Journée du LabEx P2IO
26 November 2021

Shape evolution in neutron-rich nuclei around mass A=100

Giorgia Pasqualato

G. Pasqualato[1], A. Görgen[2], J.S. Heines[2], J. Ljungvall[1], V. Modamio[2], L.G.. Pedersen[2], and W. Korten[3]

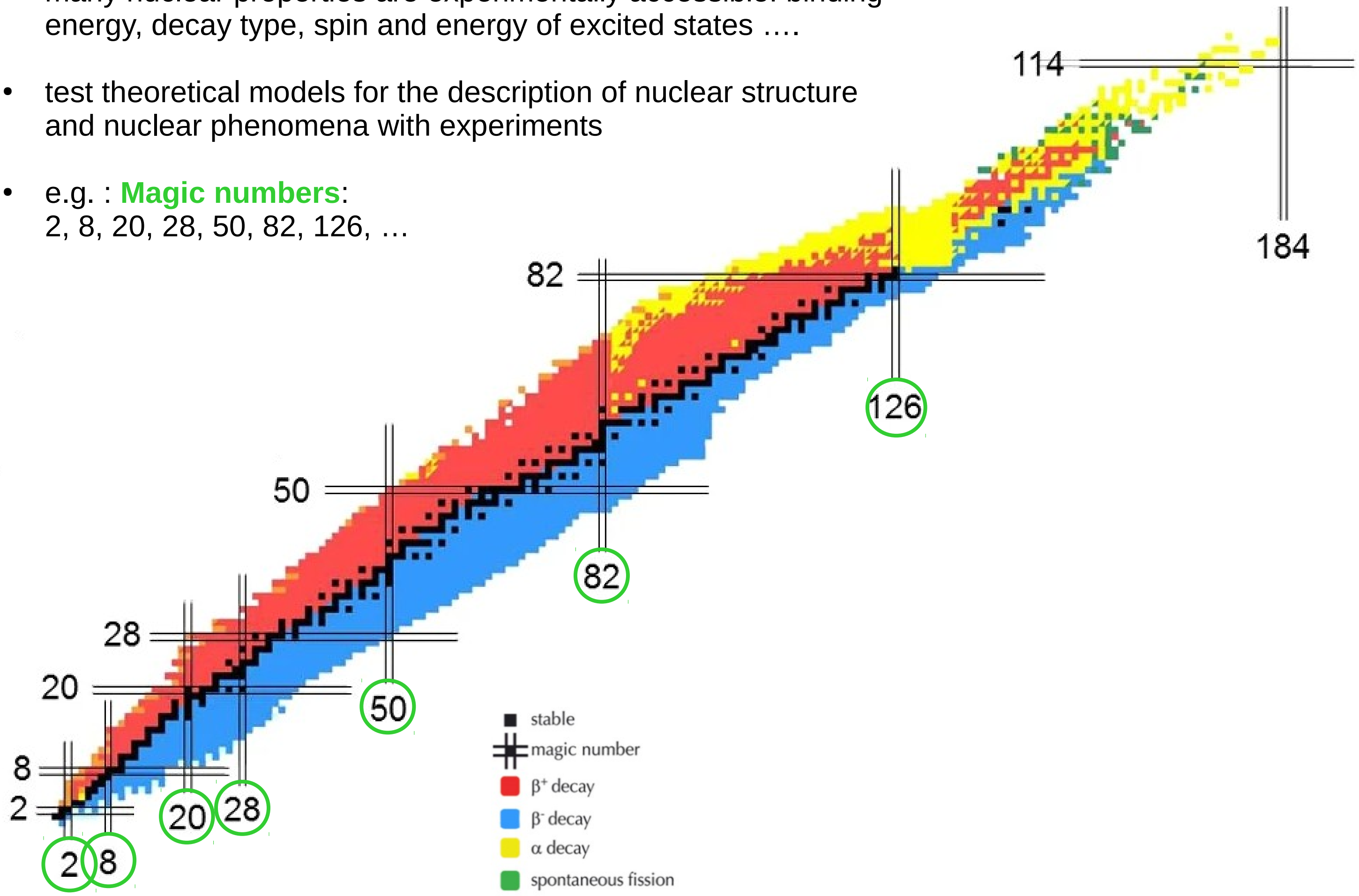
[1] *IJCLab, IN2P3/CNRS, Université Paris-Saclay, Orsay, France.*
[2] *Department of Physics, University of Oslo, Norway.*
[3] *CEA Paris-Saclay, DRF/IRFU/DPhN, Gif-sur-Yvette, France.*

The nuclear landscape

- many nuclear properties are experimentally accessible: binding energy, decay type, spin and energy of excited states ….

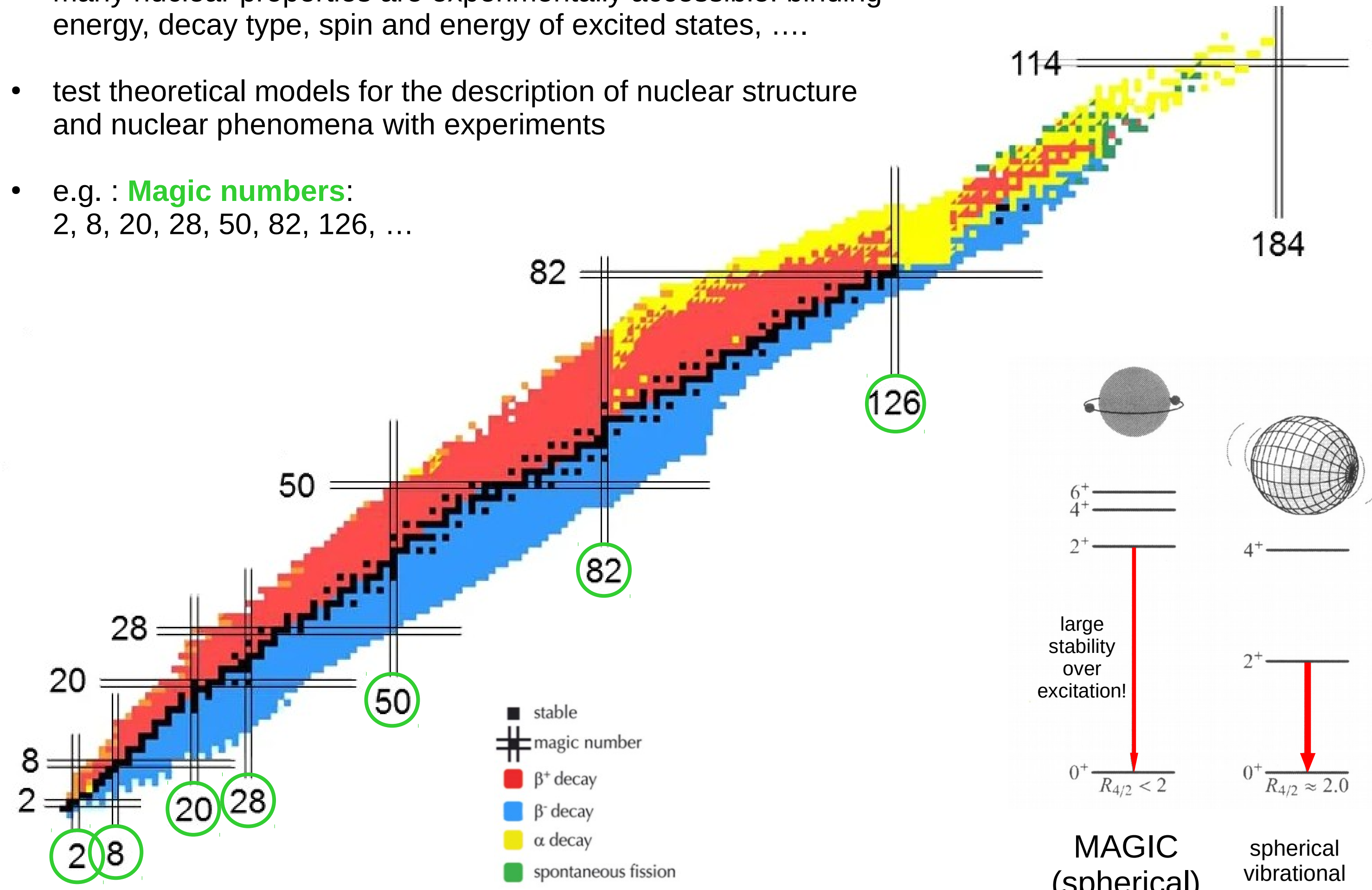
- test theoretical models for the description of nuclear structure and nuclear phenomena with experiments

- e.g. : **Magic numbers**:
  2, 8, 20, 28, 50, 82, 126, …

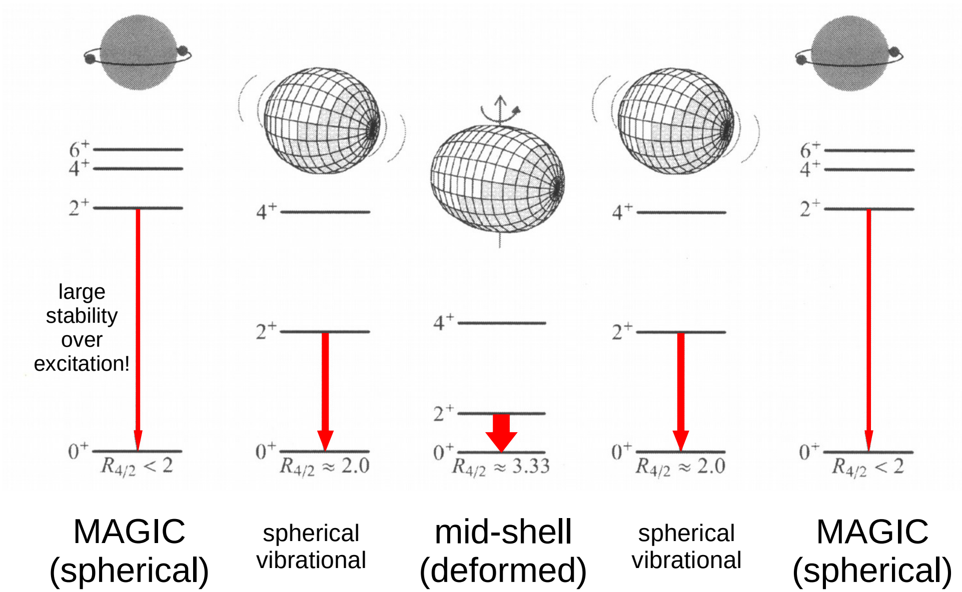


The nuclear landscape

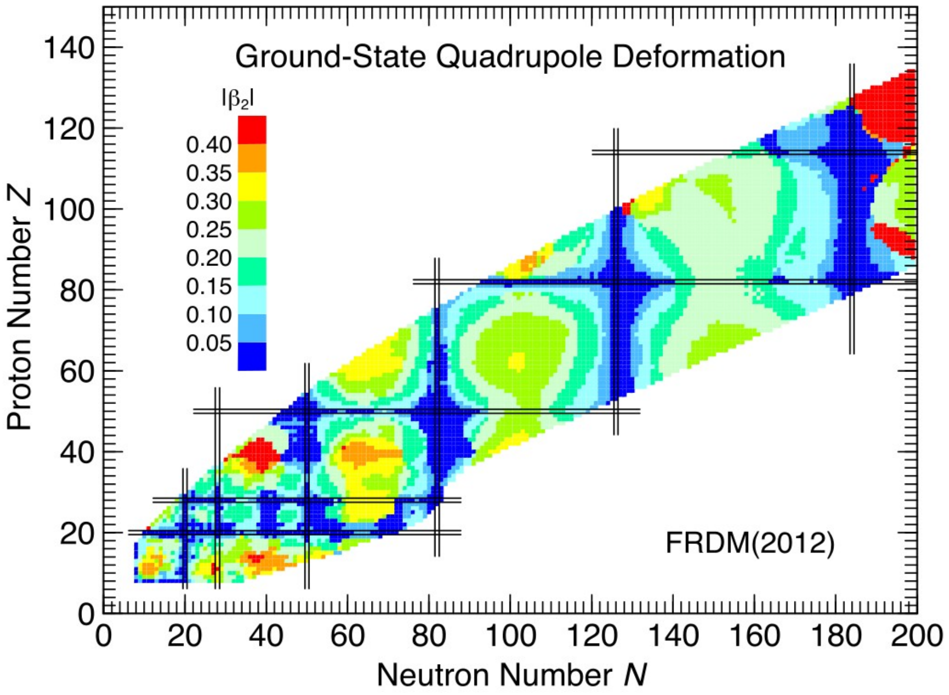
- many nuclear properties are experimentally accessible: binding energy, decay type, spin and energy of excited states, ….
- test theoretical models for the description of nuclear structure and nuclear phenomena with experiments
- e.g. : **Magic numbers**:
  2, 8, 20, 28, 50, 82, 126, …



Nuclei with a number of nucleons in between magic configurations are characterized by **deformation**.

