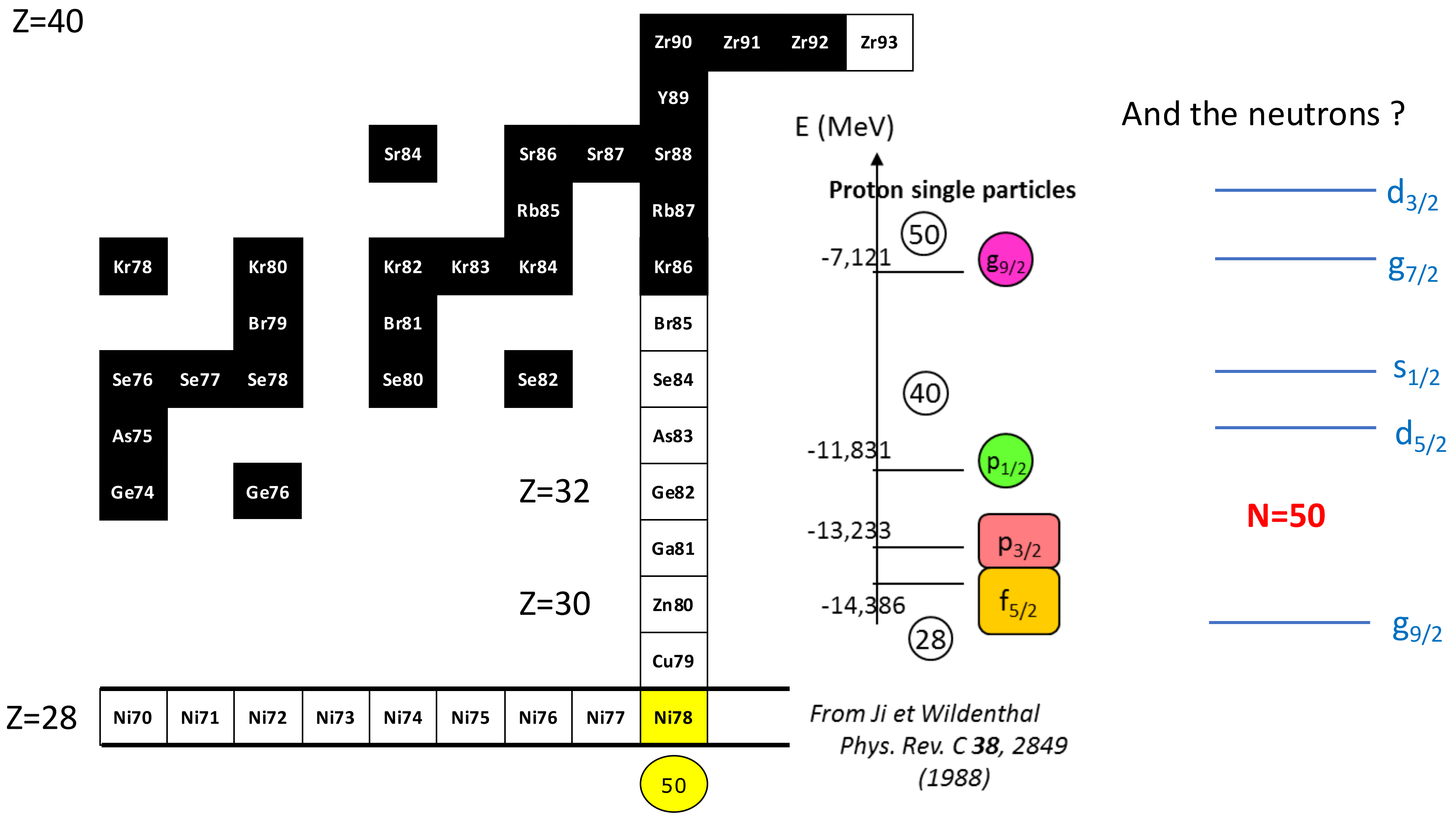
N=50 core breaking states and collectivity approaching ^{78}Ni

A. Gottardo, J.J. Valiente-Dobon, F. Angelini, D. Stramaccioni for the collaboration

Physics around the N=50 gap



The N= 50 gap: how to ~~measure~~ probe ?

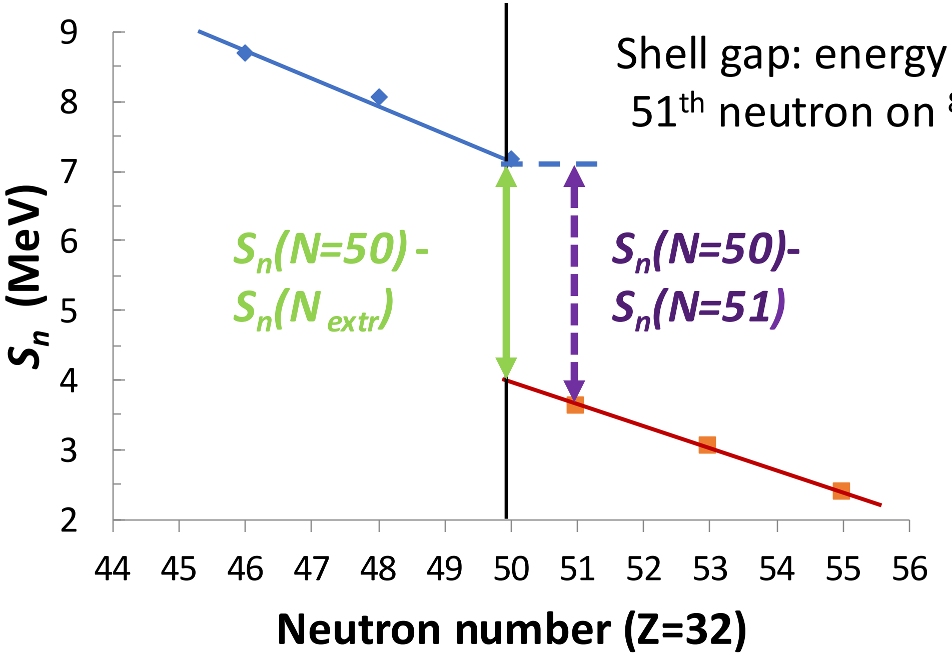
- The shell gap (and s.p. energies) is not an observable

  - «Mass gap» from mass measurements

  - «Spectroscopic gap» from core- breaking states

N=50 gap from mass measurements

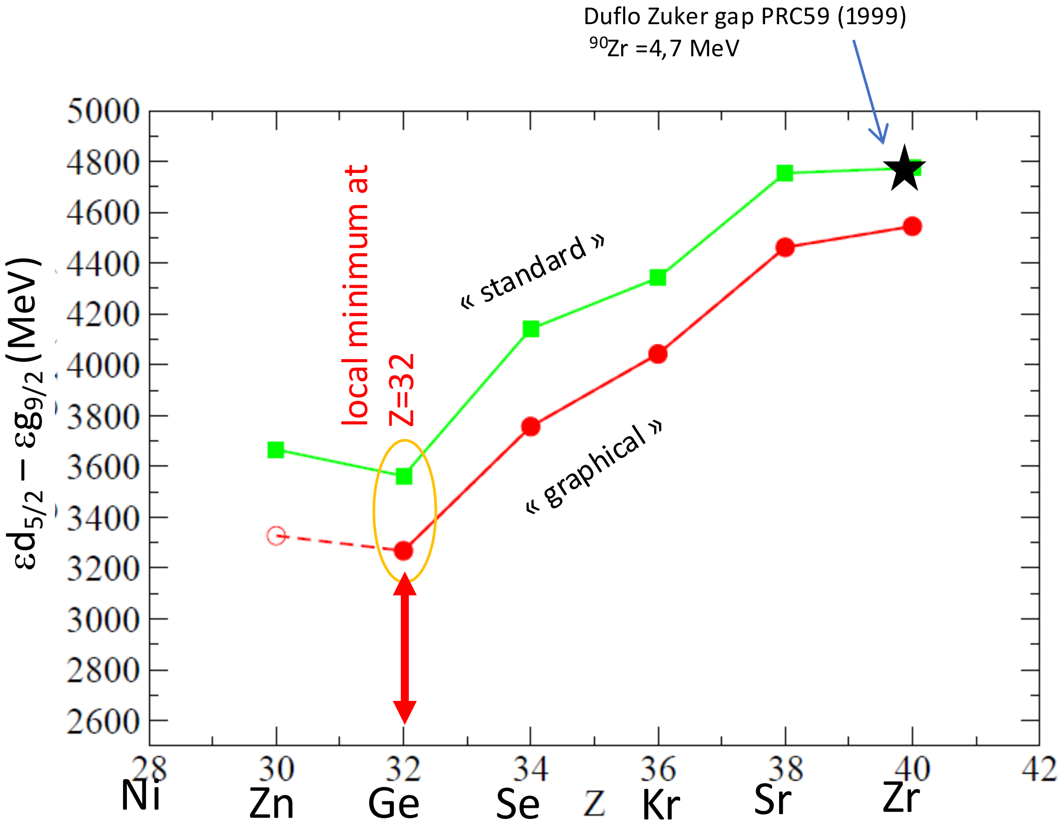
Graphical method by K. Heyde et al.: PLB176, 189 (1986)



Shell gap: energy to separate the 51[th] neutron on ^{82}Ge, **NOT** ^{83}Ge

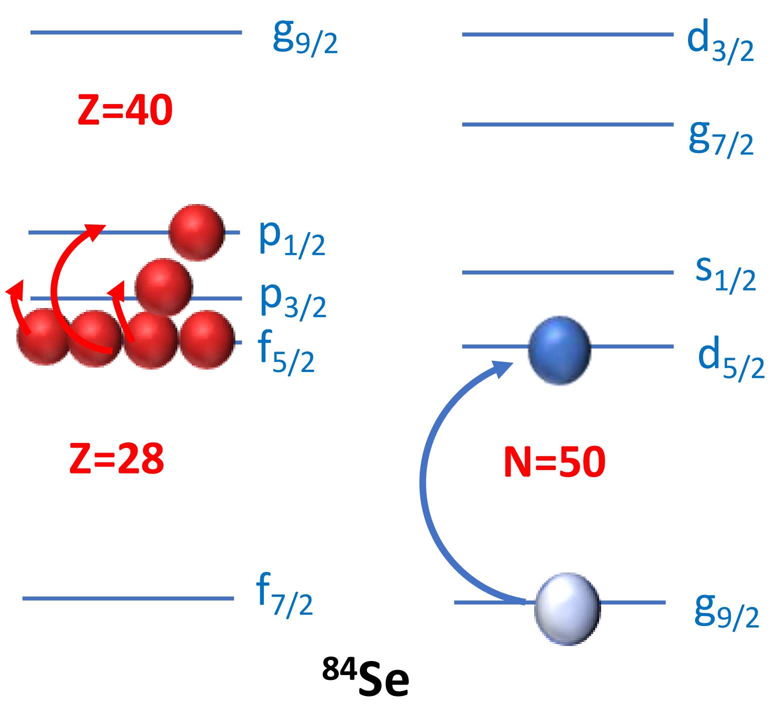
The shell gap N=50 is **overestimated** (~300 keV) by the $S_n(N+1)$-$S_n(N)$ difference

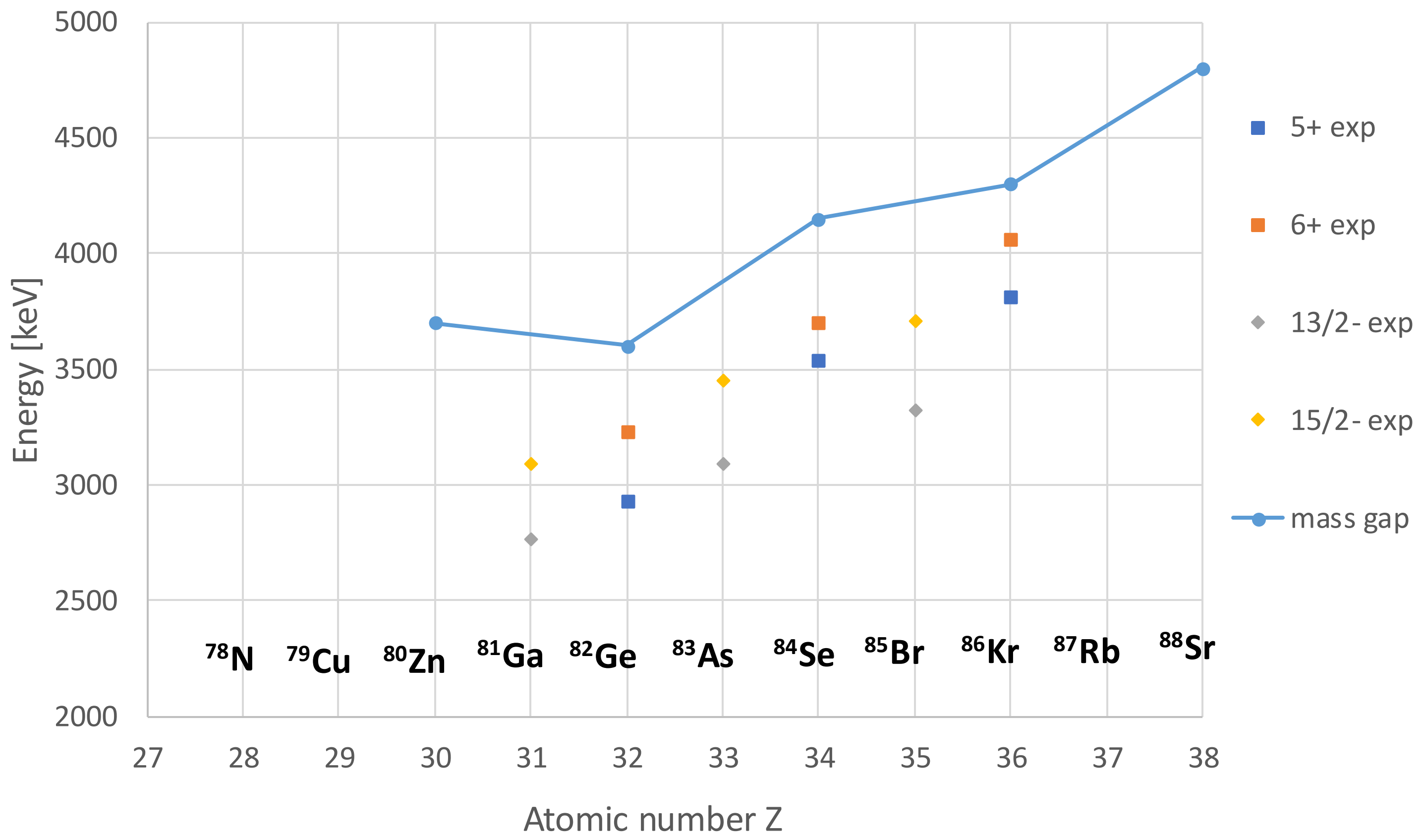
- **Mass gap**: from measured Sn values
- Quadratic behaviour of the shell gap around Z=32



