Gamma-ray spectroscopy of neutron-rich Kr isotopes using AGATA coupled to VAMOS++

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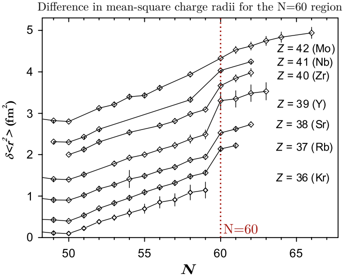
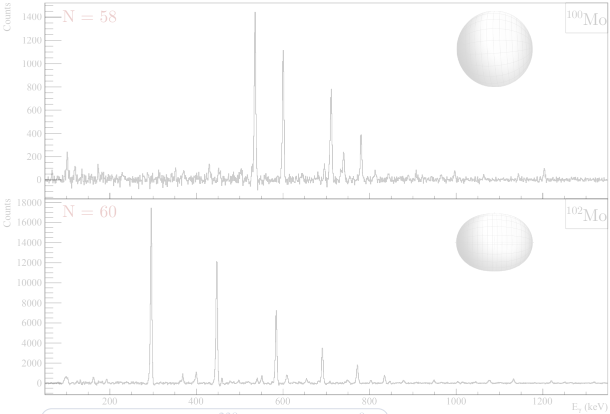
Evolution of deformation in the Z=40 and N=60 region

- 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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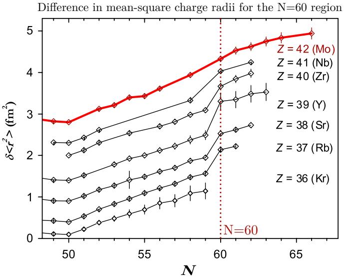

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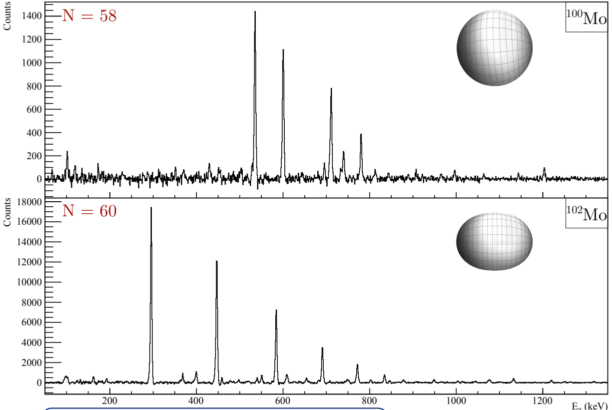

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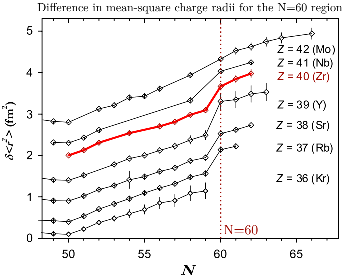

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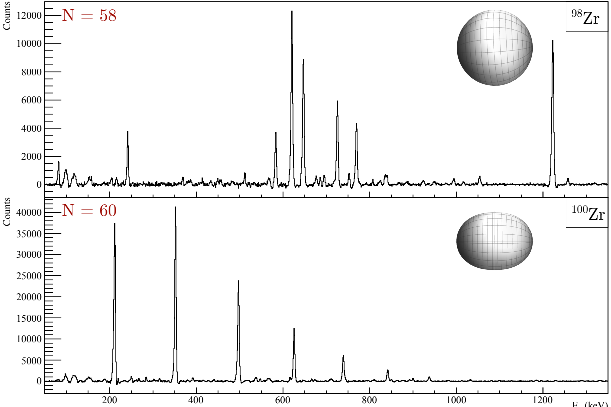

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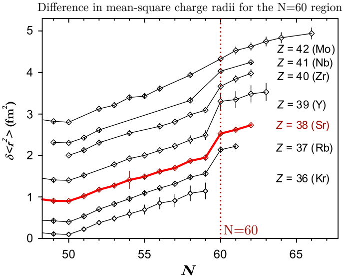

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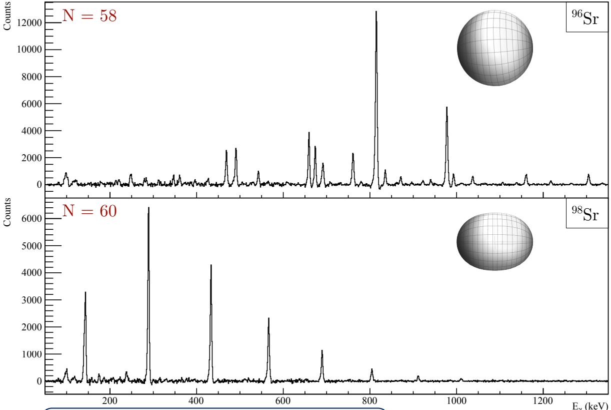

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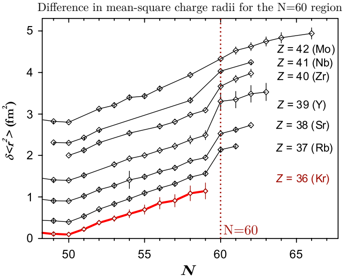

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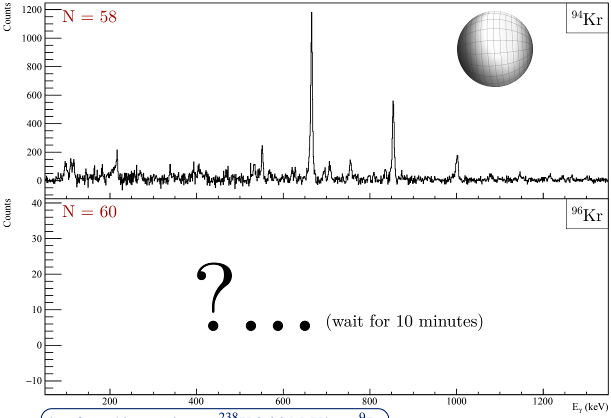

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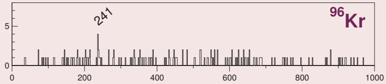
${}^{96}_{36}Kr_{60}$ in the literature

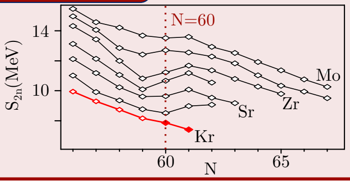
N. Marginean *et al.*, Phys. Rev. C 80, 021301 (R) (2009)

- 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



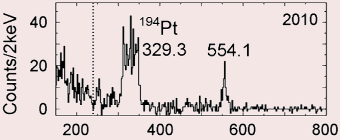
S. Naimi *et al.*, Phys. Rev. L 105, 032502 (2010)

- 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



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Quid of ^{96}Kr

- How can we resolve this contradiction on the 2_1^+ state energy ?
  - ⇒ New high resolution γ-ray spectroscopy with isotopical identification
- If the energy of 554 keV is confirmed, what are the consequences on the ^{96}Kr stucture ?
  - Transitional nucleus with a delayed onset of deformation ?
  - Shape coexistence with a strong mixing which impacts the 2_1^+ state energy ?
  - ⇒ Need spectroscopic measurements beyond the 2_1^+ state

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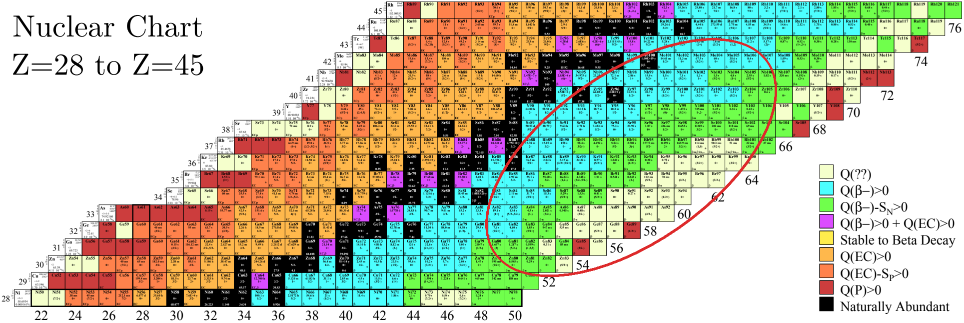
How to populate Z=40 and N=60 region ?

