Independant Fission yields measurement with the

R3B/SOFIA set up at the GSI facility

Julien Taieb – 11/03/2026 - Chamrousse

The SOFIA experiment

1. **Inverse kinematic at relativistic energies**
   - Why?
   - Which setup?
   - Which observables?
   - Which physics cases?
2. **Some results**
   - Study of fission along the uranium chain: high statistics data for application
   - Study of fission along the thorium chain: correlated data to study microscopic effects
   - Study of fission in the sub-Pb : origin of the new island of asymmetric fission

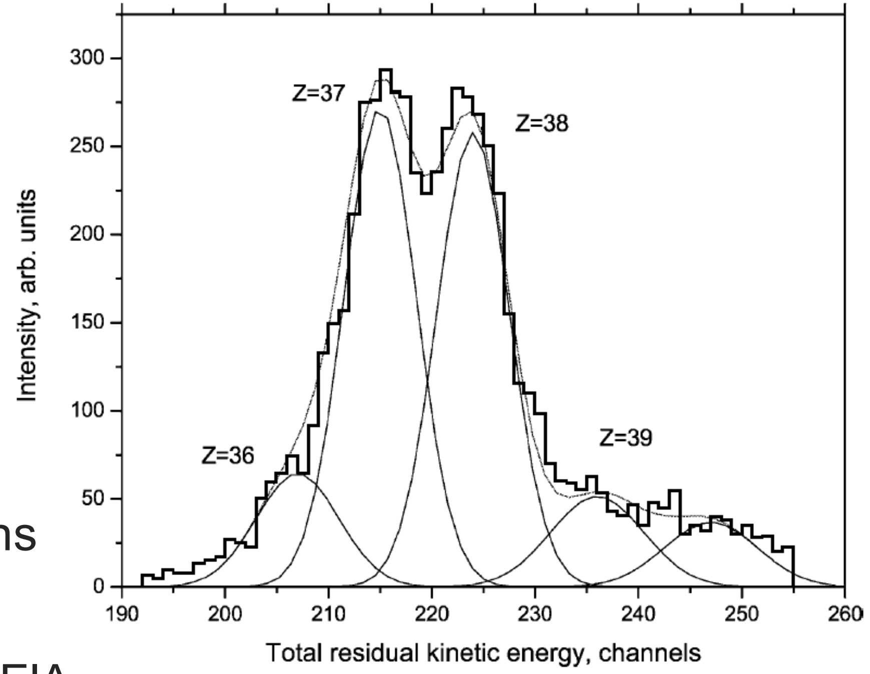
1. **Inverse** kinematics at **relativisitic** energies

An alternative method for fission studies

Limitation of the direct kinematics for independant fission yields

Nuclear charge measurement limited to Z ≤ 40 in direct kinematics

- FF are produced with low energy in the lab frame: problem of ionic charge states
- FF are emitted in 4π: low geometrical efficiency
- Long-lived actinide targets only
- Availibility of actinide targets