N=50 from core-breaking states

- $\pi\, f_{5/2}p_{3/2}p_{1/2}$ space: max 4^+ with seniority 2
- 6^+ with Z=28 core breaking or for more seniority 4
- $\nu\, g_{9/2}$-$d_{5/2}$ core breaking: up to 7^+





J. Hakala et al., Phys. Rev. Lett. 101, 052502 (2008)
S. Baruah et al., Phys. Rev. Lett. 101, 262501 (2008)
K. Heyde et al., Phys. Lett. B 176, 255 (1986).
T. Rzaca-Urban et al., Phys. Rev. C 76, 027302 (2007)

- **Spectroscopic gap**: from 5^+,6^+,7^+ levels which are a $g_{9/2}$-$d_{5/2}$ N=50 core excitation
- Spectroscopy shows a decrease until Z=31

Lifetimes as probes of configuration change

- Problem: the 5^+,6^+ states are really representatives of a N=50 core break ?
- If they are, they should have suppressed decays to the «normal» proton state 4^+

Rule of thumb:

- If going from a N=50 core broken to a N=50 core closed:

  $B(M1) \approx 10^{-2}$-10^{-3} μ_N^2

  $B(E2) \approx$ few-30 e^2fm^4

- If going from a N=50 core closed to a N=50 core closed:

  $B(M1) \approx 1$ μ_N^2

  $B(E2) \approx$ 100-500 e^2fm^4

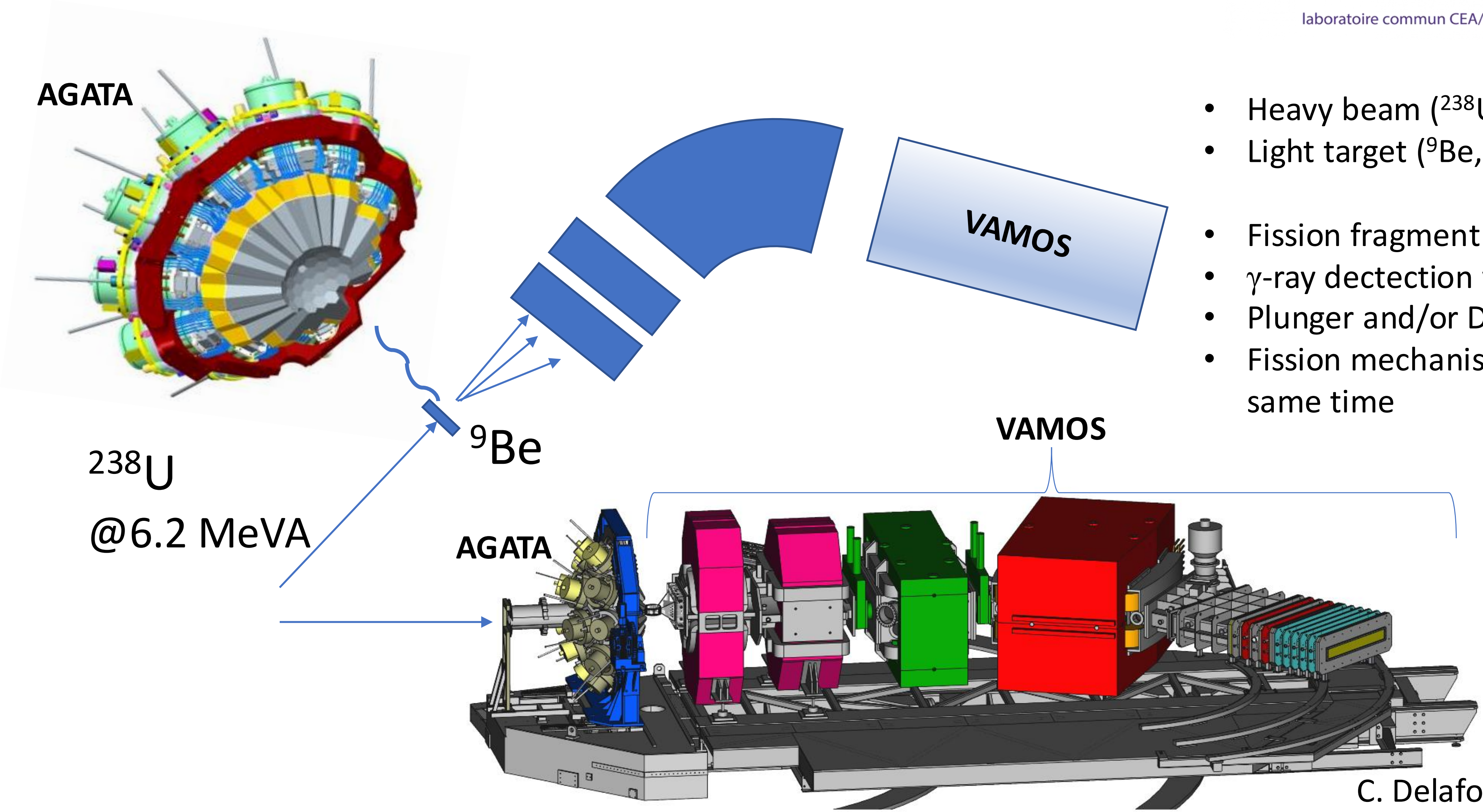
Reference for B(E2) in this region: 1 Wu ≈ 20-24 e^2fm^4

Fusion-fission experiments at GANIL (and LNL soon…)

laboratoire commun CEA/DRF CNRS/IN2P3

- Heavy beam (^{238}U, ^{208}Pb), 0.2-2 pnA
- Light target (^{9}Be, ^{12}C, ^{18}O…), 1-2 mg/cm^2

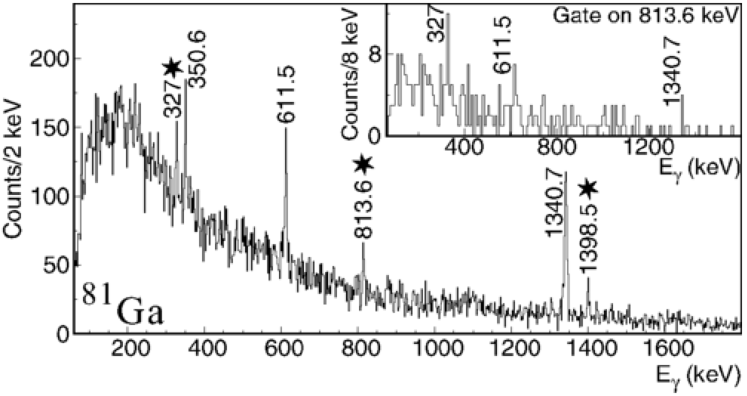
- Fission fragment detection at 20-28 deg
- γ-ray dectection with AGATA
- Plunger and/or DSAM lifetime possbile
- Fission mechanism can be studied at the same time

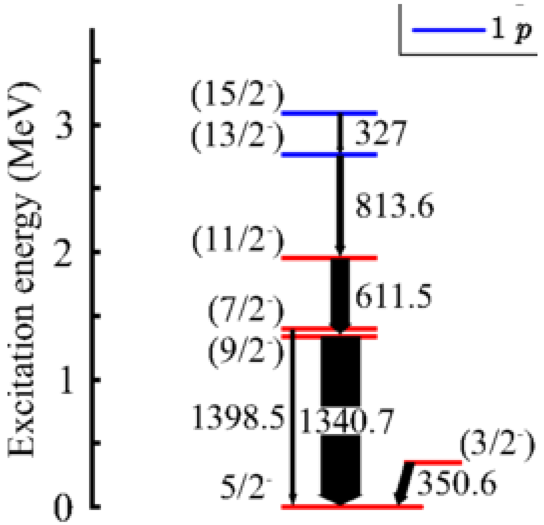


C. Delafosse – PhD thesis

Results and Spectroscopy

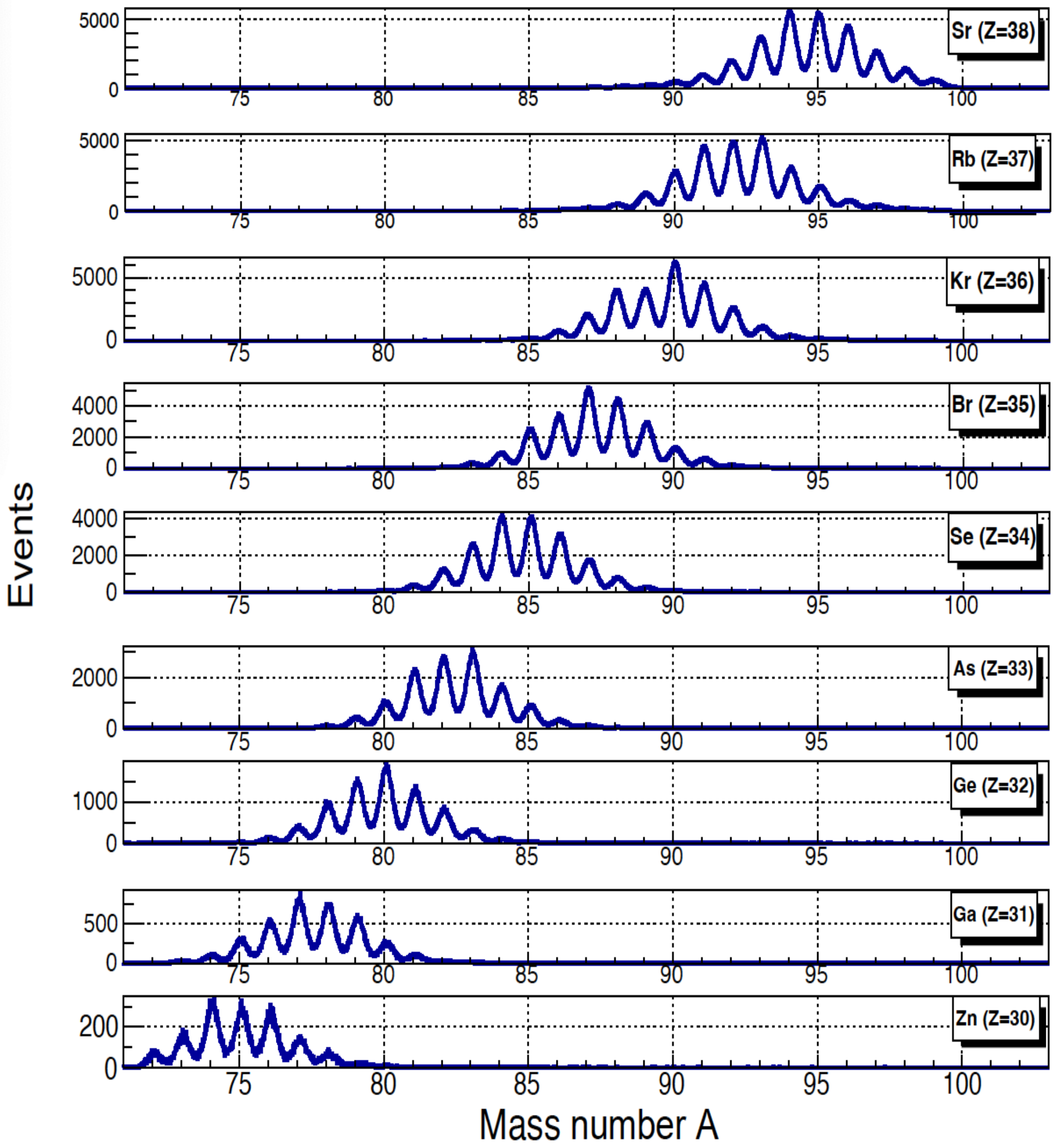
- Fusion-fission reactions tend to populate medium-spin states (6-8 unit of angular momentum)
- Many isotopes populated at the same time: event-by-event Z and A identification



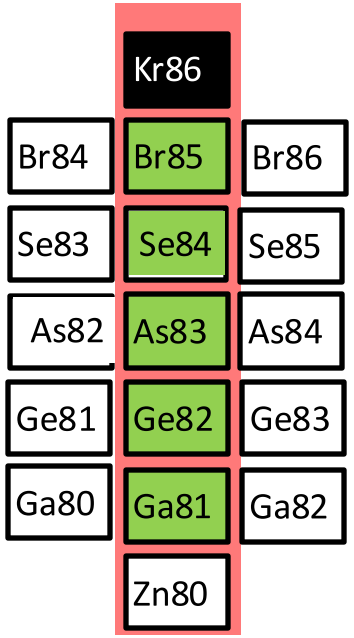


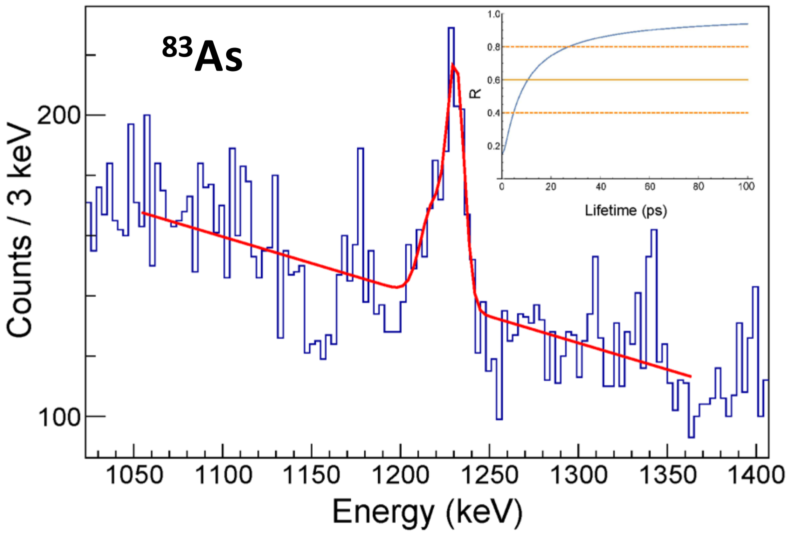
J. Dudouet *et al.*
Phys. Rev. C **100**, 011301(R) (2019)

