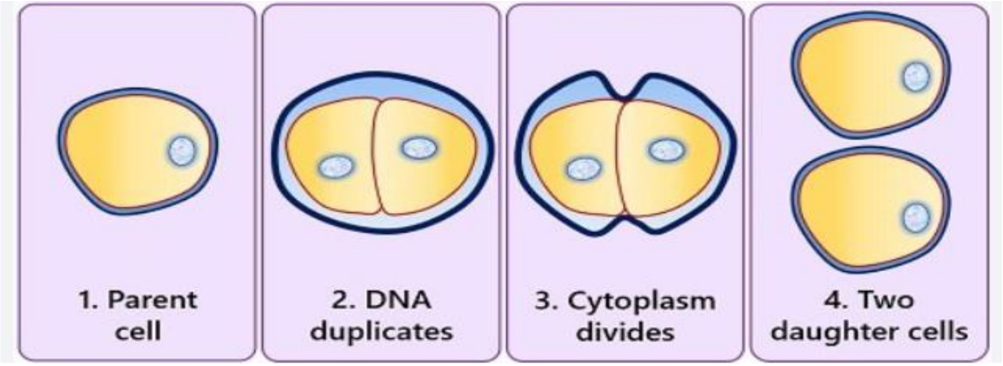
What drives fission across the nuclear chart and what can we learn from it ?

Experimental perspective



Division of a living cell: Fission at the macroscopic level

Current knowledge

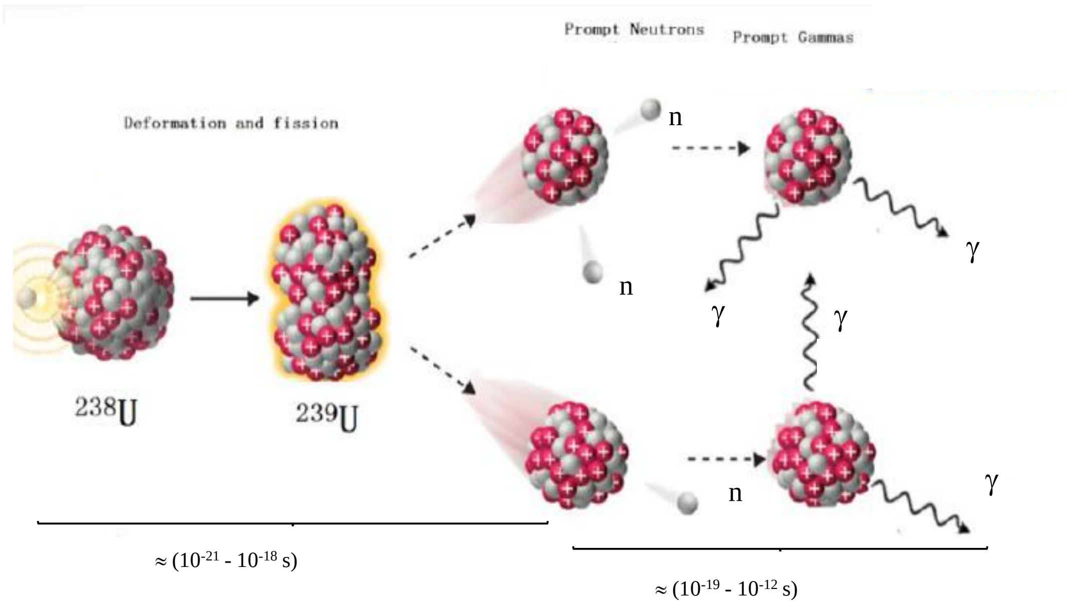
Recent results/advances

Next challenges

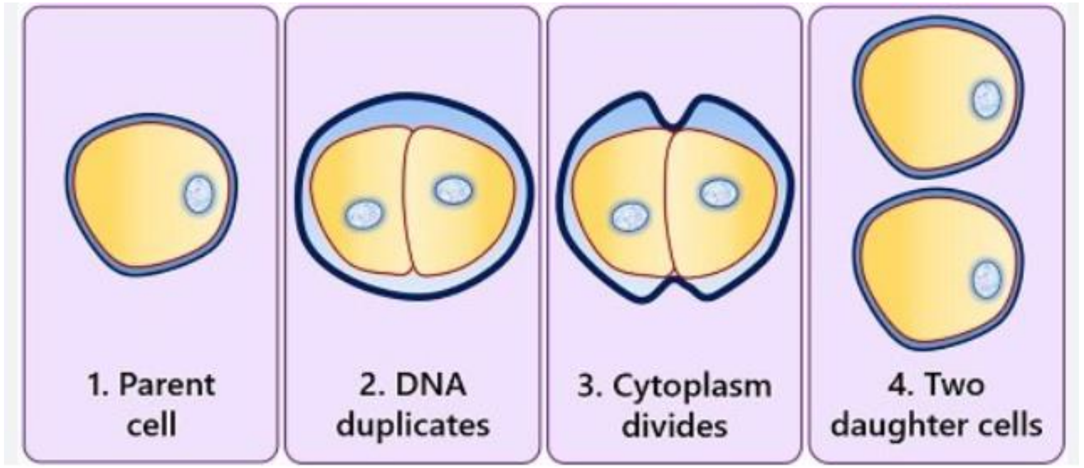
What do we talk about?

Gradual elongation of a nucleus up to scission in two fragments
↪ Re-arrangement of a many-body quantum system of protons and neutrons

"Split of a nucleus into two pieces with release of a huge amount energy.", M.S.



≈



one fissioning nucleus → two fission fragments

one parent cell → two daughter cells

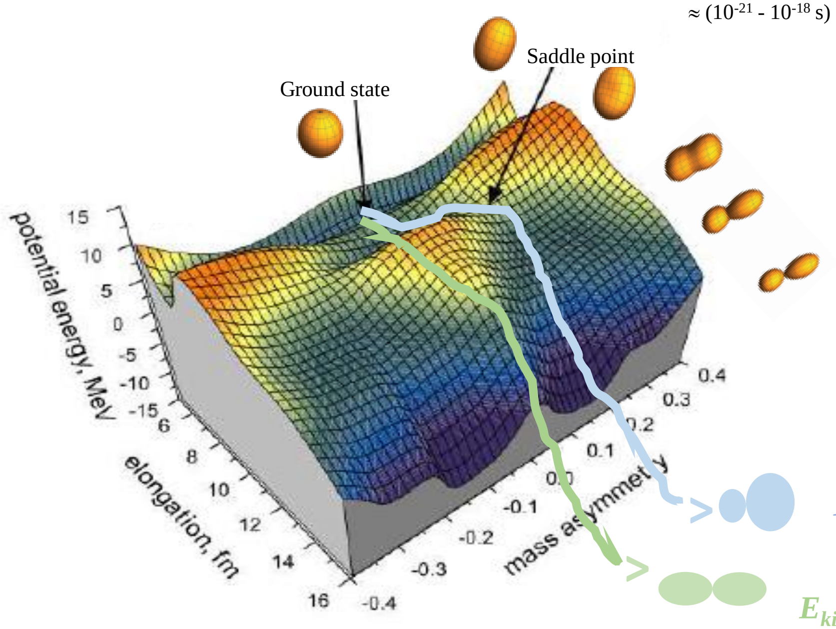
What do we talk about?