Nuclear Chart
Z=28 to Z=45



⇒ Fusion-fission mechanism in inverse kinematics:

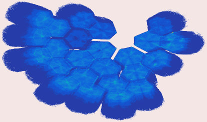
GANIL beam : ^{238}U@6.2 MeV/u on ^{9}Be

Experimental setup

The E680 experiment @ GANIL

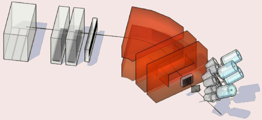
- Spokesperson: Gilbert Duchêne (IPHC, Strasbourg, France)
- Date : $14^{th} \rightarrow 28^{th}$ May 2015 (45 UT)
- Beam : ^{238}U@6.2 MeV/u, I$\sim$30 enA
- Target : ^{9}Be (1.85 mg/cm^2)
- Detectors : AGATA and VAMOS++

AGATA setup



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

VAMOS++ setup



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

VAMOS++: Mass identification

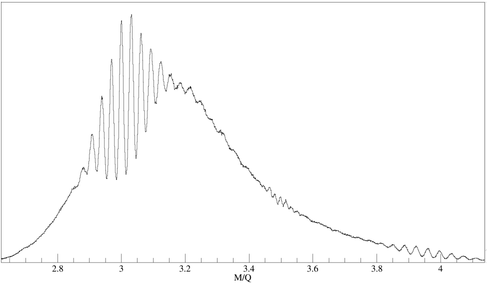
Q vs M/Q matrix ⇒ Mass identification

- ⇒ Trajectory reconstruction
- ⇒ Time of flight measurement

} M/Q

- ⇒ Total energy measurement

} Q



$$\frac{M}{Q} = \frac{B\rho}{3.105 \times \beta}$$

$$Q = \frac{2 \times E_{tot}}{931.5 \times \beta^2} \times \frac{Q}{M}$$

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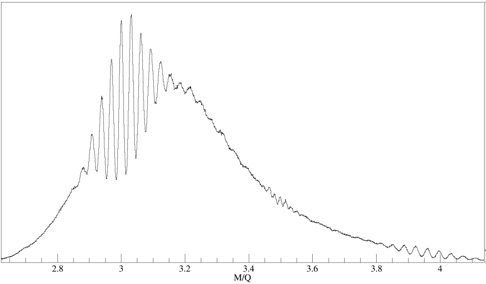

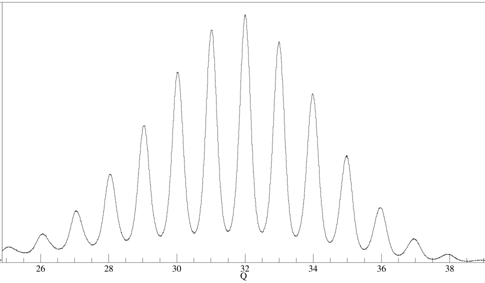

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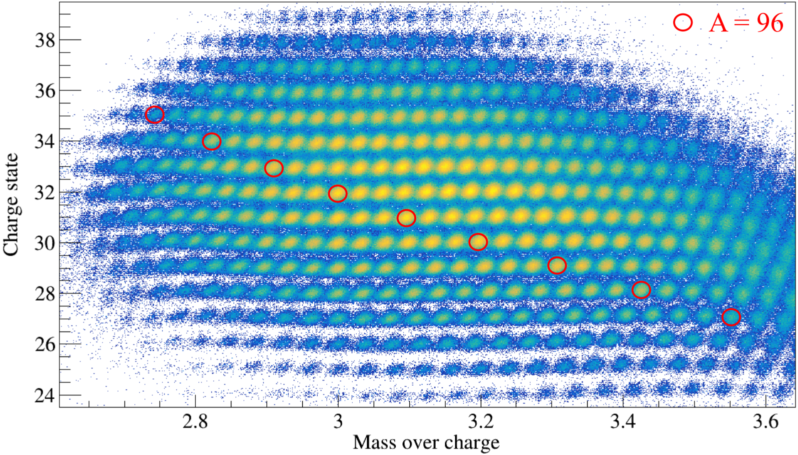

VAMOS++: Mass identification

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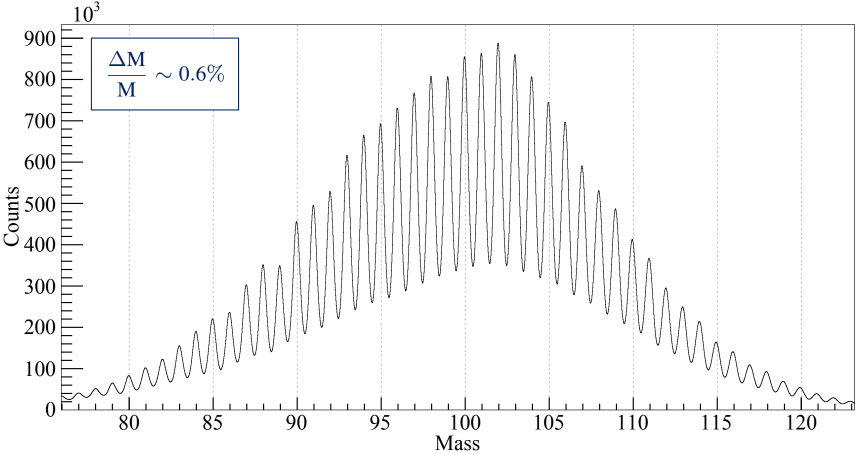
- ⇒ Total energy measurement

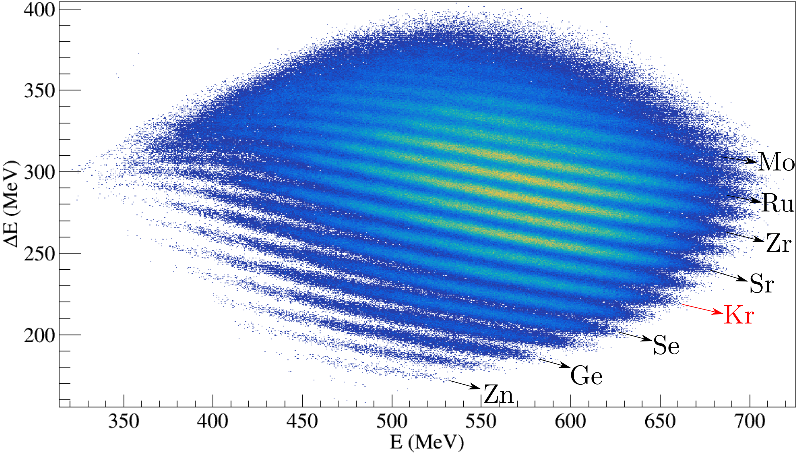
Trajectory reconstruction + Time of flight measurement → M/Q; with Total energy measurement → Q ⇒ M = M/Q x Q ∈ [70;120]