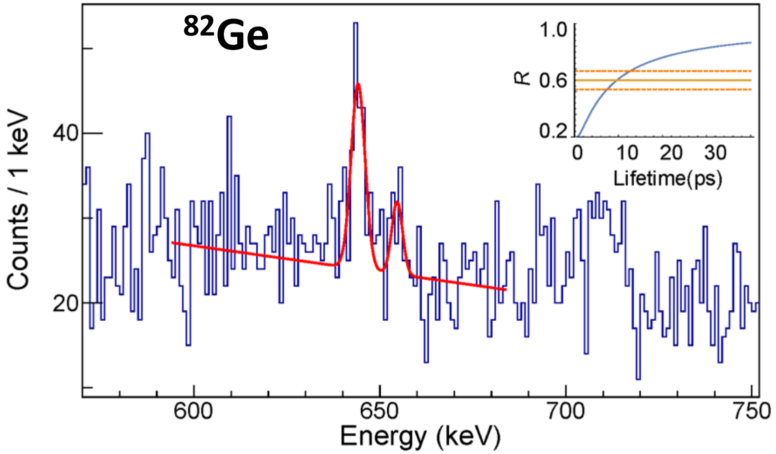
C. Delafosse – PhD thesis

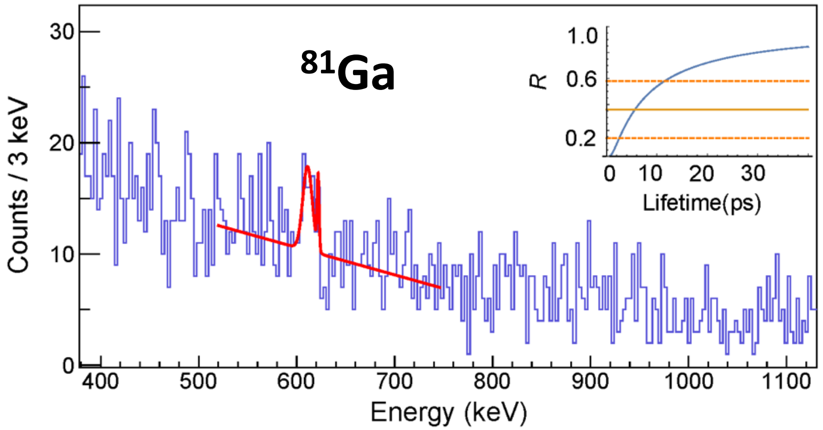


Lifetimes: results (I): N=50 isotones





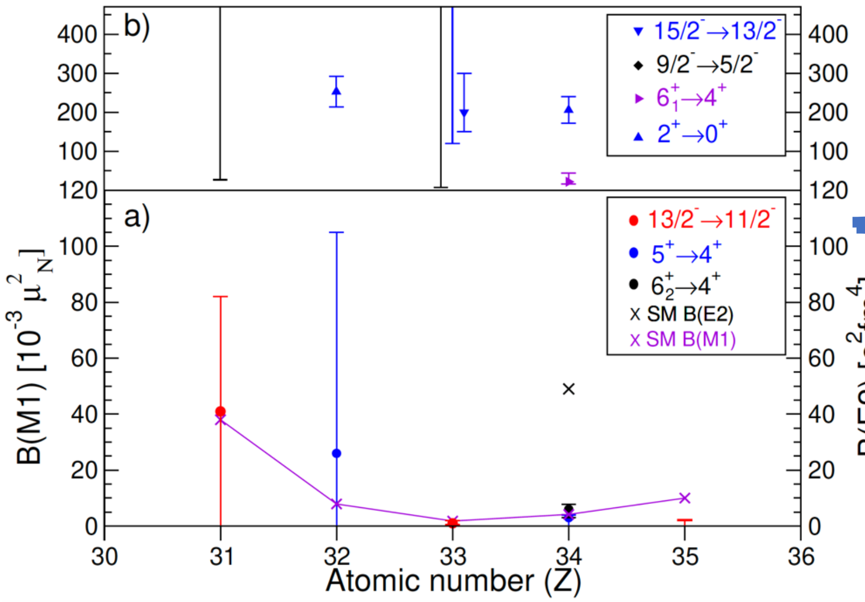




A. Gottardo, C. Delafosse, D. Verney et al., submitted to PRC

Lifetimes: results (II) : N=50 isotones

$N=50$	State Energy	Transition Energy	τ (ps)	B(E2) e^2fm^4 if $\delta^2=\infty$	B(M1) μ_N^2 if $\delta^2=0$
$^{85}_{35}$Br	$(13/2^-)$ 3326 keV	$(13/2^-)\rightarrow(11/2^-)$ 1161 keV	≥ 15	≤ 26	$\leq 2\cdot10^{-3}$
	$(11/2^-)$ 2165 keV	$(11/2^-)\rightarrow 9/2^{(-)}$ 593 keV	3^{+21}_{-3}	$>3\cdot10^2$	$>8\cdot10^{-3}$
$^{84}_{34}$Se	(6_2^+) 3702 keV	$(6_2^+)\rightarrow 4^+$ 1580 keV	14^{+7}_{-4}	4^{+2}_{-1}	-
	(5^+) 3537 keV	$(5^+)\rightarrow 4^+$ 1415 keV	6^{+2}_{-1}	24^{+5}_{-6}	$3^{+1}_{-2}\cdot10^{-3}$
$^{83}_{33}$As	$(15/2^-)$ 3457 keV	$(15/2^-)\rightarrow(13/2^-)$ 363 keV	6^{+2}_{-2}	$2^{+1.1}_{-0.5}\cdot10^4$	$0.2^{+0.1}_{-0.05}$
	$(13/2^-)$ 3094 keV	$(13/2^-)\rightarrow(11/2^-)$ 1228 keV	24^{+23}_{-9}	12^{+5}_{-12}	$1^{+0.4}_{-1.0}\cdot10^{-3}$
	$(9/2^-)$ 1543 keV	$(9/2^-)\rightarrow(5/2^-)$ 1543 keV	≤ 12	≥ 8	-
	$(11/2^-)$ 1866 keV	$(11/2^-)\rightarrow(9/2^-)$ 323 keV	≤ 14	$\geq 16\cdot10^4$	≥ 0.12
$^{82}_{32}$Ge	(5^+) 2932 keV	$(5^+)\rightarrow(4^+)$ 646 keV	8^{+21}_{-6}	$9^{+27}_{-7}\cdot10^2$	$26^{+79}_{-19}\cdot10^{-3}$
$^{81}_{31}$Ga	$(11/2^-)$ 1952 keV	$(11/2^-)\rightarrow(9/2^-)$ 611 keV	6^{+6}_{-3}	$1.6^{+1.6}_{-0.7}\cdot10^3$	$41^{+41}_{-20}\cdot10^{-3}$
	$(9/2^-)$ 1341 keV	$(9/2^-)\rightarrow(5/2^-)$ 1341 keV	≤ 7	≥ 27	-

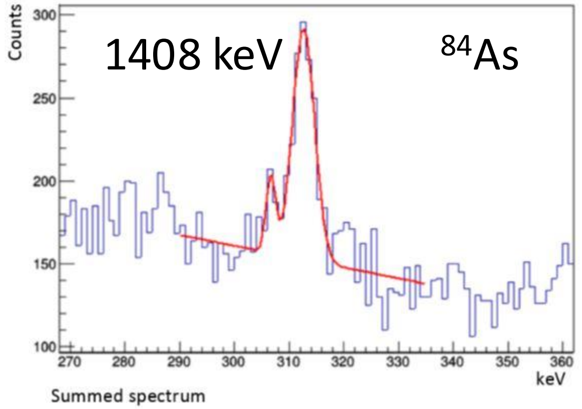


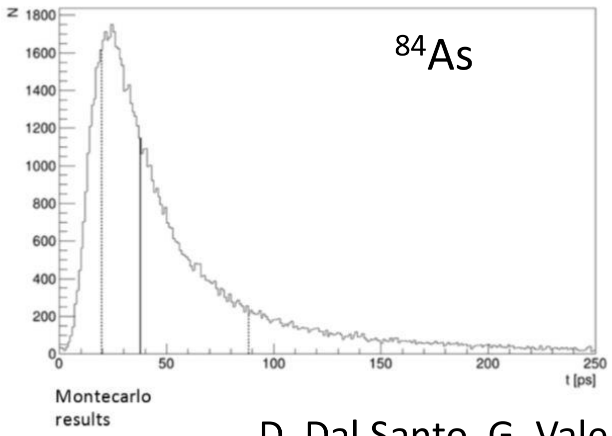
Large matrix elements

Small matrix elements

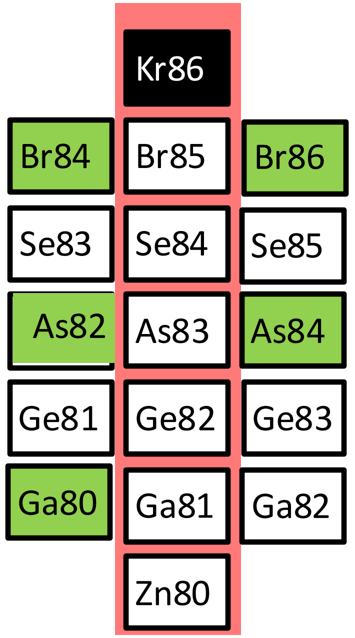
A. Gottardo, C. Delafosse, D. Verney et al., in preparation

Lifetime results (III): N=51 odd-odd nuclei





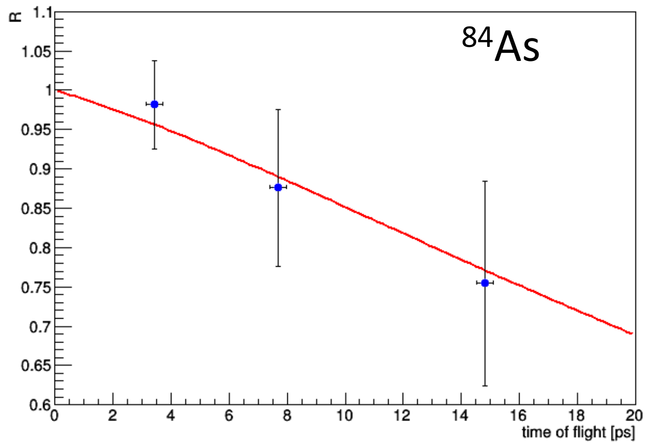
1408 keV lifetime determination with sum of three distances



N=49 N=50 N=51

D. Dal Santo, G. Valerin University of Padova students

313 keV lifetime fit

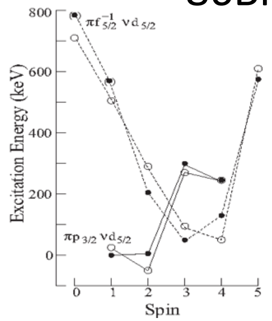


^{84}As scheme built based on $\gamma\gamma$ coincidences:

Nuclide	E_γ [keV]	Transition	$\tau[ps]$	$B(E, M\lambda)$ [W.u.]
^{86}Br	331	$5^- \to 4^-$ (M1)	7.4 ± 1.8	$1.2 \pm 0.3 \cdot 10^{-1}$
^{84}Br	194	$8^+ \to 7^+$ (M1)	$12.6^{+8.2}_{-4.5}$	$3.5^{+1.2}_{-2.2} \cdot 10^{-1}$
	972	$7^+ \to 7^-$ (E1)	$4.1^{+5.4}_{-2.8}$	$1.4^{+0.9}_{-1.4} \cdot 10^{-4}$
	530	$7^- \to 6^-$ (M1)	$25.9^{+18.1}_{-8.8}$	$8.2^{+2.8}_{-5.7} \cdot 10^{-3}$
^{84}As	1408	$7^+ \to 5^-$ (M2)	$7.2^{+4.5}_{-3.0}$	$5.9^{+2.4}_{-3.7} \cdot 10^{1}$
	313	$5^- \to 4^-$ (M1)	43 ± 22	$2.4 \pm 1.2 \cdot 10^{-2}$
	1019	$6^- \to 4^-$ (E2)	$3.8^{+2.4}_{-1.7}$	$8.9^{+4.0}_{-5.6} \cdot 10^{0}$
^{82}As	218	unknown	9.0 ± 3.0	
	278	unknown	6.6 ± 2.0	
	656	unknown	$9.8^{+5.5}_{-3.4}$	
	410	unknown	> 40	
^{80}Ga	401	unknown	$12.5^{+9.4}_{-4.7}$	

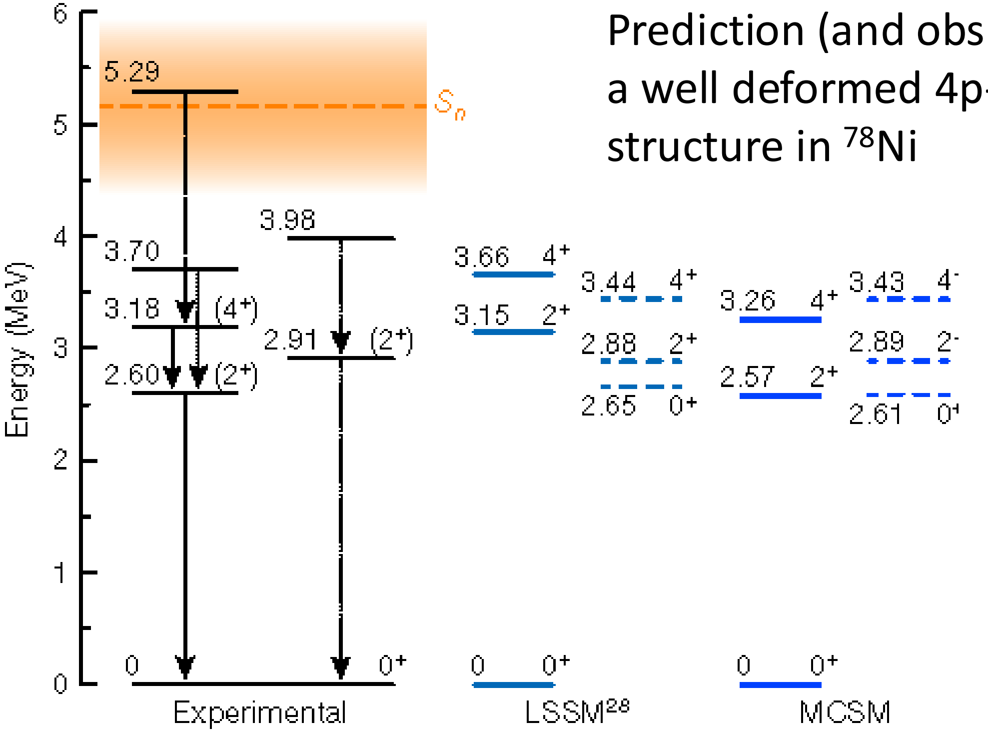
N=51: $\nu d_{5/2}s_{1/2}$-$\pi f_{5/2}p_{3/2}p_{1/2}$ coupling

86Br



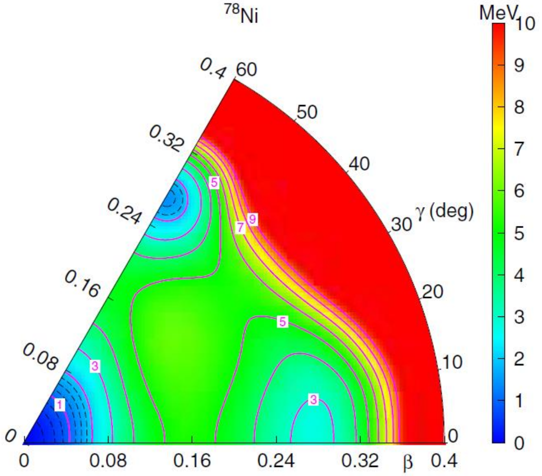
Level	Configuration $\pi p_{3/2}\ \nu d_{5/2}$	Configuration $\pi f^{-1}_{5/2}\ \nu d_{5/2}$
0_1		67 %
1_1	74 %	
1_2	8 %	54 %
2_1	66 %	
2_2	5 %	65 %
3_1	37 %	28 %
3_2	41 %	34 %
4_1		61 %
4_2	84 %	
5_1		67 %

^{78}Ni: the end of N=50 shell closure ?