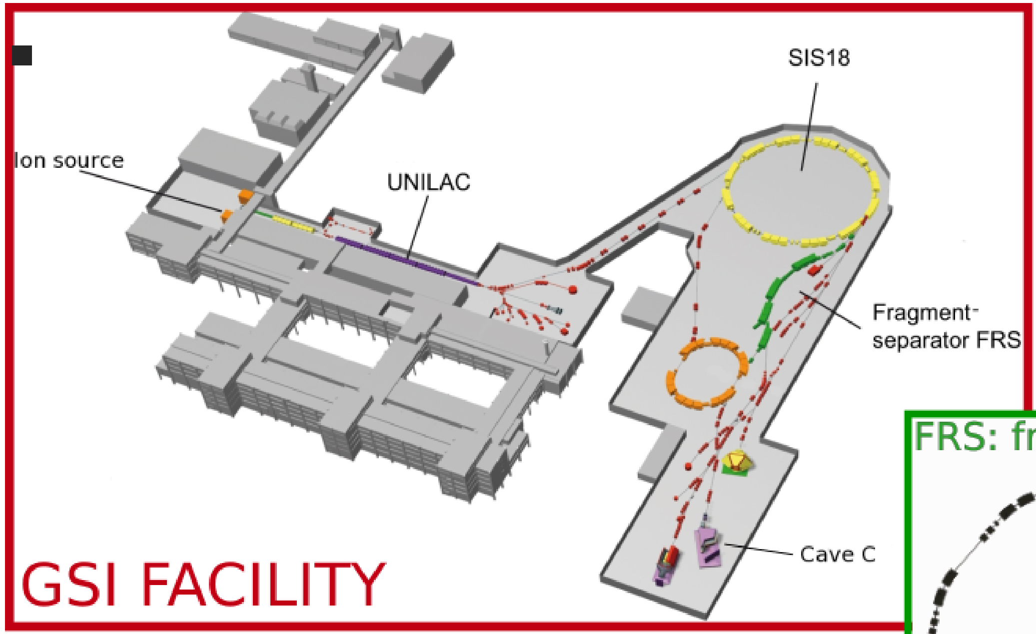


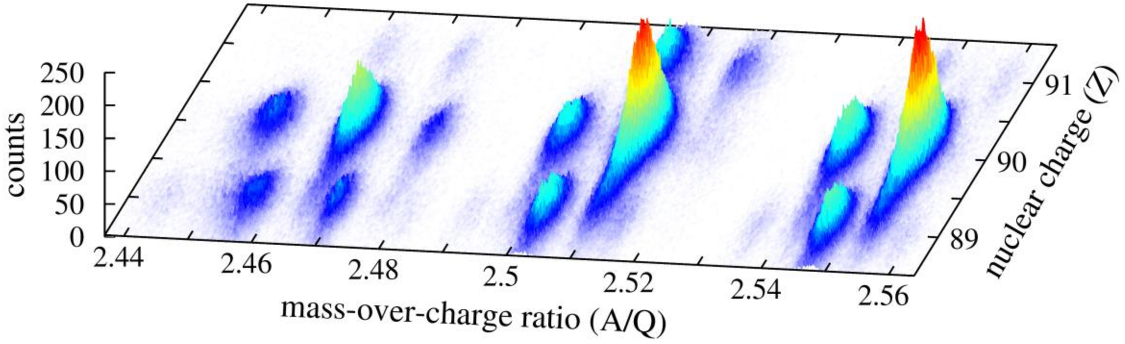
→ (90's)Paradigm change: induce fission reactions of beam ions

→ Current programs at GANIL / VAMOS and GSI / SOFIA

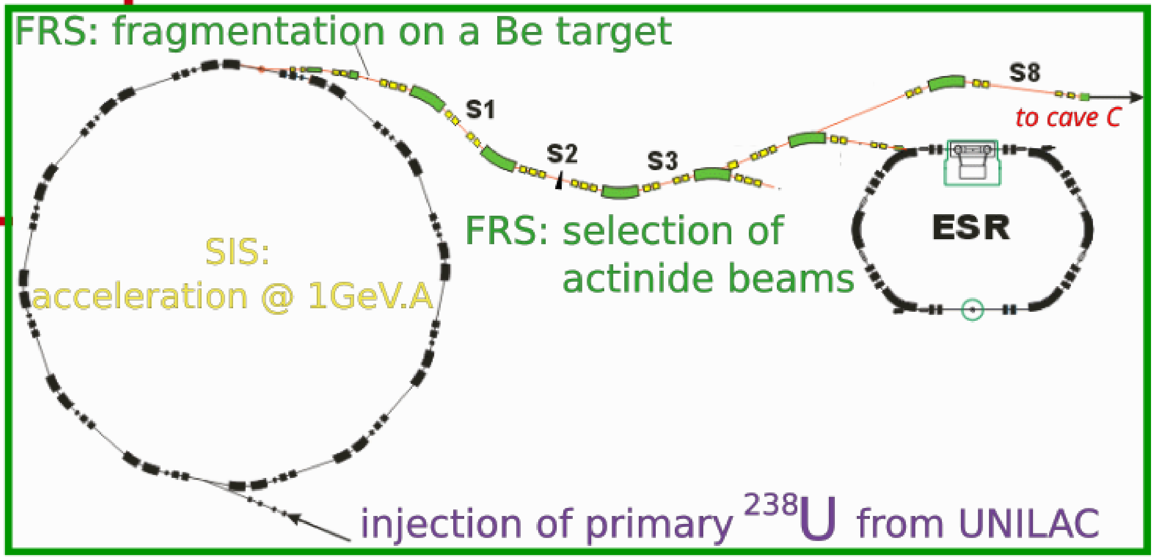
Inverse kinematics: at relativistic energy

At GSI, production of relativistic beam @ FRS (~750 A.MeV)