VAMOS++: Z identification

ΔE vs E matrix ⇒ Z identification

⇒ Z discrimination obtained from ΔE vs E matrix



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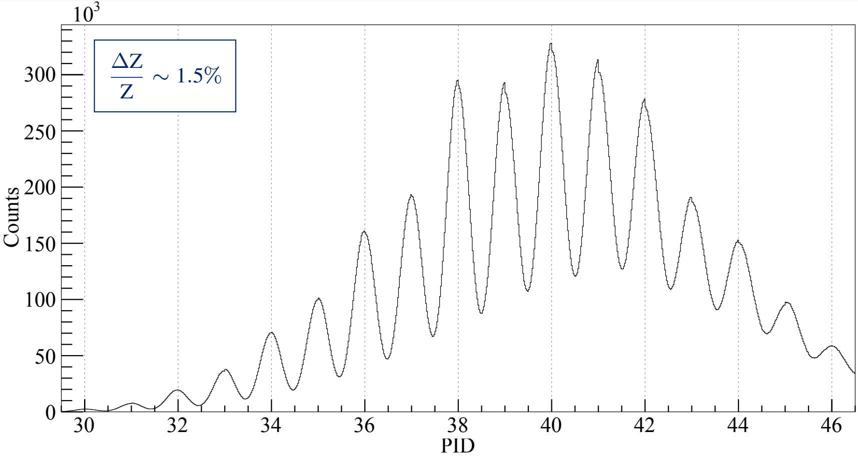
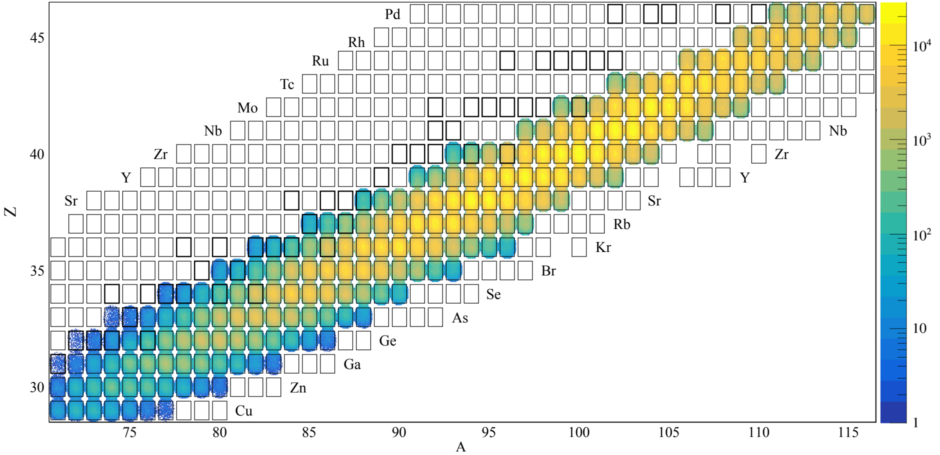


VAMOS++: Conclusions on VAMOS analysis

Results

⇒ A set of 205 "well identified" nuclei has been obtained



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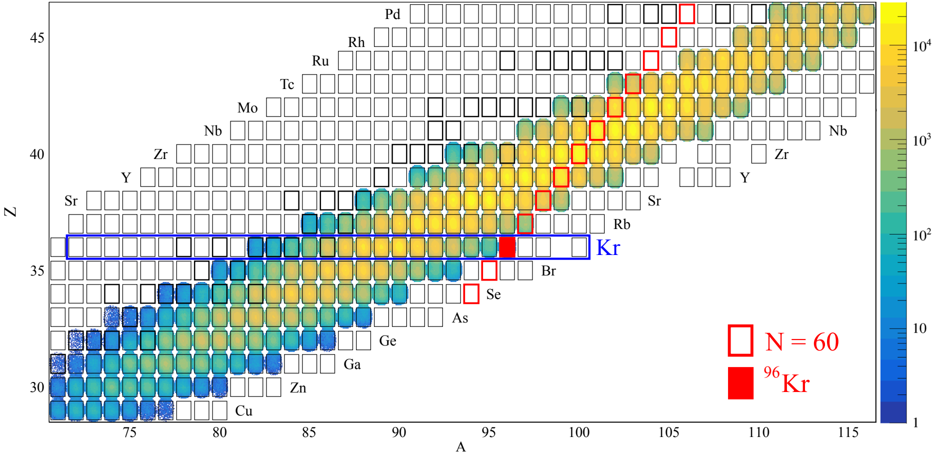

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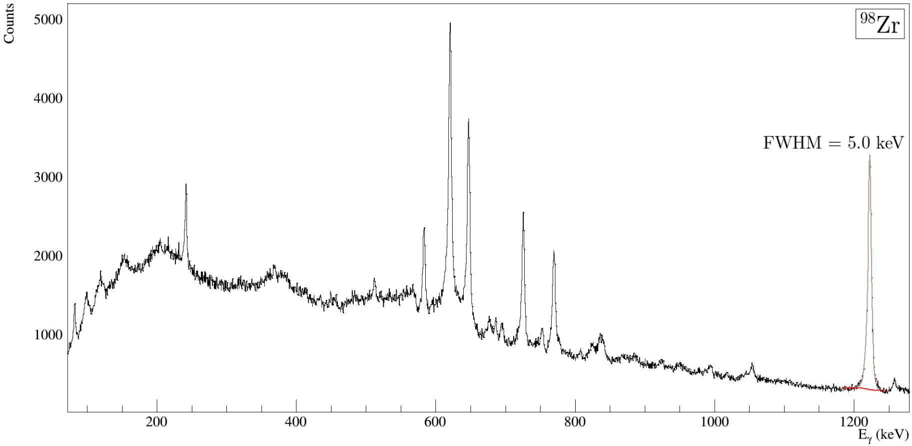

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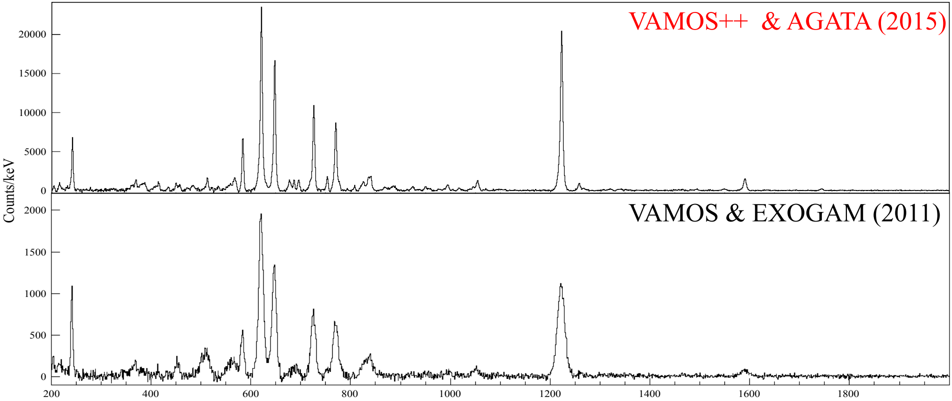

