Study of single particle and shape evolution in neutron-rich nuclei produced in fusion-fission reactions using AGATA coupled to VAMOS++ and other devices

G. Duchêne

for the AGATA collaboration

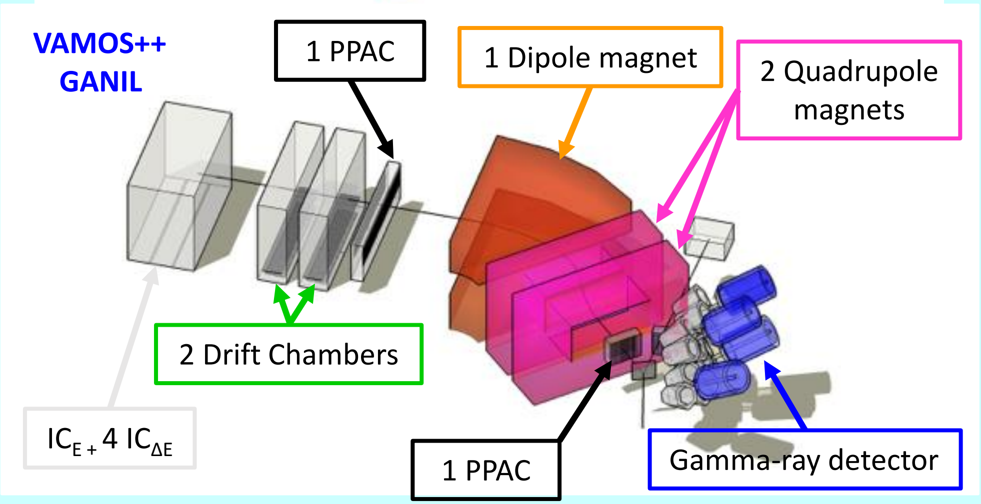
Summary

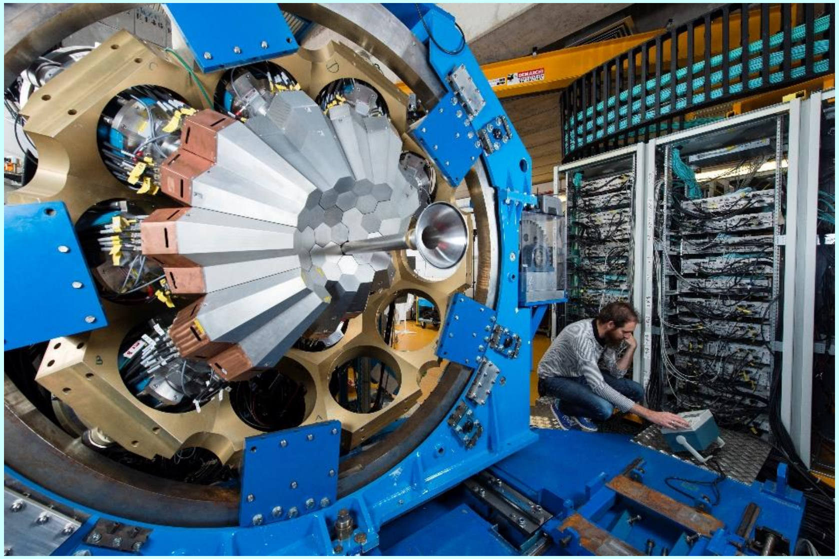
- Introduction
- Exp e680: gamma-ray spectroscopy in the N=50 ^{81}Ga nucleus
- Exp e669: lifetime determination in A~80 mass region (^{84}Ge)
- Exp e706: lifetime determination around N=60 in the island of deformation (Zr,Mo and Ru)
- Exp e680: explore in ^{96}Kr the lower-Z boundary of the N=60 island of deformation
- Exp e661: isomers lifetime determination around ^{132}Sn in Sb and In neutron-rich isotopes
- Conclusions

AGATA-VAMOS++ physics campaign 2015-2017

❑ 4 fusion-fission experiments

- ➢ Intense U beam
- ➢ Inverse kinematics
- ➢ Forward boost
  - ❖ Fission fragments forward focussed
  - ❖ Enhances VAMOS acceptance
- ➢ Compact AGATA geometry

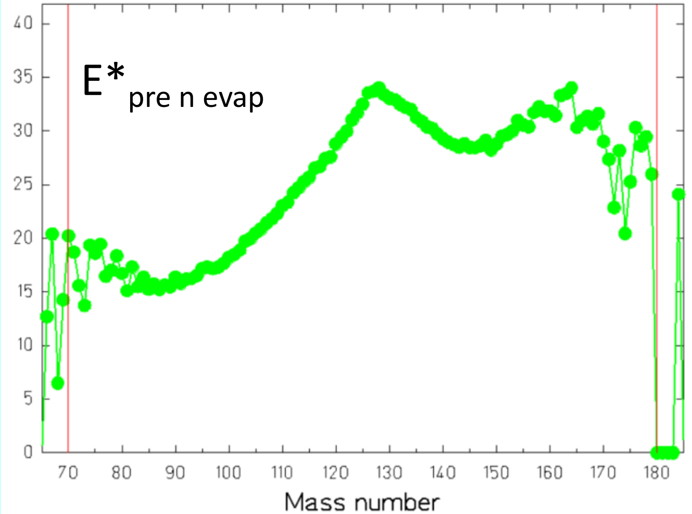


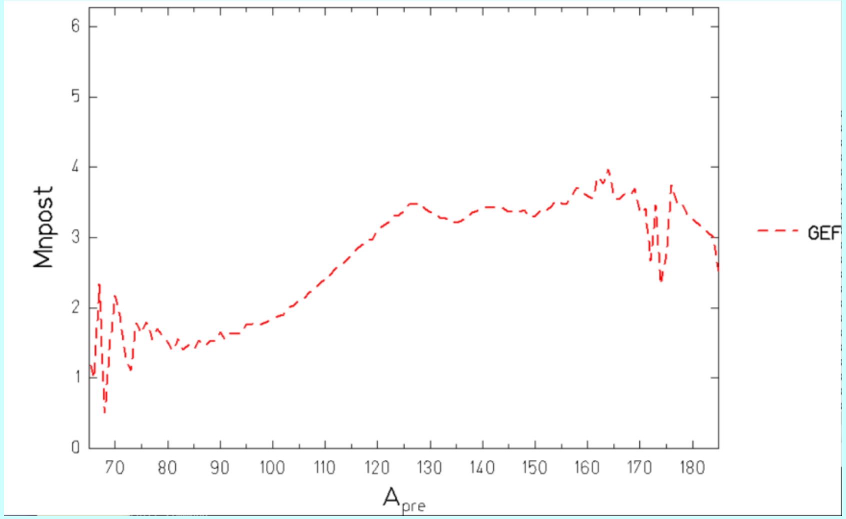


AGATA-VAMOS++ physics campaign 2015-2017

Fusion-fission mécanisme

- ^{238}U (~6.2 AMeV) + ^{9}Be --> $^{247}Cm^*$
- E*(CN) ~ 47 MeV
- <L>(CN) ~ 23 hbar
- θ_{VAMOS} = 28°
- GEF calculations
  - $\langle n_{pre\text{-}scission} \rangle$ ~ 2,6
  - $E^*_{fissioning\ nucleus}$ ~31 MeV
  - $E^*_{LF/HF}$ ~ 16/30 MeV
  - $\langle n_{LF/HF} \rangle$ ~ 2,4/3,3
  - $\langle E^*_{As} \rangle$~ 5-7 MeV
  - $\langle I_{LF} \rangle$ ~ 5 +/- 1 hbar