> *"Split of a nucleus into two pieces with release of a huge amount energy.", M.S.*

Gradual elongation of a nucleus up to scission in two fragments

↪ Re-arrangement of a many-body quantum system of protons and neutrons

≈ (10^{-21} - 10^{-18} s) | ≈ (10^{-19} - 10^{-12} s) | ≈ (ms - s)

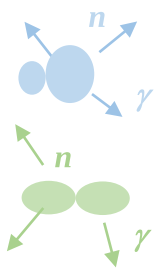


<u>Primary fragments</u>

$A_{1,2}$, $Z_{1,2}$,
$E_{kin1,2}$, $E^*_{1,2}$, $L_{1,2}$

$A_{1,2}$, $Z_{1,2}$
$E_{kin1,2}$, $E^*_{1,2}$, $L_{1,2}$

<u>Secondary fragments</u>



A_1', Z_1', $E_{1\,kin}'$

A_2, Z_2, $E_{2\,kin}'$

Radioactive decay (e.g. β)

- **P**otential **E**nergy **L**andscape (mainly CN)

- PEL (mainly fragment shell effects)
- Dynamics (inertia, friction)

- Nuclear Level Density
- γ Strength Function

What do we talk about?

> *"Split of a nucleus into two pieces with release of a huge amount energy.", M.S.*

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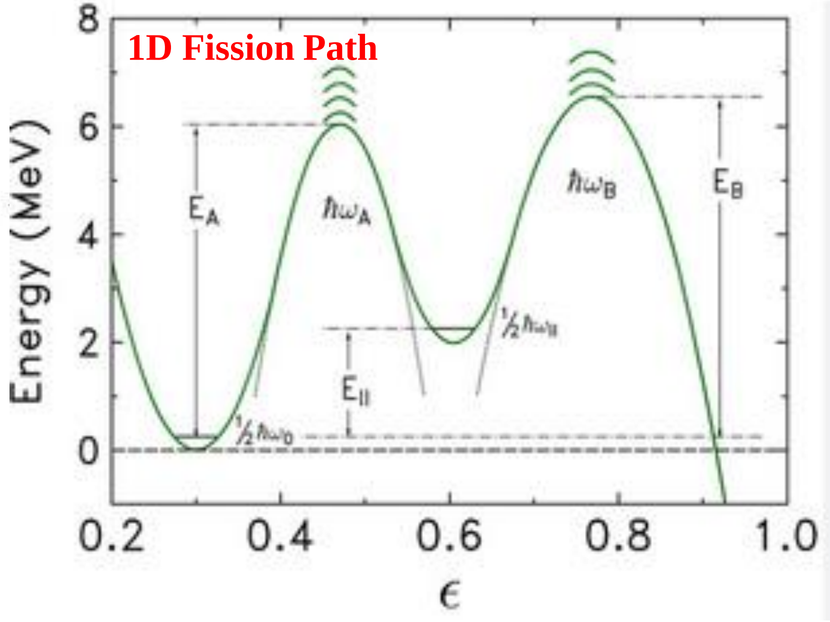

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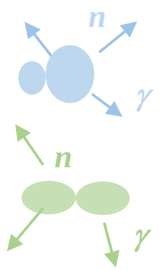

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How to probe fission? What are “good” signatures?

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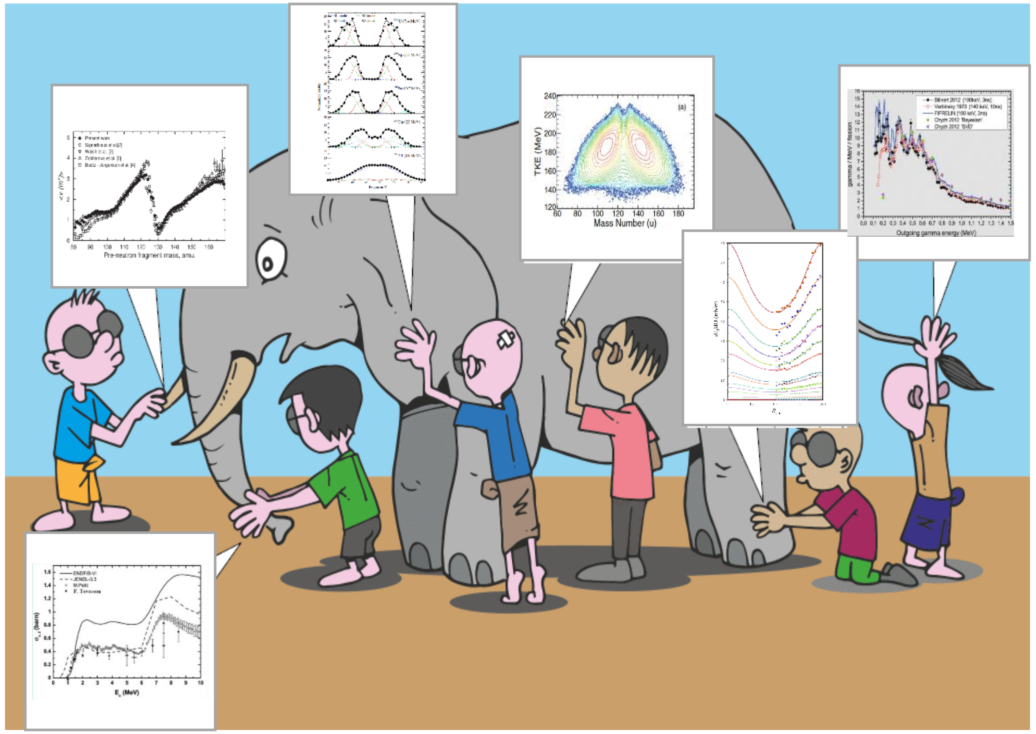


Various and many observables:

- fission cross sections/probabilities
- fragment *A*, *Z*, and *T*otal *K*inetic *E*nergy distributions
- fragment anisotropy
- fragment isomeric ratios
- multiplicity, energy and angular, inclusive and exclusive, distributions of the promptly emitted neutrons and γ-rays
- multiplicity and energy of delayed neutrons and γ-ray
- …

TODAY

Fragment *A* and *Z* yields

Prompt γ-ray spectrum

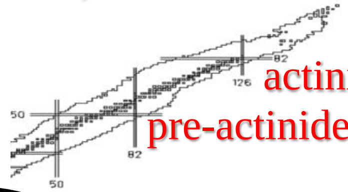
Crucial developments in detection and computing

“Shaking” decades of knowledge!