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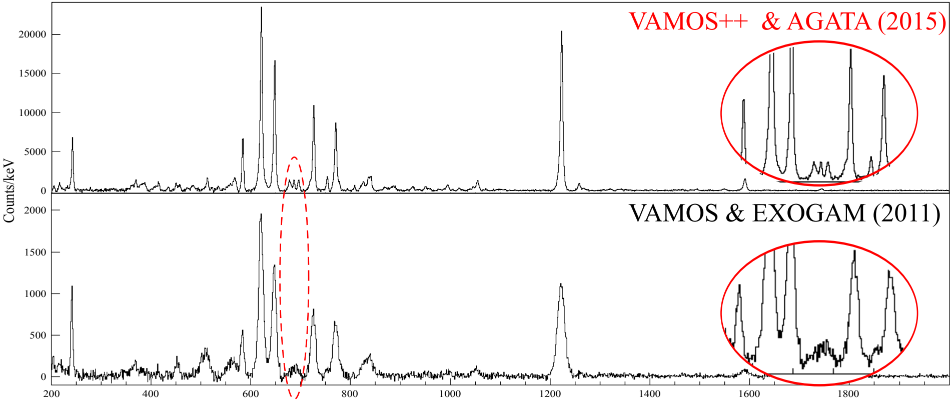
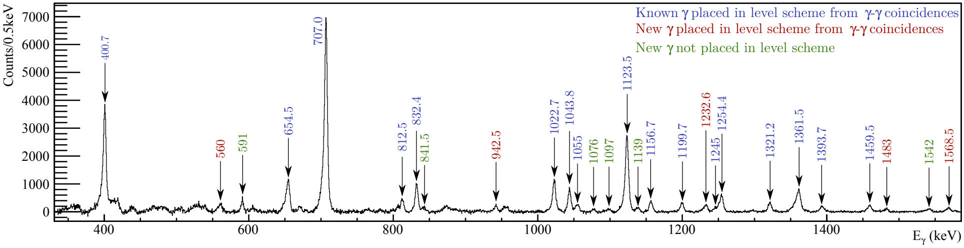
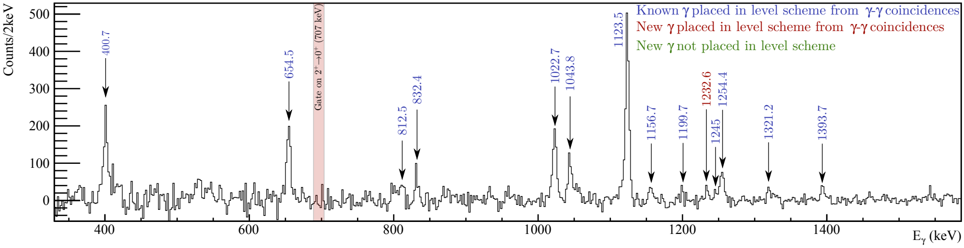


Spectroscopic results for Kr isotopes: ^{90}Kr

^{90}Kr spectrum



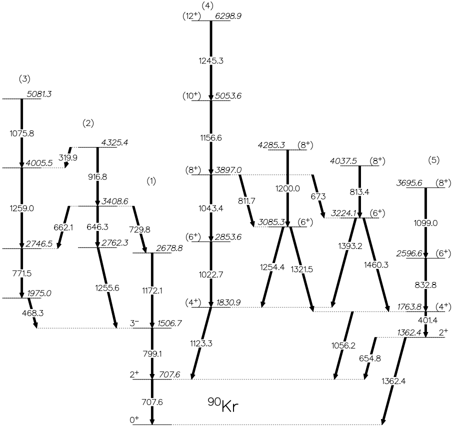
^{90}Kr spectrum gated on the $2_1^+ \rightarrow 0_1^+$ transition (707 keV)



Spectroscopic results for Kr isotopes: ^{90}Kr Level Scheme (LS)

Hamilton et. al. 2011

^{90}Kr



- Spontaneous fission of ^{252}Cf
  - $\Rightarrow$ Gammasphere full array
  - $\Rightarrow 5.7 \times 10^{11}$ γ coincidences of fold ≥ 3

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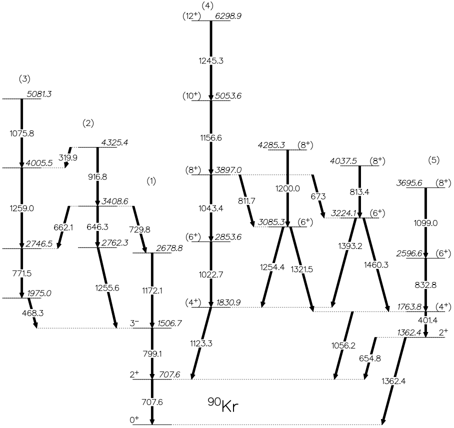

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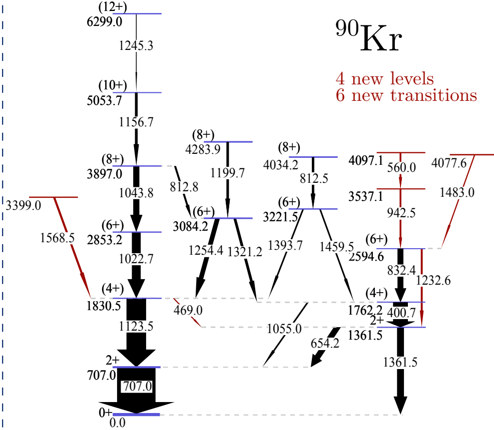

• ^{238}U + Be @ GANIL
  ⇒ 24 AGATA crystals
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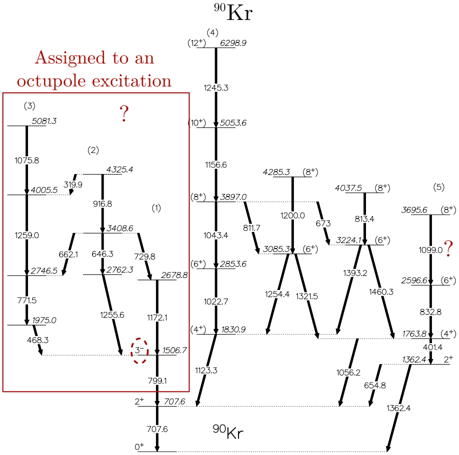
Hamilton et. al. 2011



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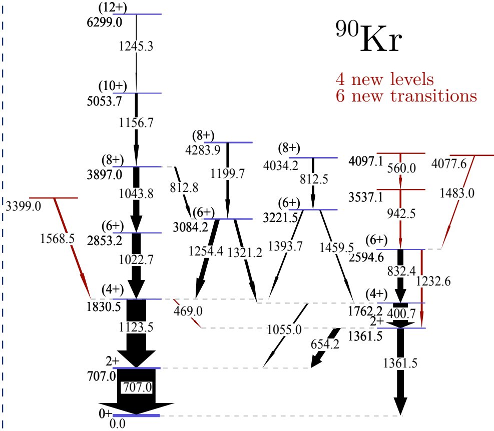