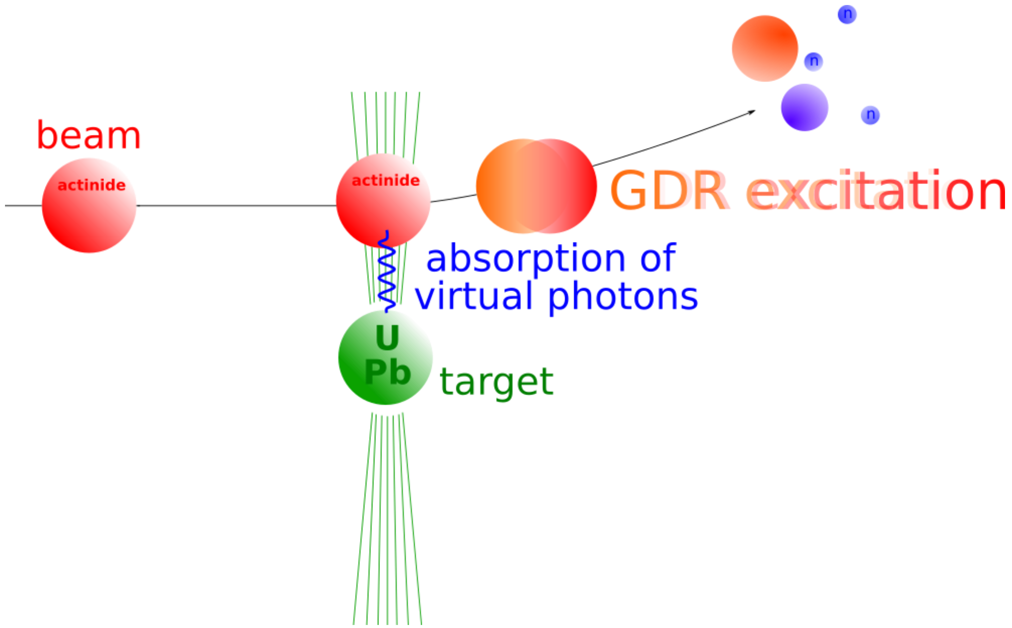
SECONDARY BEAM PRODUCTION

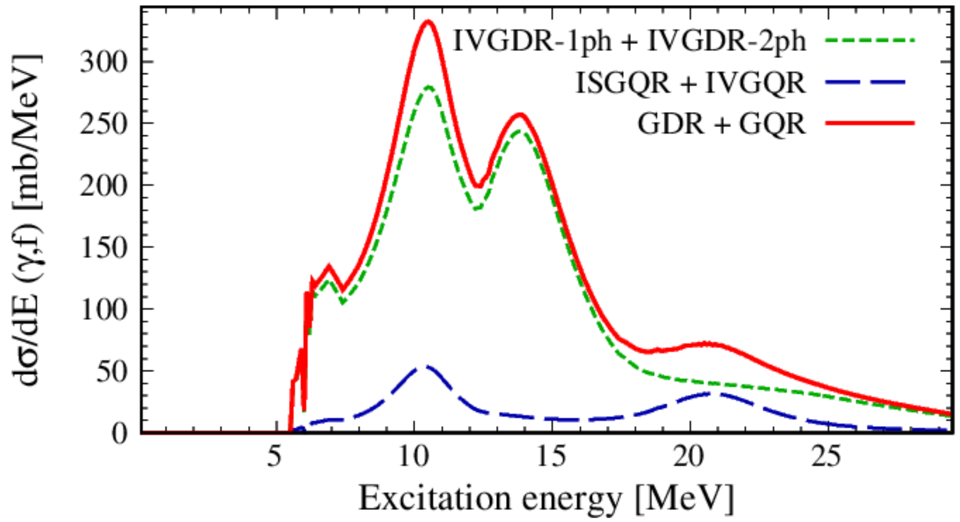


- SIS: ^{238}U primary beam at 1 A.GeV
- FRS: ^{238}U fragmentation on a Be target
- → cocktail beams ~750 A.MeV

Inverse kinematics: Coulomb induced fission

A surrogate reaction with large cross section to study low energy fission at relativistic energies



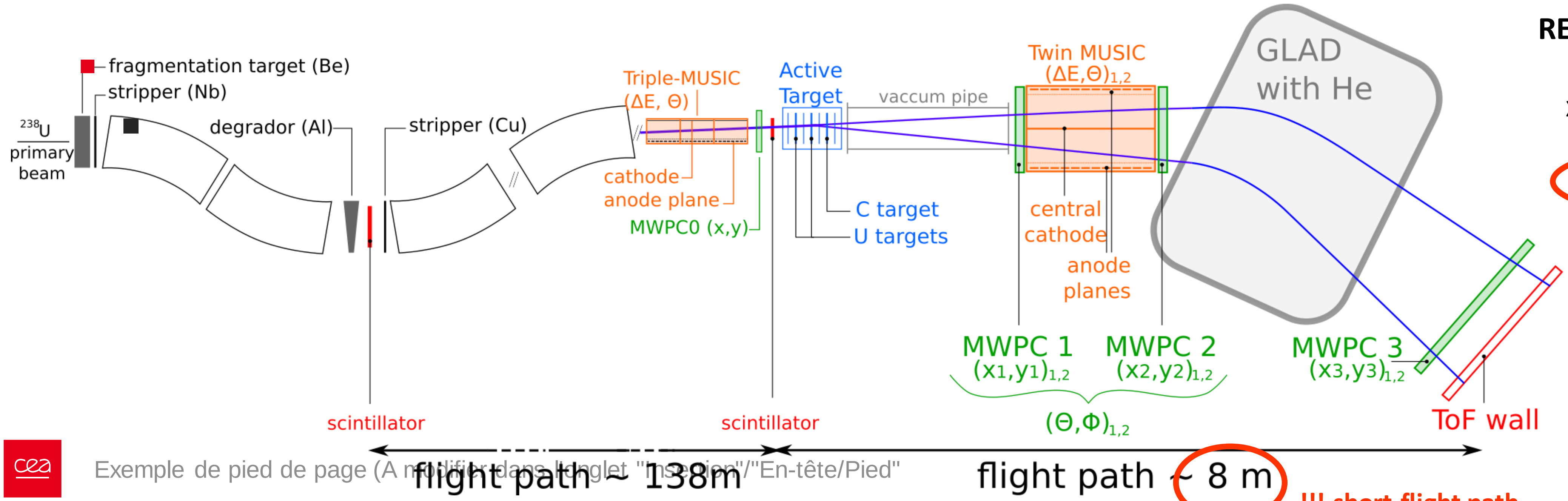


- Average excitation energy: ⟨E*⟩ ~ 14.4 MeV
- Average electromagnetic induced fission: $\sigma^{236}{}_{U(\gamma,f)}$ ~ 2.5 barns
- Surrogate reaction: $^{236}U(\gamma,f) \Leftrightarrow {}^{235}U(n_{9\ MeV},f)$