Chapter I.

Fission (A, Z) Yields

Previous knowledge (from direct kinematics)



Actinides

1950-2000: <u>Mass</u> distributions with $\Delta A \sim 4$

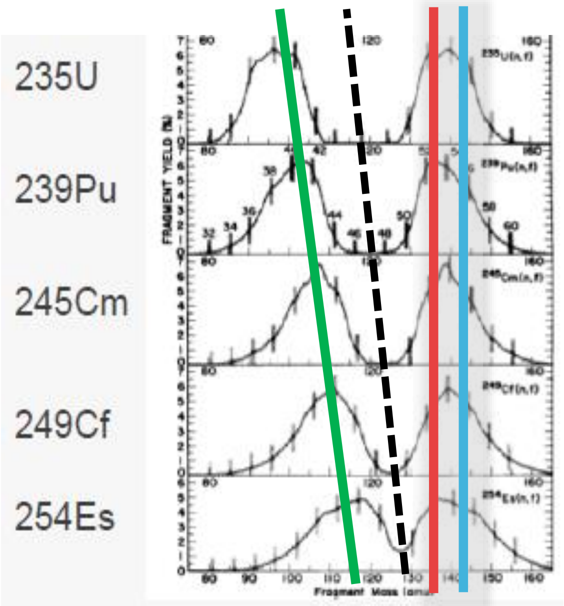
→ *Low-energy* fission of actinides is asymmetric

→ Heavy fragment « sitting » at A~130-150

due to shell stabilized heavy fragments

S1 mode attracted by N=82 (sph. shell)

S2 mode attracted by N~88 (def. shell)



Unik et al., PRC (1973)

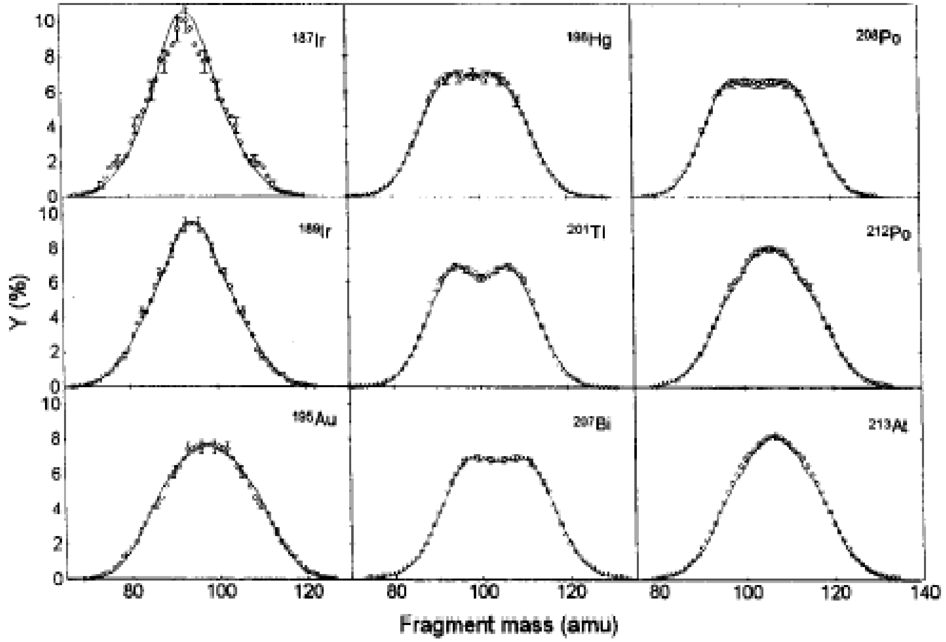
Pre-actinides

1970-2000: <u>Mass</u> distributions with $\Delta A \sim 4$

→ Fission of pre-actinides is roughly symmetric at *intermediate excitation energy* ($E^* \sim 30$MeV)

→ ***No specific shell effect***

→ ***Symmetric mode due to macroscopic energy***



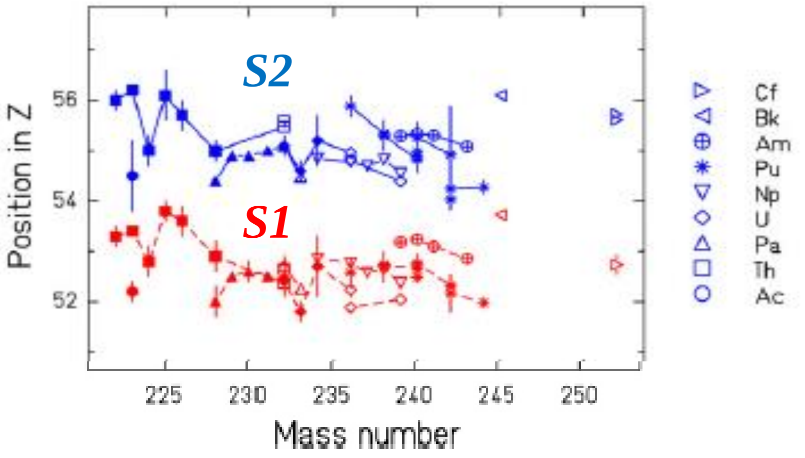
Itkis et al. (1980-1990)

Previous knowledge questioned !

Actinides

2000: <u>Charge</u> distributions of actinides (GSI)

→ Heavy fragment « sitting » at
Z~52 in S1
Z~55 in S2



Schmidt et al., NPA (2000)
Bockstiegel et al., NPA (2008)

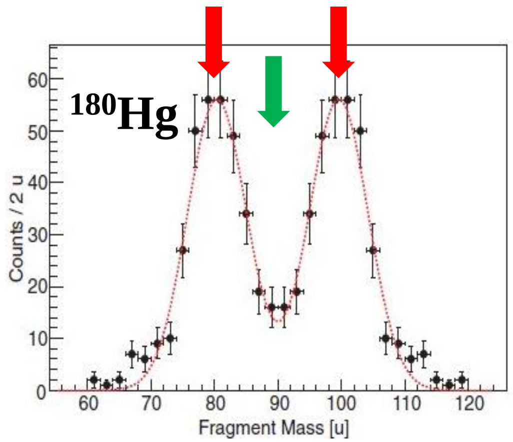
Pre-actinides

2010: <u>Low-E^*</u> fission of a pre-actinide (ISOLDE)

→ Possibility of an island of asymmetric fission resembling the actinide island
→ Is it shell effects driven? Which shells?

expected:
$2 \times {}^{90}Zr_{50}$

observed:
$A_{1,2}$ ~ 80/100



Andreyev et al., PRL (2010)

Role of
n and p ?