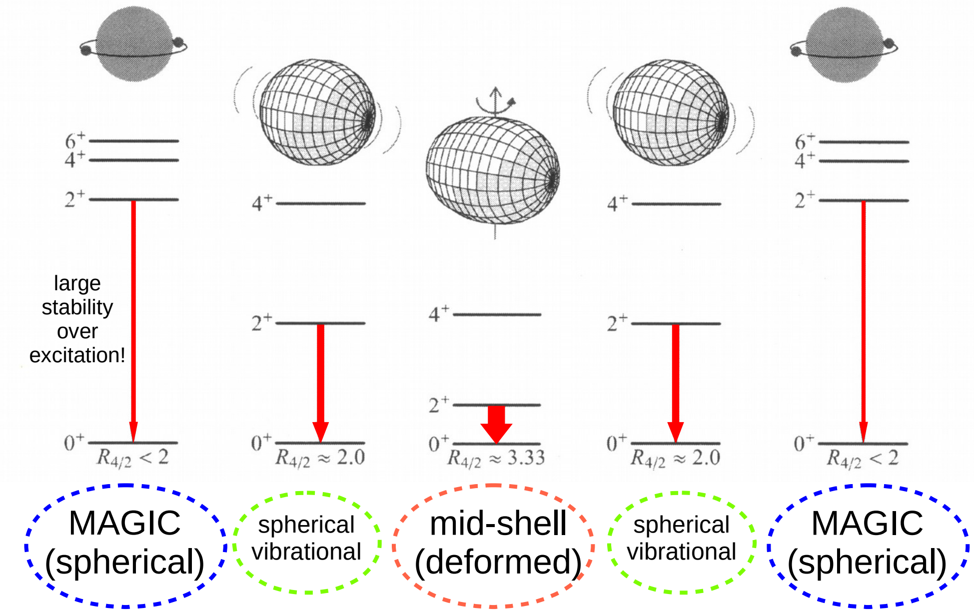


Shape evolution in nuclei

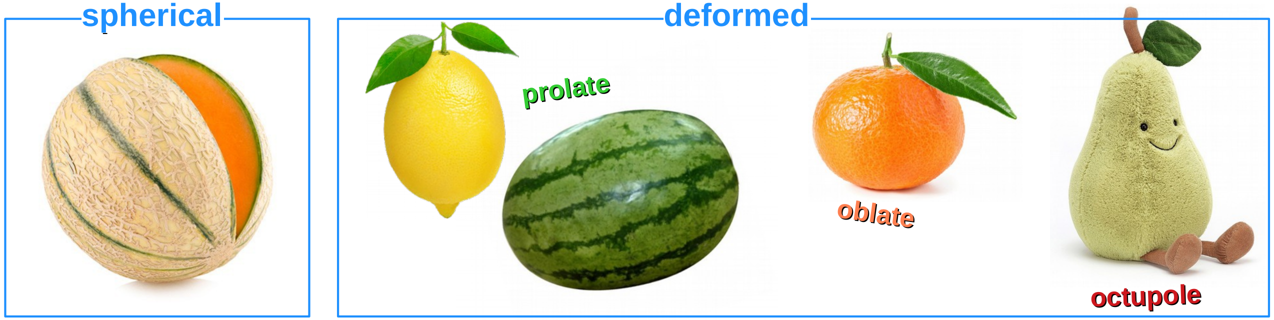


P. Möller, A.J. Sierk, T. Ichikawa, H. Sagawa,
Nuclear ground-state masses and deformations: FRDM(2012),
Atomic Data and Nuclear Data Tables, 109–110, (2016),

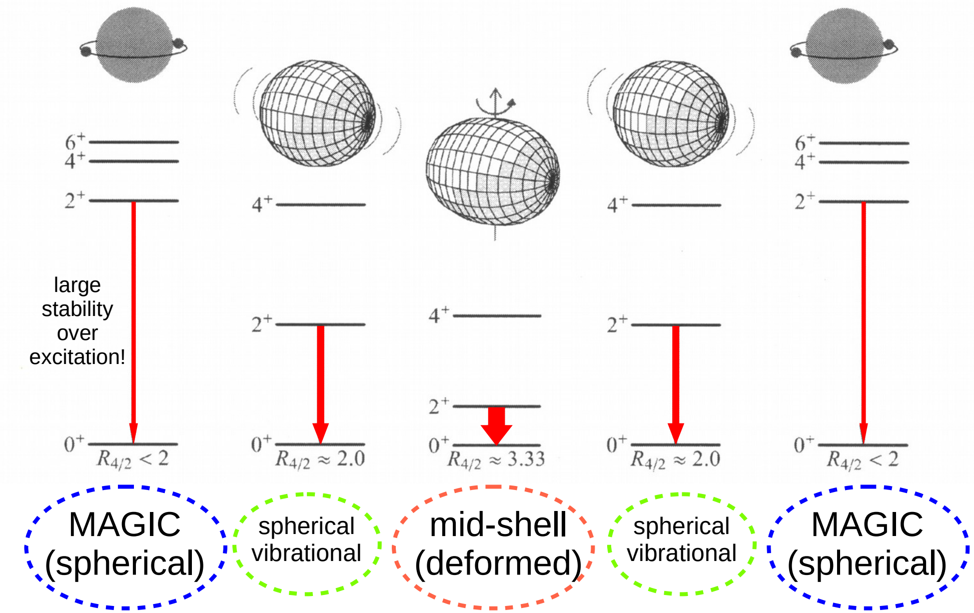
Nuclei with a number of nucleons in between magic configurations are characterized by **deformation**.



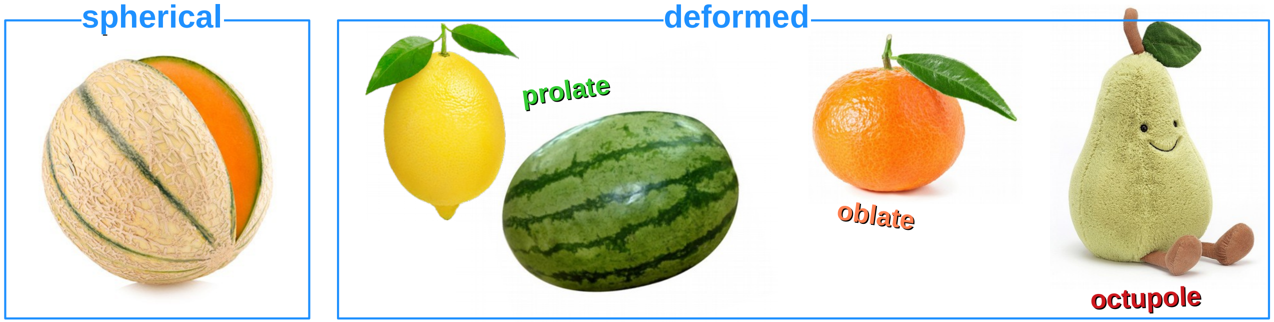
Shape evolution in nuclei



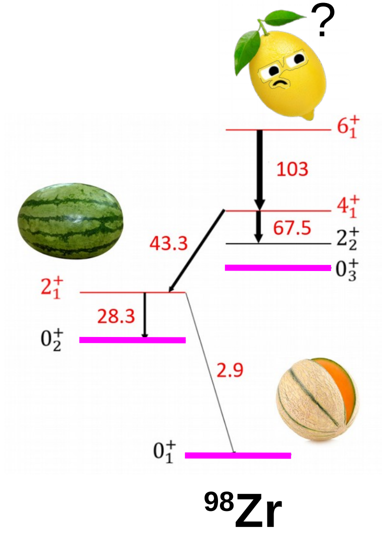
Deformed nuclei can manifest different shape.



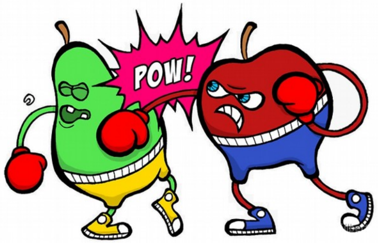
Shape evolution in nuclei

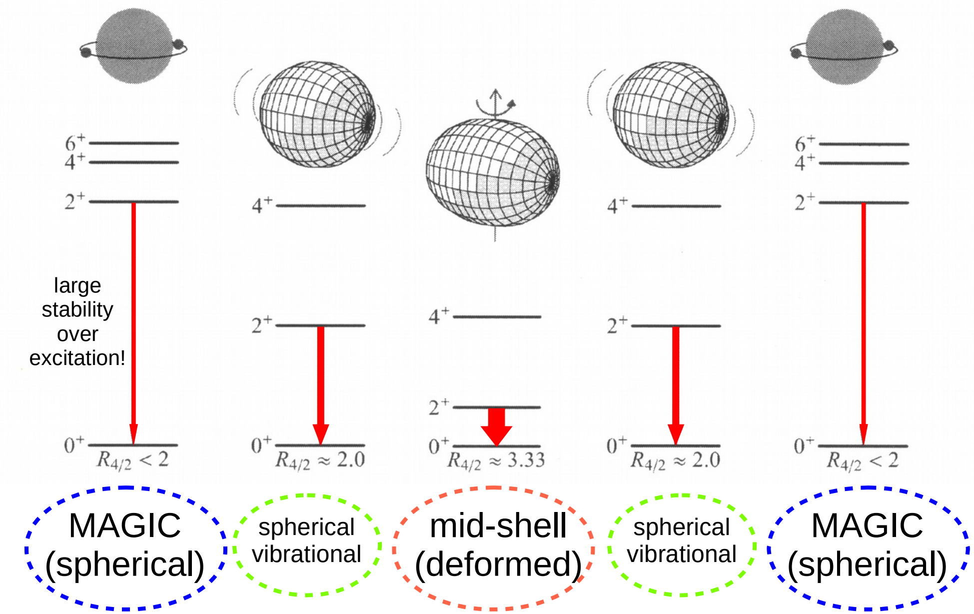


The systematic study of deformation and shape coexistence along the nuclear chart is a powerful way to test nuclear models !

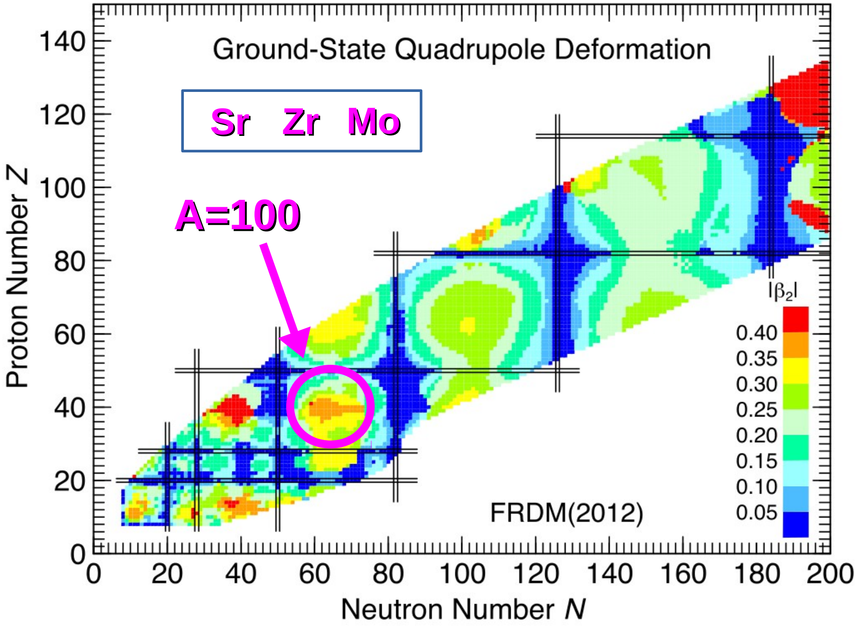


- Shape coexistence





Shape evolution in nuclei around A=100

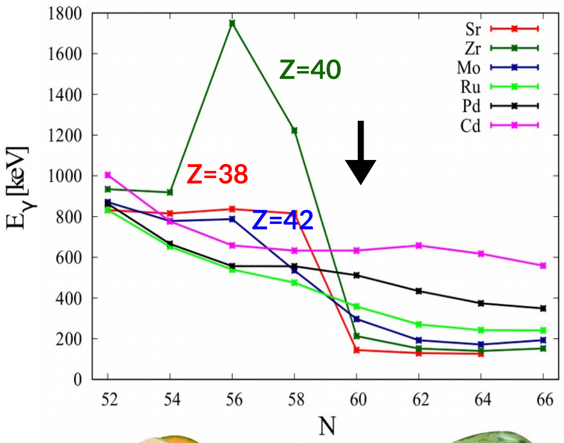


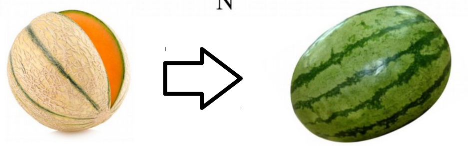
Rapid onset of deformation observed in the region around mass A=100.

Shape evolution in nuclei around A=100

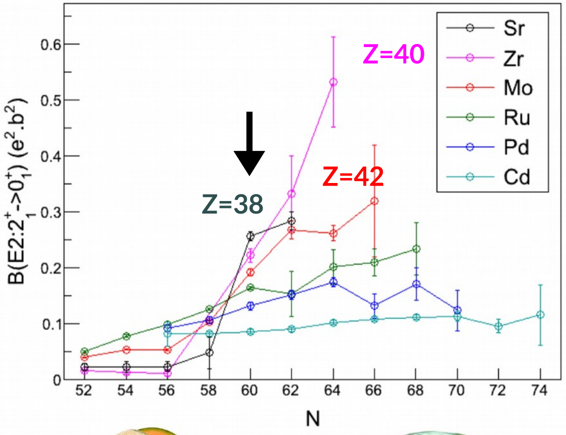
Drastic change in nuclear properties as a function of N (and Z) !