Inverse kinematics

Unique tool to measure nuclear charges up to the heavy fragments

- At GSI, production of relativistic beam @ FRS (~750 A.MeV)
- Ions are fully stripped: ionic charge directly gives atomic number
- Mass: spectrometer to apply ΔE – Bρ – ToF
- Lorentz boost: ~90% efficiency thanks to the large transmission



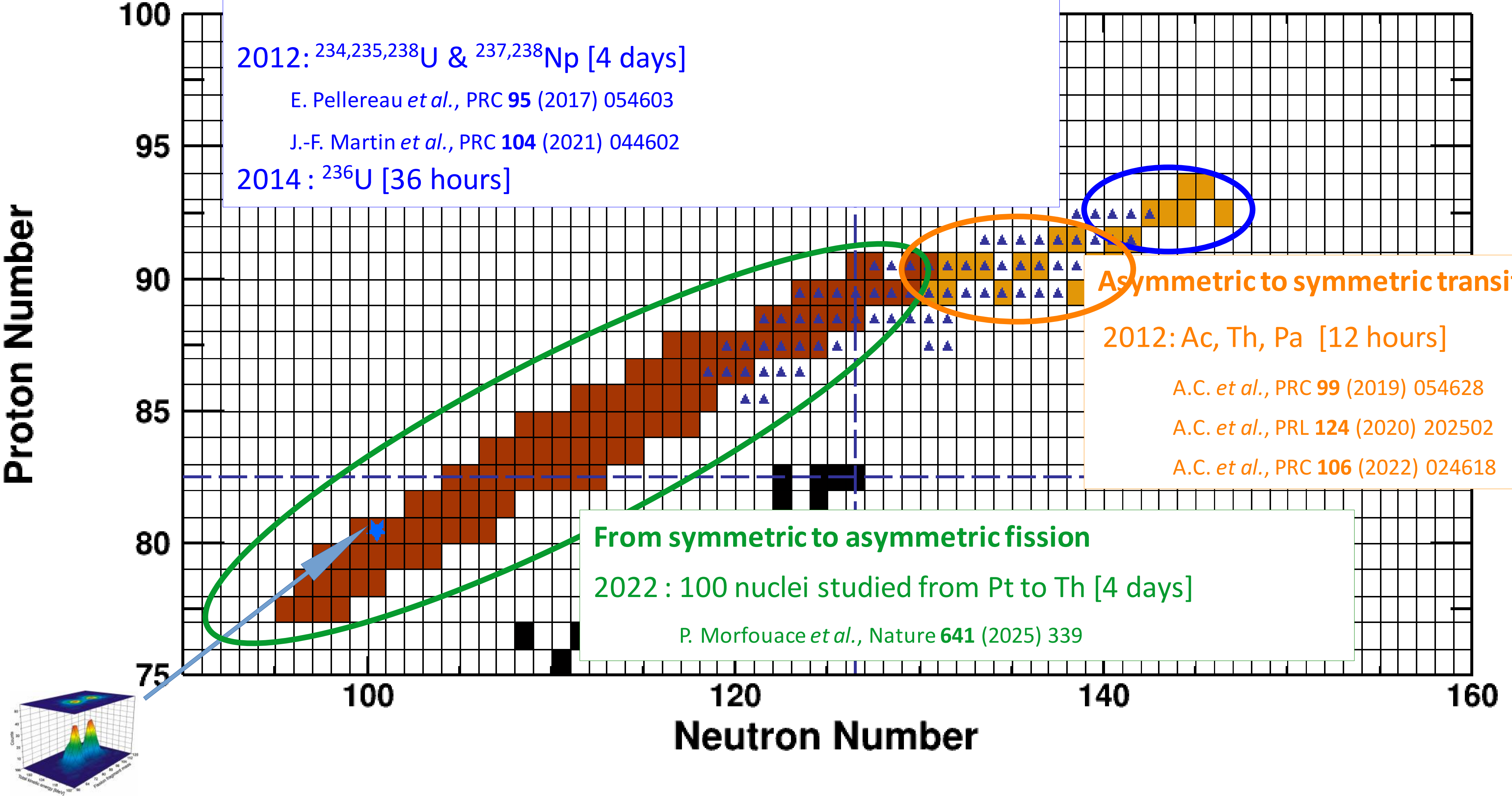
RESOLUTION [FWHM]

x = 100 to 300 µm

ToF = 35 ps

!!! short flight path

The SOFIA experiments



U, Np asymmetric fission studied with high statistics

2012: ^{234,235,238}U & ^{237,238}Np [4 days]

E. Pellereau *et al.*, PRC **95** (2017) 054603

J.-F. Martin *et al.*, PRC **104** (2021) 044602

2014 : ^{236}U [36 hours]