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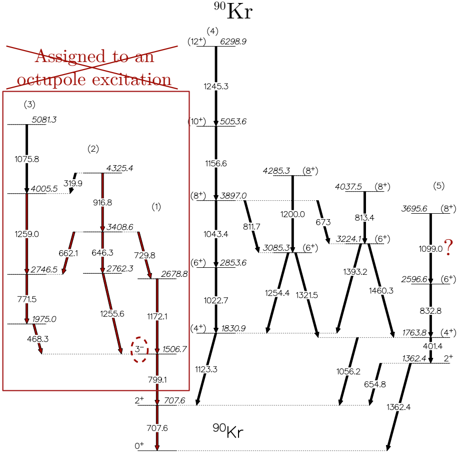

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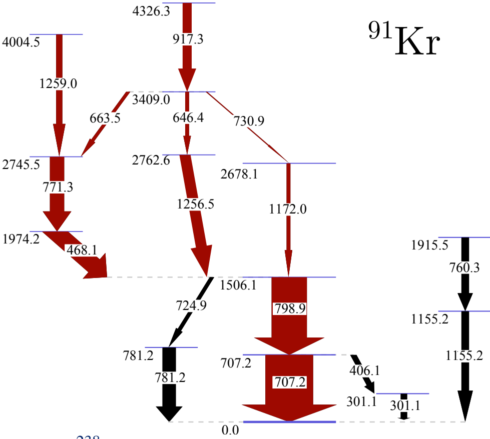

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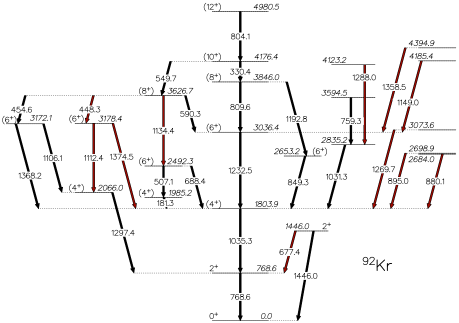
Spectroscopic results for Kr isotopes: ^{92}Kr LS

Hamilton et. al. 2011

^{92}Kr



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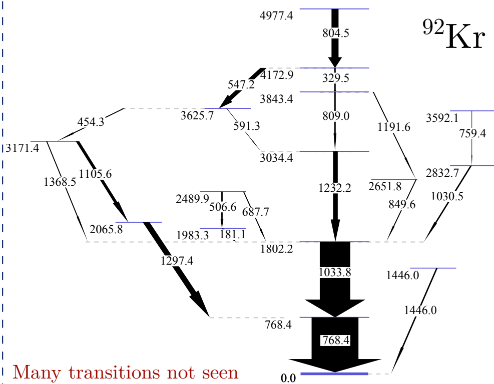


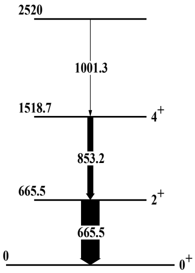
Many transitions not seen
No new transition

- Spontaneous fission of ^{252}Cf
  - ⇒ Gammasphere full array
  - ⇒ 5.7×10^{11} γ coincidences of fold ≥ 3

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

Spectroscopic results for Kr isotopes: ^{94}Kr LS

Urban et. al. 2000



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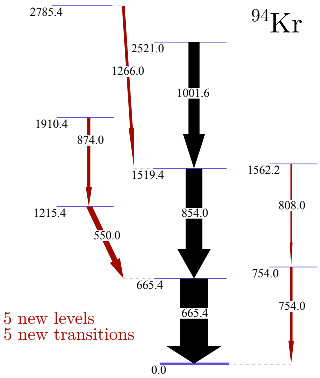
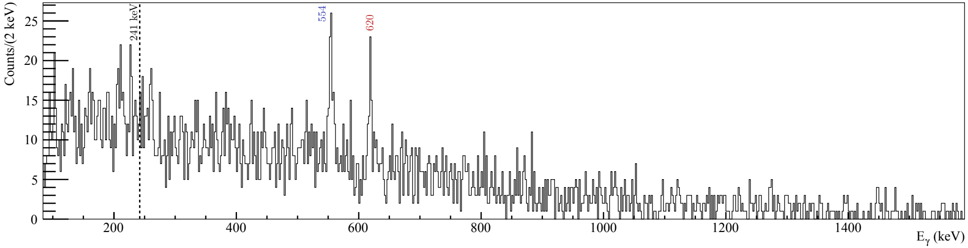


- Spontaneous fission of ^{248}Cm
  $\Rightarrow$ EUROGAM 2 array
  $\Rightarrow$ 2.5×10^9 γ coincidences of fold ≥ 3

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

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

^{96}Kr spectrum



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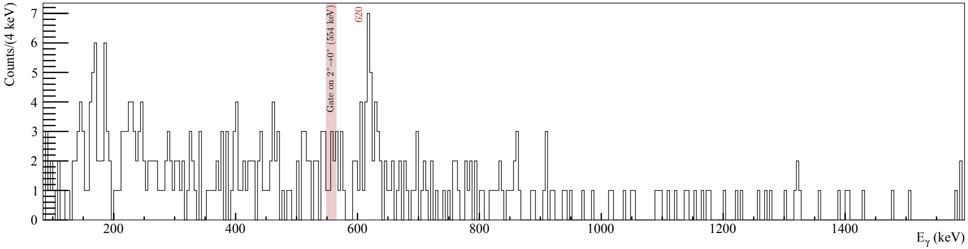
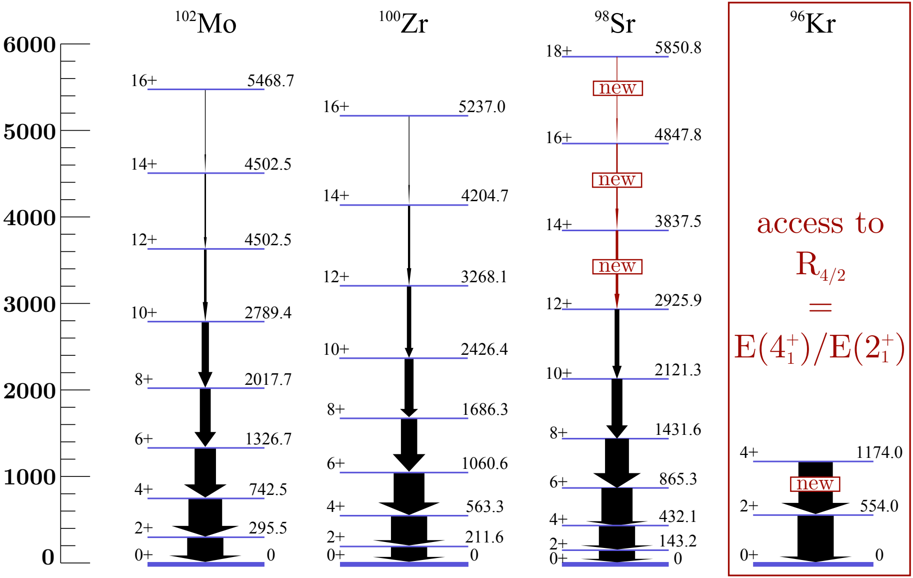