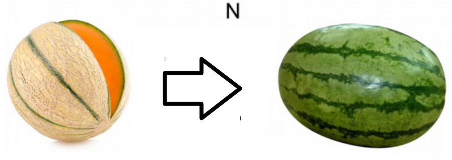
- **<u>Energies</u> of the first 2_1^+**

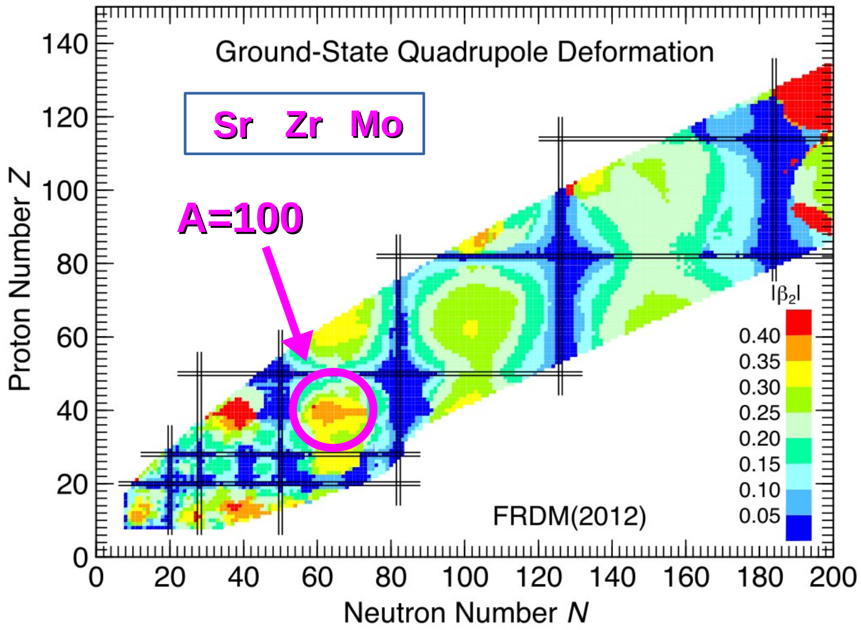




- <u>Decay probability</u> **B(E2; $2_1^+ \rightarrow 0_1^+$)**







Rapid onset of deformation observed in the region around mass A=100.

E. Cheifetz, R.C. Jared, S.G. Thompson and J.B. Wilhelmy, 1970, Phys. Rev. Lett. 25, 38.
P. Federman and S. Pittel, 1977, Phys. Lett. B 69, 385.
P. Federman and S. Pittel, 1979, Phys. Rev. C 20, 820.
L. Bettermann et al., Phys. Rev. C 82 (4) 044310 (2010).
A.G. Smith et al., Physics Letters B 591 1–2, 55–60 (2004).
K. Heyde and J.L. Wood, Rev. Mod. Phys. 83, 1467 (2011).

Shape-phase transition in Zr isotopes

For the Zr chain, the onset of deformation at N=60 has been studied by many theoretical approaches.

generator coordinate method (GCM):
J. Skalski, P.-H. Heenen, and P. Bonche, Nucl. Phys. A 559, 221 (1993).
J.-P. Delaroche et al., Phys. Rev. C 81, 014303 (2010).

macroscopic-microscopic method:
J. Skalski, S. Mizutory, and W. Nazarewicz, Nucl. Phys. A 617, 282 (1997).

shell model:
P. G. Reinhard, et al., Phys. Rev. C 60, 014316 (1999).
A. Holt, T. Engeland, M. Hjorth-Jensen, and E. Osnes, Phys. Rev. C 61, 064318 (2000).
K. Sieja, F. Nowacki, K. Langanke, and G. Martínez-Pinedo, Phys. Rev. C 79, 064310 (2009).
Y.-X. Liu et al., Nucl. Phys. A 858, 11 (2011).

Shell Model Monte Carlo
C. Özen and D. J. Dean, Phys. Rev. C 73, 014302 (2006).

Monte Carlo Shell Model:
T. Togashi, Y. Tsunoda, T. Otsuka and N. Shimizu, Phys. Rev. Lett. 117, 172502 (2016).

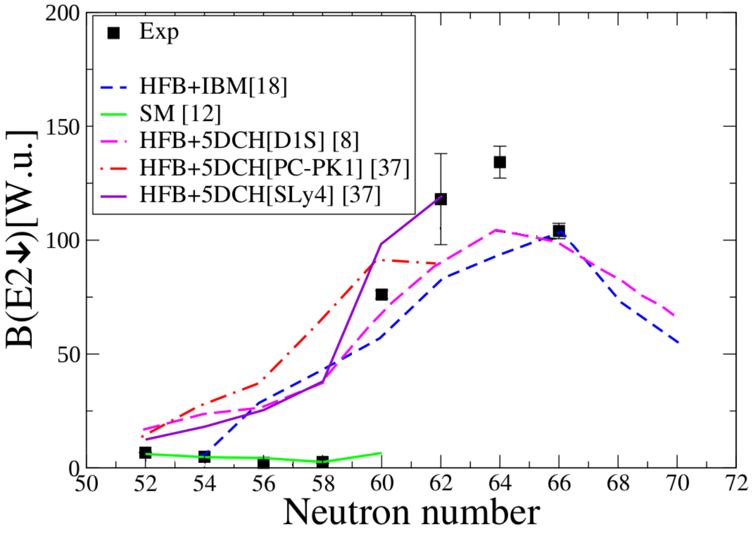
interacting boson model (IBM) approximation:
J. E. García-Ramos et al., Eur. Phys. J. A 26, 221 (2005).
M. Böyükata, P. Van Isacker and İ. Uluer, J. Phys. G: Nucl. Part. Phys. 37, 105102 (2010).
K. Nomura, R. Rodríguez-Guzmán, and L. M. Robledo, Phys. Rev. C 94, 044314 (2016).

Hartree-Fock (HF) and Hartree-Fock-Bogoliubov (HFB) models:
R. Rodríguez-Guzmán et al., Phys. Lett. B 691, 202 (2010).

VAMPIR model:
A. Petrovici,Phys. Rev. C 85, 034337 (2012).

covariant density functional (DF) theory:
J. Xiang et al., Nucl. Phys. A 873, 1 (2012).

P. Singh et al., Phys. Rev. Lett. 121 (19), 192501 (2018).



Shape-phase transition in Zr isotopes

For the Zr chain, the onset of deformation at N=60 has been studied by many theoretical approaches.

generator coordinate method (GCM):
J. Skalski, P.-H. Heenen, and P. Bonche, Nucl. Phys. A 559, 221 (1993).
J.-P. Delaroche et al., Phys. Rev. C 81, 014303 (2010).

macroscopic-microscopic method:
J. Skalski, S. Mizutory, and W. Nazarewicz, Nucl. Phys. A 617, 282 (1997).

shell model:
P. G. Reinhard, et al., Phys. Rev. C 60, 014316 (1999).
A. Holt, T. Engeland, M. Hjorth-Jensen, and E. Osnes, Phys. Rev. C 61, 064318 (2000).
K. Sieja, F. Nowacki, K. Langanke, and G. Martinez-Pinedo, Phys. Rev. C 79, 064310 (2009).
Y.-X. Liu et al., Nucl. Phys. A 858, 11 (2011).

Shell Model Monte Carlo
C. Özen and D. J. Dean, Phys. Rev. C 73, 014302 (2006).

Monte Carlo Shell Model:
T. Togashi, Y. Tsunoda, T. Otsuka and N. Shimizu, Phys. Rev. Lett. 117, 172502 (2016).

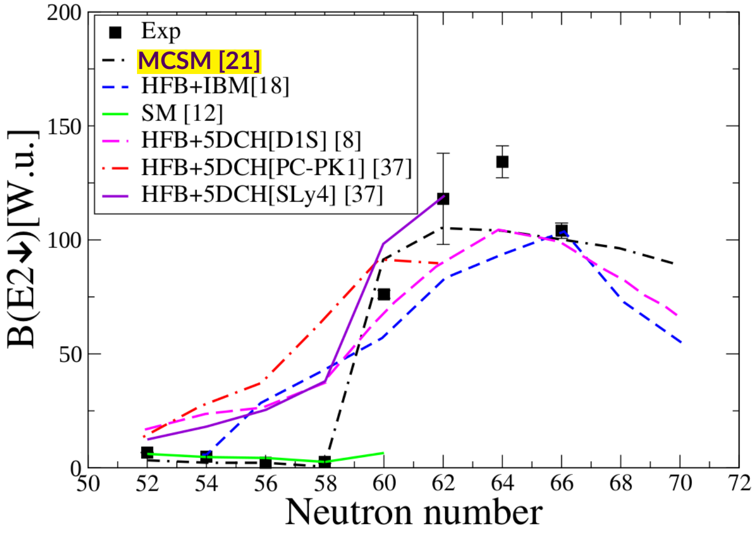
interacting boson model (IBM) approximation:
J. E. García-Ramos et al., Eur. Phys. J. A 26, 221 (2005).
M. Böyükata, P. Van Isacker and İ. Uluer, J. Phys. G: Nucl. Part. Phys. 37, 105102 (2010).
K. Nomura, R. Rodríguez-Guzmán, and L. M. Robledo, Phys. Rev. C 94, 044314 (2016).

Hartree-Fock (HF) and Hartree-Fock-Bogoliubov (HFB) models:
R. Rodríguez-Guzmán et al., Phys. Lett. B 691, 202 (2010).

VAMPIR model:
A. Petrovici,Phys. Rev. C 85, 034337 (2012).

covariant density functional (DF) theory:
J. Xiang et al., Nucl. Phys. A 873, 1 (2012).

P. Singh et al., Phys. Rev. Lett. 121 (19), 192501 (2018).

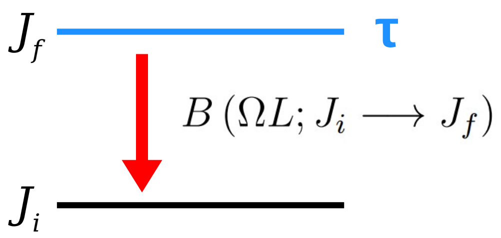


- Description of the rapid shape chance + shape coexistence

→ further experimental investigation in this region are needed !

Study nuclear shape through electromagnetic transition strengths

→ **GOAL :** obtain precise experimental information on nuclear deformation with **electromagnetic transition strengths T** through the measurement of the **lifetime τ** of nuclear excited states.



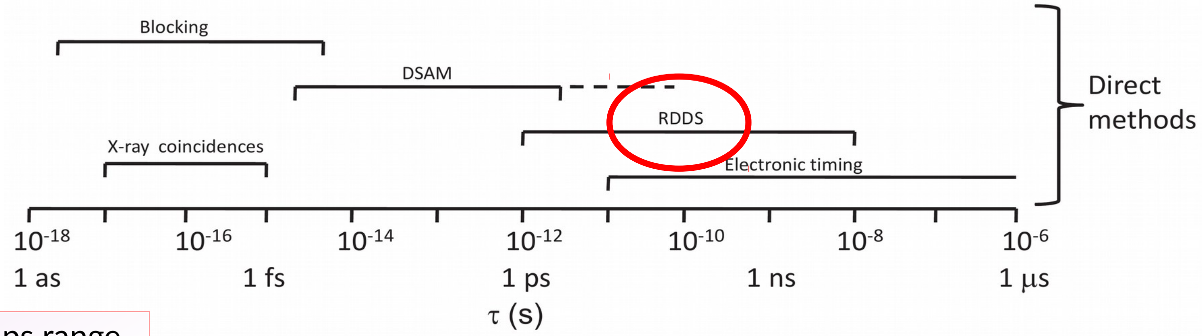
$$\tau = T^{-1} \quad \rightarrow \quad B(\Omega L; J_i \longrightarrow J_f) = \frac{1}{2J_i + 1} \left| \langle J_f || M(\Omega L) || J_i \rangle \right|^2$$

EXPERIMENT : <u>lifetimes</u> → → → THEORY : <u>matrix elements</u>

LIFETIME MEASUREMENTS

The lifetime of a nuclear state can range from 10^{-20} seconds to billions of years ……

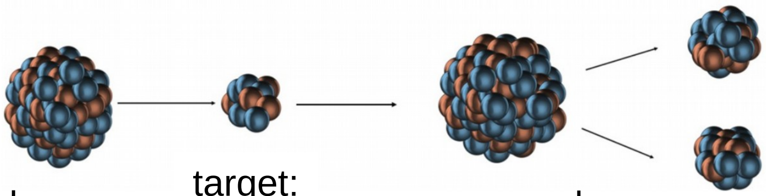
different techniques have been implemented