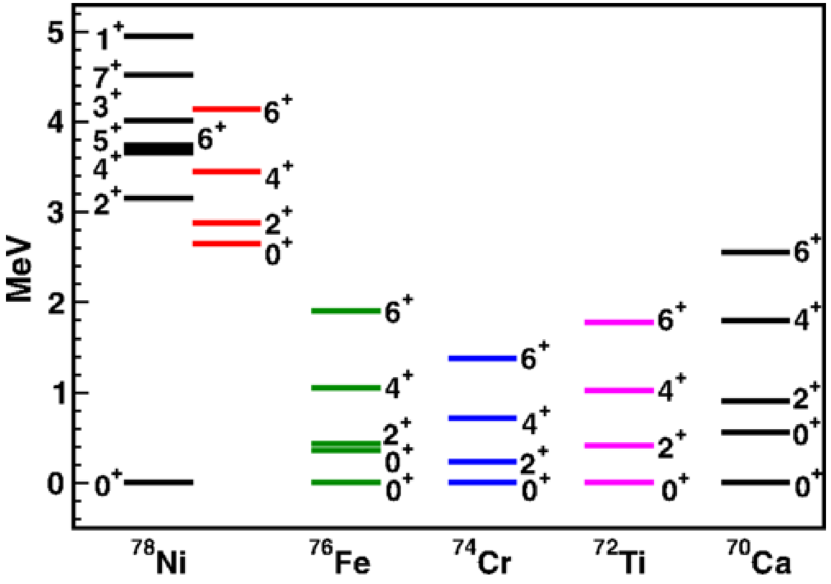
R. Taniuchi et al., Nature 569, 53–58 (2019)

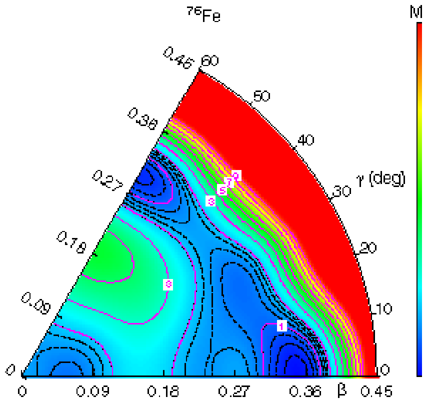
Prediction (and observation ?) of a well deformed 4p-4h intruder structure in ^{78}Ni



F. Nowacki et al., Phys. Rev. Lett. 117, 272501 (2016)

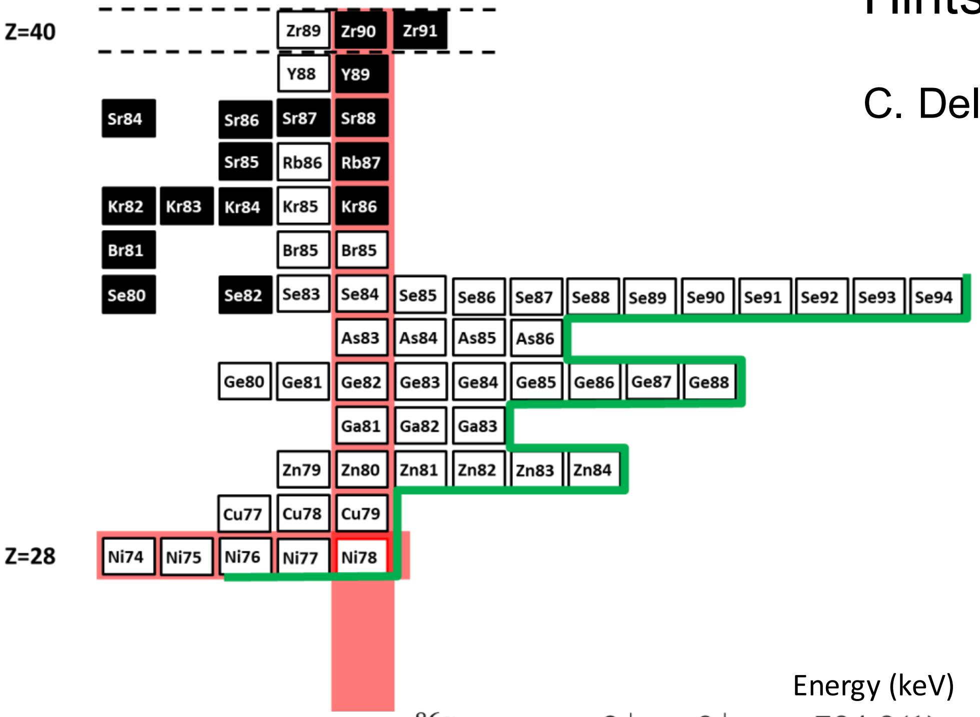
- **Island of inversion below Z=28**





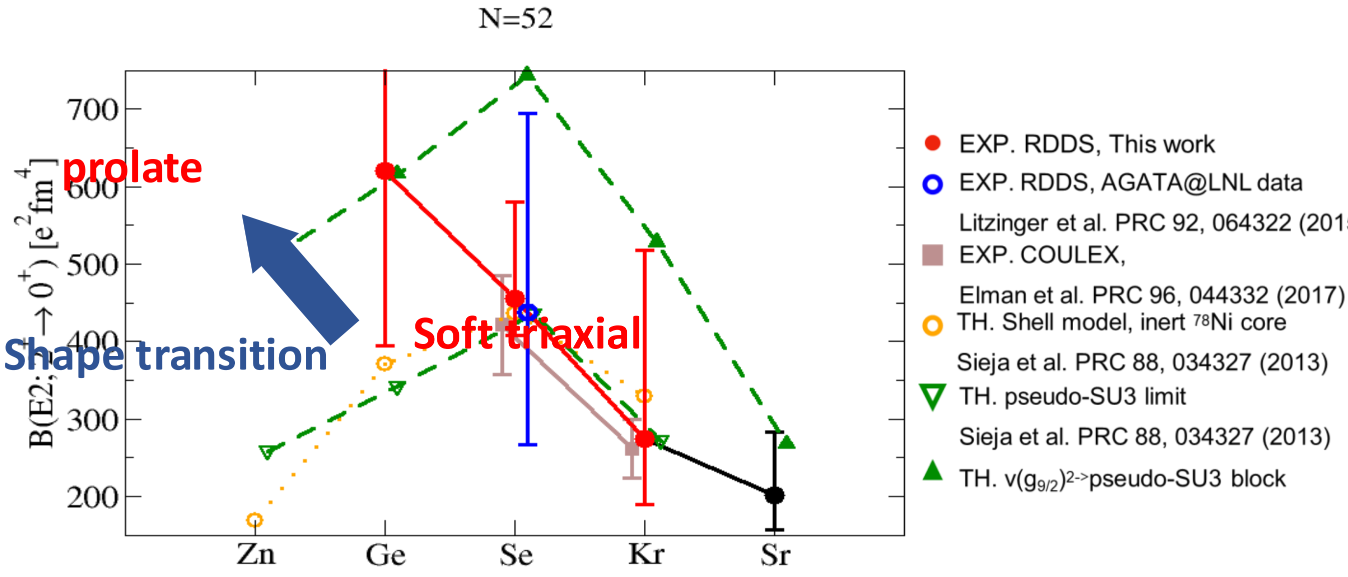
F. Nowacki et al., Phys. Rev. Lett. 117, 272501 (2016)

Lifetimes to identify intruder components



Hints of a shape transition along the N=52 isotonic line

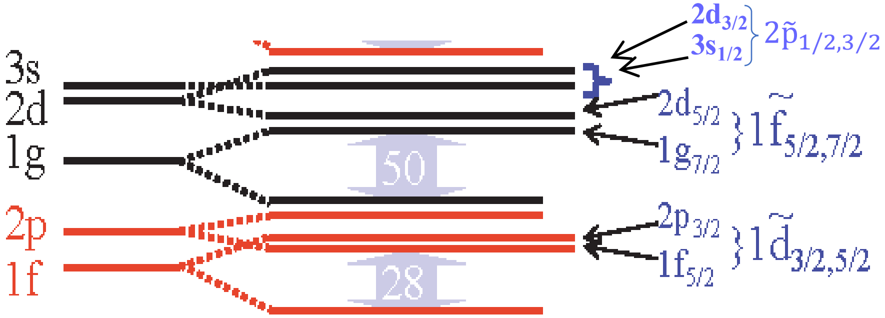
C. Delafosse et al. Phys. Rev. Lett. 121 192502(2018)

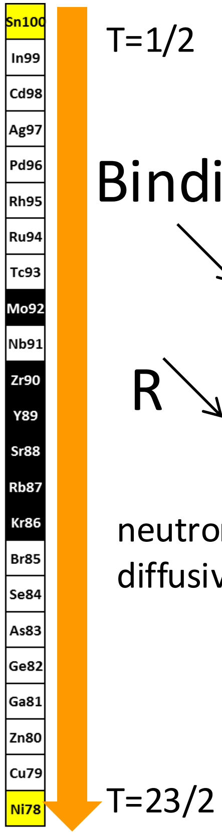


		Energy (keV)	τ (ps)
^{86}Se	$2^+ \rightarrow 0^+$	704.0(1)	$10.3^{+1.2}_{-2.2}$
^{84}Ge	$2^+ \rightarrow 0^+$	624.3(9)	$13.8^{+7.9}_{-9.8}$
	$4^+ \rightarrow 2^+$	805.4(11)	$10.3^{+3.0}_{-6.5}$ (*)

- Monotonic increase of the B(E2) along N=52: no midshell maximum ?
- Is the large B(E2) a signature of an intruder configuration in ^{84}Ge ?

A pseudo-spin mechanism ?





Binding Σ_n ↘

R ↘

neutron diffusivity ↗

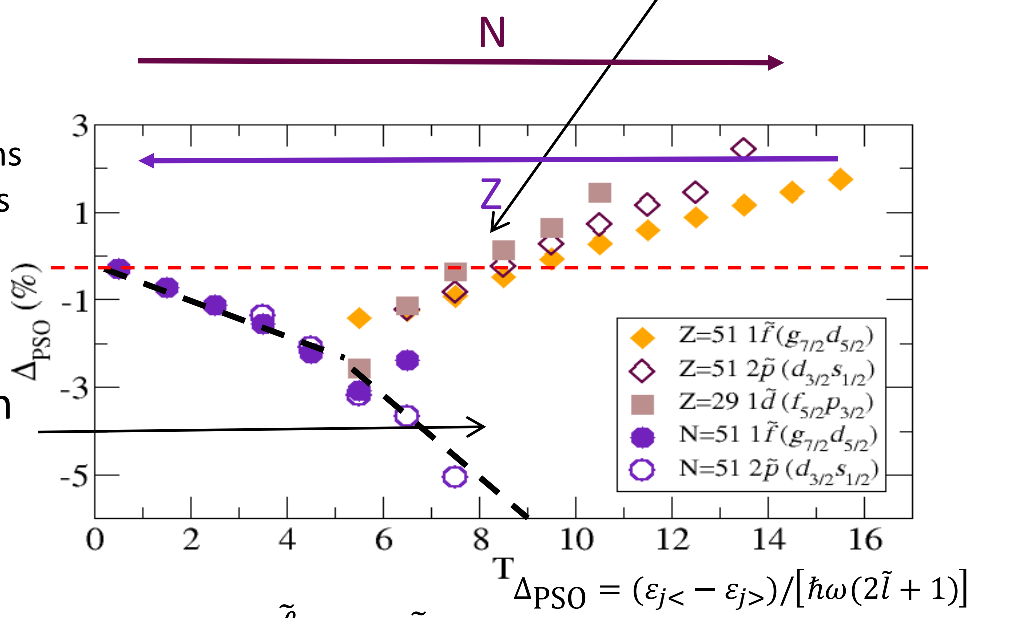
ρ meson interaction, in neutron rich nuclei :

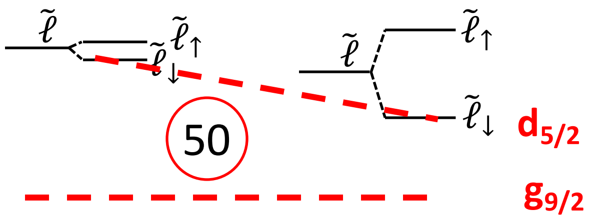
- repulsive for the neutrons
- attractive for the protons

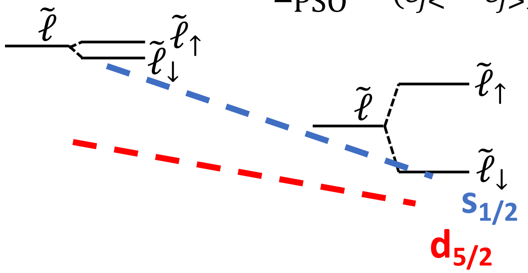
$$V = V_\omega + V_\rho = V_\omega \pm \frac{g_\rho}{2}\rho_0$$

neutron skin formation ?