Level scheme of the N=60 GS band

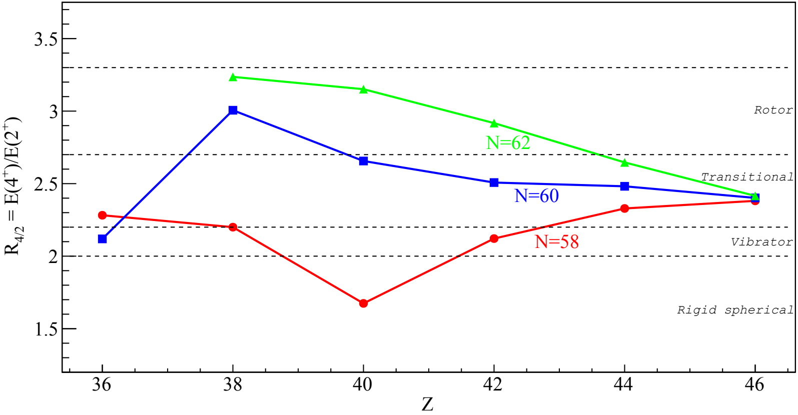


The ^{96}Kr case : low Z shore of the A∼ 100 island of inversion

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 validates previous observations: ^{96}Kr is not highly deformed



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

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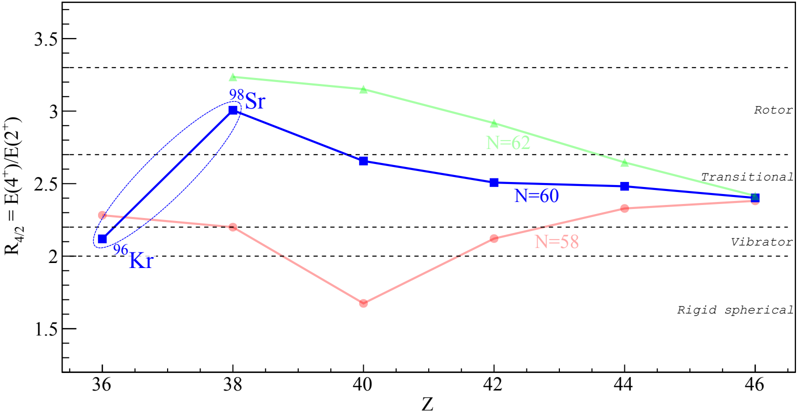
Informations from the $R_{4/2} = E(4^+)/E(2^+)$ ratio

⇒ Sharp transition at N=60 when moving from Sr to Kr

⇒ $R_{4/2}$ value validates previous observations: ^{96}Kr is not highly deformed



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

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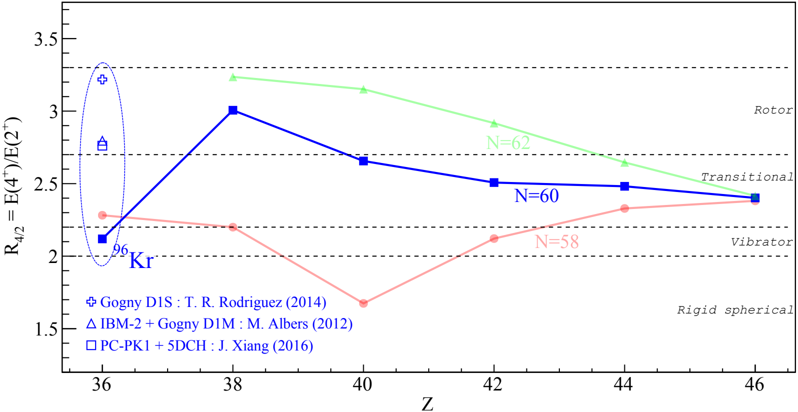
⇒ Predictions from mean field calculations not able for the moment to reproduce this transition



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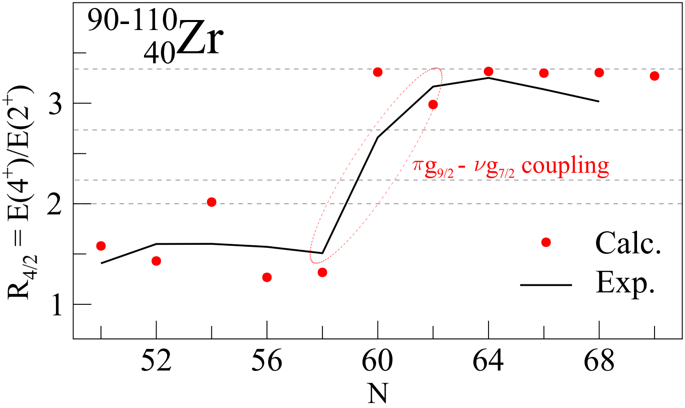
The ^{96}Kr case : calculation perspectives

Monte Carlo Shell-Model results

⇒ New calculations performed along the Zr isotopic chain (T. Togashi *et al., PRL (2016)*)

⇒ Agreement for the first time with the $R_{4/2}$, B(E2;$2^+ \rightarrow 0^+$) and 0_2^+ along the isotopic chain

⇒ Could such a model reproduce the sharp transition observed between $^{98}Sr_{60}$ and $^{96}Kr_{60}$?



adapted from: T. Togashi, Y. Tsunoda, T. Otsuka, and N. Shimizu, accepted in Phys. Rev. Lett.(2016)

Conclusions

- New levels and γ added in LS of the Kr isotopic chain (^{90}Kr$\rightarrow$^{96}Kr)
- Particle-γ gating allowed to correct the ^{90}Kr LS $\rightarrow$ Discard low energy octupole excitation
- ^{96}Kr case (N=60):
  - No γ observed at 241 keV as reported by N. Marginean *et al.*
  - Confirmation of the 554 keV transition, assigned to $2^+ \rightarrow 0^+$ by S. Albers *et al.*
  - Discovery of a 620 keV transition ($\gamma - \gamma$ coinc), assigned to $4^+ \rightarrow 2^+$

$\Rightarrow$ ^{96}Kr appears to be the low Z shore of the A$\sim$100 island of inversion:
$\Rightarrow$ $R_{4/2}$ value suggests ^{96}Kr as a slightly deformed spherical vibrator nucleus

$\Rightarrow$ Available models are not able to reproduce this sharp transition between $^{98}_{38}$Sr$_{60}$ and $^{96}_{36}$Kr$_{60}$ isotopes

Thank you for your attention!