RDDS : Recoil Distance Doppler Shift technique for the ps range

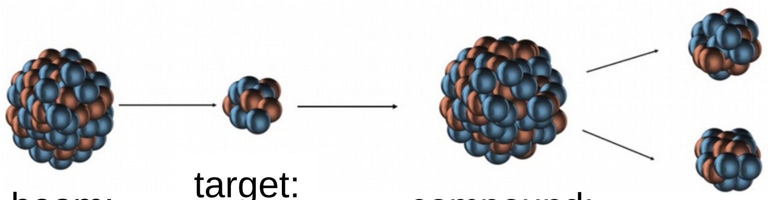
Production and identification of fission fragments

fusion-fission reaction



Production and identification of fission fragments

fusion-fission reaction



beam: ^{238}U @ 6.2 MeV/A

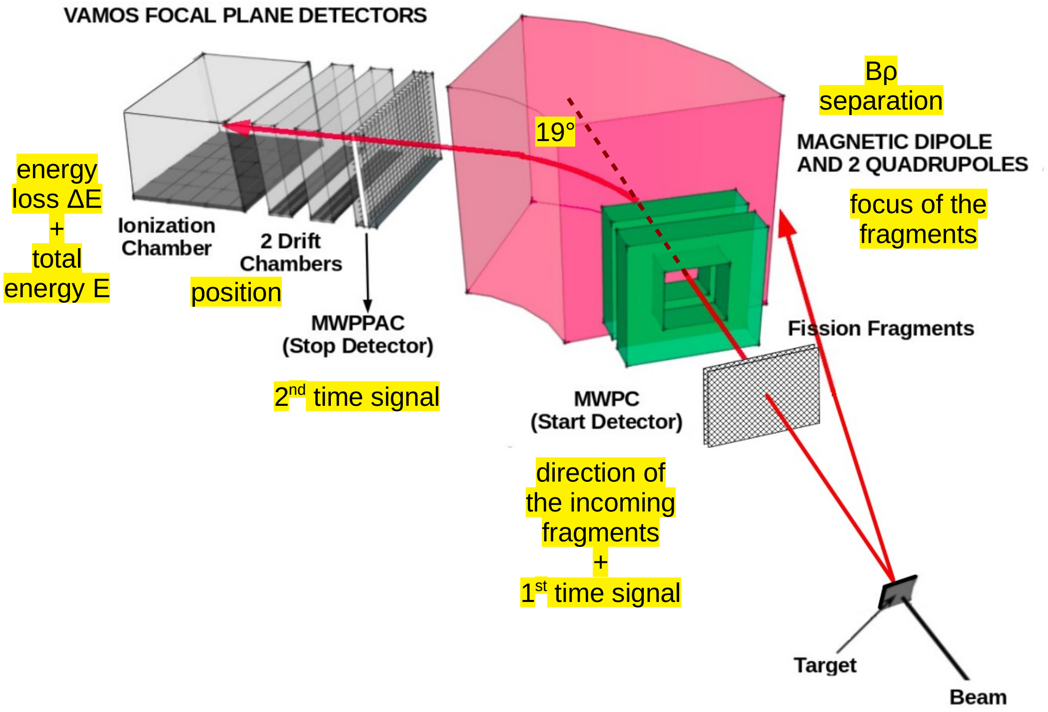
target: ^{9}Be

compound: ^{247}Cm

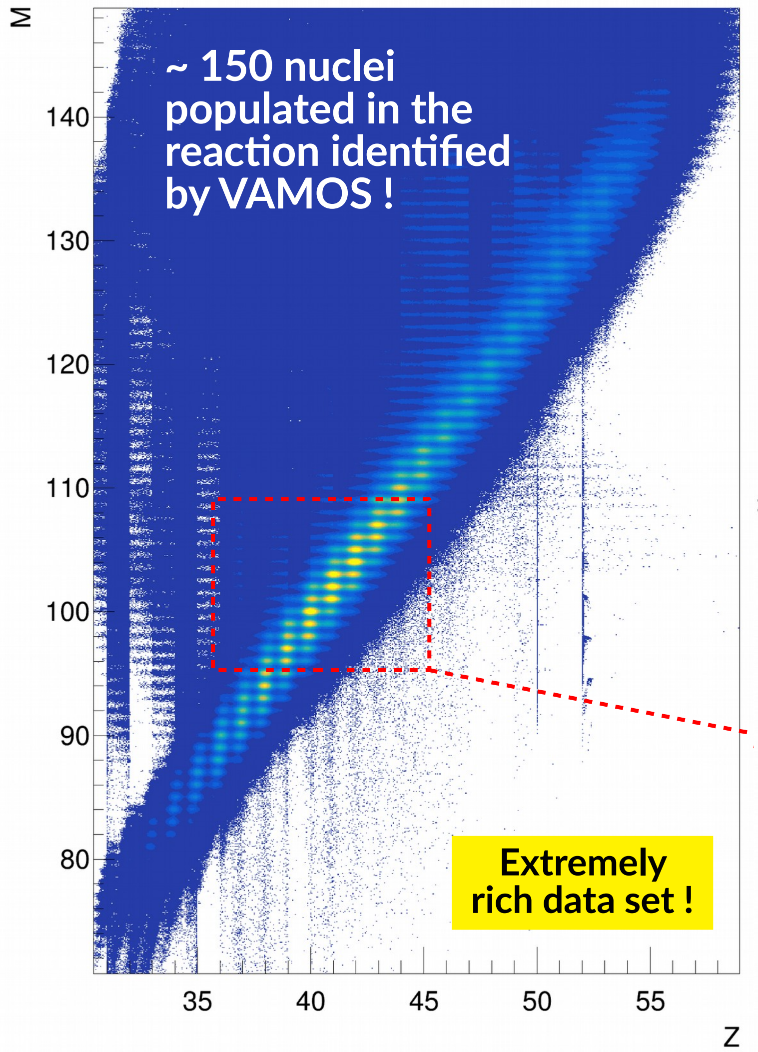
fission fragments

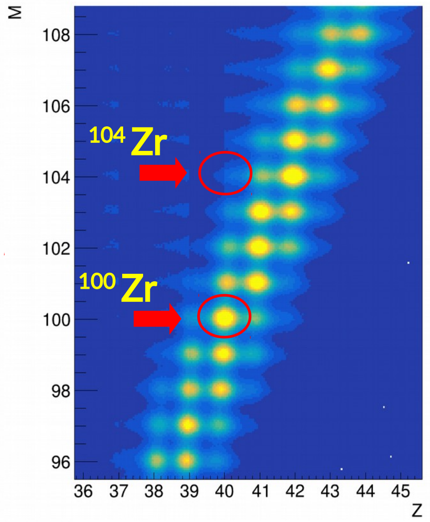
VAMOS large acceptance magnetic spectrometer

fragment identification based on atomic number Z, mass M and charge Q



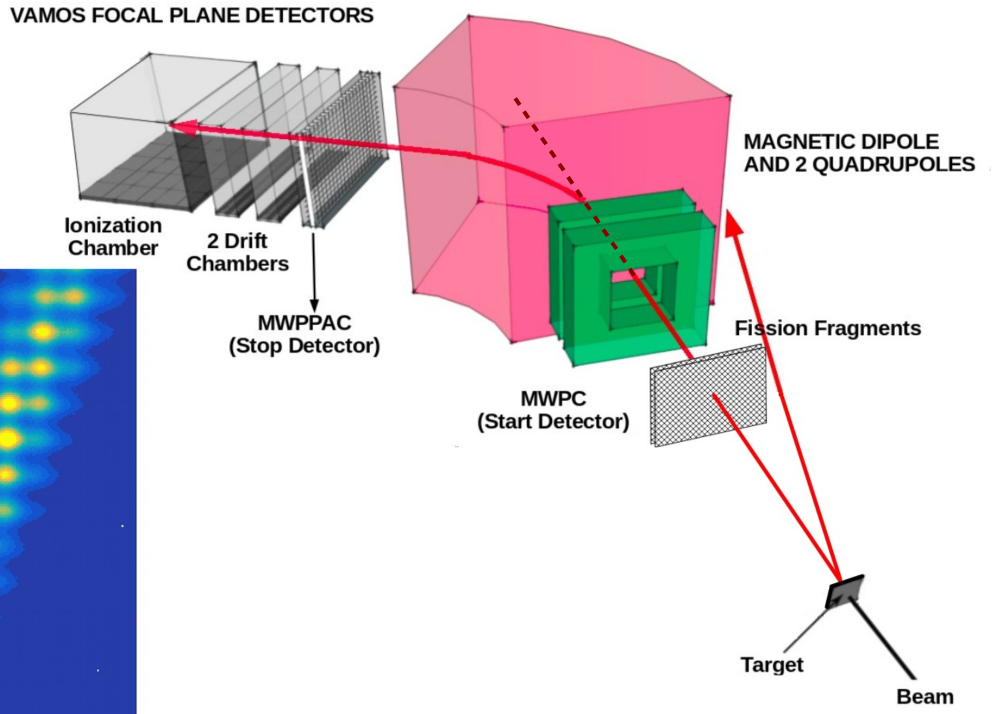
Production and identification of fission fragments



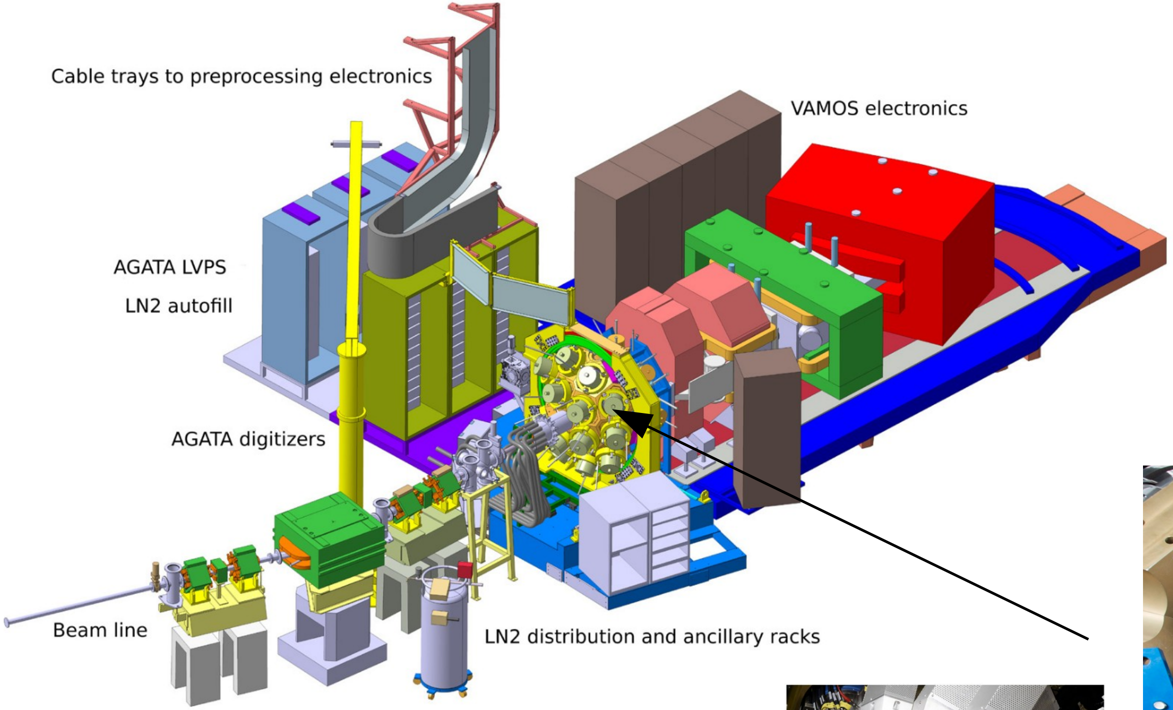


VAMOS large acceptance magnetic spectrometer

fragment identification based on atomic number Z, mass M and charge Q

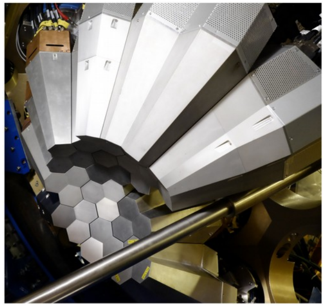


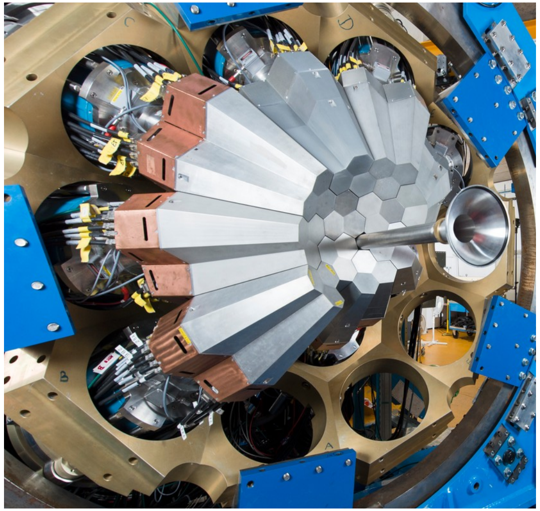
Detection of γ rays with AGATA

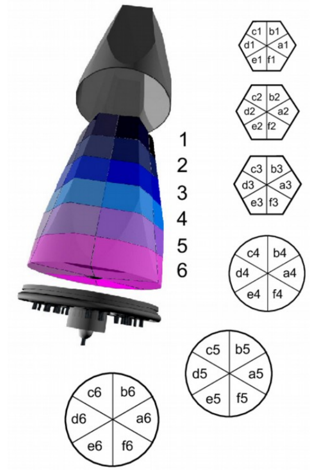


Advanced **Ga**mma **T**racking **A**rray
AGATA

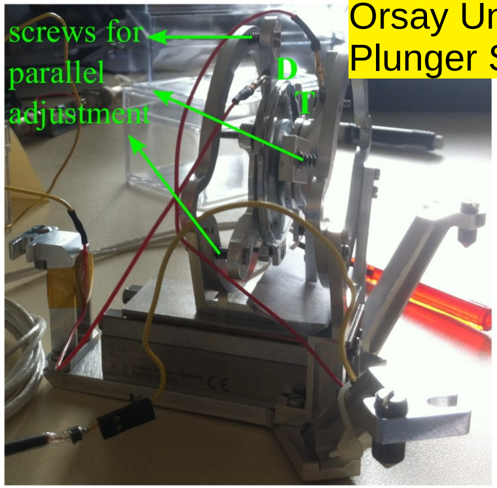
Excellent energy resolution of HPGe detectors
+
unprecedented photo-peak efficiency
+
Pulse Shape Analysis (PSA) and γ-ray tracking