proton 5/2 - 3/2 inversion in Cu: restauration of PSS







C. Delafosse et al. Phys. Rev. Lett. 121 192502(2018)

Shape evolution beyond N=50

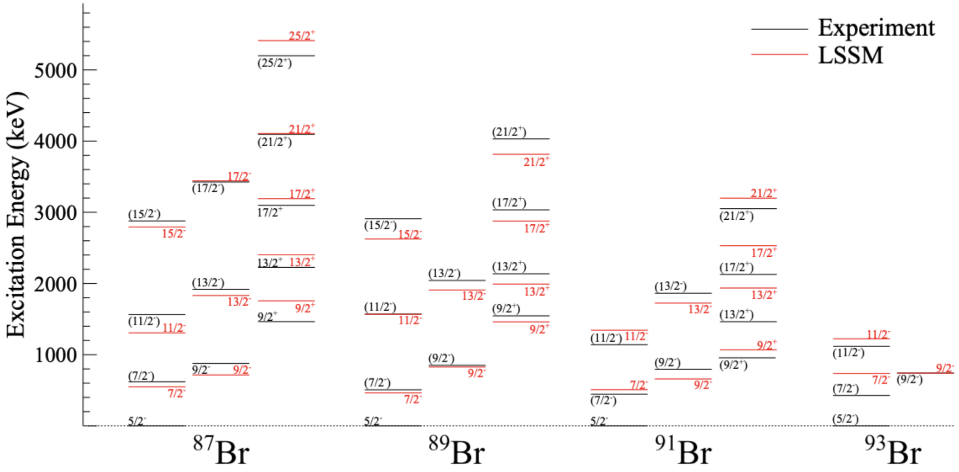
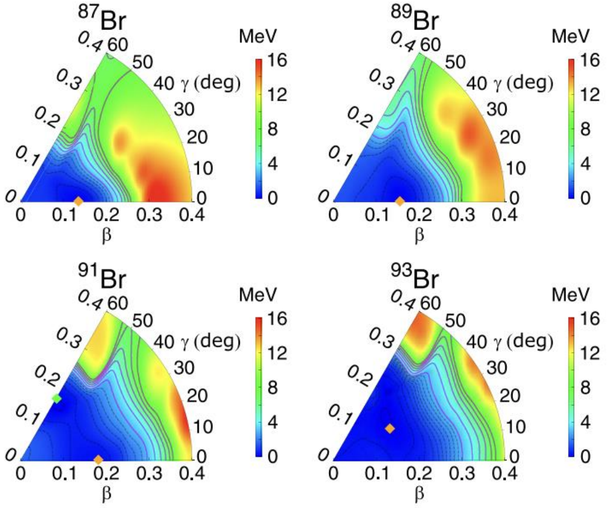
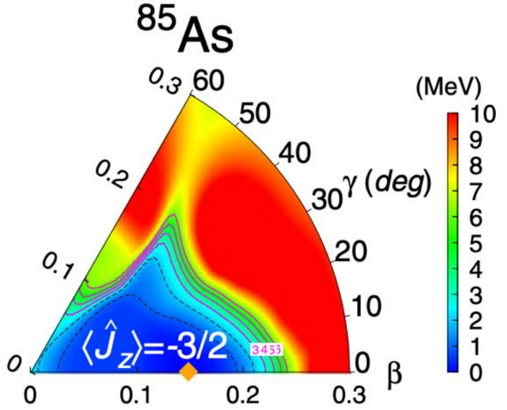


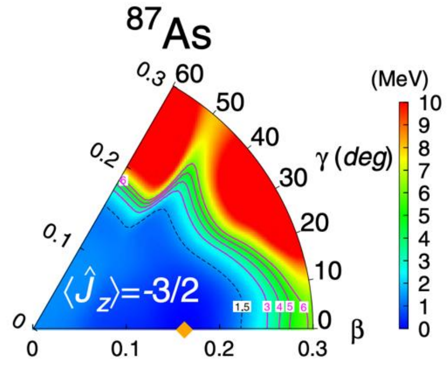
FIG. 18. Global comparison between LSSM calculations and experiment for the yrast states of Br isotopes.

shape transition from prolate ^{87,89}Br to oblate ^{91,93}Br for both natural and non-natural parity bands



Phys. Rev. C 110, 034304 (2024)





From prolate deformation ot γ softness from ^{84}Ge to ^{86,88}Ge, and from ^{85}As to ^{87}As. Rigid triaxiality also put forward

Phys. Rev. C 96, 011301R (2017) Phys. Rev. C 106, 014320 (2022)

AGATA-PRISMA @ LNL

INFN
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI LEGNARO

- AGATA – PRISMA setup

	AGATA-VAMOS	AGATA-PRISMA	Improvement factor
Beam	238U @ 6.3 MeV/u, 25enA: 0.2 pnA at 28 degrees	238U @ 7.2 MeV/u: ~0.5 pnA at 28 degrees	~2
Dead Time	0.5kHz of trigger (no deadtime)	1kHz (no deadtime)	1
Crystals	24	33	
Agata position	Compact (14cm to target)	Compact	
Single efficiency	~2% *	~6.5% (measured 1 MeV)	3
Target	9Be, 10um (1.85mg/cm2)	9Be, 10um (1.85 mg/cm2) to have 0.2 ps TOF in the Be target	1
Beam Time	8 days	21 days	2.6
Acceptance	Δθ _± 6◦;Δφ _± 10◦	Δθ _± 6◦;Δφ _± 9◦	0.8
Total			12

Ideally 4-5 distances

Main Physics goals

a) New lifetimes ^{80}Zn (4^+, 5^+), maybe lifetime limit on ^{79}Cu summing up all distances

b) Gap N=50: Searching for single-particle E2 or suppressed M1 transitions in ^{85,87}Se, ^{82,83}Ge, ^{80,81,82}Ga

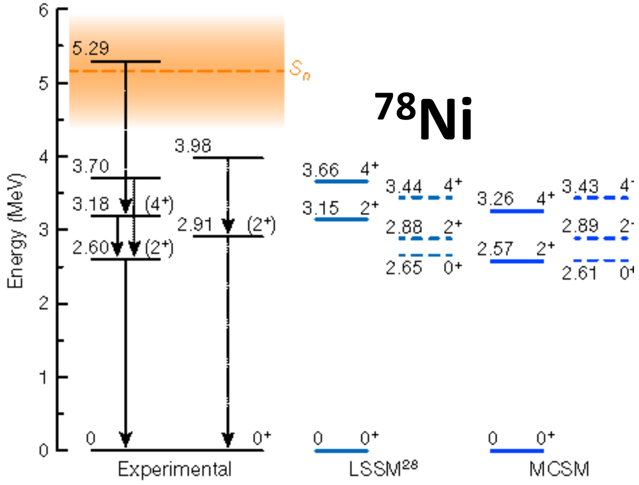
c) Shape evolution beyond N=50: Measuring lifetimes of yrast and yrare 2^+, 4^+ and 6^+ states in ^{87}Br-^{91}Br, ^{86}Se,^{88}Se, $^{85\text{-}87}$As, ^{84,86}Ge (to confirm the large B(E2) found at GANIL) and ^{86}Ge. The lifetime of the 4^+ of ^{80}Zn could also be an aim.

d) Large dataset for students

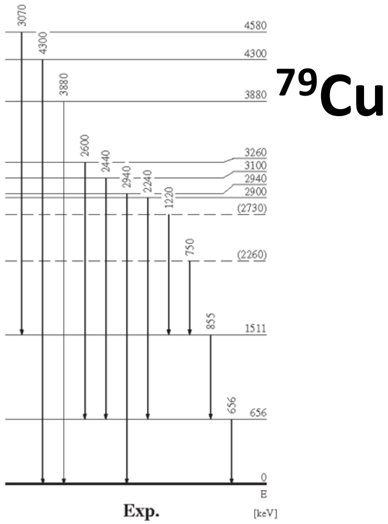
Thanks for the attention !

^{78}Ni and N=50 isotones: recent results in a key region for shell structure

- Many results from in-flight beams **proton knockout** at RIKEN: first in-beam spectroscopy of ^{78}Ni, ^{79}Cu
- High-resolution γ-ray spectroscopy with HiCARI



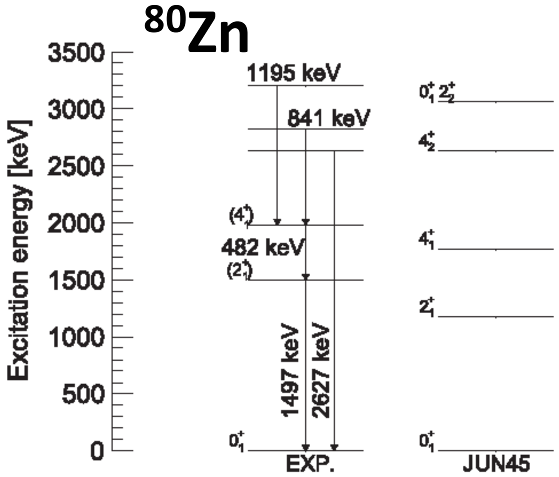
R. Taniuchi et al., Nature 569, 53–58 (2019)



L. Olivier et al., Phys. Rev. Lett. 119, 192501 (2017)

- Proton knockout technique: low spin levels, proton s.p. wave function

Need for complementary measurements to populate medium-spin states

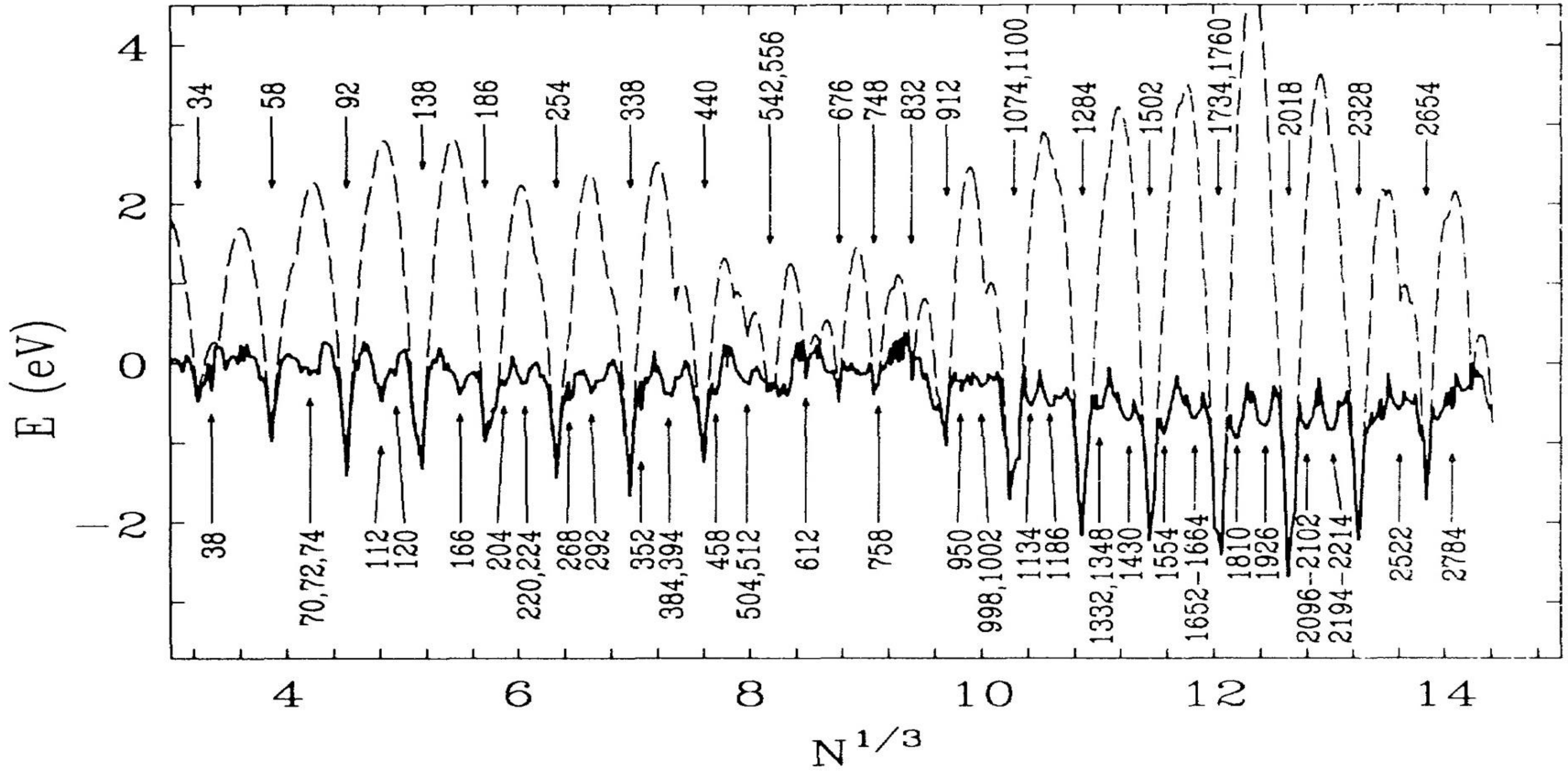


Y. Shiga et al. Phys. Rev. C 93, (2016)

Cornerstones or perturbation ?

Nuclear physics: collectivity as a “perturbation” of the shell structure

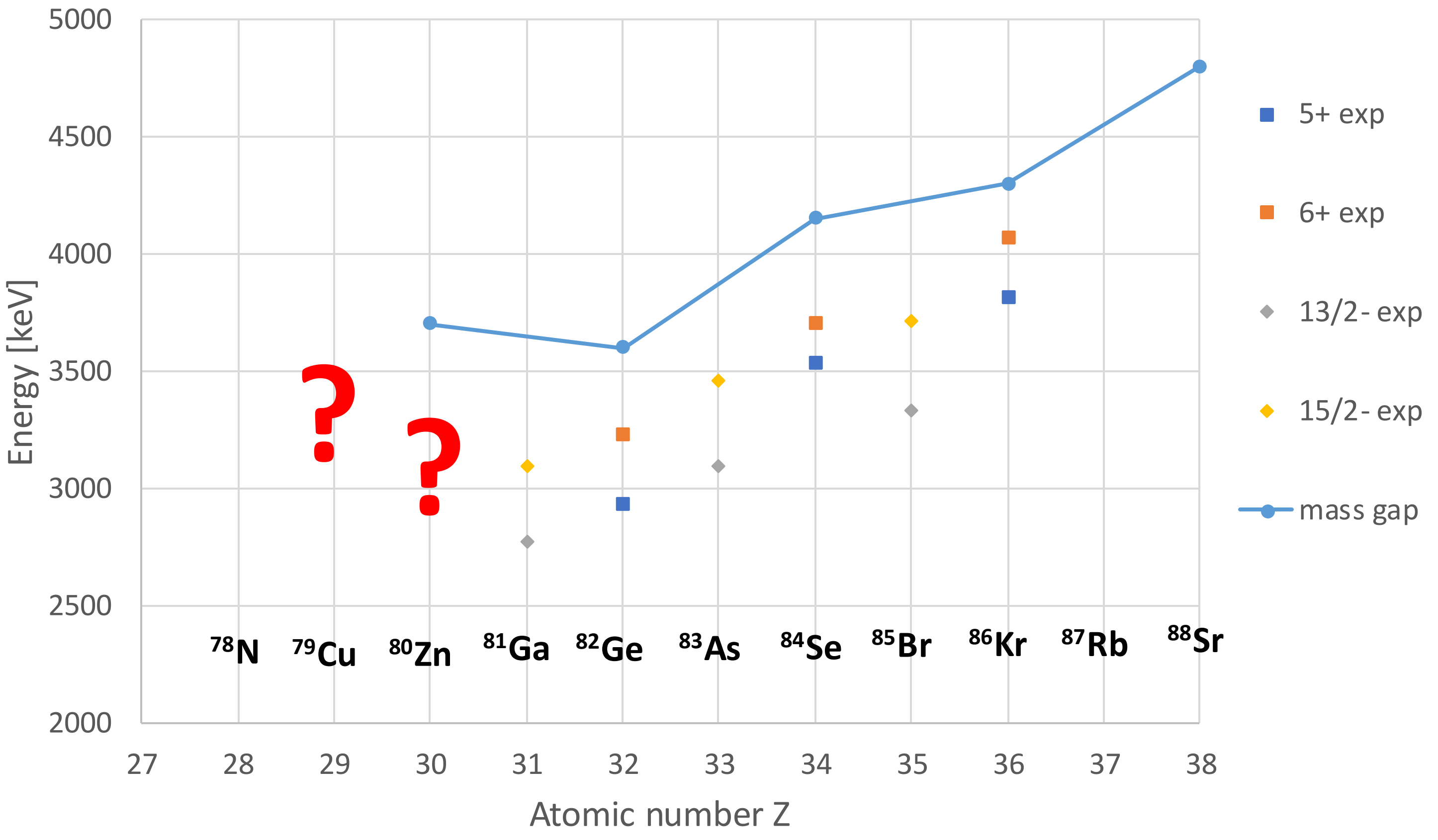
Atomic/molecular physics: shell structure perturbing the collectivity