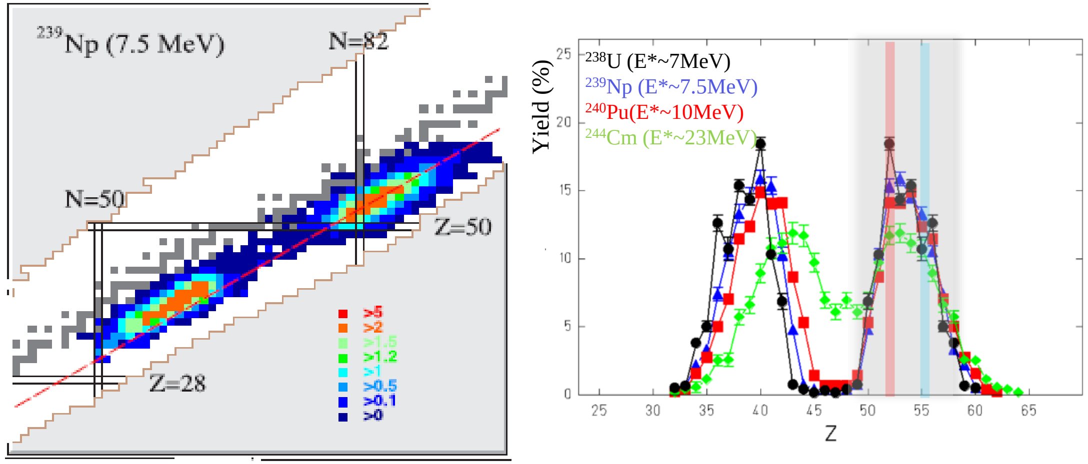
Need of *A* <u>and</u> *Z* with unique precision

Step forward for actinides (thanks to inverse kinematics and state-of-the art spectrometers)

2013 on: Isotopic (*N*, *Z*) fragment identification

With VAMOS++ @ GANIL

With SOFIA @ R^{3}B-GSI

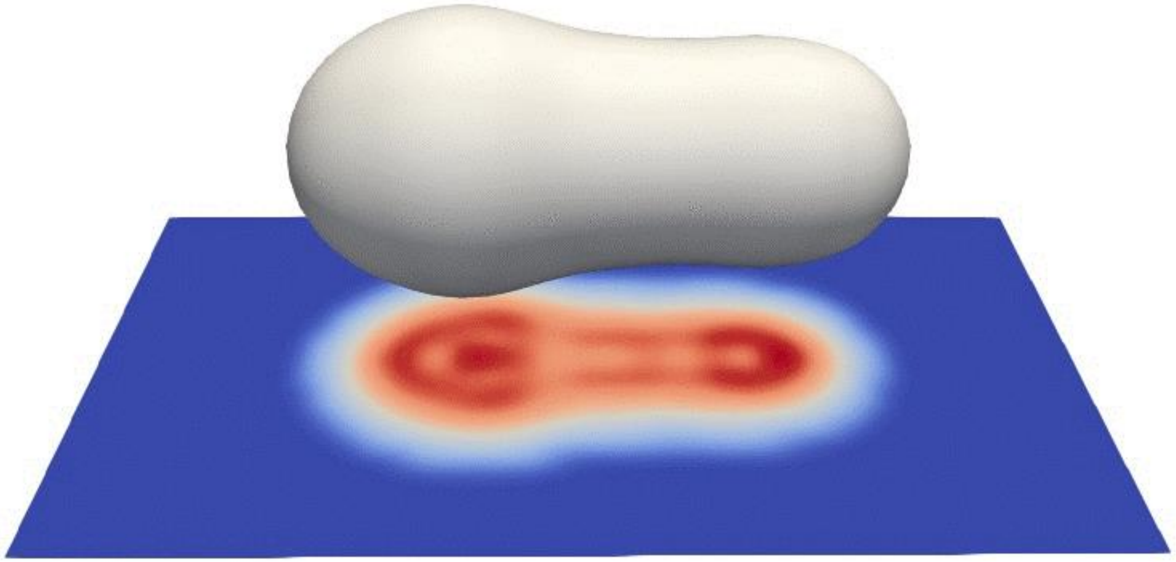


D. Ramos et al., PRC (2019)

- ➥ Shell effects in the nascent fragments drive asymmetric fission of actinides
- ➥ Specific stabilized **proton** configurations in the **heavy** fragment
  - ***S1*** ~ 52 is due to $Z = 50$ shell
  - ***S2*** ~ 55 due to stable octupole configurations

Scamps and Simenel, Nature (2018)

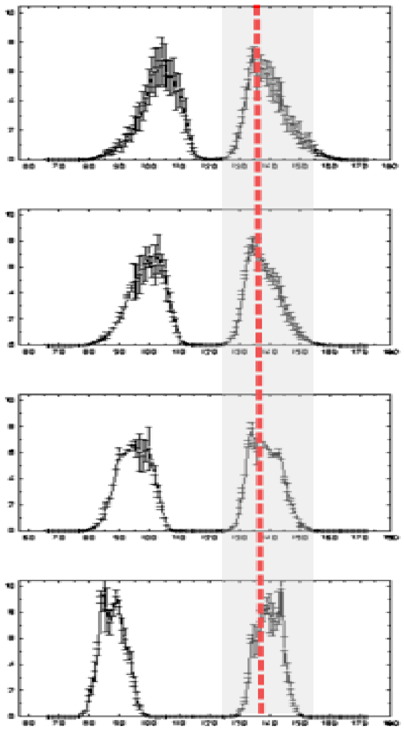
- ➥ *N/Z*, M_n, *TKE*
- ➥ Even-Odd effect



Courtesy Guillaume Scamps

Thorium anomaly

<u>Observed 50 years ago</u>:
Displacement of the heavy-fragment peak in low-energy fission of light actinides
➥ **Suppression of compact S1 mode**

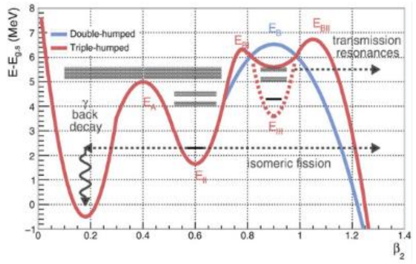


➥ Fundamental interest
Huge importance for Th-U cycle

<u>Explained in 2024 (!)</u>:

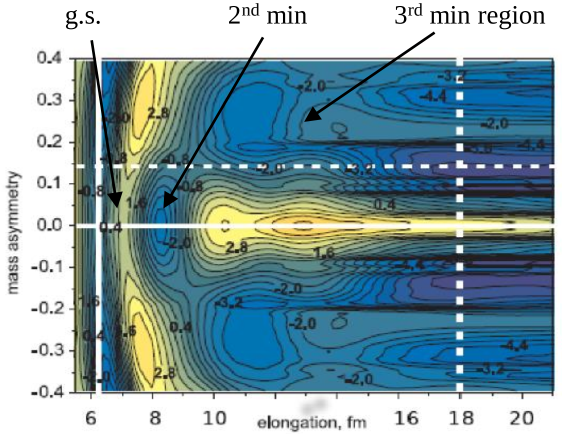
Occurrence of a **third barrier** along the fission path

K.-H. Schmidt, C. S. et al., An. Nucl. En. (2024)



Triple-humped barrier in the Th corner

Möller and Nix, IAEA Symposium (1973)



Karpov et al., J Nucl Phys Part G (2008)

Small change of asymmetry between the 2nd and 3rd barriers

Sensitivity of accurate data !

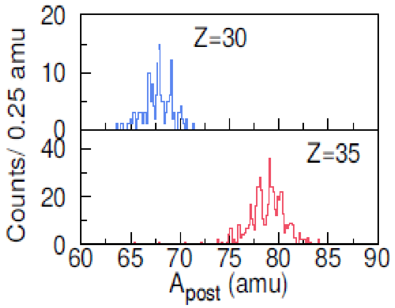
K.-H. Schmidt, C. S. et al., submitted (2025)

Still many open questions (*e.g.* system and E^* dependence):
➥ Recent experiment with ^{232}Th beam at VAMOS@GANIL

Step forward for pre-actinides (thanks to inverse kinematics and state-of-the art spectrometers)

2021: Isotopic (*A*, *Z*) fragment identification

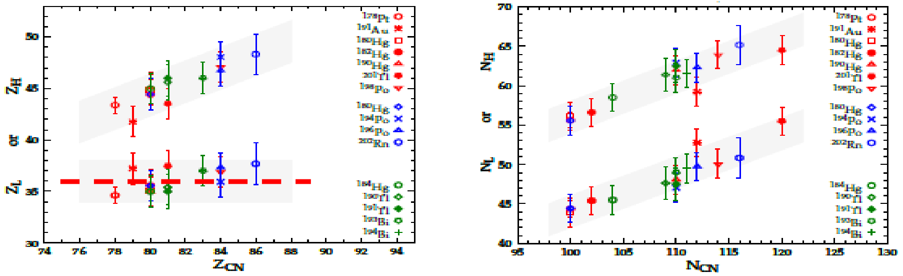
With VAMOS++ @ GANIL: ^{178}Hg (E^* =34MeV)



C.S. et al., PRL (2021)

2022: Re-analysis of existing mass data

→ empirical estimate of Z_L, Z_H, N_L, N_H



K. Mahata, C.S. et al., PLB (2022)

➥ Specific stabilized **proton** configurations in the **light** fragment

Z ~ 36 NEW FISSION MODE

due to stable octupole configurations

Scamps and Simenel, PRC (2019)

2025: *Z* distribution for tens of pre-actinides

P. Morfouace et al., Nature (2025)

With SOFIA @ R^{3}B-GSI

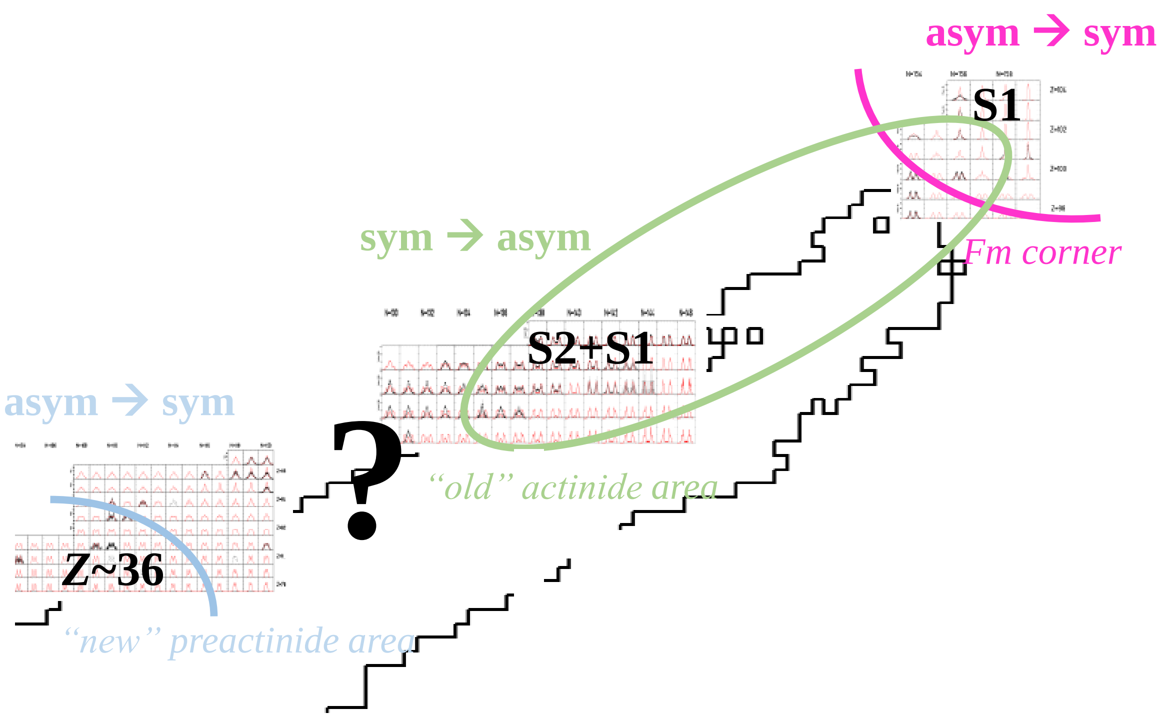
➥ from Ir to Th (E^*~14MeV)

➥ firmly established the ***Z* ~ 36** mode

➥ N/Z, M_n, TKE

➥ Even-Odd effect

Evolution across the nuclear chart



Inventory

⏩ ⏩ ⏩ **What we know at day**

- **Leading proton effects**
  - Z ~ 50/52 spherical configuration (*S1*)
  - Z ~ 55 deformed octupole configuration (*S2*)
  - Z ~ 36 deformed octupole configuration

⏩ ⏩ ⏩ **What we need/want to know**

- Variety of modes → **Revisit the role of neutrons**
- Co-existence, competition, transition between modes
  → strength of the corresponding shell effects

… Work ongoing …

Europe, Australia, Russia, India, United States

Fragment isotopic identification over the entire fission population specific to GANIL and R³B-GSI

Chapter II.