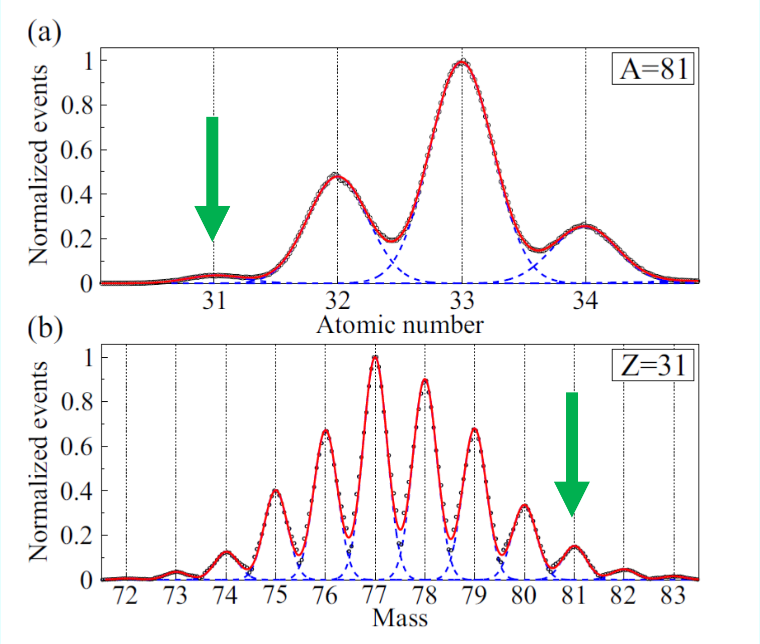
Courtesy Ch. Schmitt

AGATA-VAMOS++ physics campaign 2015-2017

Spokesp. year	Exp n°	Goal	Setup	θ_{VAMOS} Distance Shifts	Nuclei	Publications
G. Duchêne 2015	**e680**	ϒ spectro	AGATA-24 VAMOS++	28° d=13.3 cm 46 shifts	^{96}Kr ^{81}Ga ^{83,85,87}As Ge and Zn	PRL 118 162501 2017 PRC 100 011301(R) 2019 Rezynkina (post-doc) In preparation On-going analysis
D. Verney 2015	**e669**	lifetime	AGATA-24 VAMOS++ Diff plunger	28° d=18.6 cm 30 shifts	^{88}Kr, ^{86}Se, ^{84}Ge 15 nuclei 38 τ Ga-Kr	PRL 121 192502 2018 ActPhysPol B 50 633 2019 Delafosse (PhD)
N. Alahari 2016	**e661**	ϒ spectro lifetime	AGATA-32 VAMOS++ Clover at focal plan	20° d=13.5 cm 46 shifts	$^{121-131}$Sb $^{119-121}$In	PRC 99 064302 2019 PRC 102 014326 2020 EPJA 53 162 2017 Biswas (Post-doc)
W. Korten 2017	**e706**	lifetime	AGATA-35 VAMOS++ Diff plunger 24 FATIMA	19° d= 23.3 cm 31 shifts	$^{98-104}$Zr $^{100-108}$Mo $^{106-112}$Ru	Ansari (PhD)

e680 – ϒ spectro above ^{78}Ni

- ϒ spectroscopy in ^{78}Ni vicinity
  - Explore the structure of nuclei around $^{78}Ni_{50}$
  - ^{238}U (~6.2 AMeV) + ^{9}Be --> ^{247}Cm*
  - 46 shifts
  - 205 fission fragments identified
  - $^{81}_{31}Ga_{50}$ nuclear structure
  - Lowest reachable N=50 nucleus



e680 – ϒ spectro above ^{78}Ni

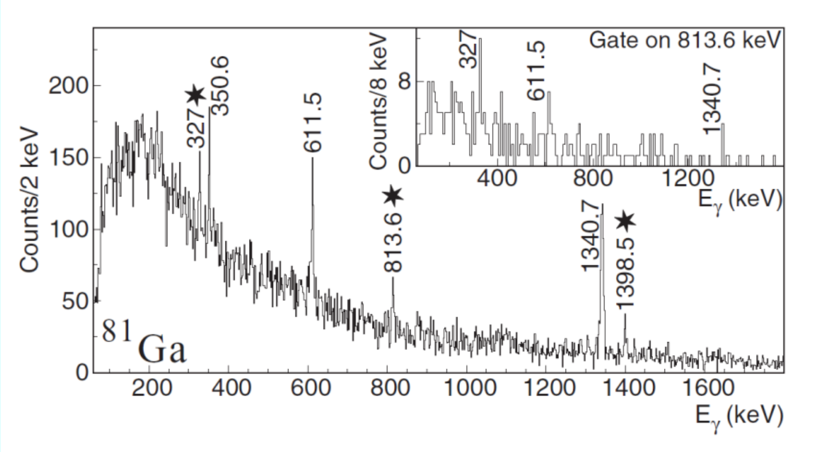
- Data analysis
  - 2 new transitions in cascade with known lines
  - Tentative spin/parity assignment based on dominant feeding of yrast states in fission
- LSSM calculations
  - PFSDG-U interaction
  - Valence space: *pf* π orbitals and *sdg* ν orbitals
  - ^{60}Ca inert core

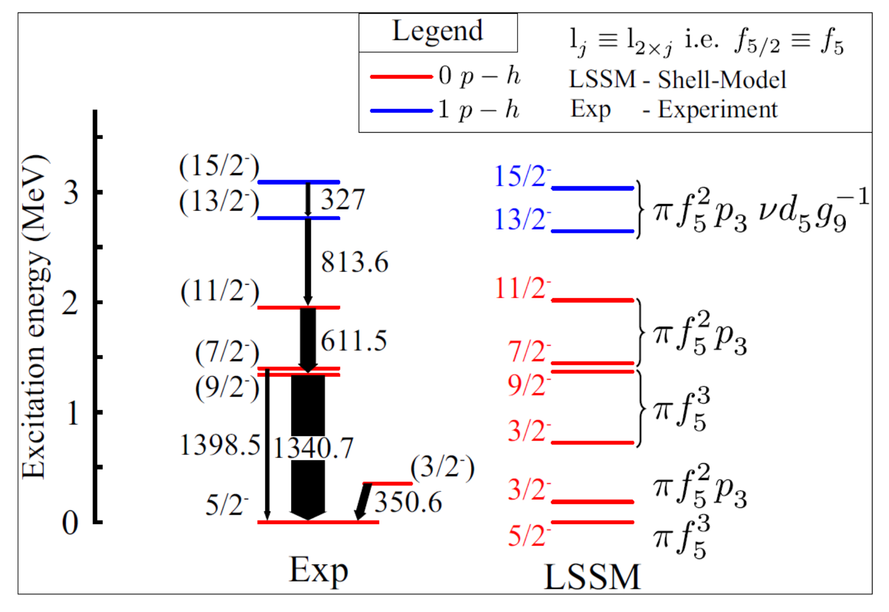
  *F. Nowacki et al., PRL **117**, 272501 (2016)*
  - N=50 neutron-core breaking