Asymmetric to symmetric transition study

2012: Ac, Th, Pa [12 hours]

A.C. *et al.*, PRC **99** (2019) 054628

A.C. *et al.*, PRL **124** (2020) 202502

A.C. *et al.*, PRC **106** (2022) 024618

From symmetric to asymmetric fission

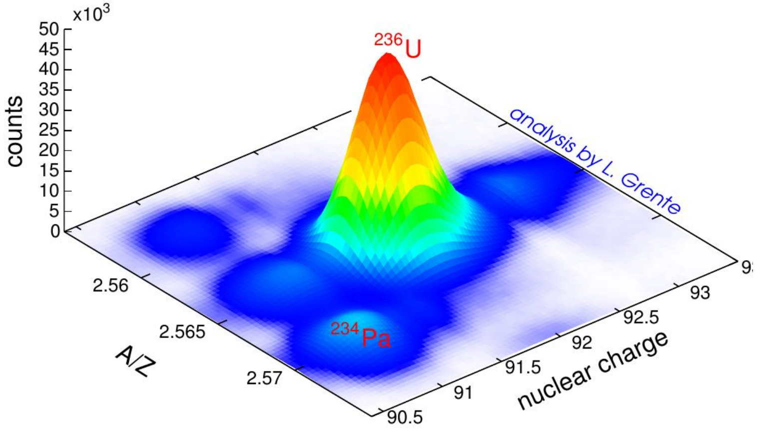
2022 : 100 nuclei studied from Pt to Th [4 days]

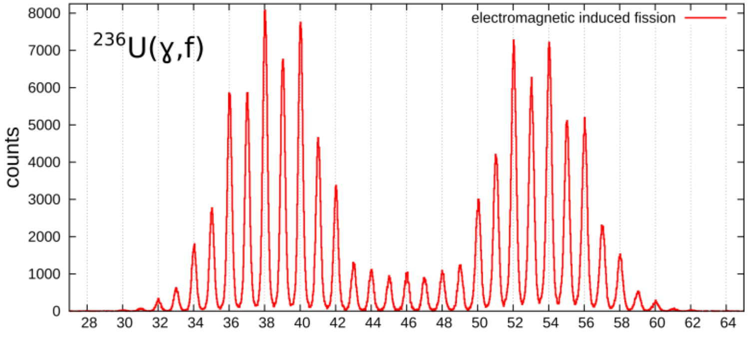
P. Morfouace *et al.*, Nature **641** (2025) 339