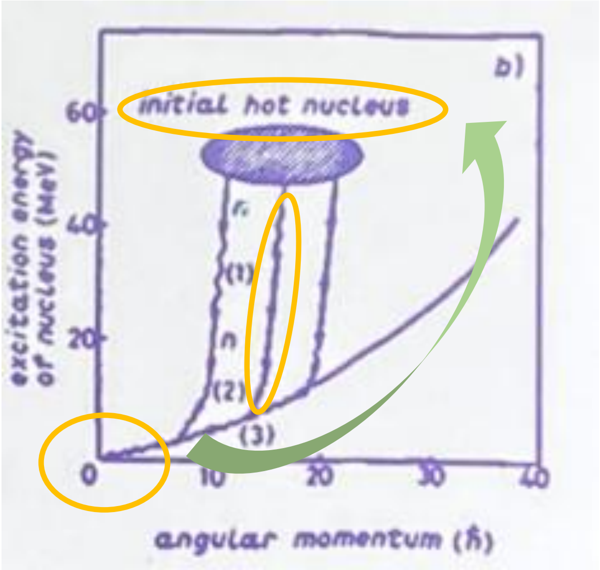
Prompt γ-ray emission

The γ-bump, a specific decay mode

Prompt de-excitation of the fragments after scission

- Depends on the dynamics of fission:
  - Generation of E^* and L in fission
  - Sharing at scission
- Depends on fundamental nuclear properties:
  - Nuclear level density
  - γ strength function

De-excitation of a fission fragment after scission



Complete

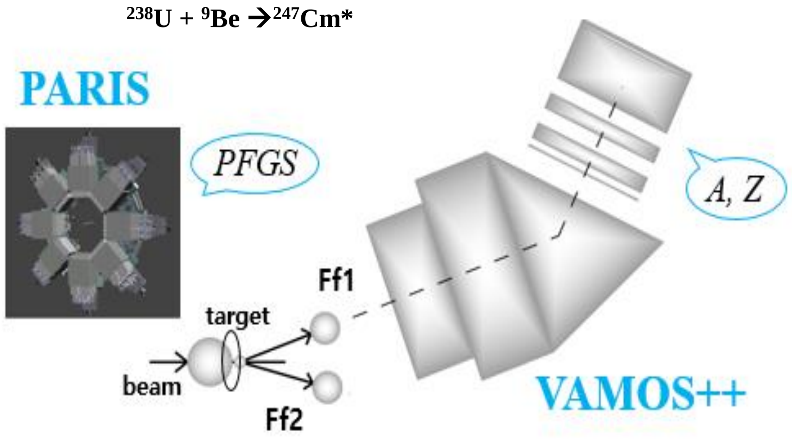
Fission

Exp**E**riments

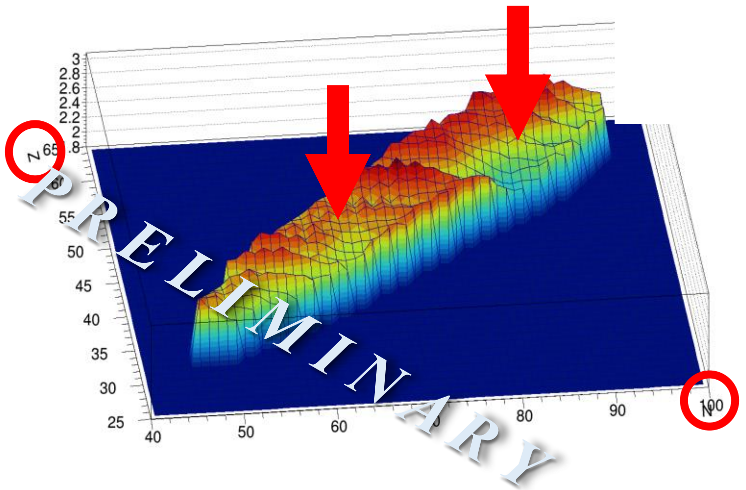
Measurement of the properties of the prompt neutrons and γ rays in coincidence with fragment (A, Z)

- Reconstruct the de-excitation path
  - Deduce the primary fragment E^* and L

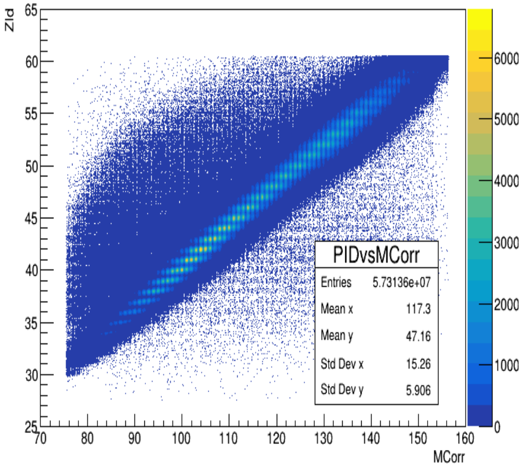
Towards a complete measurement with PARIS@VAMOS++