  Excellent exp-th agreement
  - Coupling of the *pf* π to p-h excitations

Persistence of N=50 gap for Z>28

NB: ^{96}Kr will be discussed later on



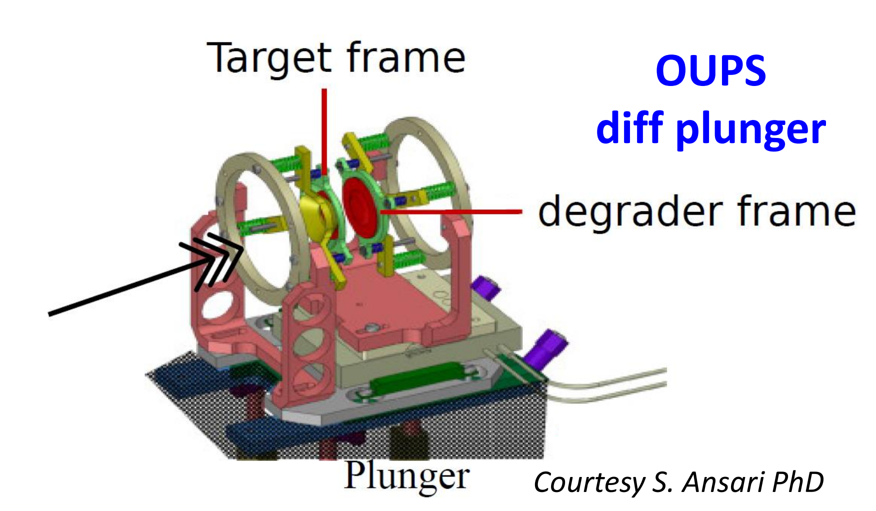


J. Dudouet et al., PRC 100 011301(R) 2019

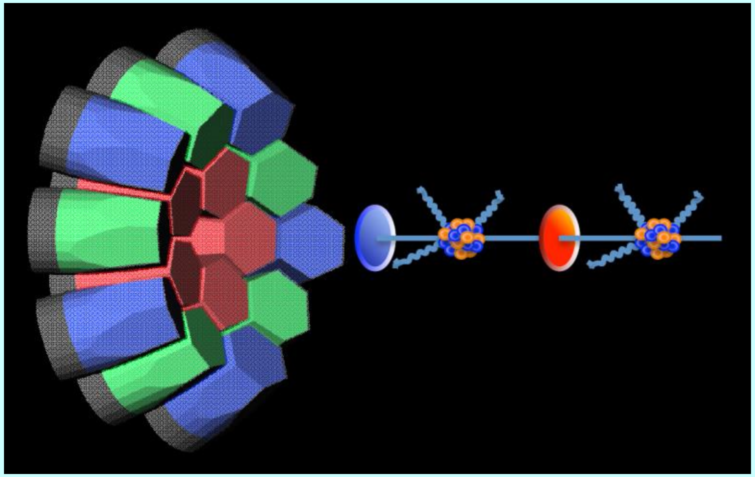
e669 – Single part./collectivity near N=50

- Neutron monopole drifts near the N=50 closed shell towards ^{78}Ni
  - Low-lying state evolution in N=51 nuclei
    - Single particule vs collectivity

      C. Delafosse et al., in preparation



  - AGATA + VAMOS++ + OUPS differential plunger
  - Recoil Distance Doppler Shift (RDDS) method
  - $R(x) = I_U(x)/(I_U(x)+I_S(x))$
  - Bateman equation
  - Lifetime determination
  - Ex.: $^{84}Ge_{52}$ nucleus



Courtesy F Didierjean

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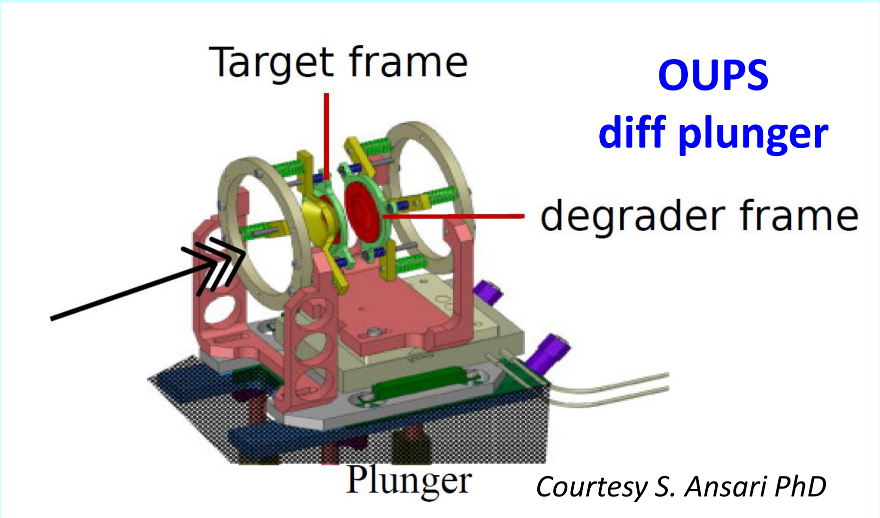
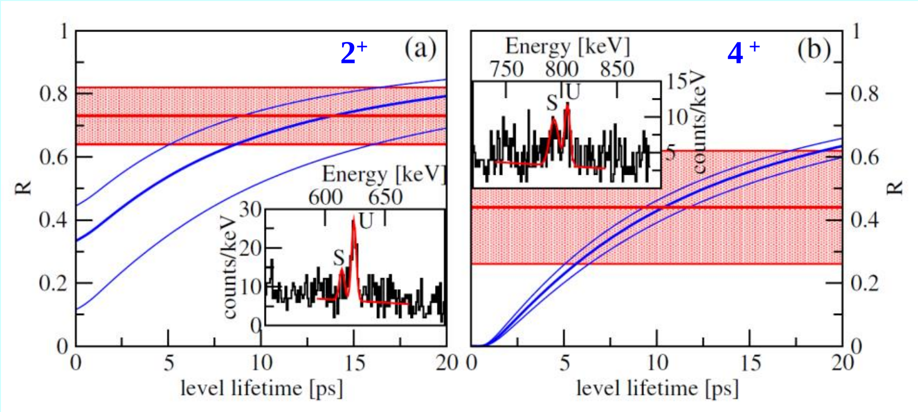


Courtesy S. Ansari PhD



Courtesy F Didierjean

e669 – Single part./collectivity near N=50

N = 52

Nucleus	$J_i^\pi \to J_f^\pi$	E_γ [keV]	This work τ [ps]	This work $B(E2; J_i^\pi \to J_f^\pi)$ [e^2 fm^4]	Literature τ [ps]	Literature $B(E2; J_i^\pi \to J_f^\pi)$ [e^2 fm^4]
^{88}Kr	$2^+ \to 0^+$	775.4(1)	$10.6^{+4.8}_{-5.0}$	$273.6^{+244.3}_{-85.3}$	16.0(17) [30]	262(38) [31]
^{86}Se	$2^+ \to 0^+$	704.0(1)	$10.3^{+1.2}_{-2.2}$	456^{+124}_{-48}	$10.8^{+6.9}_{-3.7-0.3}$ [25]	422(64) [31]
^{84}Ge	$2^+ \to 0^+$	624.3(9)	$13.8^{+7.9}_{-9.8}$	$621.2^{+1522.0}_{-226.2}$	...	...
	$4^+ \to 2^+$	805.4(11)	$10.3^{+3.0}_{-6.5}$ (*)	$232.9^{+398.4}_{-52.5}$	...	...

- 2^+ lifetimes of ^{88}Kr, ^{86}Se, ^{84}Ge
- Agreement with Kr, Se coulex data

  *B. Elman et al., PRC **96** 044332 (2017)*
- Unexpectedly large B(E2) values in ^{84}Ge
- Theoretical approach
  - "DD-PC1": beyond meanfield calculations using the relativistic functional DD-PC1; this work
  - "SM,Ni78-I" shell-model calculations

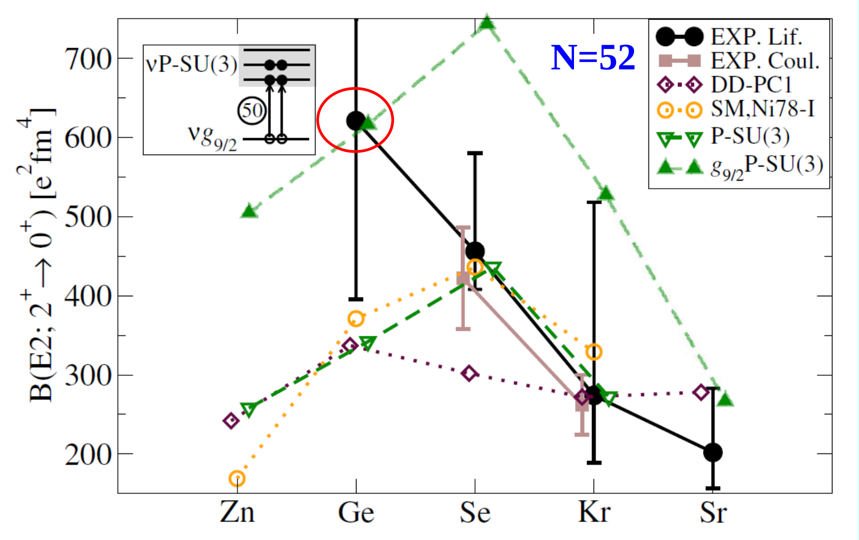
    *K. Sieja et al., PRC **88** 034327 (2013)*
  - P-SU(3)": pseudo-SU(3) limit
  - "($g_{9/2}$) P-SU(3)": pseudo-SU(3) limit including one N=50 core-breaking $g_{9/2}$ ν pair promotion