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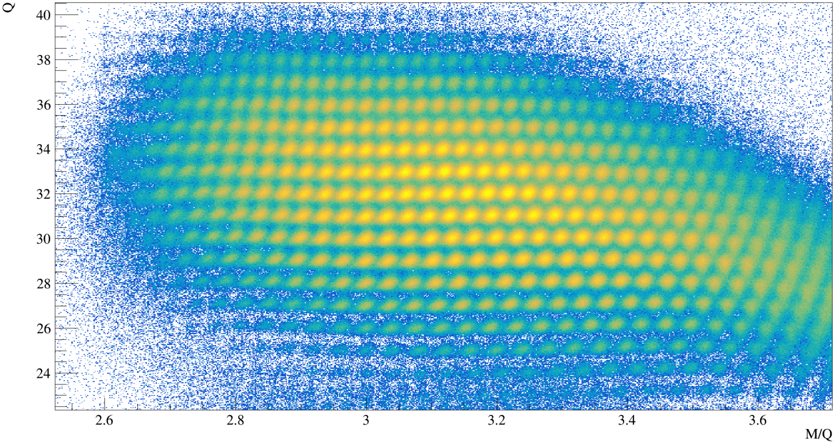
Annexe : VAMOS++: Mass identification

Q vs M/Q matrix ⇒ Mass identification

⇒ Trajectory reconstruction
⇒ Time of flight measurement } M/Q
⇒ Total energy measurement } Q ⇒ $M = M/Q \times Q \in [70;120]$

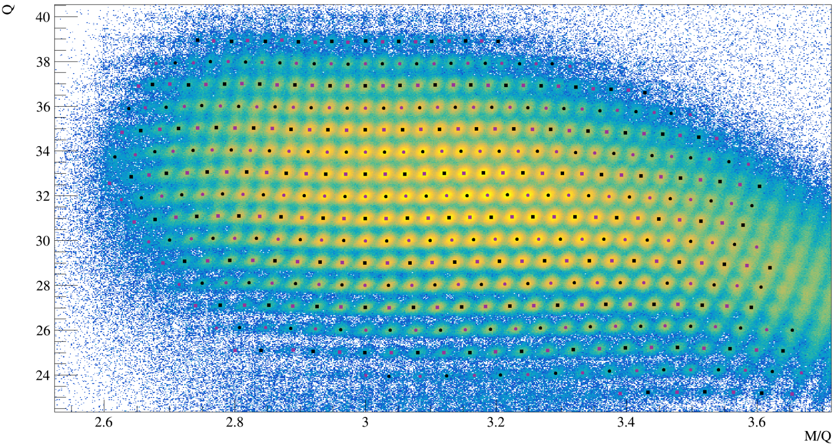


Annexe : VAMOS++: Mass identification

Q vs M/Q matrix ⇒ Mass identification

⇒ Final identification is done using markers:

- ⇒ Q and M are the one of the closest marker.
- ⇒ Distance to marker is used as a quality factor (useful to identify contaminants).



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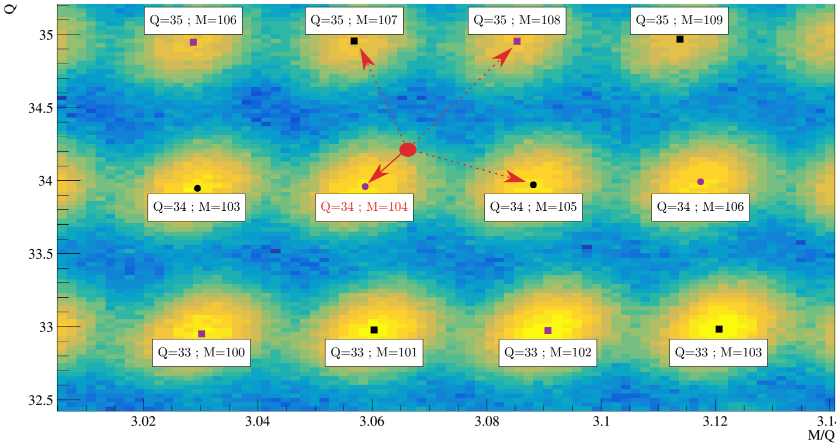
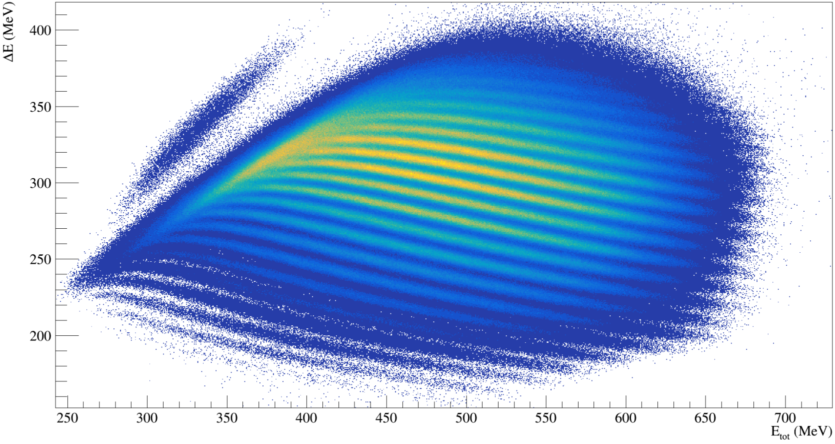


Annexe : VAMOS++: Z identification

ΔE vs E matrix ⇒ Z identification

⇒ Z discrimination obtained from ΔE vs E matrix.

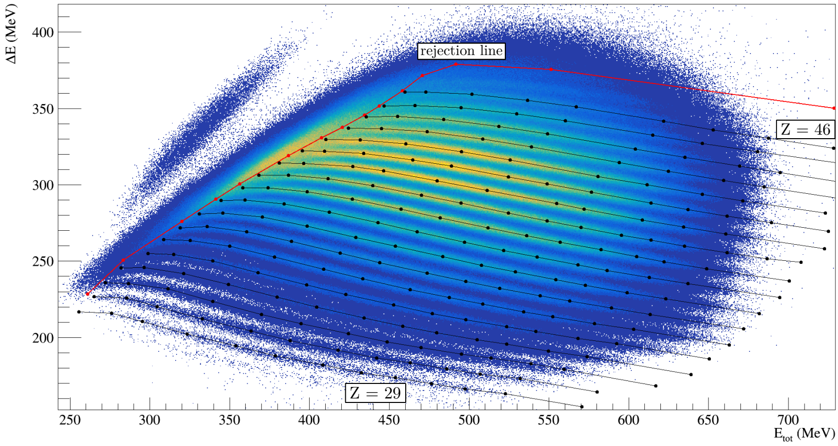


Annexe : VAMOS++: Z identification

ΔE vs E matrix $\Rightarrow$ Z identification

$\Rightarrow$ Final identification is done using identification lines (INDRA style):

- $\Rightarrow$ Z value is the one of the closest line.
- $\Rightarrow$ Distance to line is used as a quality factor (useful to identify contaminants).