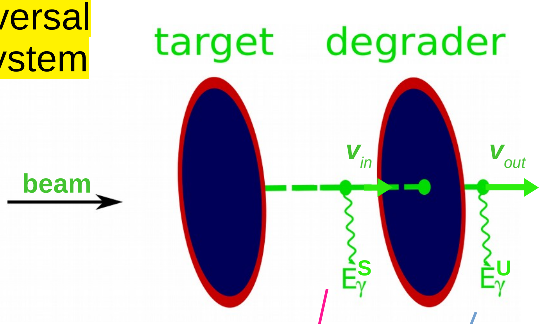


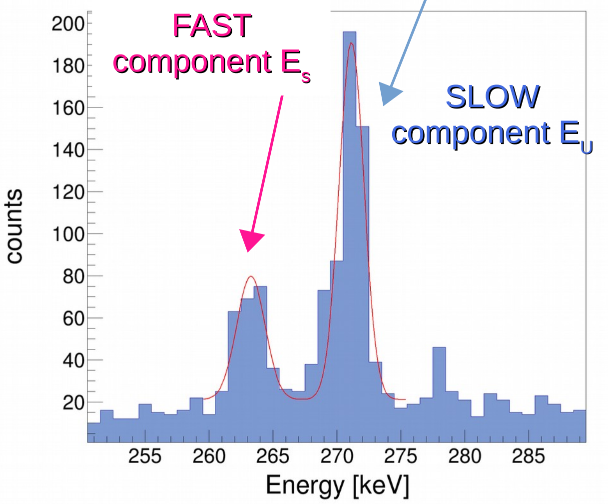


Recoil Distance Doppler Shift technique



Orsay Universal Plunger System





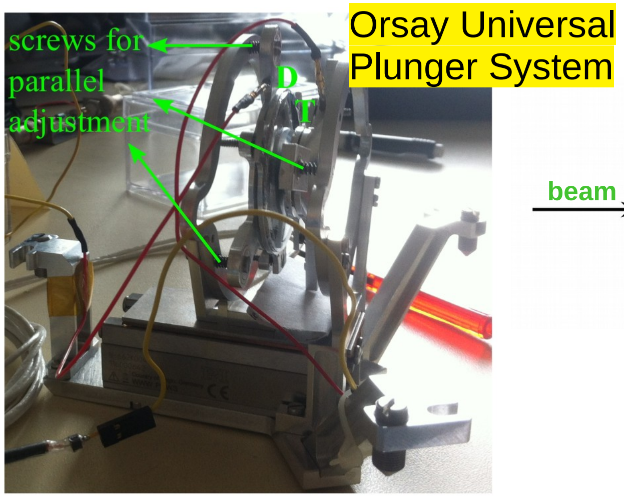
the energy detected is Doppler-shifted:

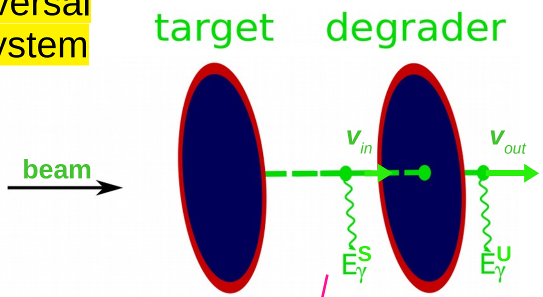
$$E = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\Theta}$$

recoil velocity

angle of emission

Recoil Distance Doppler Shift technique



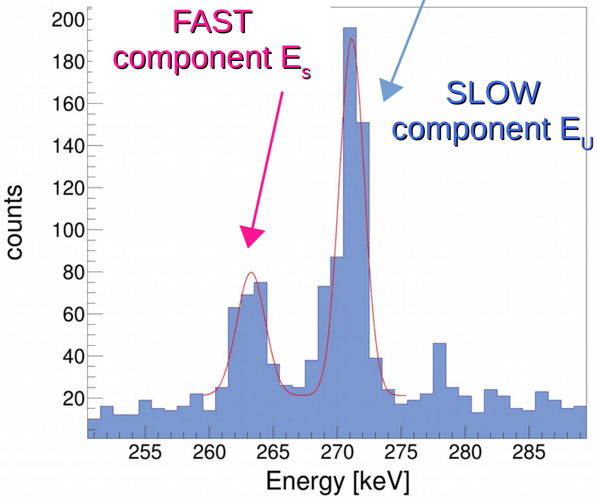


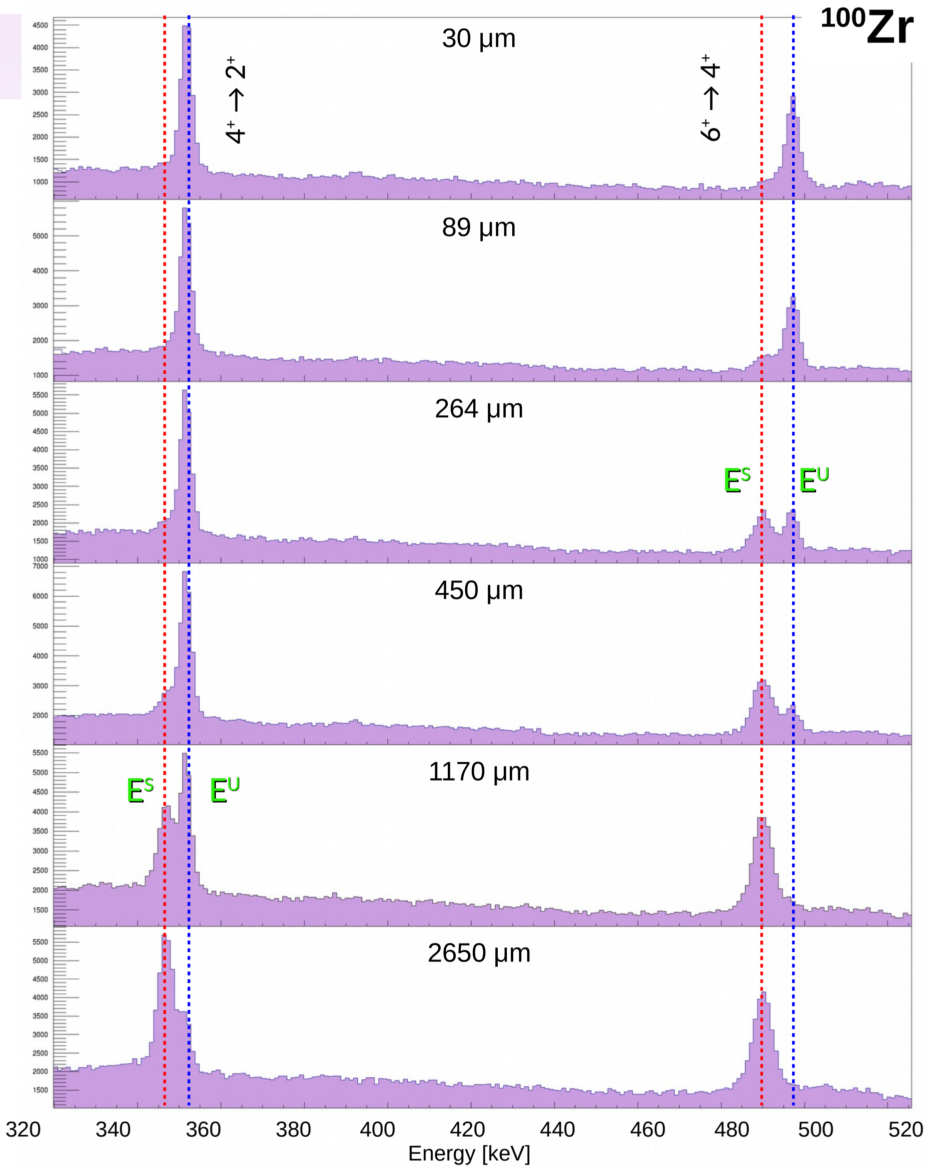
the energy detected is Doppler-shifted:

$$E = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\Theta}$$

recoil velocity

angle of emission





Status of the analysis

- Many lifetimes extracted for many even-even isotopes:

  → New values for ^{104}Zr, ^{108}Mo, ^{106,108,110,112}Ru

- Goals of the present analysis:

  → Refine the analysis procedure

  → Error determination

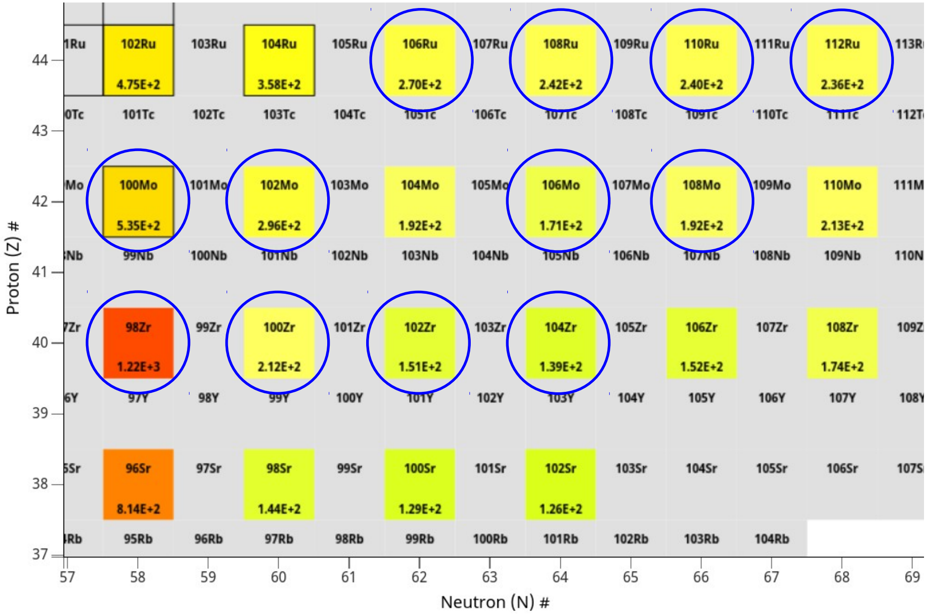
  → Go further : odd systems, low-statistics cases.

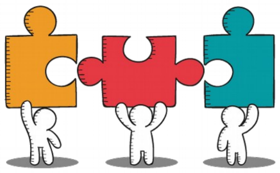
- follow: Preliminary results for ^{100}Zr and ^{104}Zr.

Ru

Mo

Zr





G. Pasqualato[1], A. Görgen[2], J.S. Heines[2], J. Ljungvall[1], V. Modamio[2], L.G.. Pedersen[2], and W. Korten[3]

[1] *IJCLab, IN2P3/CNRS, Université Paris-Saclay, Orsay, France.*
[2] *Department of Physics, University of Oslo, Norway.*
[3] *CEA Paris-Saclay, DRF/IRFU/DPhN, Gif-sur-Yvette, France.*

Preliminary results for ^{100}Zr in single γ and coincidence γγ

- Lifetime measurements in gamma single and gamma-gamma coincidence.
- Comparison with previous results for the levels 4^+, 6^+, 8^+, 10^+ of the yrast band :

→ The adopted value for the 4^+ may be overestimated.

→ The 6^+ and 8^+ adopted lifetimes also result larger.