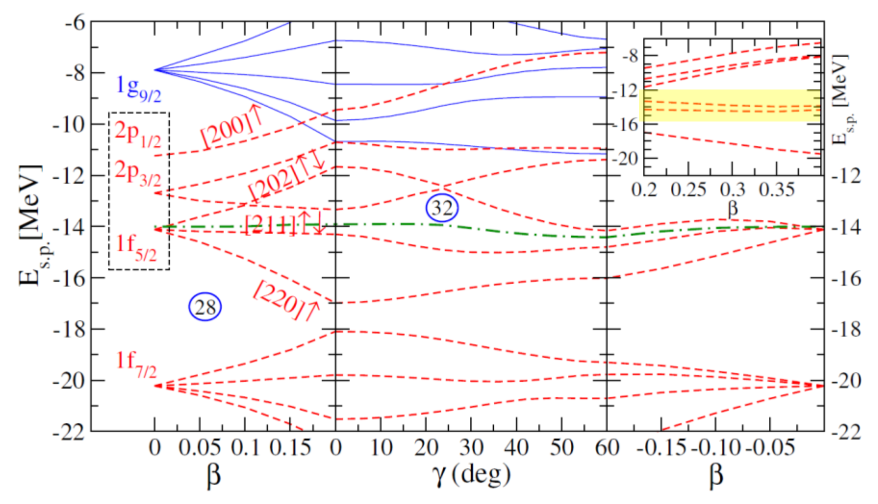
    *K. Sieja et al., PRC **88** 034327 (2013)*

e669 – Single part./collectivity near N=50

- Discussion
  - Both the SM and $B(E2)_{exp}$ values in Kr and Se exhaust the limit for pure Pseudo-SU(3) symmetry
  - In ^{84}Ge consider the 2p-2h excitation from $\nu g_{9/2}$ to $\nu g_{7/2}ds$ orbits (P-SU(3) $\tilde{f}\tilde{p}$ block)
  - DD-PC1 calculations indicate the appearence of a K=1/2 and K=3/2 π doublet ($\tilde{\Lambda}$+/-1/2) in a prolate Ge

The authors conclude that the $\pi f_{5/2}p$ single-particle arrangement triggers quadrupole coherence in ^{84}Ge and emerges from pseudo-spin symmetry

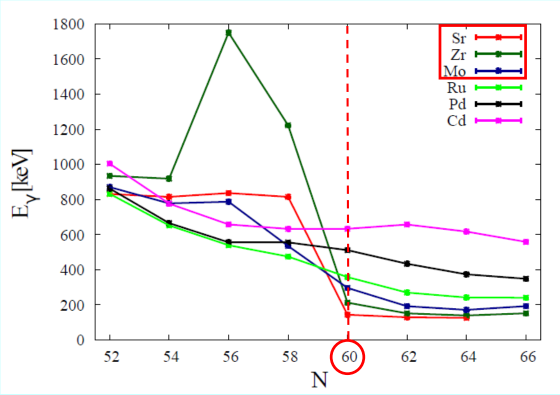


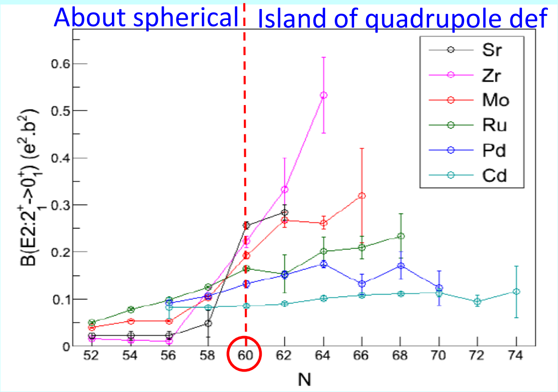


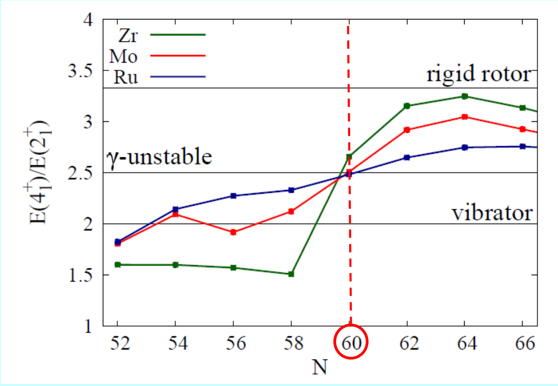
C. Delafosse et al., PRL 100 011301(R) 2019

e706 – Island of deformation at N=60

- Drastic shape change at N=60
  - E*(2^+) drop from N=58 to N=60 strongly for Sr, Zr and Mo
  - B(E2; $2^+ \rightarrow 0^+$) values show an onset of collectivity
  - E(4^+)/E(2^+) rises above 3 in Zr isotopes
  - Arises from the strong $\pi g_{9/2}$-$\nu g_{7/2}$ interaction
  - Reduction of the $\nu g_{7/2}$-$d_{5/2}$ gap as well as the $\pi p_{1/2}$- $g_{9/2}$ gap
  - Favores the deformation building
  - Lowering of E*(0_2^+) from ^{96}Zr to ^{98}Zr and which becomes the g.s. in ^{100}Zr







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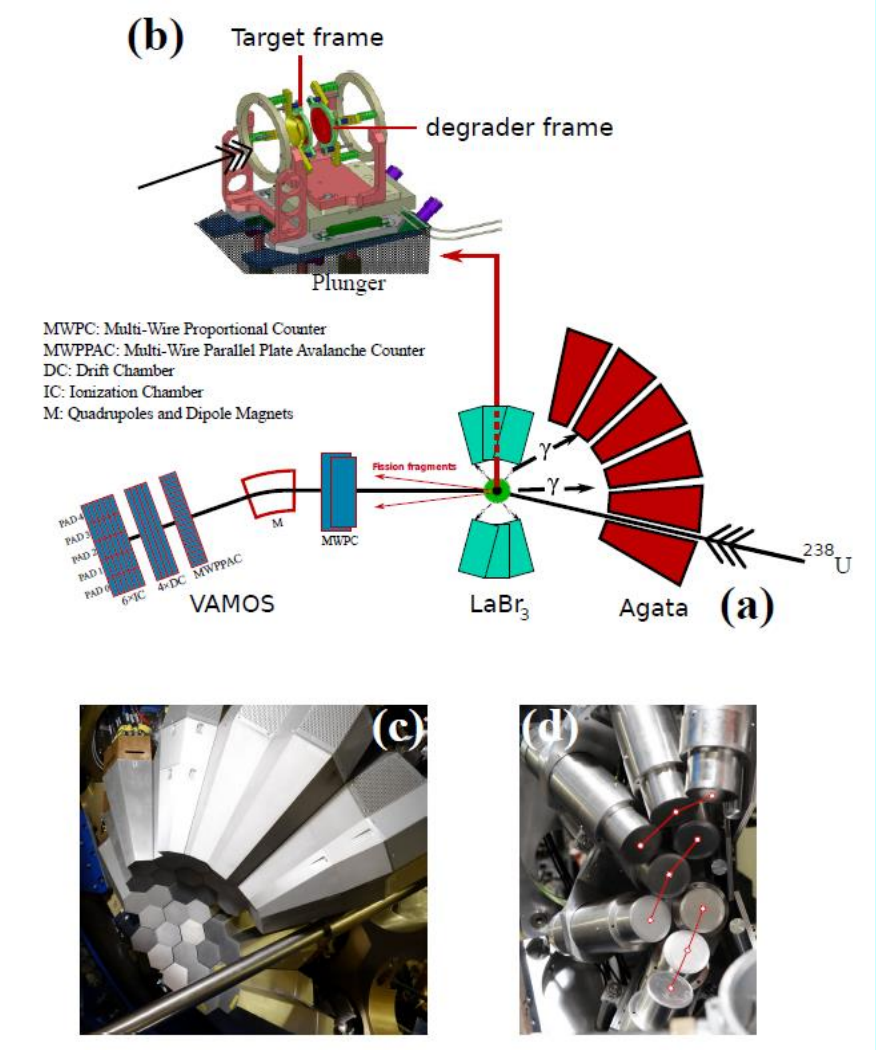
e706 – Island of deformation at N=60