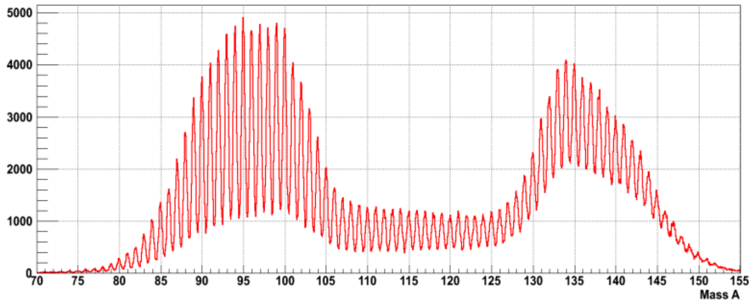
2.1 Along the U-chain

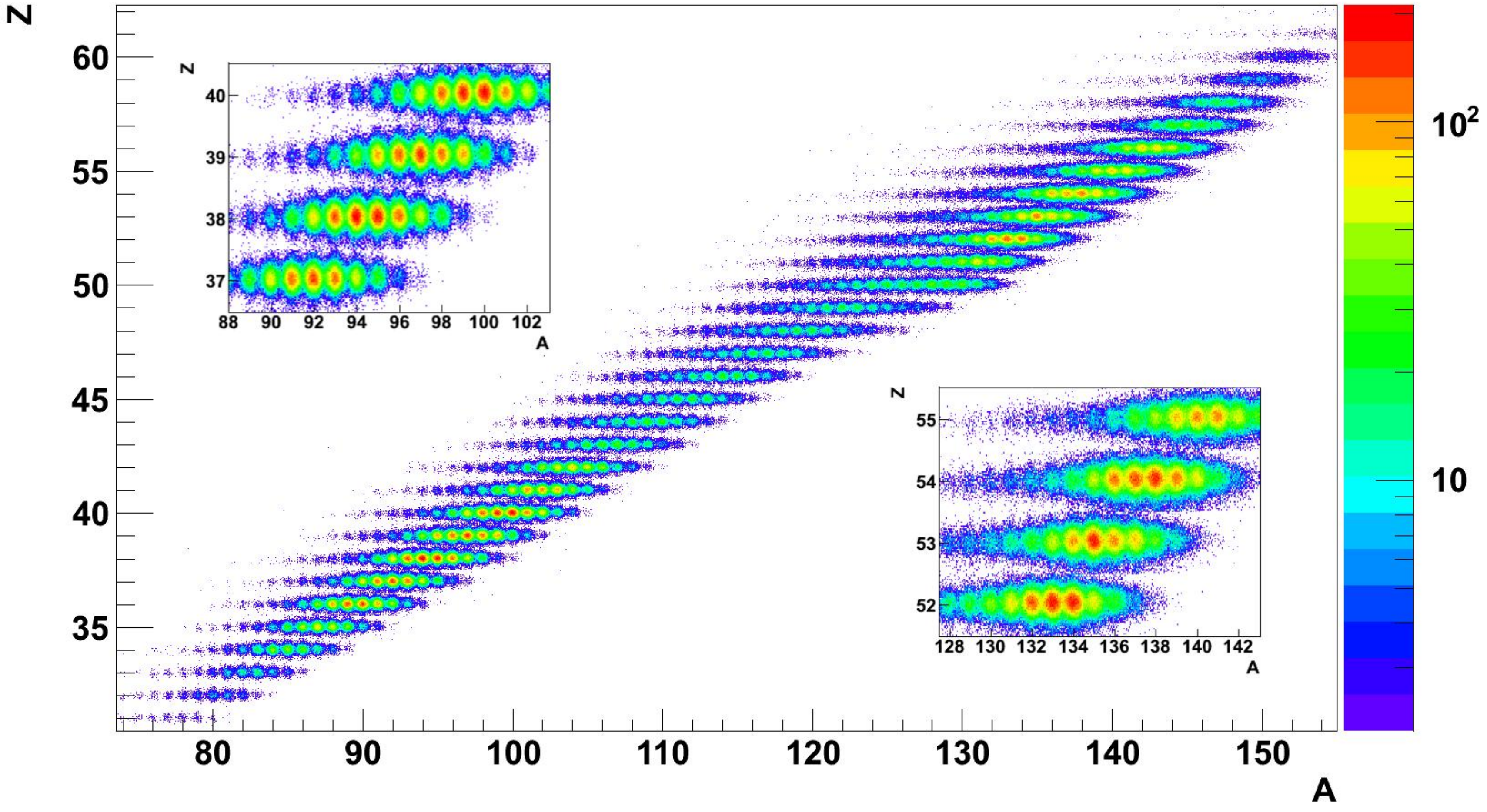
Accurate data for nuclear data need

(Z,A) identification capability [$^{236}U(\gamma,f)$]