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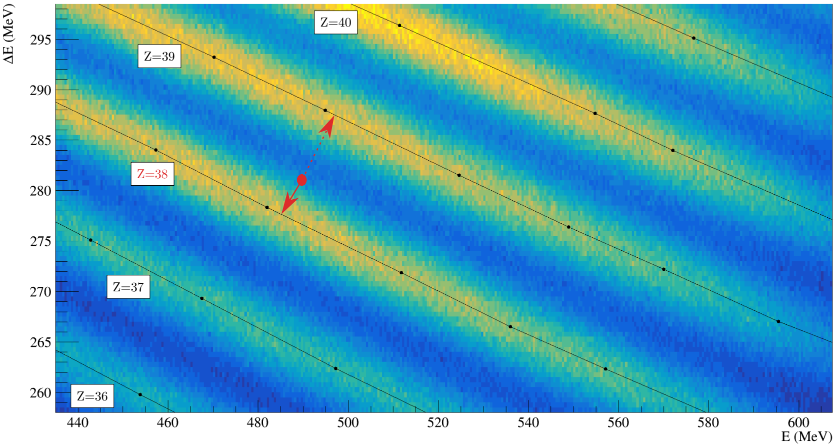

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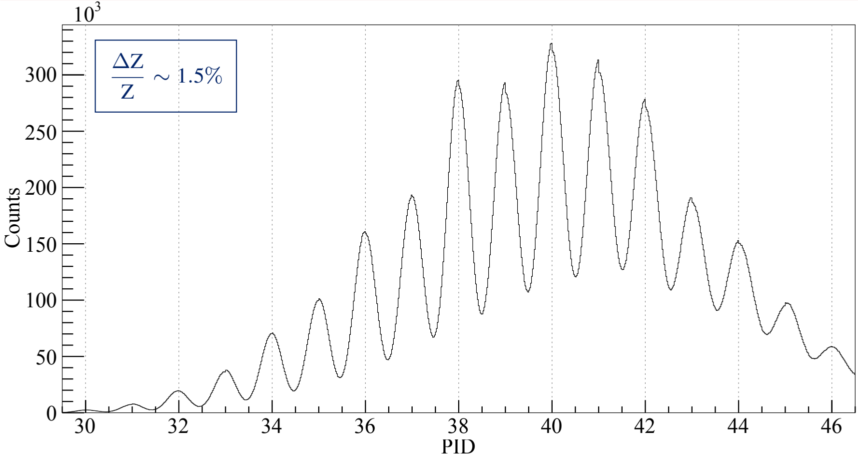
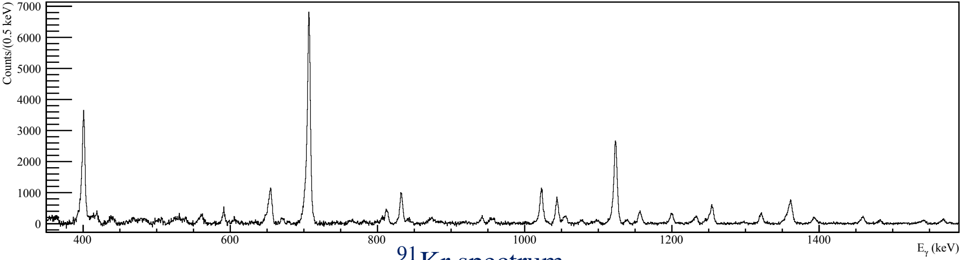
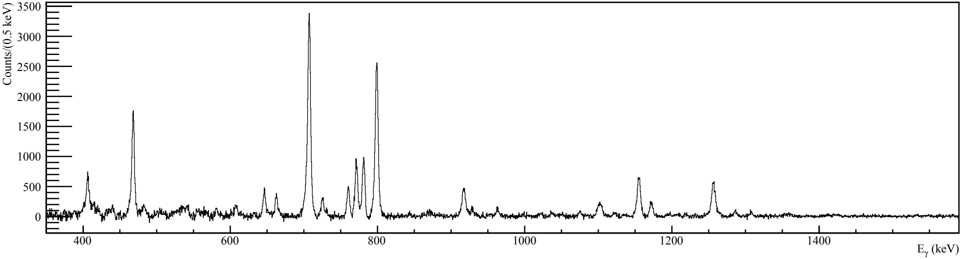


Annexe : Spectroscopic results for Kr isotopes: ^{90}Kr-^{90}Kr

^{90}Kr spectrum

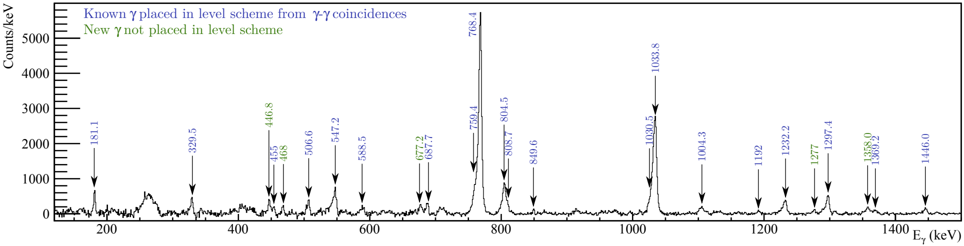


^{91}Kr spectrum

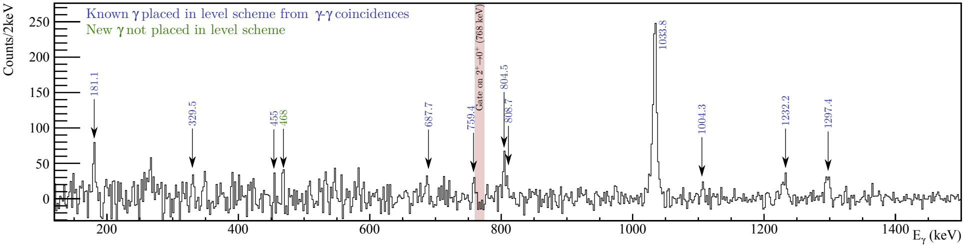


Annexe : Spectroscopic results for Kr isotopes: ^{92}Kr

^{92}Kr spectrum

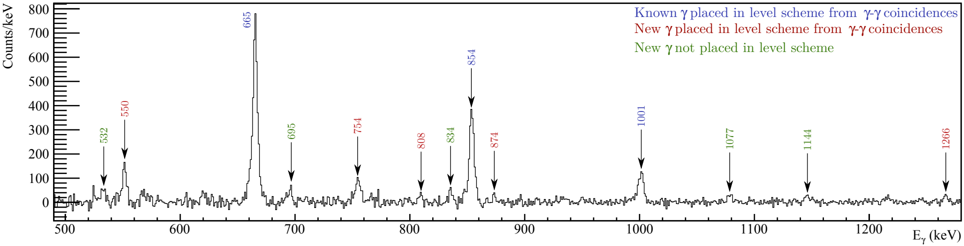


^{92}Kr spectrum gated on the $2_1^+ \rightarrow 0_1^+$ transition (768 keV)

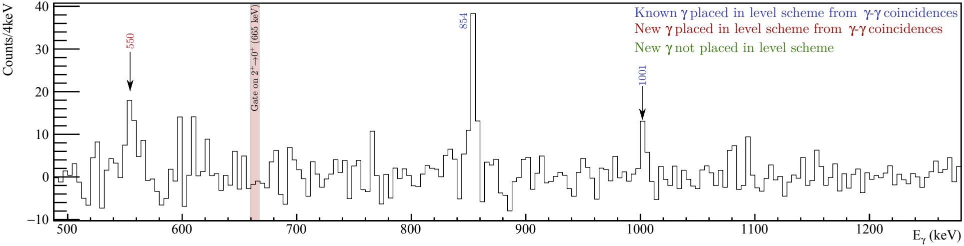


Annexe : Spectroscopic results for Kr isotopes: ^{94}Kr

^{94}Kr spectrum



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



Annexe : The ^{96}Kr case : Correlations between B(E2↓)/A and $R_{4/2}$

Informations from B(E2↓)/A and $R_{4/2}$

⇒ Exclusion of shape coexistence with high mixing

⇒ According to "R. F. Casten and N. V. Zamfir, Phys. Rev. Lett. 70, 402 (1993)":

⇒ ^{96}Kr is a slightly deformed spherical vibrator nucleus.