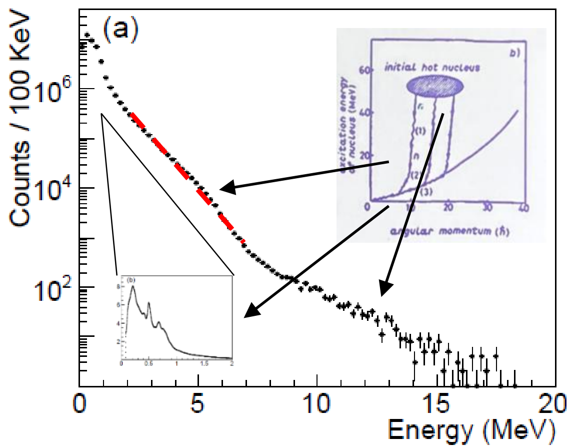
γ fold in PARIS vs. (Z,N) in VAMOS++



Fragment **(Z,N)** in VAMOS++



Prompt **F**ission **γ S**pectrum in PARIS

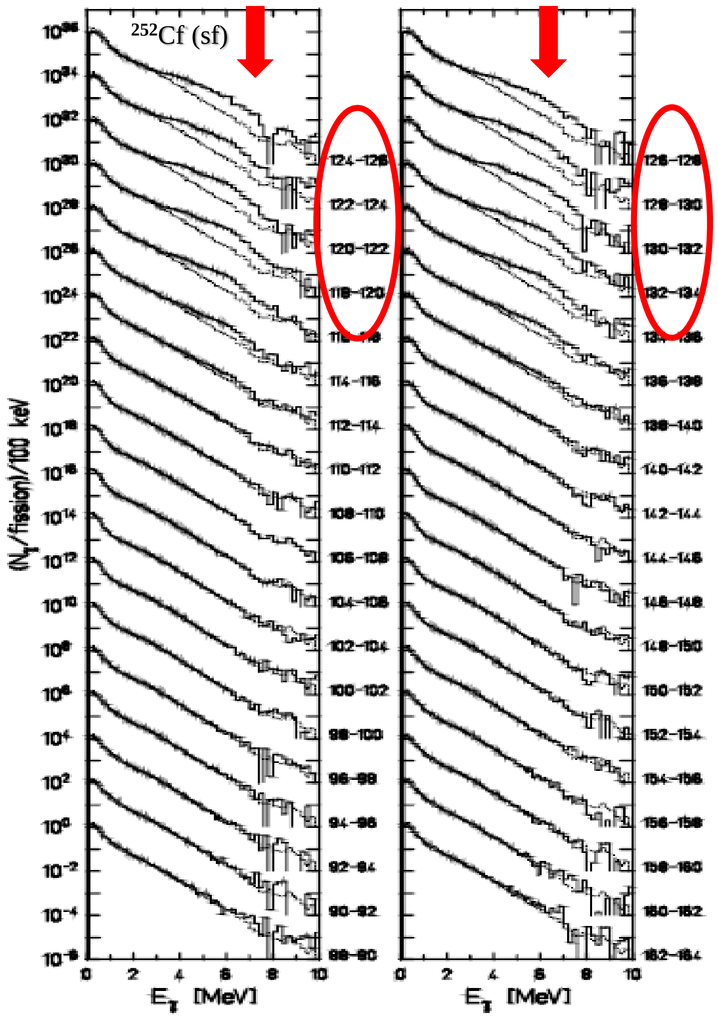


<u>Available data set</u>:

- ~ 500 PFGS (Z,N) tagged in VAMOS++
  - ➥ M_γ, $<E_\gamma>$, $E_\gamma^{\,sum}$
  - ➥ Exponential tail = *f* (NLD, **T**)
- Neutrons

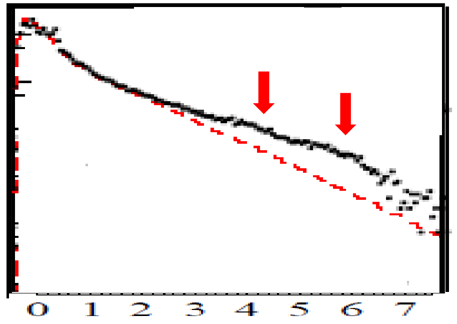
The intriguing “ γ bump ”

1980’s: Evidence of an excess of γ’s at high E_γ for some splits



Holtzel et al., Z Phys. (1996)

2019 onwards: γ bump profile



Francheteau et al., PRC (2025)

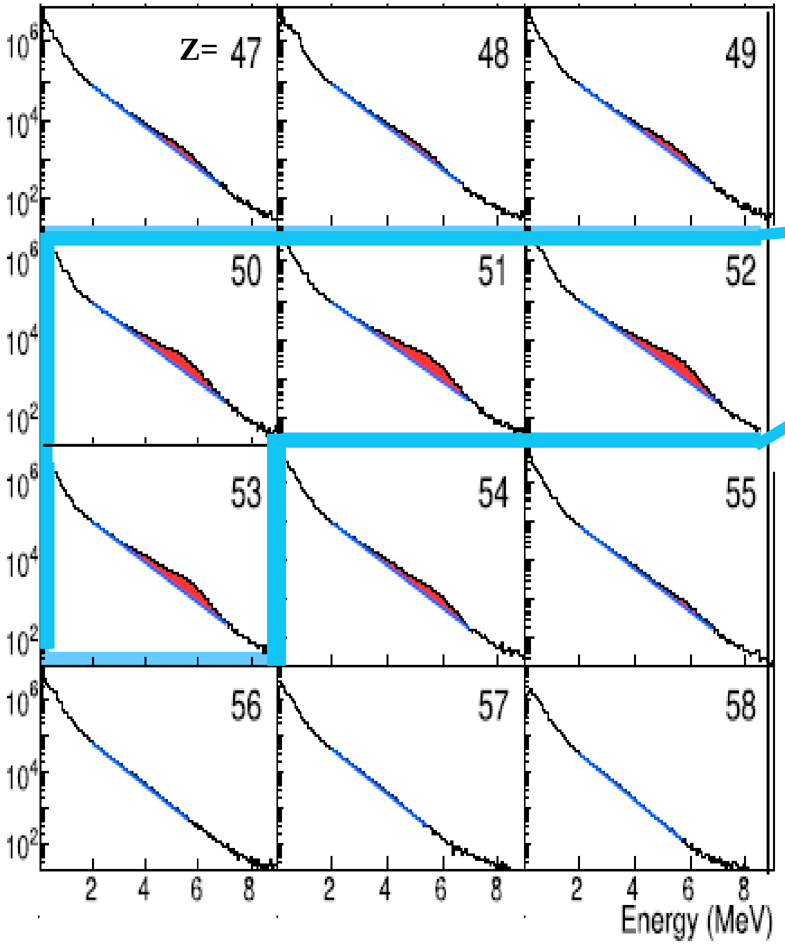
Early 2025: Heated debate about origin

Structural? Statistical?
Collective or Single-particle nature?
Due to *n* (N~68,82) and/or *p* (Z~40,50)?

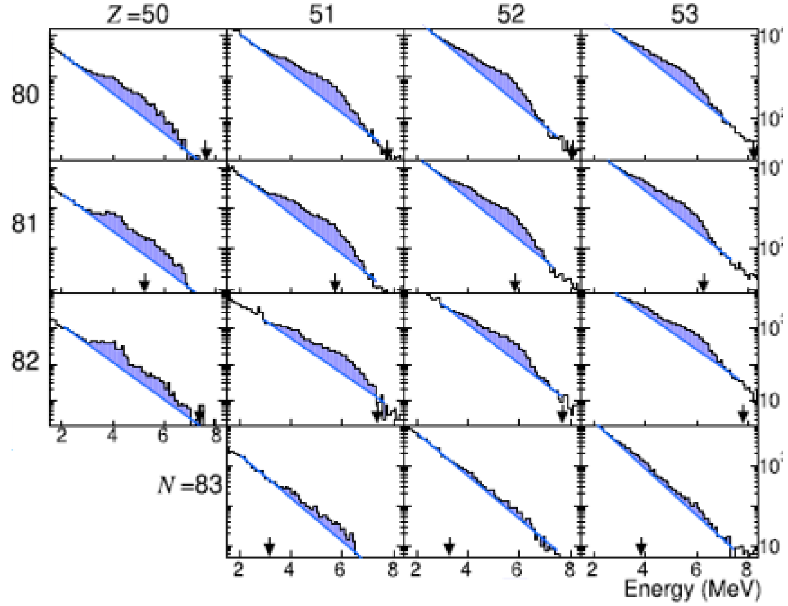
Need of *A* and *Z* identification of the emitter