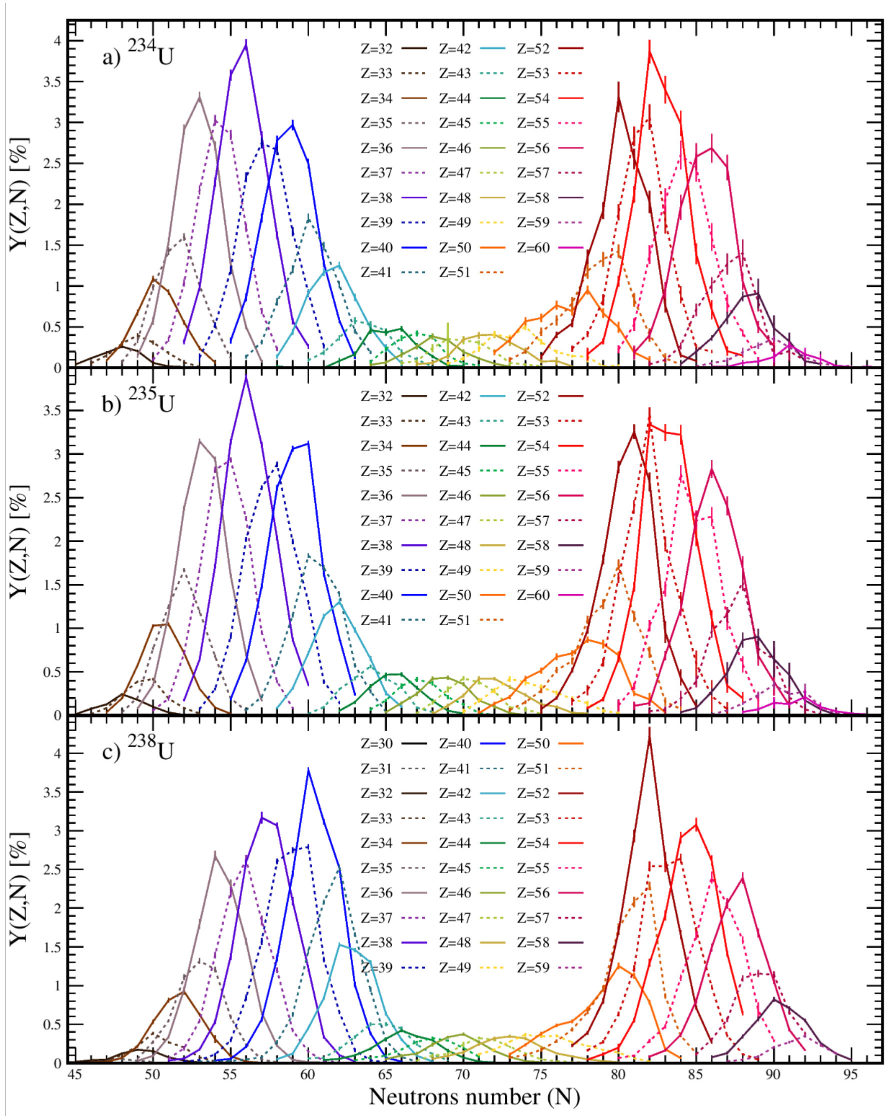


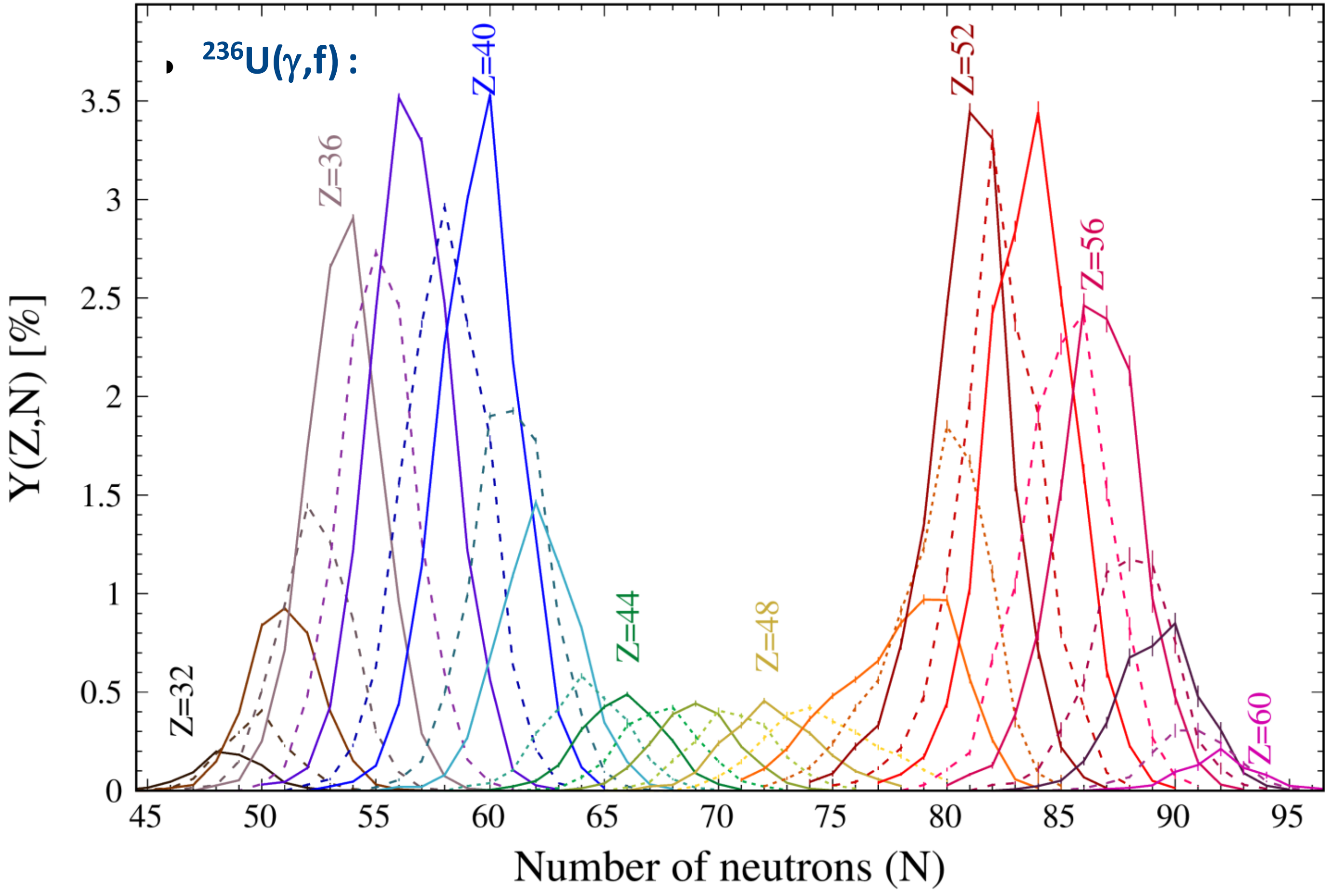






Isotopic yields





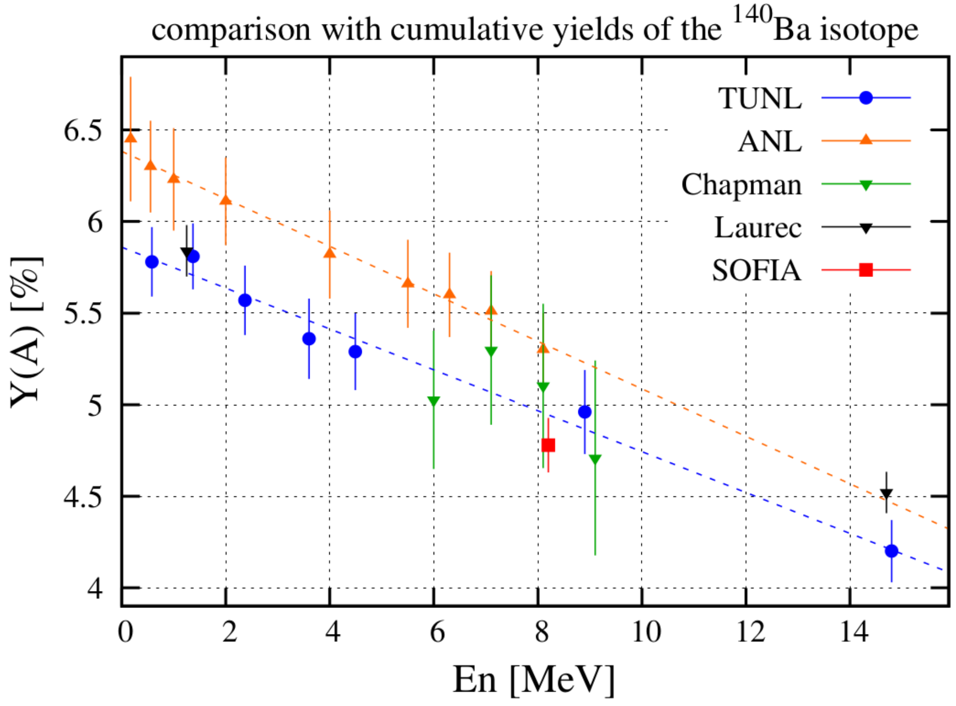
$0.5 \leq \sigma_Y \leq 1.5$ %