Experiment

- Differential plunger/RDDS method (~1- few100 ps)
- FATIMA detectors/fast-timing method (few 10 – few 100 ps): not part of this study
- Measurement of lifetimes up to 8^+ in $^{98\text{-}104}_{40}$Zr, $^{100\text{-}108}_{42}$Mo and $^{106\text{-}112}_{44}$Ru

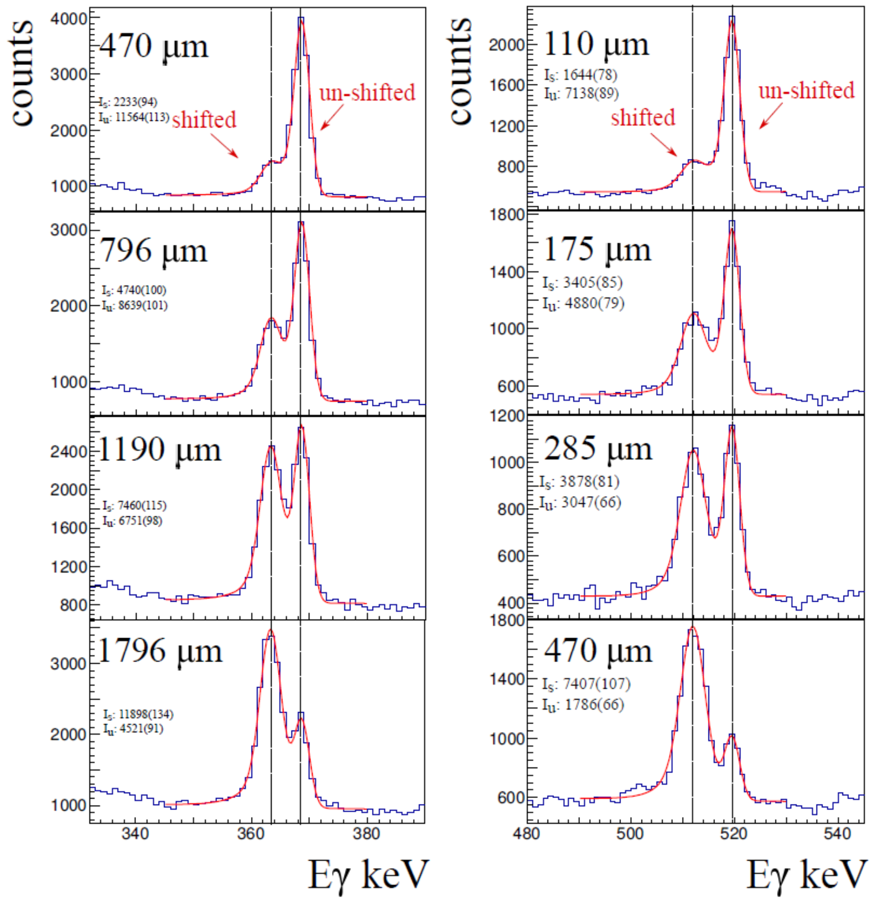


Analysis

- Decay Curve Method (DCM)
- Differential Decay Curve Method (DDCM)
- ϒ-ϒ coincidence DCM or DDCM
- Sum method