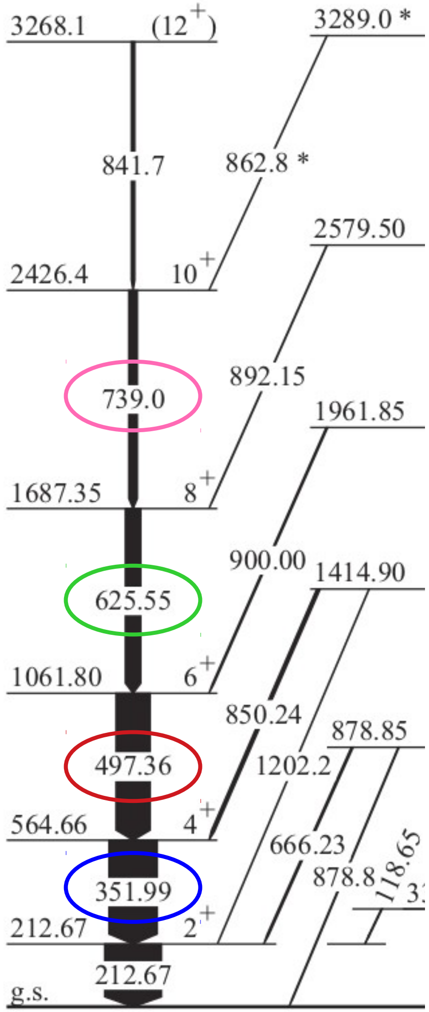
unseen feeding ?

→ Measurements in γγ gives shorter lifetimes (4^+ and 6^+) as expected.

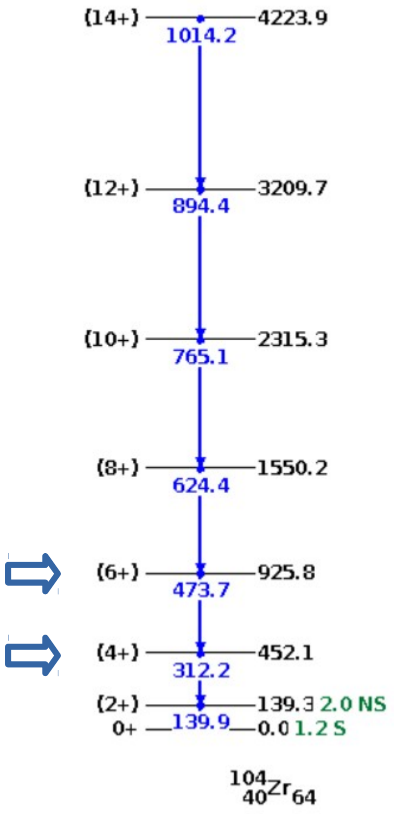
→ The lifetime of the 8^+ is accurate in single γ due to the short-living feeding.

J^π	Energy [keV]	τ [ps] adopted	τ [ps] single γ	τ [ps] coincid γγ
4+	352.0	53.4 (6)	36.9 (6)	30 (2) *
6+	497.4	7.5 (1.6)	5.7 (3)	5.0 (6)
8+	625.6	2.5 (2)	1.0 (1)	1.7 (4)
10+	739.0	0.53 (6)	0.6 (2)	/

*The feeding transition at 840.2 keV is not considered : difficult to resolve its shifted component from the 841.7 keV $12^+ \rightarrow 10^+$.

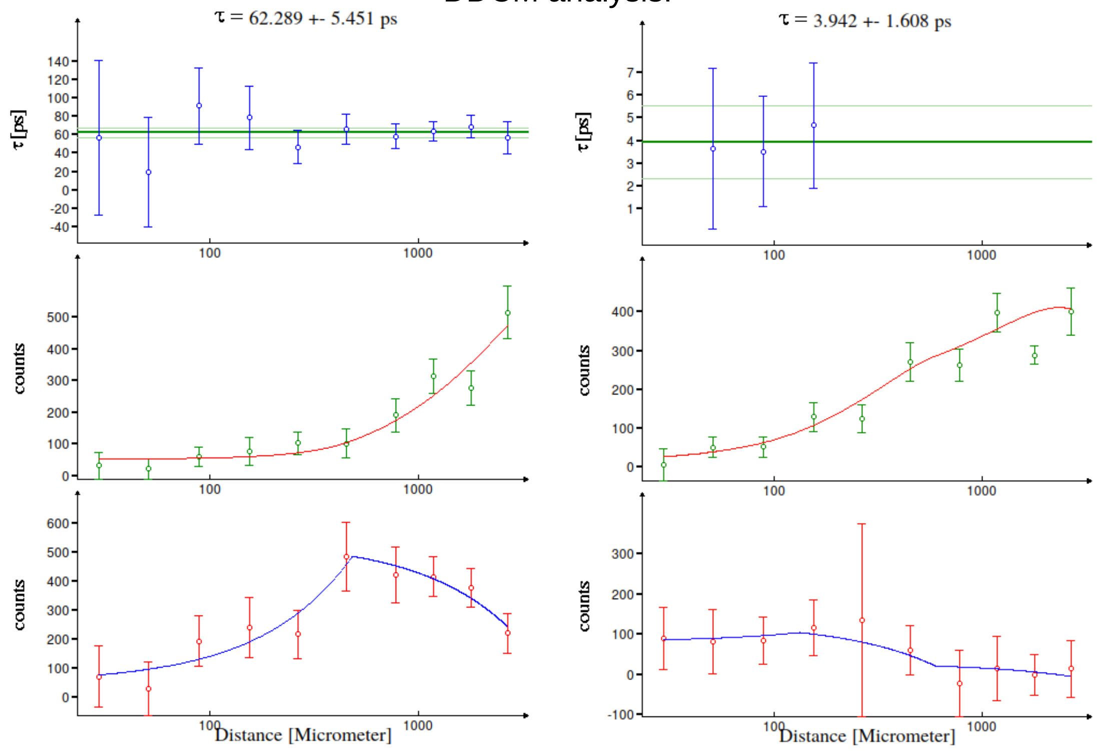


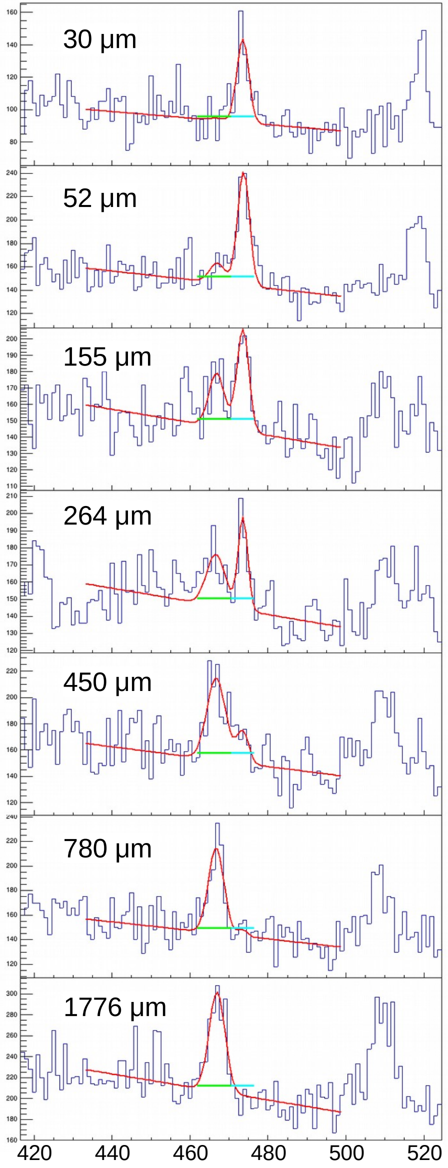
Preliminary results for ^{104}Zr in single γ



Jπ	Energy [keV]	τ [ps] single γ
4+	312.3	62 (5)
6+	473.7	4 (2)

DDCM analysis:





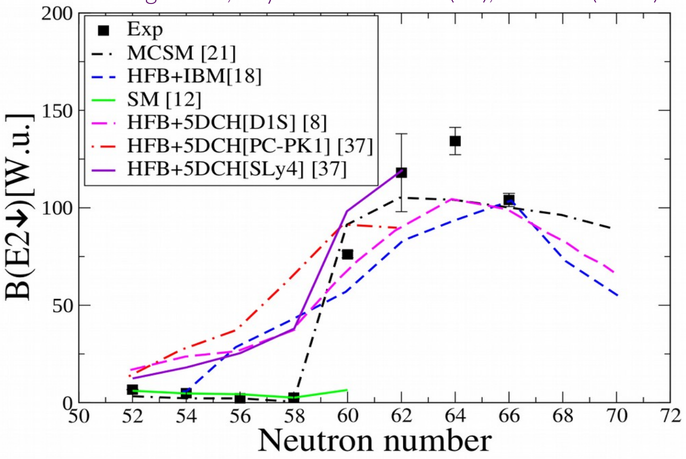
Conclusions

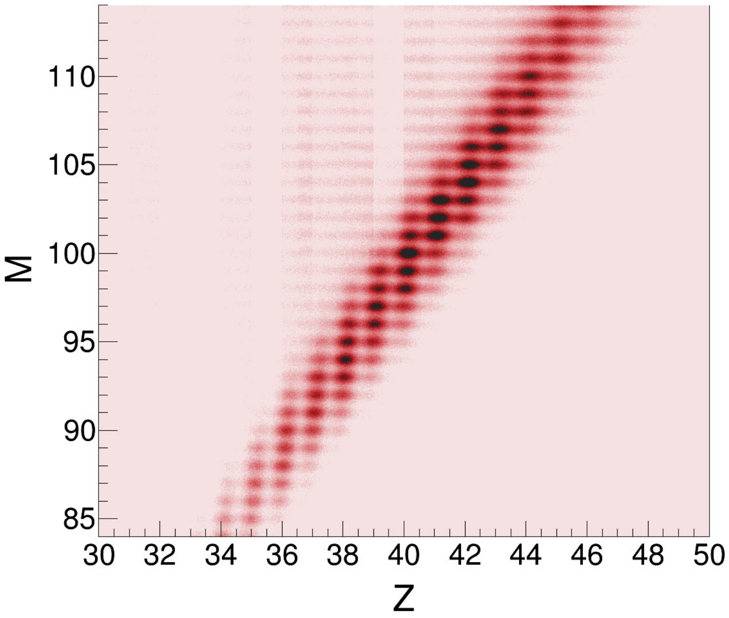
- The value of the lifetimes obtained for ^{100}**Zr confirm the strong deformed character** of this system, as predicted from different nuclear models and experimentally investigated.

- The **high efficiency of AGATA** and the **resolution of the VAMOS identification** allow us to measure the lifetime of exotic systems like ^{104}Zr

  → investigation of the trend and the limits of deformation in the A~100 region.

P. Singh et al., Phys. Rev. Lett. 121 (19), 192501 (2018).





- Many lifetimes have been already extracted for even-even isotopes in Zr, Mo and Ru, among which new values for ^{104}Zr, ^{108}Mo, ^{106,108,110,112}Ru.

- Precise values of lifetimes and errors estimation in progress → many new results in this region.

Thanks for listening

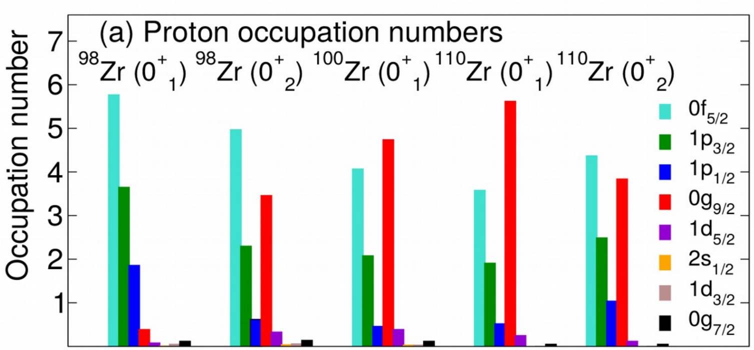
G. Pasqualato[1], A. Görgen[2], J.S. Heines[2], J. Ljungvall[1], V. Modamio[2], L.G.. Pedersen[2], and W. Korten[3]

[1] *IJCLab, IN2P3/CNRS, Université Paris-Saclay, Orsay, France.*
[2] *Department of Physics, University of Oslo, Norway. and*
[3] *CEA Paris-Saclay, DRF/IRFU/DPhN, Gif-sur-Yvette, France.*

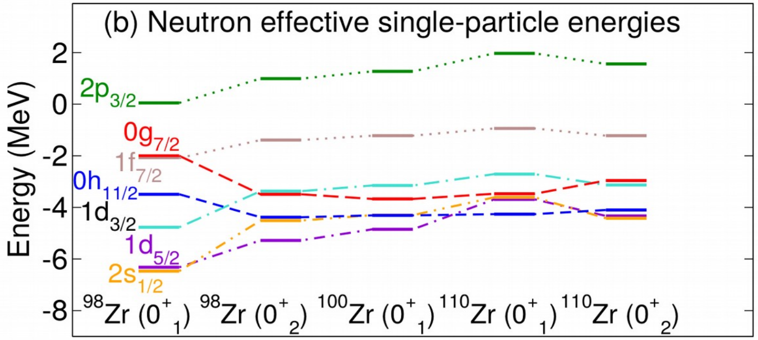
Shape-phase transition in Zr isotopes

Results from recent MCSM calculations: T. Togashi, Y. Tsunoda, T. Otsuka and N. Shimizu, Phys. Rev. Lett. 117, 172502 (2016).

The rapid shape change at N=60 appears as a results of shell evolution associated with <u>proton excitation</u> in the $g_{9/2}$.



