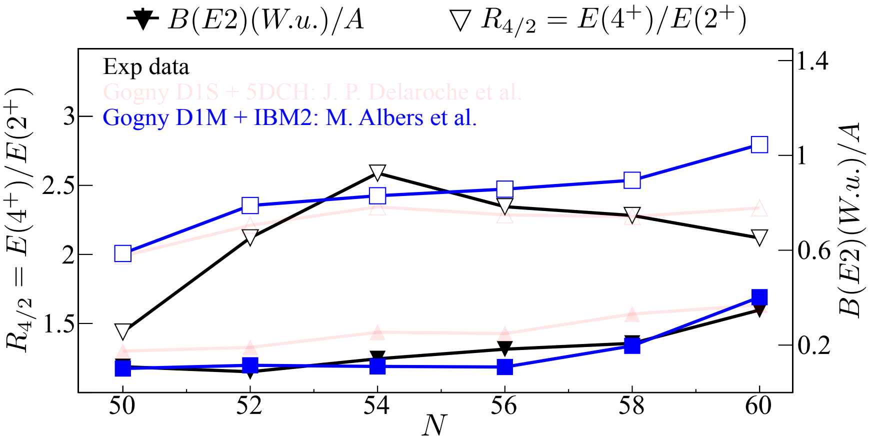

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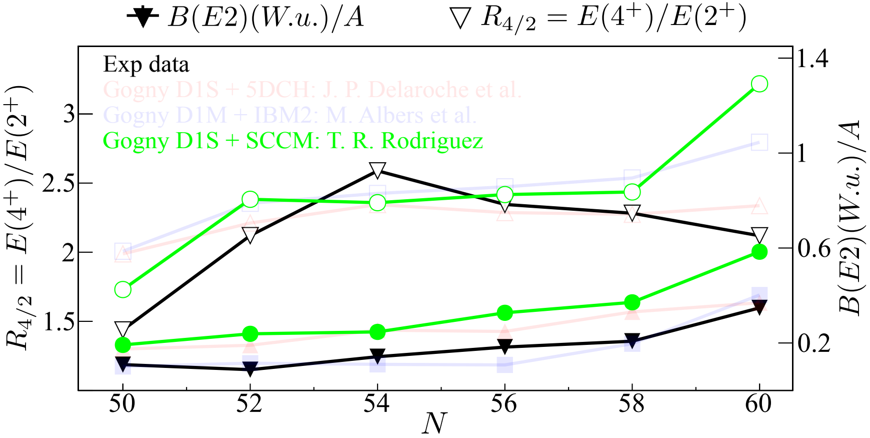
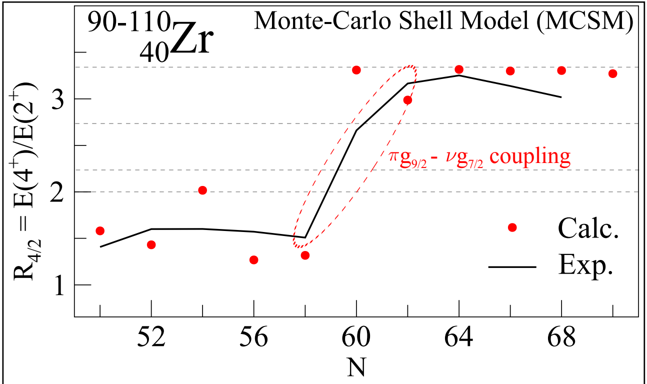


Comparisons to theoretical calculations

- Predictions from mean field calculations not able for the moment to reproduce this transition
- New Monte Carlo Shell-Model calculations performed along the Zr isotopic chain reproduce for the first time the N=60 transition along the Zr isotopic chain
- Could such a model help to understand this strange behavior in the Kr chain ?



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

Conclusions

Experimental results

- The powerful coupling between AGATA and VAMOS allowed to add new spectroscopic information to the Kr isotopic chain.
- 4_1^+ level established for the first time in ^{96}Kr.
  - ⇒ $R_{4/2}$ value confirms the non observation of sharp transition at N=60 in Kr
  - ⇒ contradicting trend between $R_{4/2}$ and $B(E2; 2^+ \rightarrow 0^+)$ evidenced

Interpretation

- Mean-field approaches fail to reproduce the observed phenomena.
  - ⇒ Opposite $R_{4/2}$ and $B(E2; 2^+ \rightarrow 0^+)$ evolution still puzzling. Could be related to a shape coexistence phenomenon affecting the $R_{4/2}$ ratio.
- MCSM calculations give the first microscopical reproduction of the N=60 transition in Zr nuclei.
  - ⇒ Z>36: transitions generated by a strong $\pi g_{9/2}$-$\nu g_{7/2}$ coupling.

Thank you for your attention!

And thank you to all the person involved in this experiment:

A. Lemasson, G. Maquart, G. Duchêne, M. Rejmund, E. Clément, F. Didierjean, C. Lizarazo, C. Michelagnoli, F. Nowacki, R. Perez, K. Sieja, O. Stezowski, C. Andreoiu, G. de Angelis, A. Astier, C. Delafosse, I. Deloncle, Z. Dombradi, G. de France, A. Gadea, A. Gottardo, B. Jacquot, P. Jones, T. Konstantinopoulos, A. Korichi, I. Kuti, F. Le Blanc, S.M. Lenzi, G. Li, R. Lozeva, B. Million, D.R. Napoli, A. Navin, C.M. Petrache, N. Pietralla, D. Ralet, M. Ramdhane, C. Schmitt, D. Sohler, D. Verney.