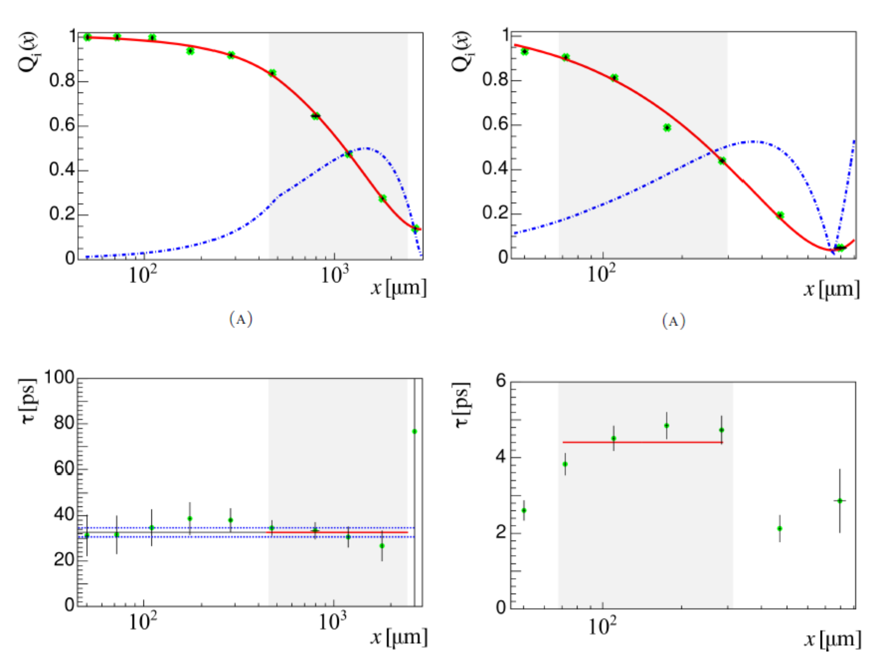
e706 – Island of deformation at N=60

^{104}Mo



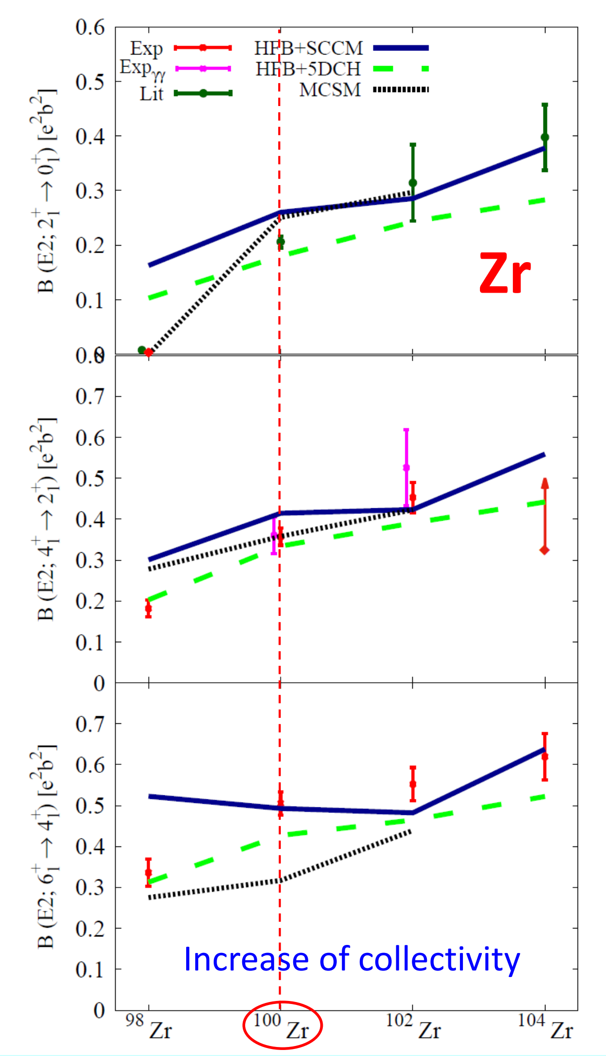
4_1^+ 6_1^+

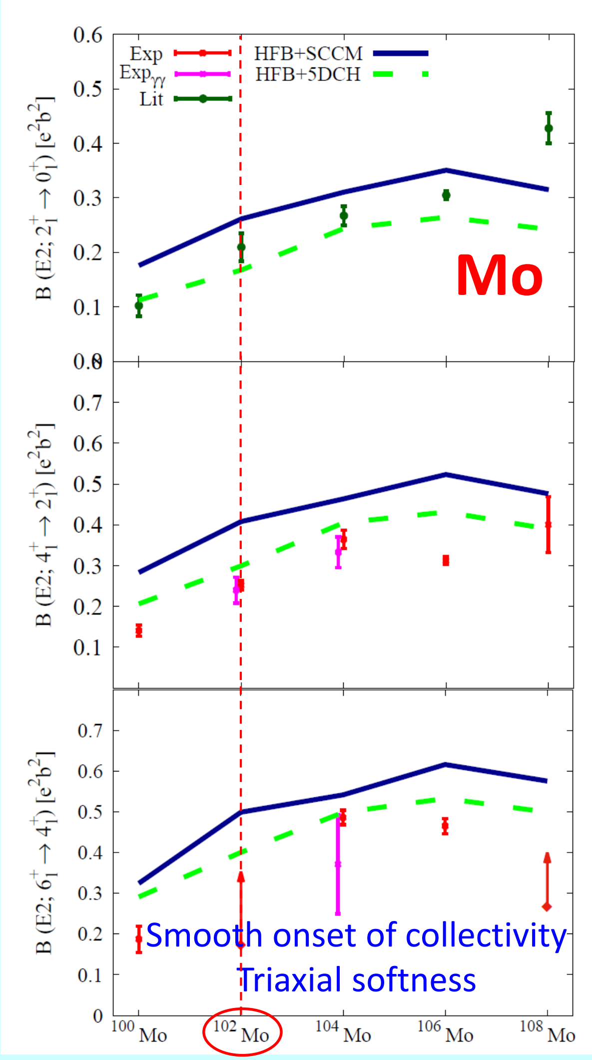
^{104}Mo

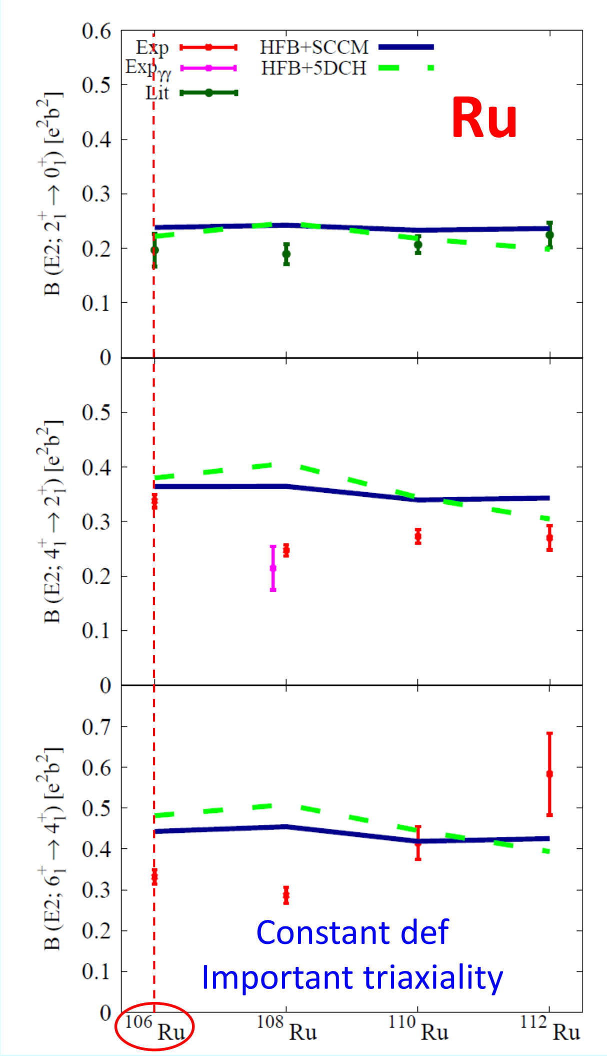


4_1^+ 6_1^+

e706 – Island of deformation at N=60







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e706 – Island of deformation at N=60

The N=60 region has been explored at higher spins confirming the drastic shape change from ^{98}Zr to ^{100}Zr, the rise of deformation with spin and with neutron numbers

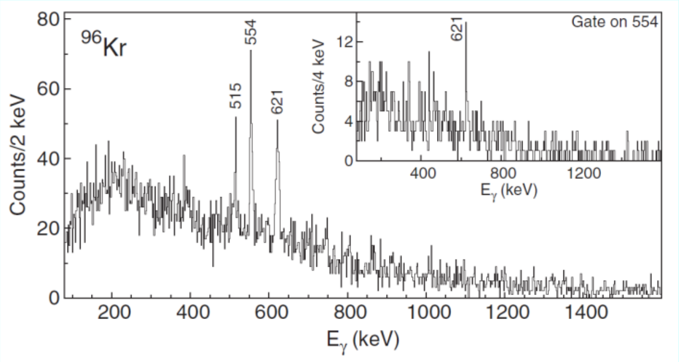
e680 – ϒ spectro above ^{78}Ni

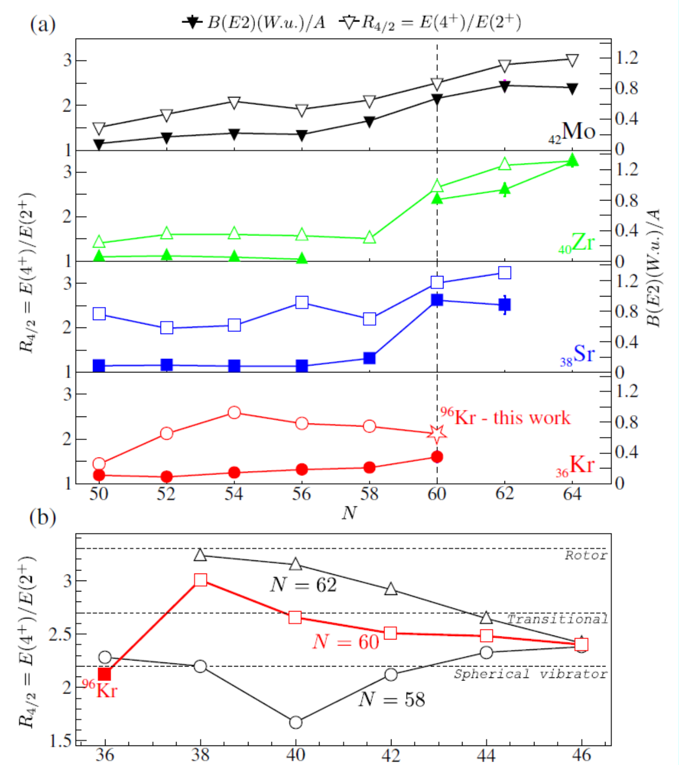
- New structure in $^{96}_{36}$Kr$_{60}$
  - Charge radii and mass measurements indicate a smooth development of collectivity in Kr chain
  - First excited state at 241 keV

    *Marginean et al., PRC **80** 021301 (2009)*
  - 2_1^+ state at 554 keV

    *Albers et al., PRL **108** 062701 (2012), NPA **899** 1 (2013)*
  - Present work
    - New 621 keV transition in coincidence with 554 keV
    - E* and B(E2) not correlated in ^{96}Kr
    - No onset of collectivity at N=60 in Kr chain

$^{96}_{36}$Kr$_{60}$ is the low-Z boundary of deformation at N=60





J. Dudouet et al., PRL 118 162501 2017

e661 – One valence proton effects around ^{132}Sn

❑ Nuclear structure around ^{132}Sn

- Sn isotopes below ^{132}Sn
  - Signature partner π orbitals $g_{9/2}$ and $g_{7/2}$ frame the Z=50 magic gap
  - The ν $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ orbitals are almost degenerated
  - Sn seniority isomers are known
    - <u>Even $^{132-x}$Sn (υ=2)</u>