The increasing number of neutrons increases the split of the spin-orbit partner $g_{7/2}$- $g_{9/2}$ thus reducing the gap at N=40. Proton particle-hole excitations in the unique-parity orbital $g_{9/2}$ lower the ESPEs of neutron $g_{7/2}$ and $h_{11/2}$ orbitals, favoring quadrupole interactions and the coherent contribution of different configurations.



The ESPEs form $s_{1/2}$ to $g_{7/2}$ shrink abruptly starting from the second 0^+ in ^{98}Zr.

Both protons and neutron act coherently to induce the deformation.

Shape-phase transition in Zr isotopes

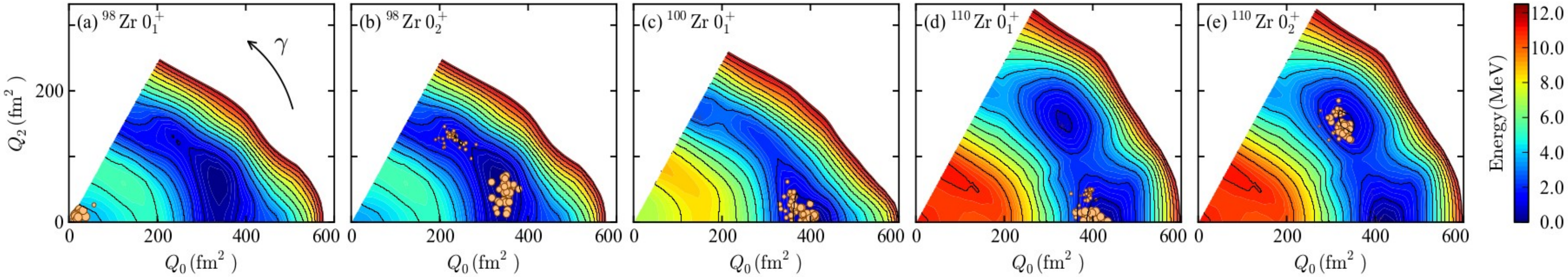
Results from recent MCSM calculations:

T. Togashi, Y. Tsunoda, T. Otsuka and N. Shimizu, Phys. Rev. Lett. 117, 172502 (2016).

The crossing of two distinct configurations at N=60 appears in the abrupt change in the ground state structure and is interpreted as a <u>Quantum Phase Transition</u> (QPT) at N=58-60 from “spherical phase” to “deformed phase”.

The lowering of the intruder 0_2^+ state from ^{96}Zr to ^{98}Zr continues in ^{100}Zr where it becomes the ground state.

T-plots for $0_{1,2}^+$ states of ^{98,100,110}Zr isotopes to analyze the intrinsic shape of SM eigenstates:

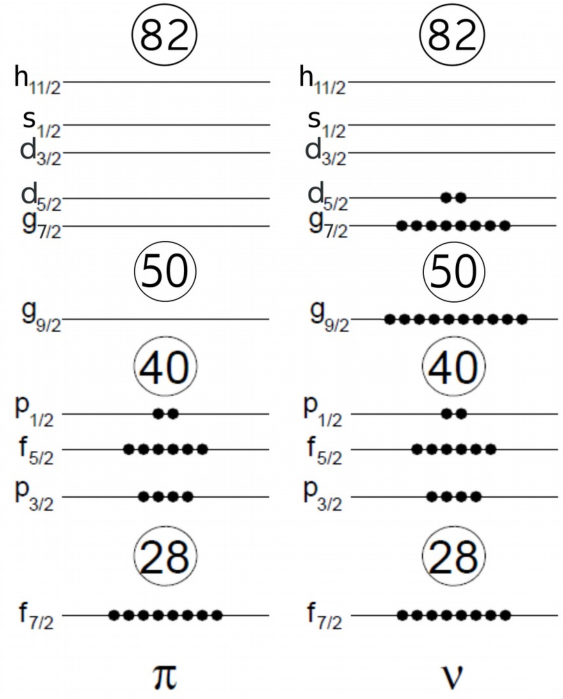


Shape coexistence have been established for ^{96,98}Sr, ^{94,96}Zr and ^{98}Zr, key nucleus for the understanding of QPT.

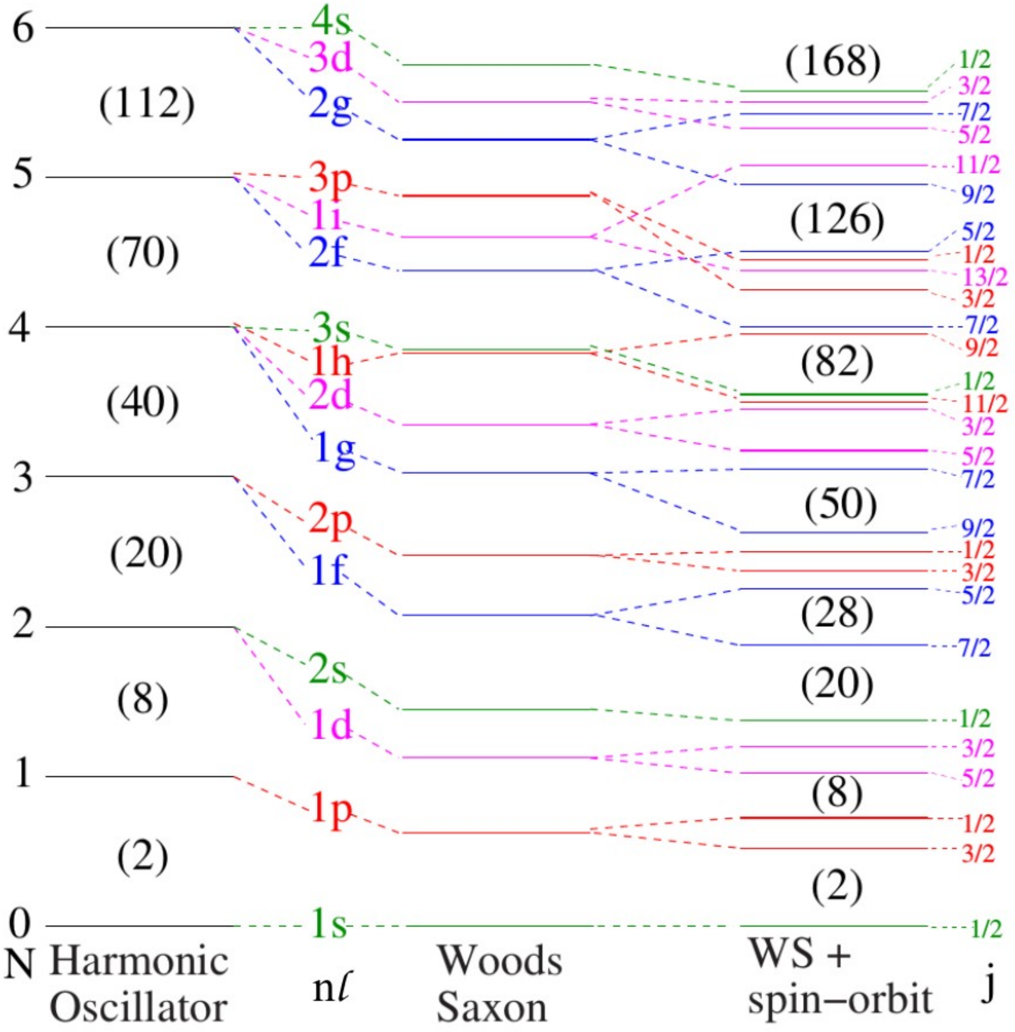
E. Clément et al., Phys. Rev. Lett. 116, 022701 (2016).
E. Clément et al.,Phys. Rev. C 94, 054326 (2016).
A. Chakraborty, E. E. Peters, B. P. Crider et al., Phys. Rev. Lett. 110, 022504 (2013).
C. Kremer et al., Phys. Rev. Lett. 117, 172503 (2016).).

K. Heyde and J. L. Wood, Rev. Mod. Phys. 83, 1467 (2011).
P. Singh et al., Phys. Rev. Lett. 121(19) 192501 (2018).

Shell model orbitals

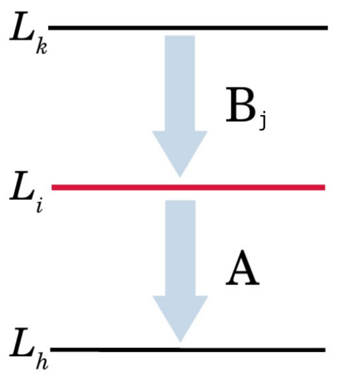


$^{100}_{40}Zr_{60}$



Lifetime measurements with the DDCM

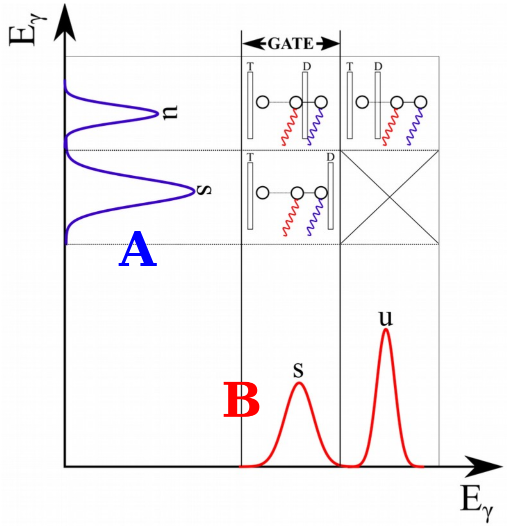
- Lifetime in single γ measurements are analyzed with the DDCM by using the following experimental information:
  - the fast (S) and the slow (U) components of the transition A depopulating the state of interest L_i,
  - the fast and the slow components of all observed feeding transitions B_j in the γ-rays spectrum (the α coefficient take into account the feeding contribution form B_j in the lifetime calculation).
  - the velocity of the recoiling fragment before the target v_{in}.



$$\tau(x_p) = \frac{-A^U(x_p) + \sum_j b_j \alpha_j B_j^U(x_p)}{v_{in} \frac{dA^U(x_p)}{dx}} \qquad \alpha_j(x_p) = \frac{B_j^U(x_p) + B_j^S(x_p)}{A^U(x_p) + A^S(x_p)} \cdot \frac{\epsilon_A}{\epsilon_B}$$

- Lifetime in coincidence γγ are analyzed with the DDCM by gating in the shifted component of a direct feeding transition B of the state of interest. No other information about the feeding are needed

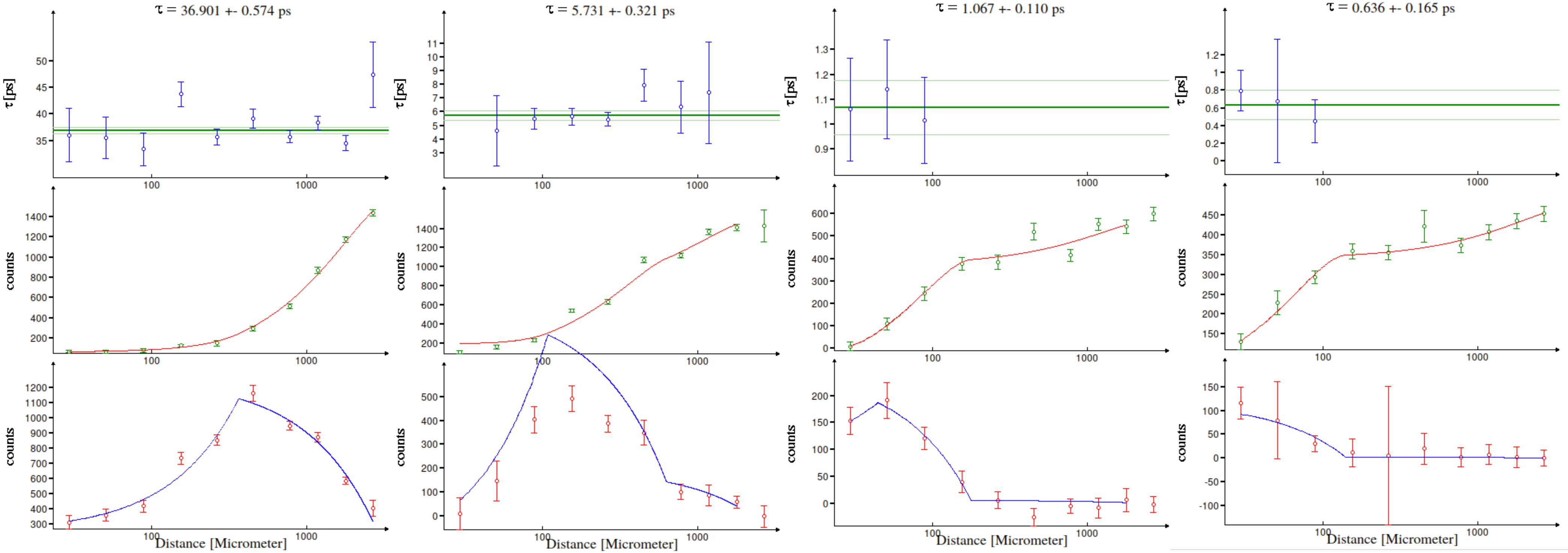
$$\tau(x_p) = \frac{\{A_S, B_U\}(x_p)}{\frac{d}{dx}\{A_S, B_S\}(x_p)} \cdot \frac{x_p}{\beta c}$$