A. Bulgac and C. Lewenkopf, Phys. Rev. Lett. 71, 4130 (1993)

The N=50 gap: mass and γ-ray spectroscopy

- Mass gap: from measured Sn values
- Spectroscopic gap: from levels which are made with a g9/2-1d5/2 core excitation
- Parabolic behaviour of the shell gap
- Re-increase in Z=30 ^{80}Zn verified from masses
- Spectroscopy sees a decrease until Z=31

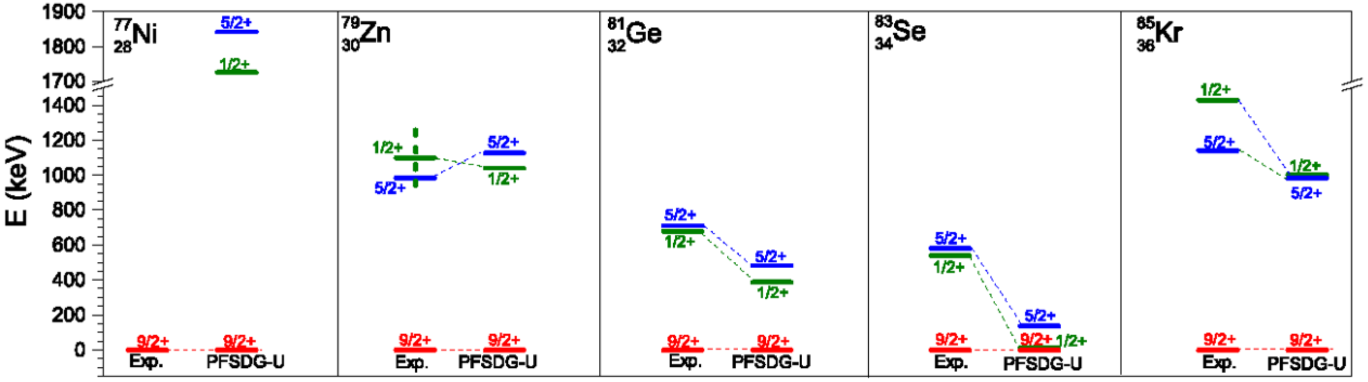


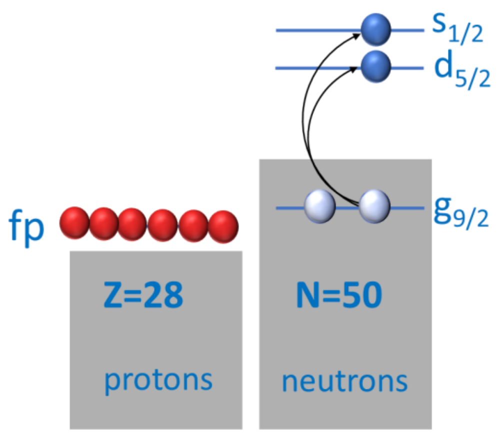
J. Hakala et al., Phys. Rev. Lett. 101, 052502 (2008)
S. Baruah et al., Phys. Rev. Lett. 101, 262501 (2008)
K. Heyde et al., Phys. Lett. B 176, 255 (1986).
T. Rzaca-Urban et al., Phys. Rev. C 76, 027302 (2007)

How does the spectroscopic N=50 gap evolve in ^{80}Zn ? Is there the re-increase seen by mass measurements ?

Collectivity along N=50 and intruder configurations

C. Wraith et al., Phys. Lett. B 771 (2017) 385391





many particle – many hole across N=50

- Spherical gap :

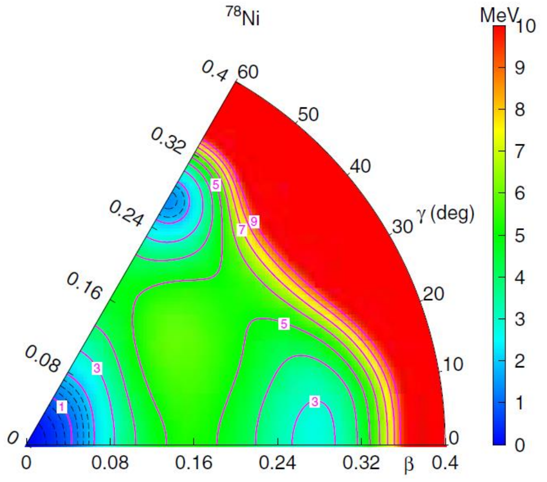
  energy cost

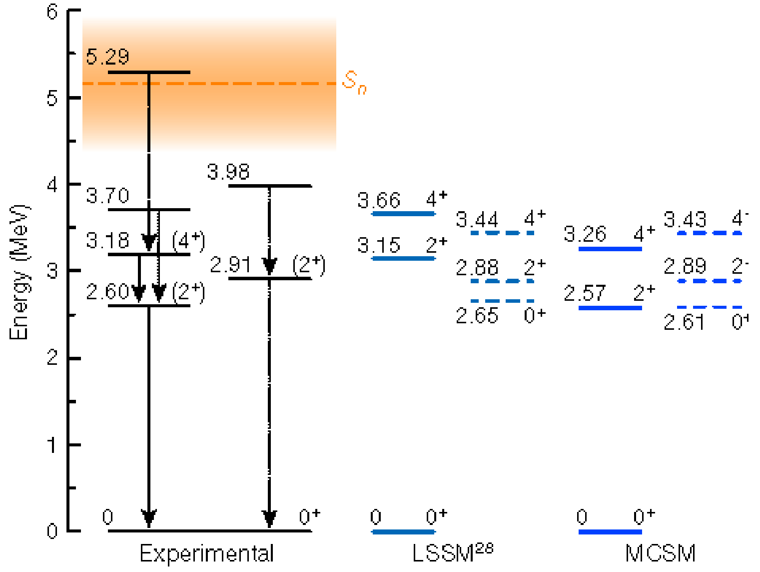
- Correlations by breaking the core:

  energy gain

- Lowering of energy from Z=36 to Z=32, then reincrease
- PSDG-U shell-model interaction (by F. Nowacki) quenches the N=50 gap at Z=34 at variance with data

Prediction (and observation ?) of a well deformed 4p-4h intruder structure in ^{78}Ni

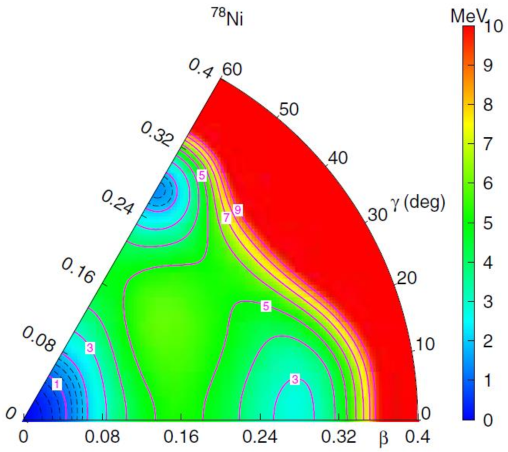




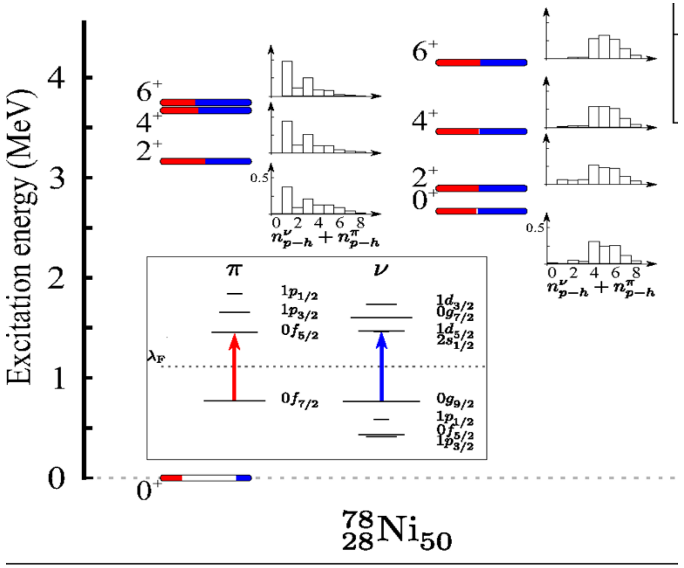
F. Nowacki et al., Phys. Rev. Lett. 117, 272501 (2016)

Collectivity in ^{78}Ni and weak-coupling in ^{79}Cu

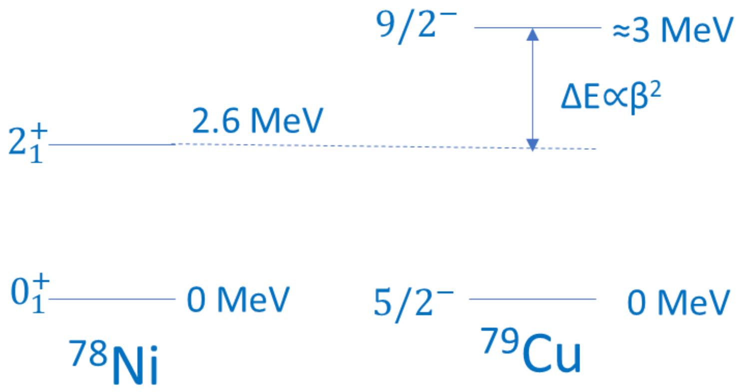
- The 2_1^+ state in ^{78}Ni is the spherical or the deformed 4p-4h ?
- Large consequence on the spectroscopy of ^{79}Cu: weak couplir $\pi f_{5/2} \otimes 2^+_{^{78}Ni}$ proportional to β^2

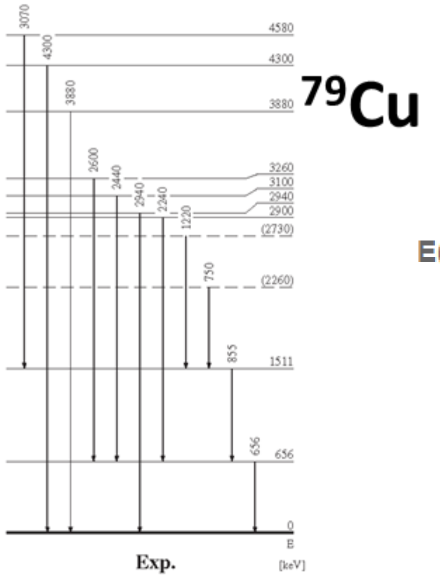


β can range from 0.05 to 0.27 !

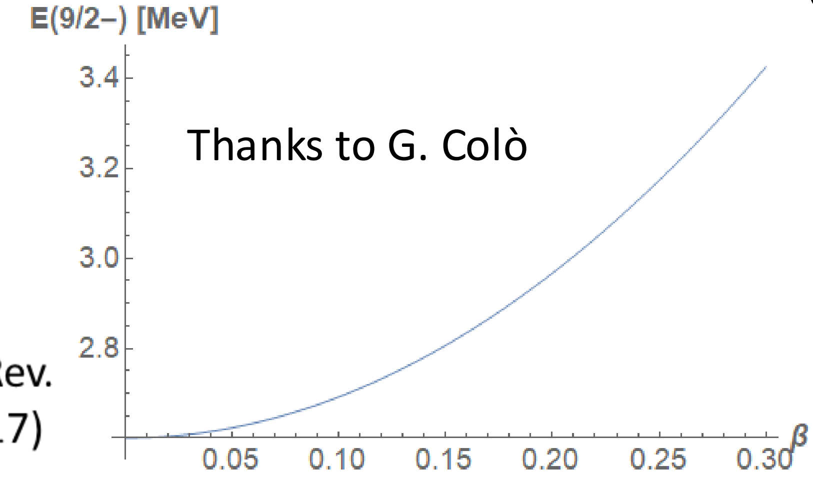


F. Nowacki et al., Phys. Rev. Lett. 117, 272501 (2016)





L. Olivier et al., Phys. Rev. Lett. 119, 192501 (2017)



From B&M PV coupling model

How to study these nuclei ?