      7^- with $\nu(h_{11/2})^{-1}\,(d_{3/2})^{-1}$ config

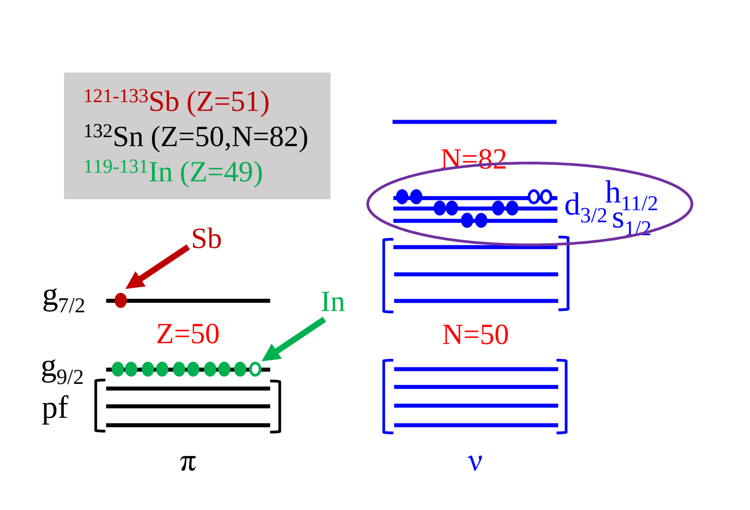
      10^+ with $\nu(h_{11/2})^{-2}$ config
    - <u>Odd $^{132-x}$Sn (υ=3)</u>

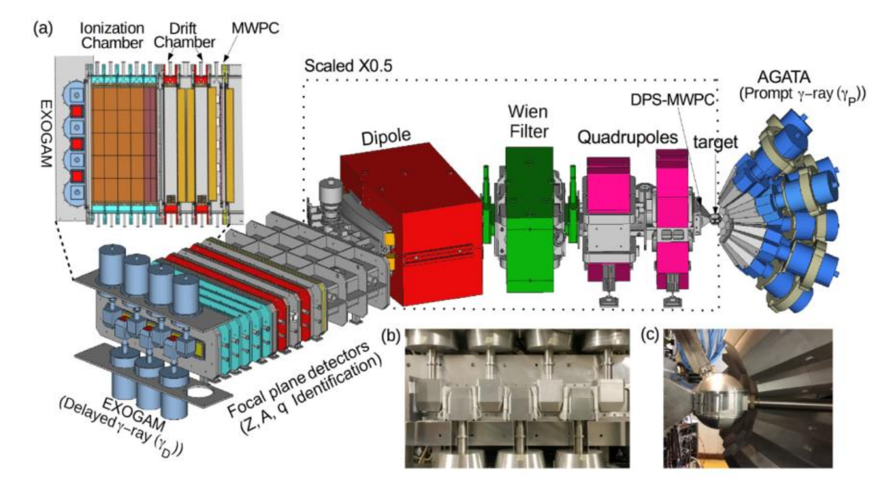
      $23/2^+$ with $\nu(h_{11/2})^{-2}\,(d_{3/2})^{-1}$ config

      $27/2^-$ with $\nu(h_{11/2})^{-3}$ config

- Sb and In isotopes below N=82
  - Add one π in $g_{7/2}$ for ν-rich Sb
  - Remove one π from $g_{9/2}$ for ν-rich In

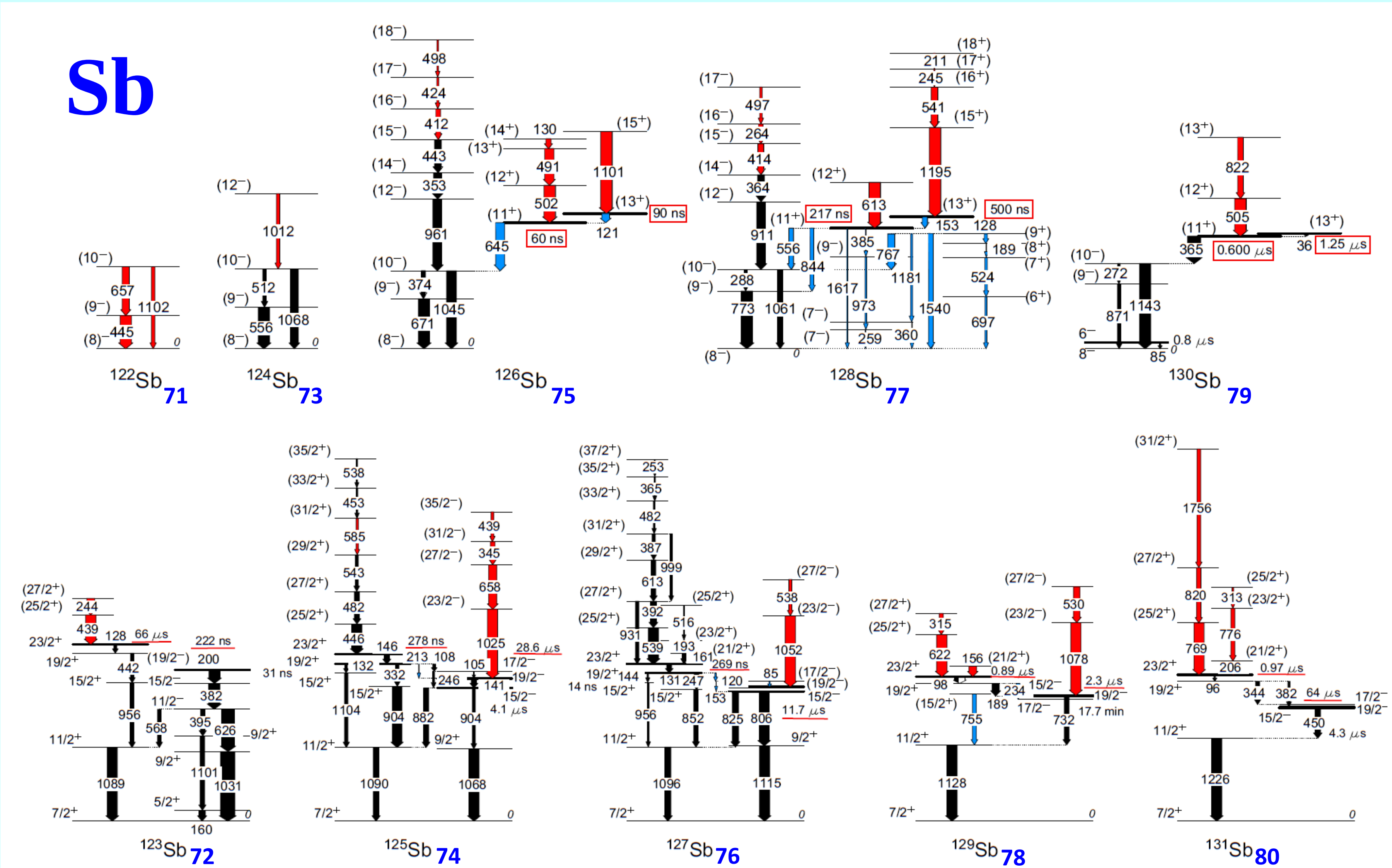
Study the effects of the πν interaction on the nuclear structure near N=82