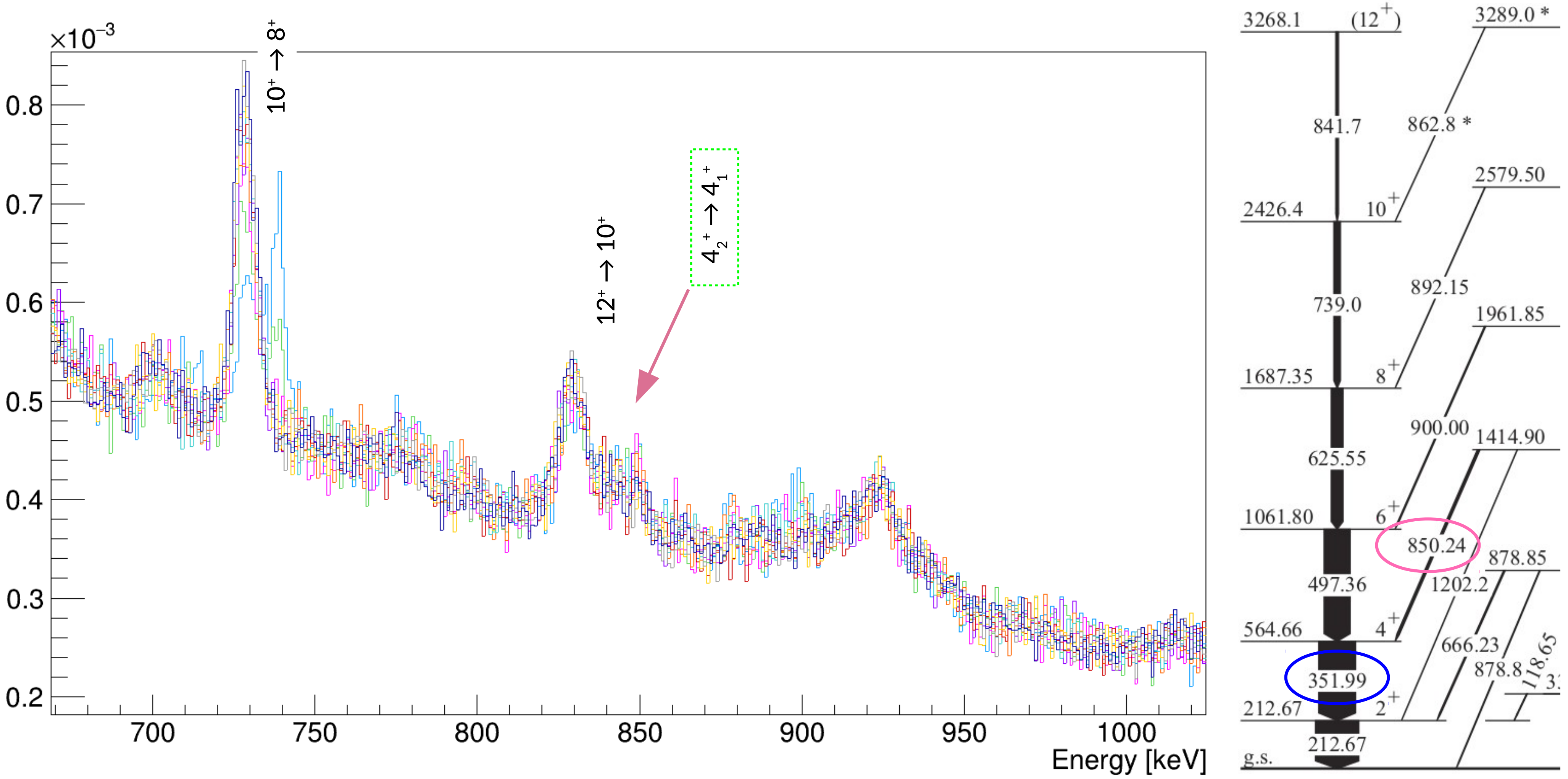
A. Dewald, S. Harissopulos, P. von Brentano, Z. Phys. A 334 (1989) 163.
A. Dewald et al., Prog. Part. Nucl. Phys. 679, 786 (2012).

Decay curves for ^{100}Zr in single γ

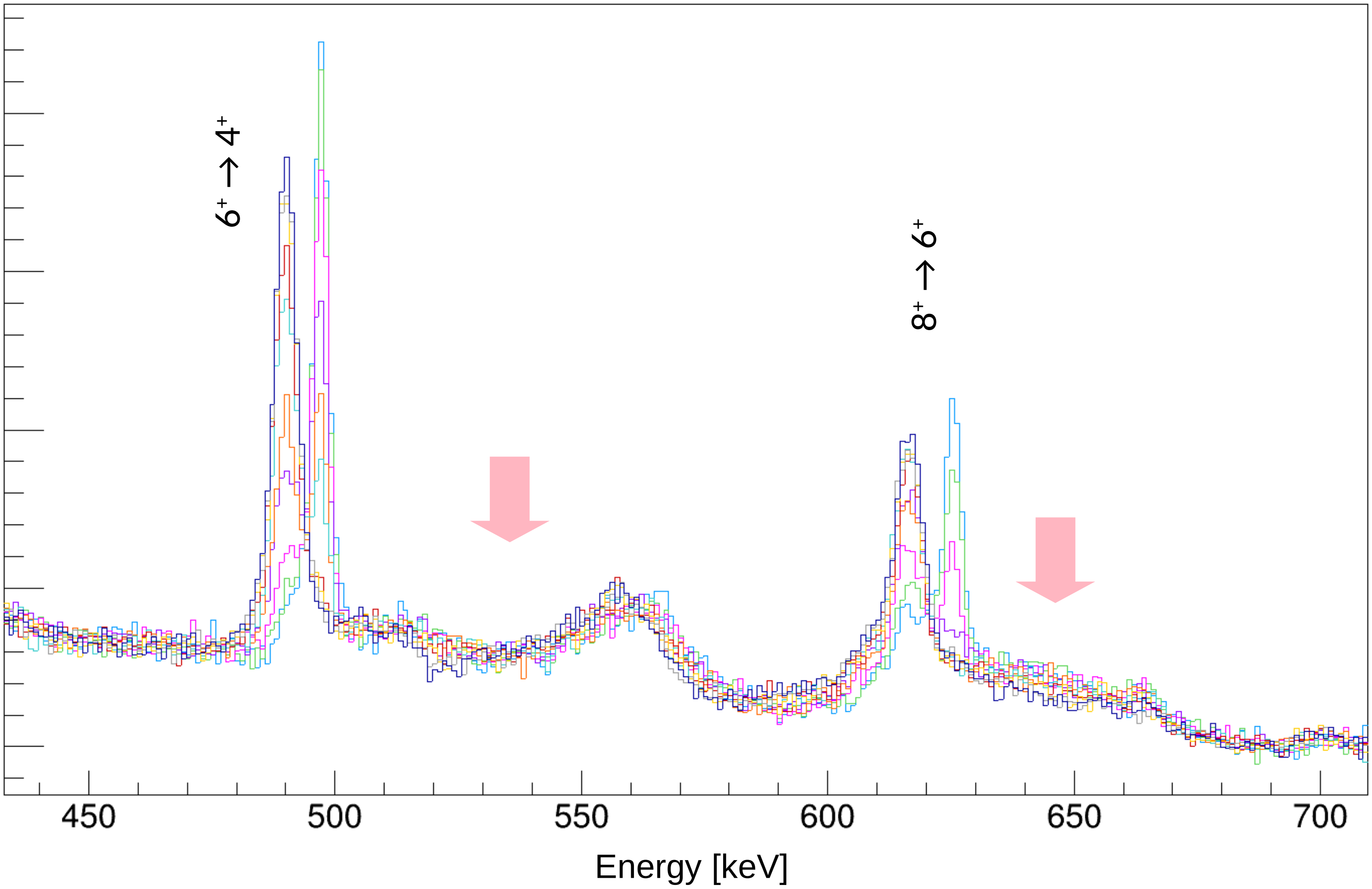
$4_1^+ \rightarrow 2_1^+$ $6_1^+ \rightarrow 4_1^+$ $8_1^+ \rightarrow 6_1^+$ $10_1^+ \rightarrow 8_1^+$

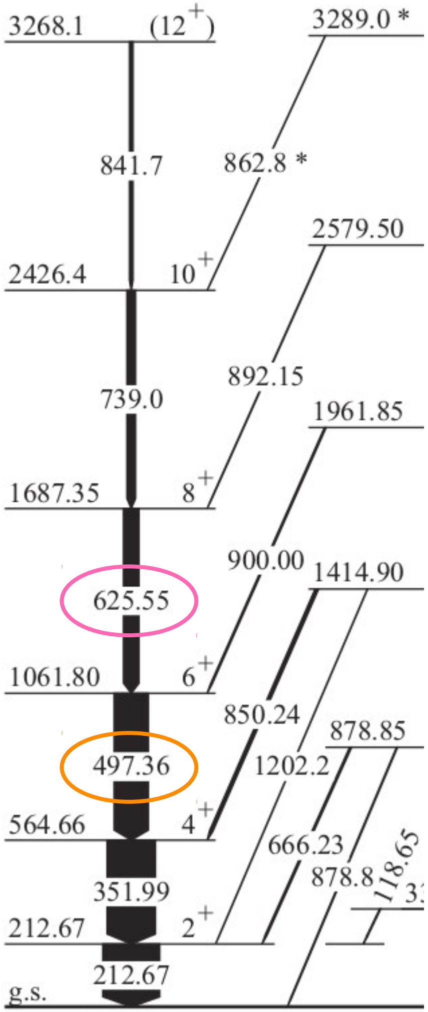


Feeding for the 4^+ state in ^{100}Zr



Background around 550 keV and 650 keV state in ^{100}Zr





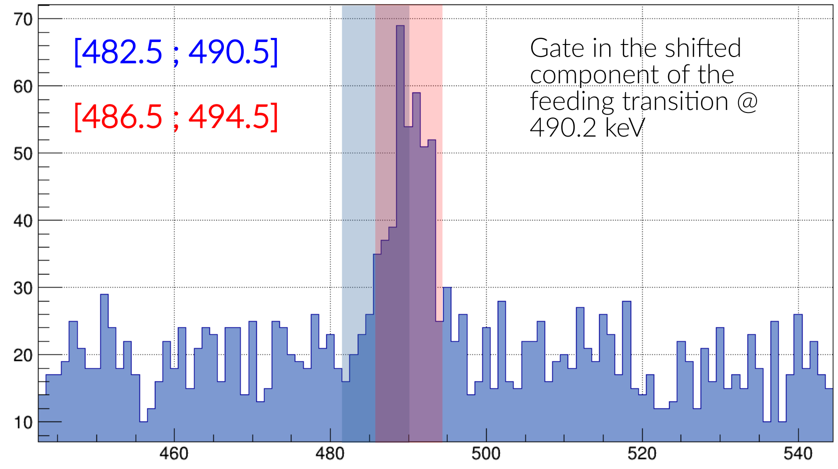
Preliminary results for ^{100}Zr in coincidence γγ – gate and BG subtraction

The analysis in γγ revealed <u>problems</u> in its applicability in this case.

→ The <u>small energy difference</u> between shifted and “stopped” peak of the feeding transition makes the set of the gate not easy:

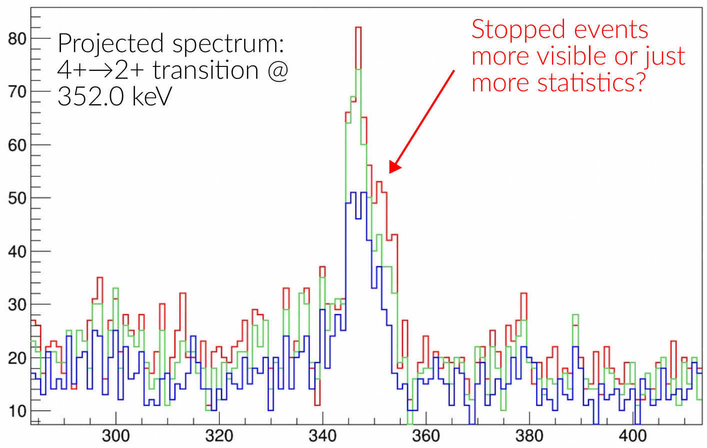
Different gates in the shifted feeding events (one left to avoid “stopped” contaminants, and one centered) lead to different results.

→ The <u>subtraction of the BG</u> also results in a different final value of tau.



When subtracting the BG and/or when using a left gate on the feeder, **the resulting lifetime is short**:

GATE [keV]	τ [ps] no BG sub	τ [ps] with BG sub
482.5, 490.5	32.8 (12)	30.0 (23)
486.5, 494.5	38.4 (25)	37.2 (38)



→ the left gate and the BG subtraction seems the best option for γγ analysis

Example of an odd-even system: ^{101}Nb in single γ

<u>Good statistics</u>: many gamma-rays transitions can be resolved in the stooped and shifted component

→ The <u>complexity of the level scheme</u> make the DDCM analysis in single γ impossible for this nucleus.