Isotopic mapping of the γ bump with PARIS @ VAMOS++

Z-gated PFGS



(Z, N)-gated PFGS



- ➥ Delimitation of the γ bump island on the fission population:
  $50 \leq Z \leq 53$ and $78 \leq N \leq 83$
- ➥ Double-humped profile for N~ 82

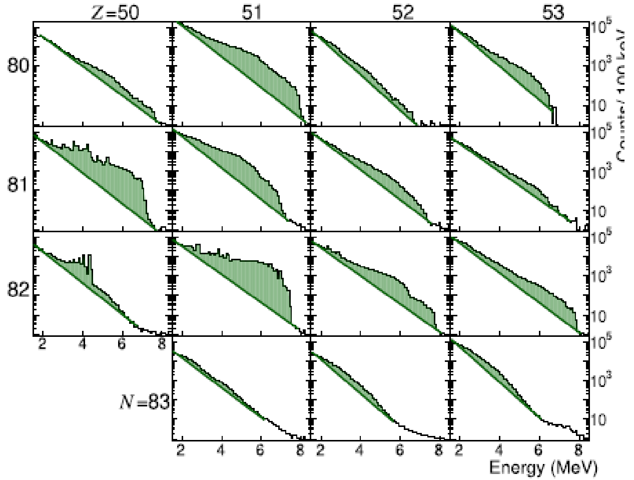
Neeraj Kumar, C.S. et al., submitted (2025)

Origin of the γ bump

Dedicated (fission+fragment deexcitation) calculations with the FIFRELIN code using microscopic nuclear level densities (D1M) and γ strength functions (D1M+QRPA)

with O. Litaize, S. Péru

Calculated PFGS



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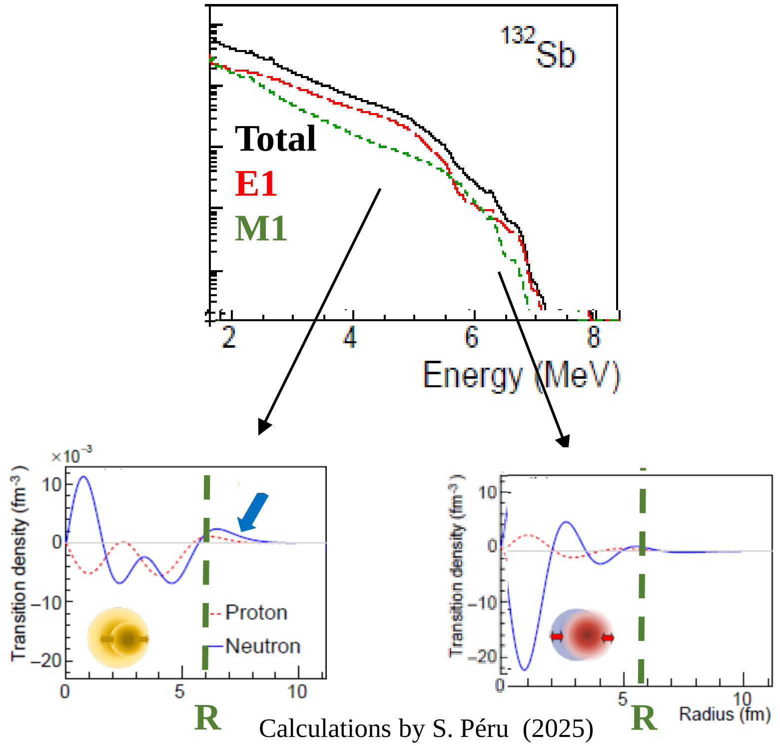

Calculations by S. Péru (2025)

- ➥ Main contribution due to the decay from E1 states
- ➥ Both IsoScalar (IS) and Isovector (IV) nature
- ➥ IS component enhanced **at *N*~82 due to vibration of the « stiff » neutron skin** about the core

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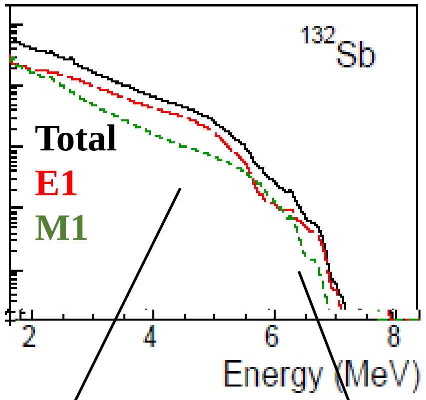

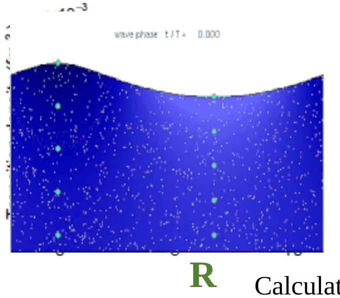

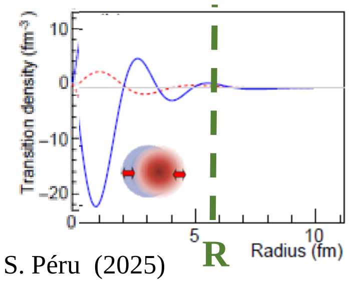

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Fission populates states in the low-energy tail of the Giant Dipole Resonance between ~ 5 and 10 MeV

! PYGMY RESONANCE !

Two-fold impact: Fission and Soft/Giant Resonances physics

- Insight into the post-scission dynamics of the fragments
- Insight into the nature of « Pygmy states »

Near future…

Chapter III.

Fission @ CCB Krakow

to be written

Conclusion

Fission, a rich mechanism of widespread impact

- Fundamental physics on reaction dynamics, and properties of nuclear matter
- « Reservoir » of exotic nuclei for nuclear structure investigations, and for radioactive beam productio
- Astrophysics and societal applications

Fission, a complex mechanism

- Challenge for modern theory

High potential of modern approaches and instruments

- Selectivity
- High resolution
- Exclusive data & high-fold coincidences

World-wide complementary tools and efforts

Thanks to: M. Ciemala, N. Kumar, A. Maj, O. Litaize, S. Péru, A. Lemasson, D. Ramos, M. Rejmund, J. Dudouet, and many more