Y.H. Kim et al., EPJA 53 162 2017

e661 – One valence proton effects around ^{132}Sn



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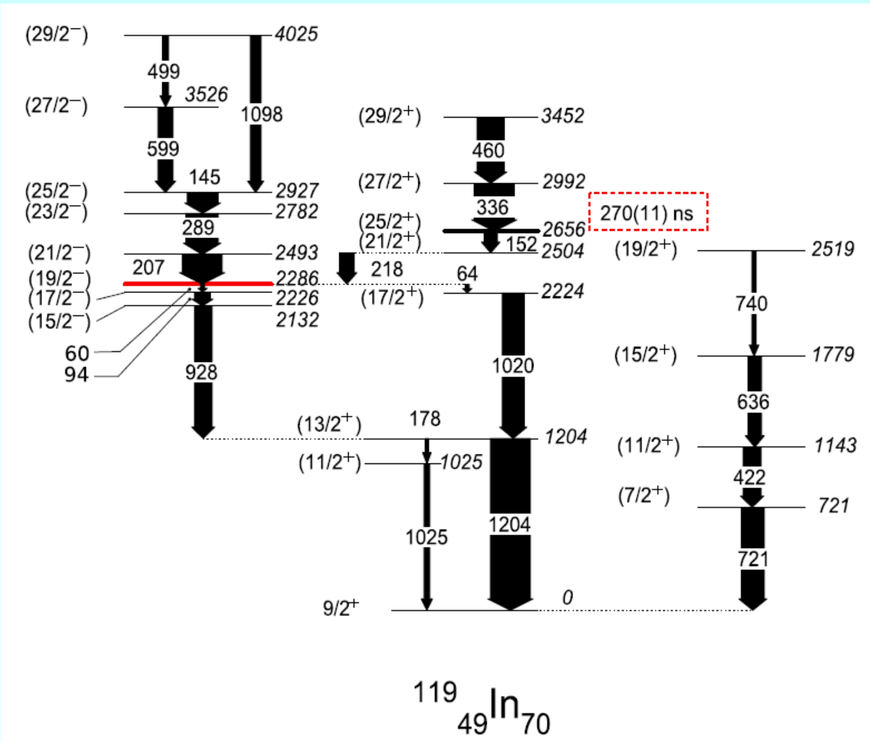
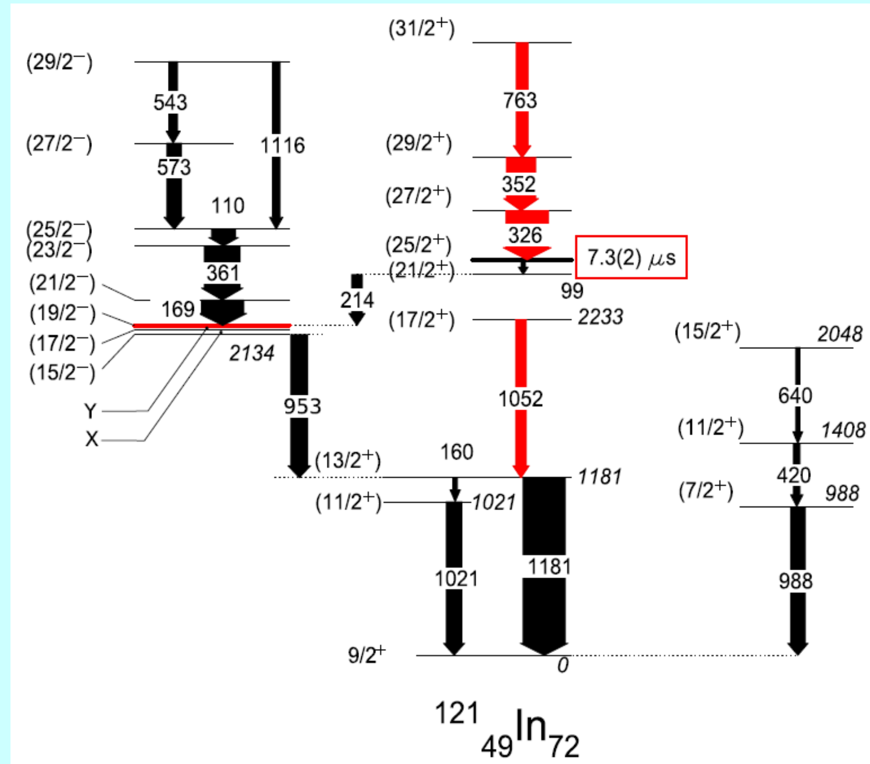
e661 – One valence proton effects around ^{132}Sn



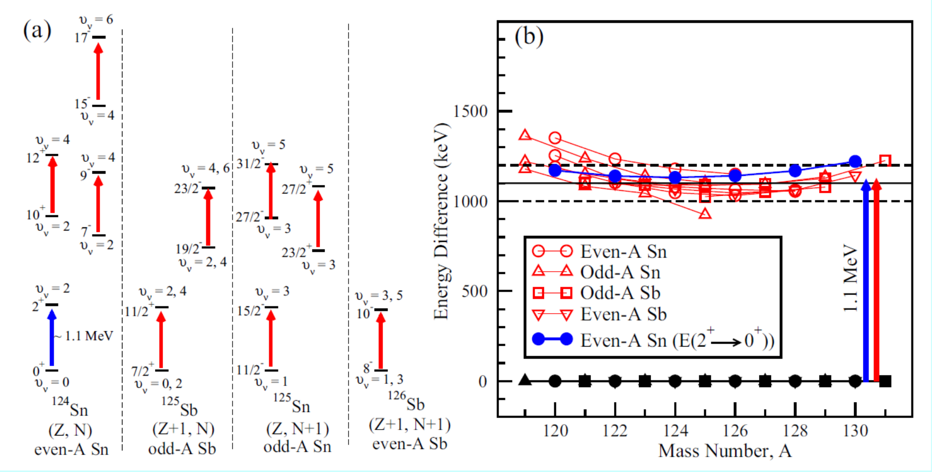


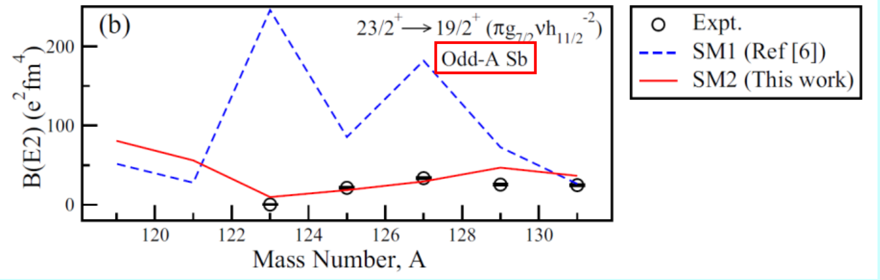
e661 – One valence proton effects around ^{132}Sn

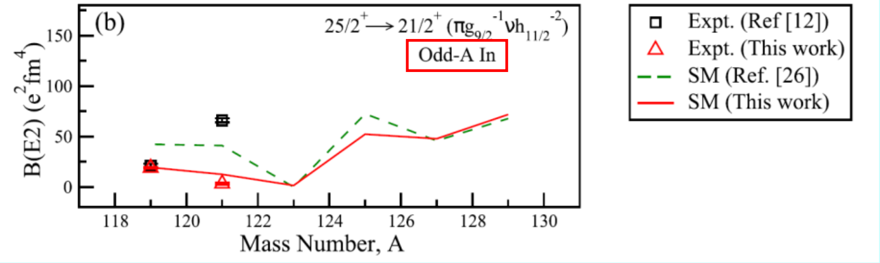
- Experimental results
  - 18 isomer lifetimes measured (16 Sb and 2 In) in the 60 ns to 7.3 μs range) among which 8 new ones
  - In addition, 2 isomers identified in In isotopes with too short lifetimes < 10 ns
  - ($25/2^{+}$) lifetime in ^{121}In τ=7.3(2) μs in contrary to previous exp data (350(50) ns and 17(2) μs)
  - Neutron pair-breaking energies (υ -> υ+2) in Sn and Sb determined to be constant at 1.1+/-0.1 MeV

- Shell-model calculations
  - Restricted shell-model space
    - ν: $d_{3/2}$, $s_{1/2}$ and $h_{11/2}$ orbitals
    - π: $g_{9/2}$ and $g_{7/2}$ orbitals
    - Matrix elements and pairing terms modified
  - Neutron seniority υ and angular- momentum I mixing are predicted
  - In Sb isotopes, both υ and I mixing increase with increasing number of valence neutrons (lower A)

Concluded to large nuclear structure effects near N=82 due to the strong interaction of the π particle ($g_{7/2}$) or hole ($g_{9/2}$) orbitals with the $\nu h_{11/2}$ orbital







S. Biswas et al., PRC 99 064302 2019
S. Biswas et al., PRC 102 014326 2020

Conclusions and perspectives

Conclusions

Despite the rather modest detection efficiency of AGATA (3-4% at 1 MeV)

- *pf* π coupling to p-h ν excitations across the N=50 gap in ^{81}Ga
- Influence of the pseudo-spin SU(3) symmetry in the unexpectedly large collectivity in ^{84}Ge
- Effects of the πν interaction around ^{132}Sn and of angular-momentum and seniority mixing
- Ilsland of deformation at N=60 explored at rather high spins in Zr, Mo and Ru isotopes
- Determination of the lower-Z boundary of the N=60 deformation island in ^{96}Kr

Perspectives

- Increase of AGATA efficiency by addition of triple clusters
- Installation at LNL on-going
- Physics campaigns with stable beams and SPES RIBs

Thanks for your attention

Thanks also to:
- the spokespersons
- Ch. Schmitt
- E. Clément
- F. Nowacki
- ???????