Proton-knockout from in-flight beams:
- very exotic nuclei (^{78}Ni, ^{79}Cu, ^{80}Zn)
- low-spin state, proton single-particle fragments

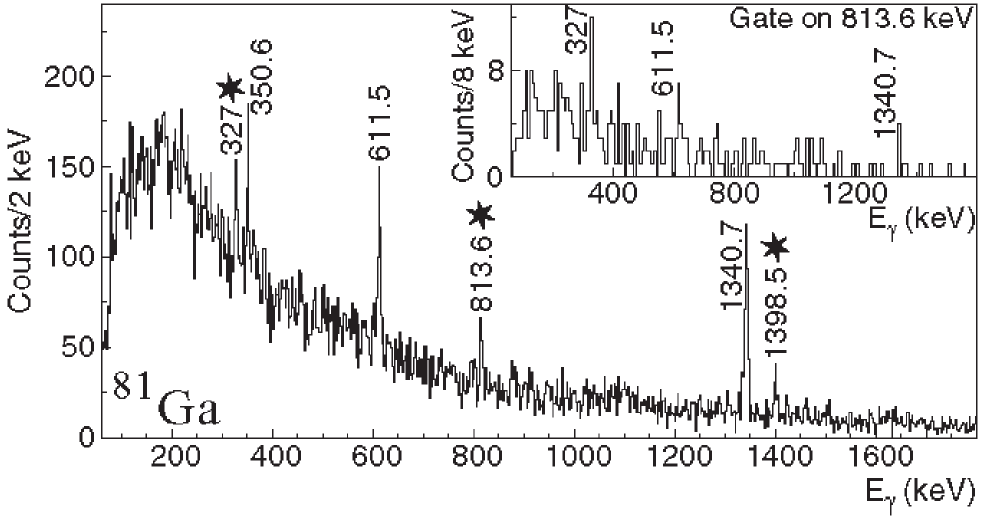
^{238}U (fusion-)fission:
- less exotic nuclei (^{81}Ga)
- medium-spin state, mainly yrast

- Problems observed with ^{238}U (fusion-)fission at AGATA-VAMOS at GANIL:

  1 - **High** ion and γ-ray **counting rate**: large dead time (50% !), limit in beam current

  2 - ^{80}Zn, ^{79}Cu represent a very small fraction of $\sigma_{fission}$ ≈700 mb !

  3 - Need to put VAMOS at a large 28° angle (-> smaller solid angle acceptance)



J. Dudouet et al, Phys. Rev. C 100, 011301(R) (2019)

<u>Is there a way to improve compared to what was done at GANIL ?</u>

Idea: we are at the tail of the fission peak-> fissioning system with a lower Z

Fusion-fission reactions: ^{238}U or ^{208}Pb ?

- GEF calculations: fission probability of $^{208}Pb+^{9}Be \approx 1/20$th of $^{238}U+^{9}Be$
- HOWEVER:
    1- lower Z of fissioning system -> higher ratio of $\sigma(\approx^{80}Zn)/\sigma_{fission}$
    2- lower Z of fissioning system -> more forward focussed fragments -> increased spectrometer acceptance
    3- lower total $\sigma_{fission}$: lower counting rate in AGATA and PRISMA-> increased beam current and target thickness

- Calculation convoluting GEF reaction model with PRISMA acceptance

	Ions/day in PRISMA	γ-ray-ion 14 days 10% efficiency
^{79}Cu	**130**	**180**
^{80}Zn	**5600**	**7800**
^{81}Ga	4E4	5.5E4

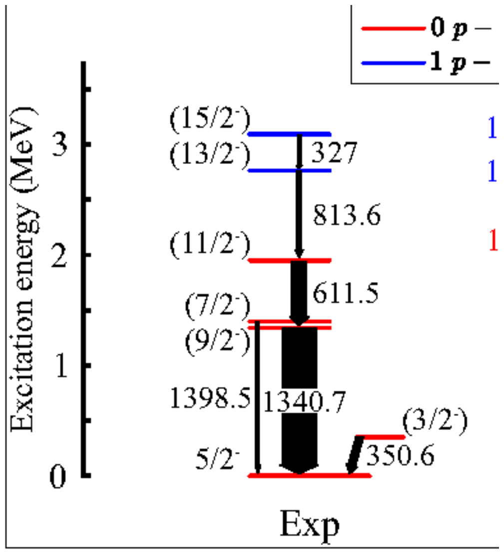
Factor ≈5 increase in ^{80}Zn, ^{79}Cu production compared to AGATA-VAMOS @ GANIL (plus X 2 efficiency, plus small dead time)

The limit of spectroscopy is significantly extended with respect to AGATA-VAMOS @ GANIL (^{81}Ga)

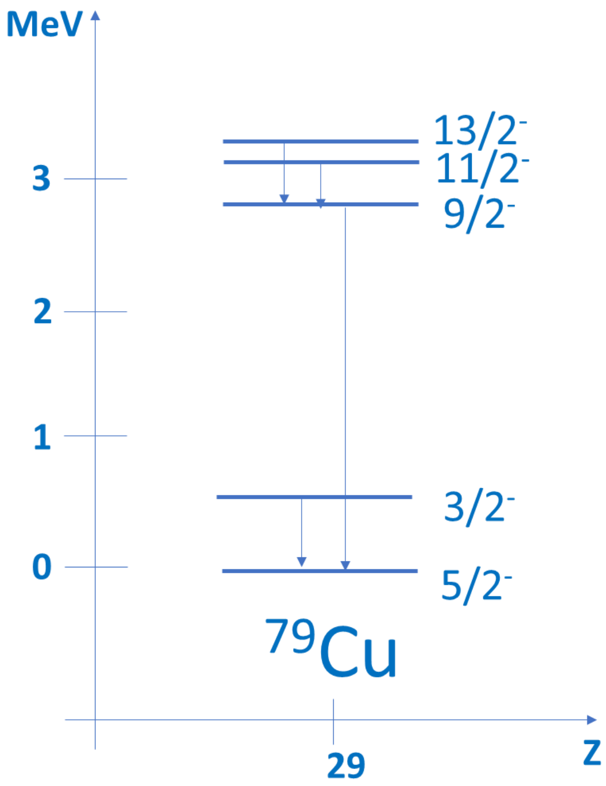
What we want to measure

^{79}Cu

From the ^{81}Ga, ^{83}As systematics from fission, we expect to observe the $9/2^-$, $13/2^-$ levels in ^{79}Cu

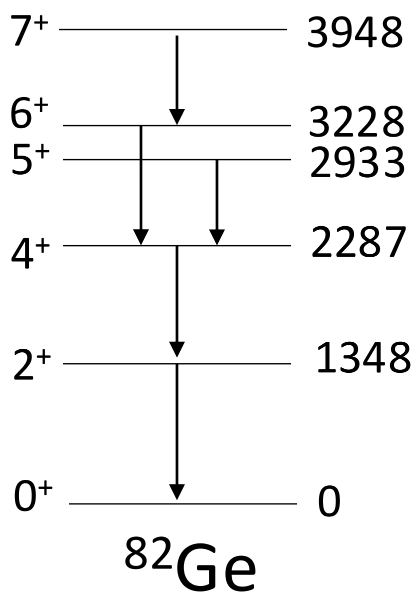


Example: ^{81}Ga from fusion-fission @AGATA-VAMOS

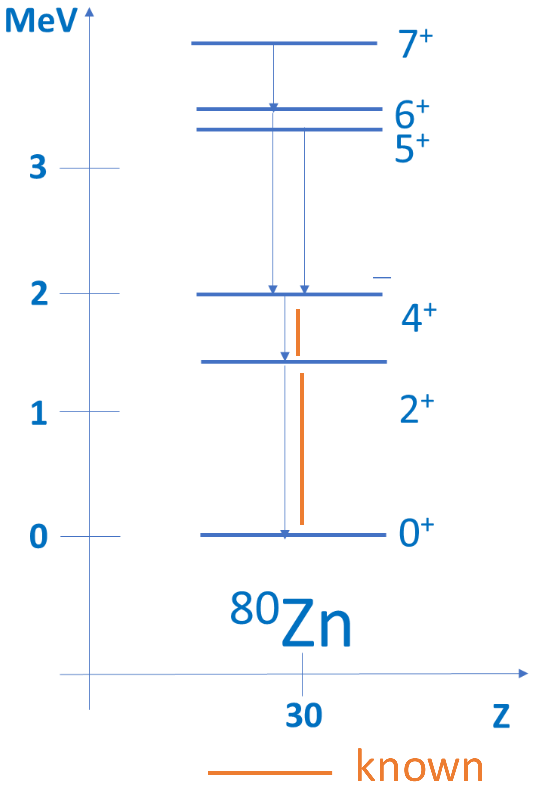


^{80}Zn

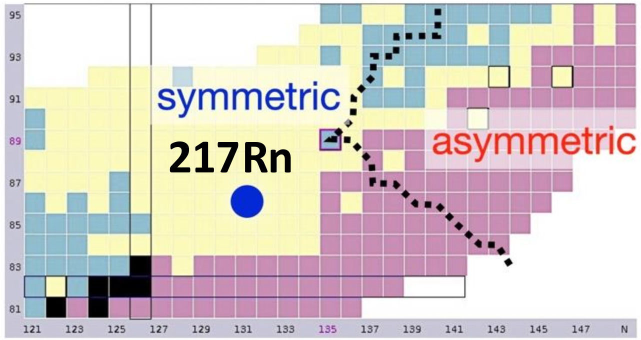
2^+, 4^+ levels know from ^{80}Zn proton-knockout
N=50 core excitations: 5^+, 6^+, 7^+ levels, typically populated by fission

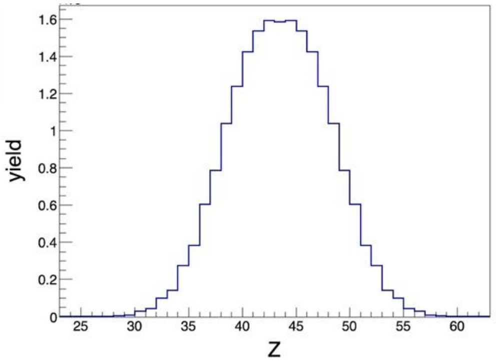


Example: ^{82}Ge from fusion-fission @AGATA-VAMOS



Fission studies: $^{208}Pb+^{9}Be$ -> ^{217}Rn

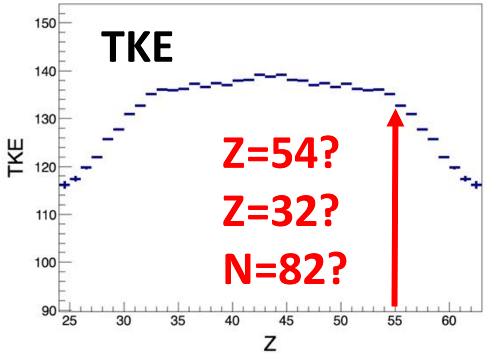


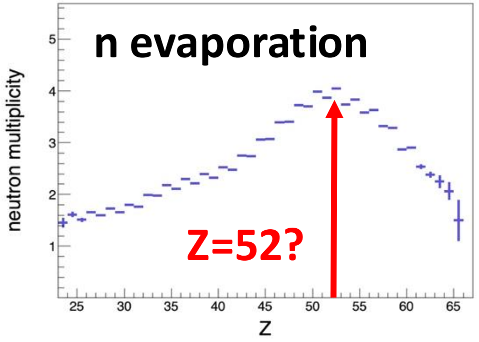


^{217}Rn is in the middle of a symmetric-fission valley, where nuclear structure seems not strong enough to overcome a liquid-drop behaviour, as in the actinide region.

However, other observables may reveal the effect of nuclear structure:

GEF predictions

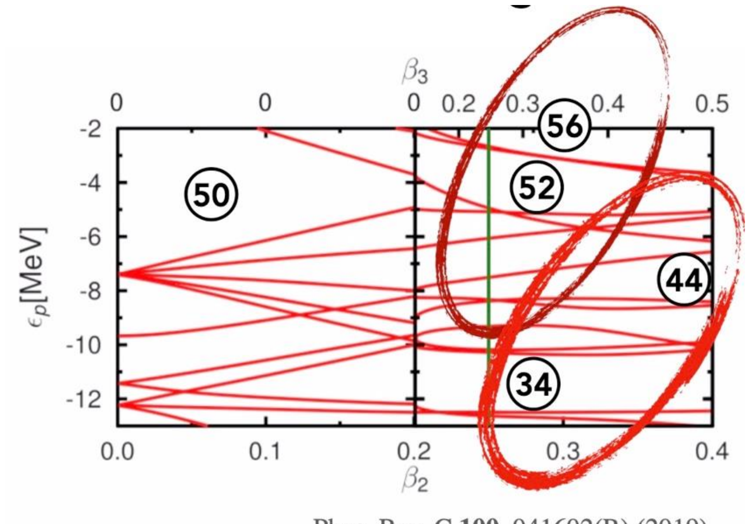




In GEF, the effect of structure is based on phenomenological extrapolations. In other models, such structures are absent.

However, no data is readily available for these observables in this region.

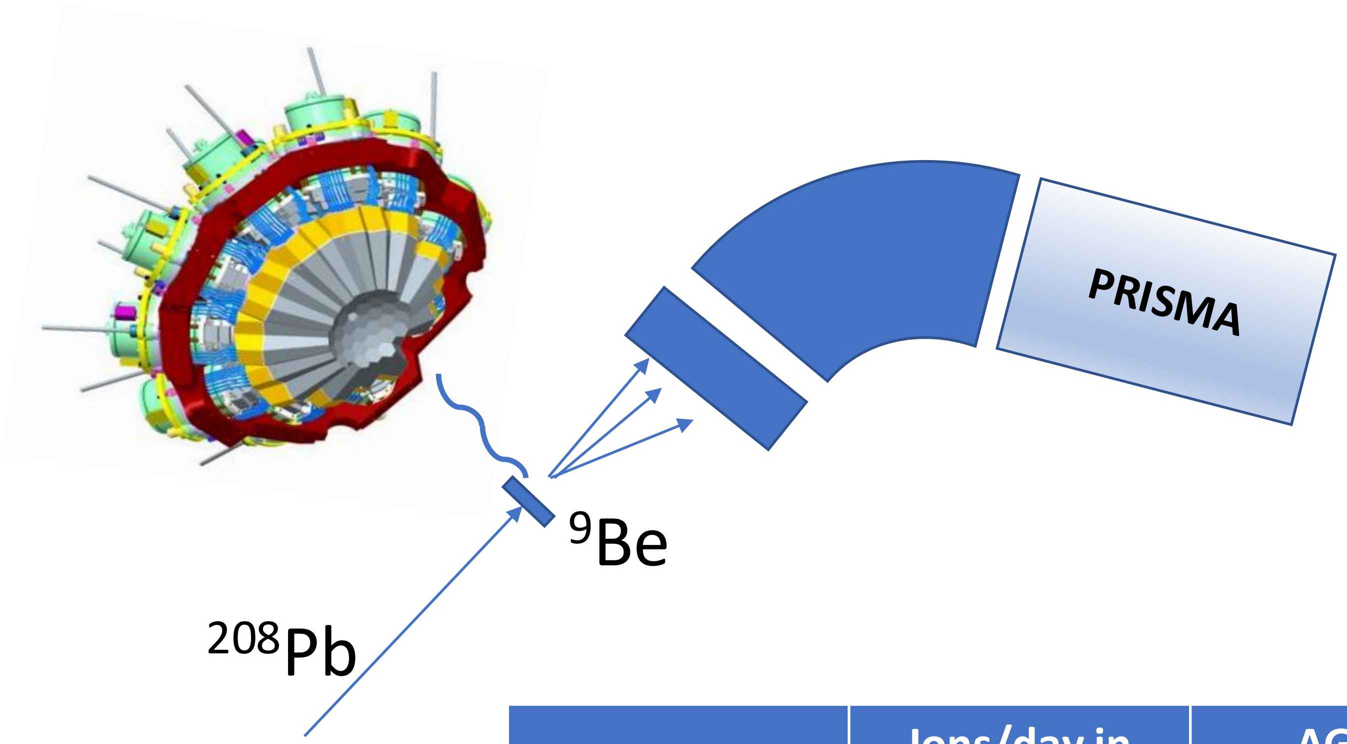
The main goal is to identify the relevant acting shells and compare them with the octupole-deformed shells recently identified as responsible for asymmetric fission:



Phys. Rev. C **100**, 041602(R) (2019)

Nature **564**, 382 (2018)

Experiment and beam time request



- Two different PRISMA angles with similar fission fragment yield useful for fission
- 2 pnA of ^{208}Pb @ 1300 MeV (PIAVE-ALPI)
- 2 mg/cm^{2} ^{9}Be target

	Ions/day in PRISMA	AGATA efficiency	γ-ray intensity	γ-ray-ion / 14 days
^{80}Zn: 5^{+},6^{+}	5600	(1400 keV) 7%	30%	1600
^{79}Cu: 9/2^{-}	130	(3000 keV) 4%	50%	40
^{79}Cu: 13/2^{-}		(600) 11%	50%	100

We request a total of 14 days for the spectroscoy of medium spin states in ^{80}Zn, ^{79}Cu and nearby isotopes

Collaboration

- Local LNL/PD: J.J Valiente, A. Goasduff, R. Menegazzo, D. Mengoni, G. de Angelis, S. Lenzi…
- From fission community: M. Caamano, D. Ramos…
- From «^{78}Ni» HiCARI @ Riken community: K. Wimmer, P. Doornenbal, R. Taniuchi, S. Franchoo, Zs. Podolyak, M. Gorska
- From fusion-fission GANIL community: D. Verney, F. Ibrahim, C. Delafosse, G. Duchene, J. Dudouet, F. Didierjean…

- Theoretical models in the ^{78}Ni region: F. Nowacki

Backup

Other isotopes

	Ions/day in PRISMA	γ-ray-ion 14 days
^{74}Ni	930	1300
^{79}Cu	**130**	**180**
^{80}Zn	**5600**	**7800**
^{81}Zn	730	1000
^{81}Ga	4E4	5.6E4
^{84}Ge	4.5E4	6.3E4

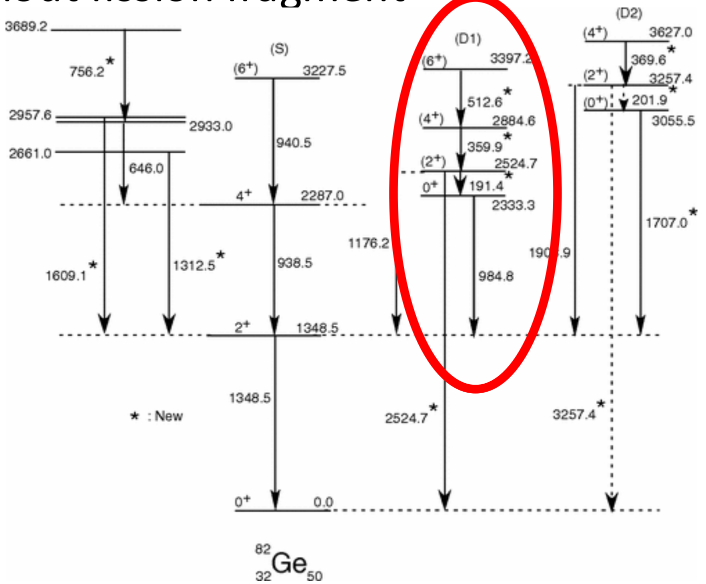
What we want to measure – other isotopes

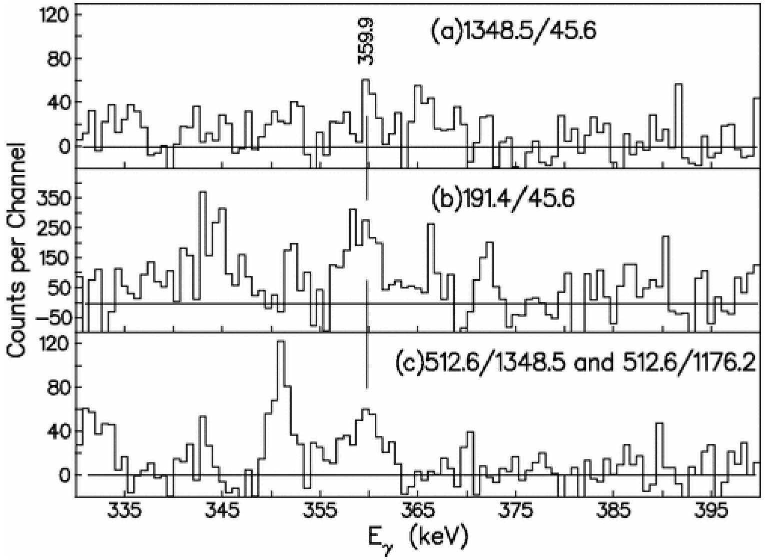
With large statistics

- higher spin states which come states that are a pure N=50 broken core as 7^+: 8^+ , 9^+, 10^+ from $g_{9/2}{}^{-1}$-$d_{5/2}{}^{1}$ coupled with fp (2+,4+) proton excitations. Can we describe the spherical 1p-1h excitations with present interaction used for ^{78}Ni ?

- Weak non yrast 2p-2h states become observable: intruder band tentatively observed observed in gamma-gamma fission studies, 2p-2h (4p-4h)

- ^{84}Se, ^{82}Ge largely produced (≈10^5 ion-γ coincidences). Strong advantage in cleanliness compared to «old-style» fission studies without fission fragment

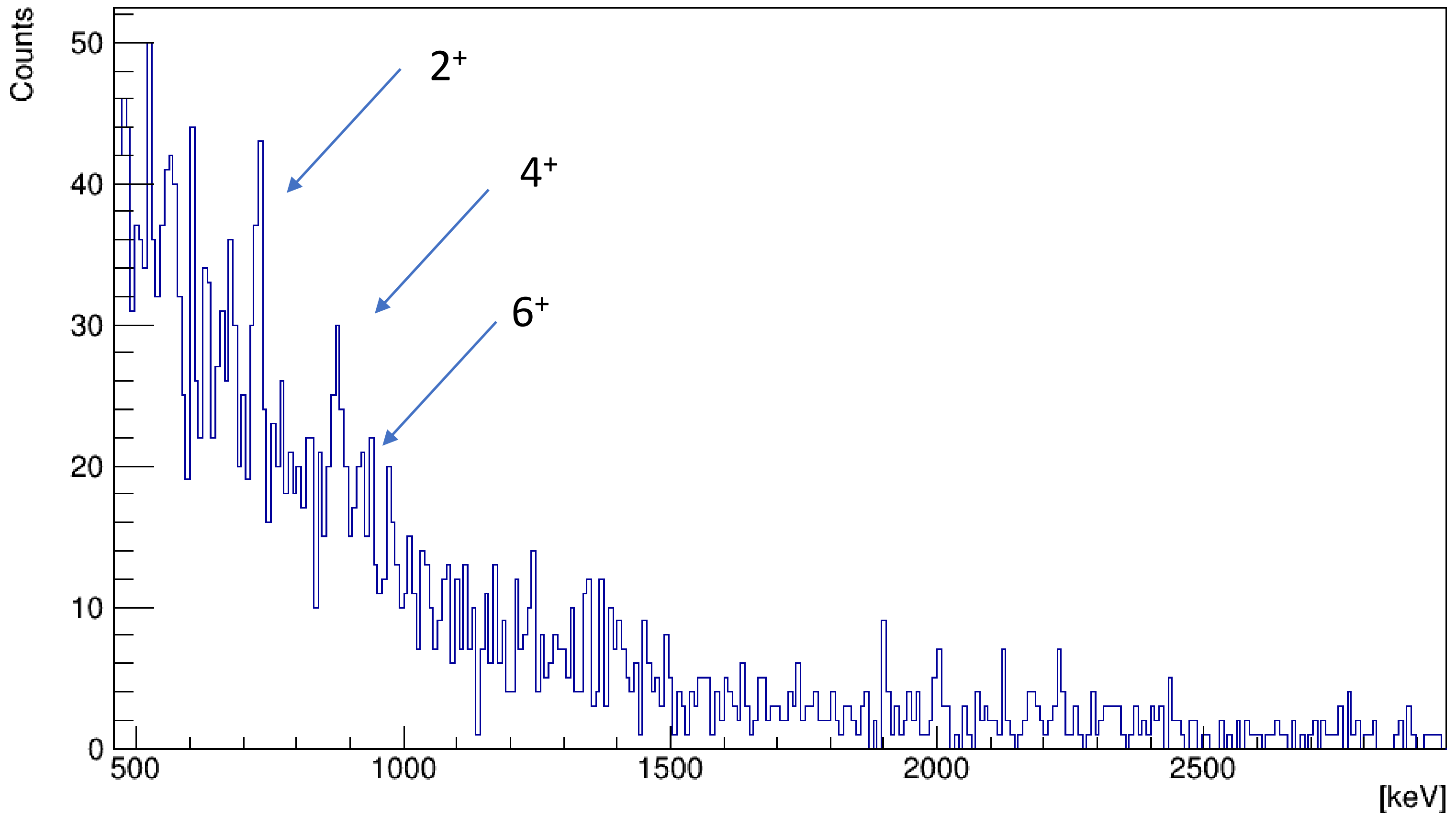


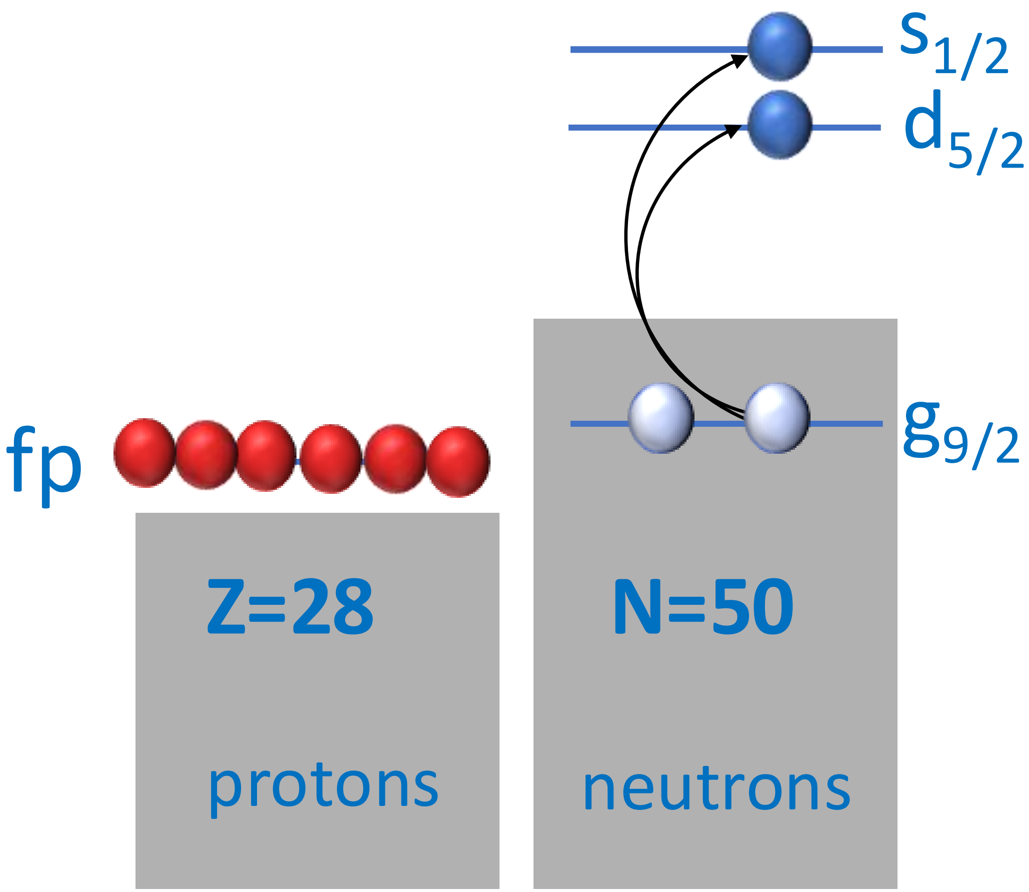


Also odd-odd and odd-even isotopes will be studied with higher statistics extending their level scheme, aund using anglur correlations: N=51 ^{84}As, ^{83}Ge, ^{82}Ga, ^{81}Zn

^{78}Zn – 20-30 counts

Plunger experiment AGATA-VAMOS (1/80th of the statistics we should collect)





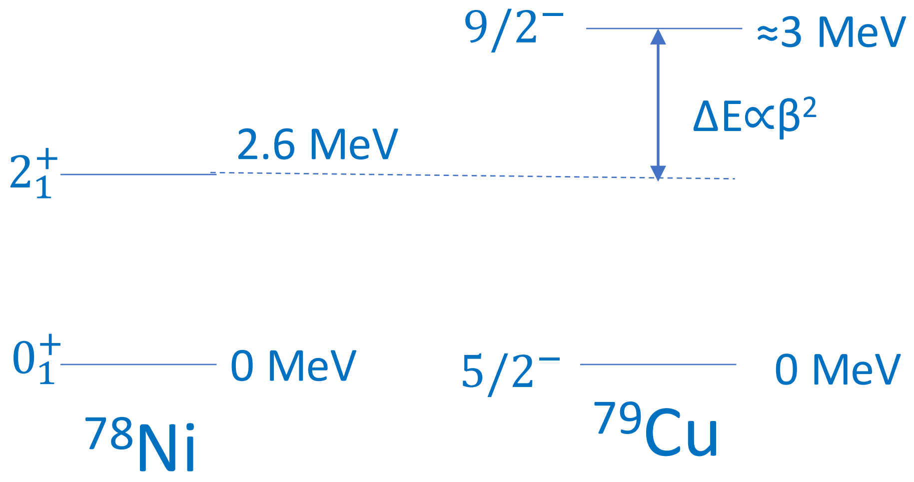
many particle – many hole across N=50

- Spherical gap :

  energy cost

- Correlations by breaking the core:

  energy gain



9/2⁻
≈3 MeV
ΔE∝β²
2.6 MeV
2_1^+
0_1^+
0 MeV
5/2⁻
0 MeV
^{78}Ni
^{79}Cu