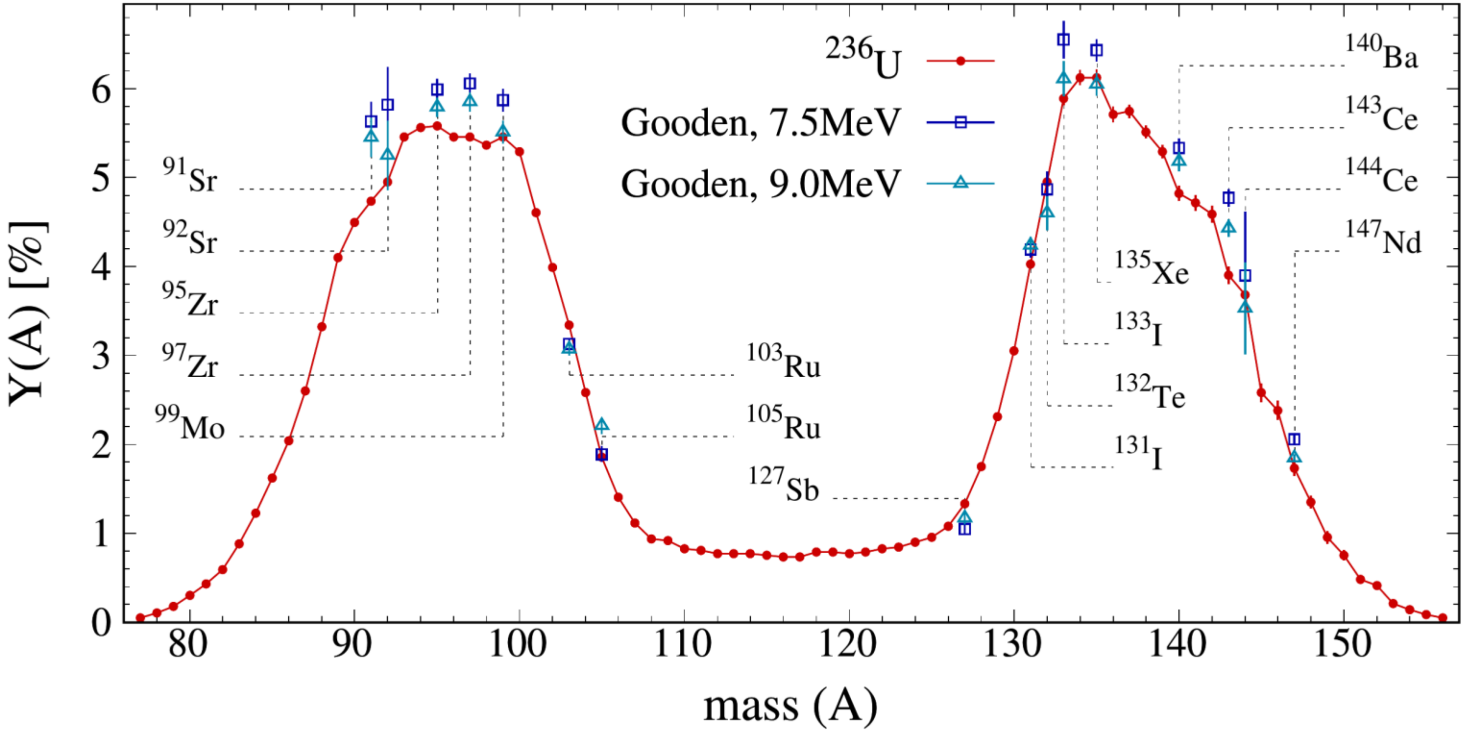
$1.3 \leq \sigma_Y \leq 3.5$ %

Analysis by L. Grente, J-F. Martin, E. Pellereau (CEA/DAM/DIF)

Isobaric yields (II)

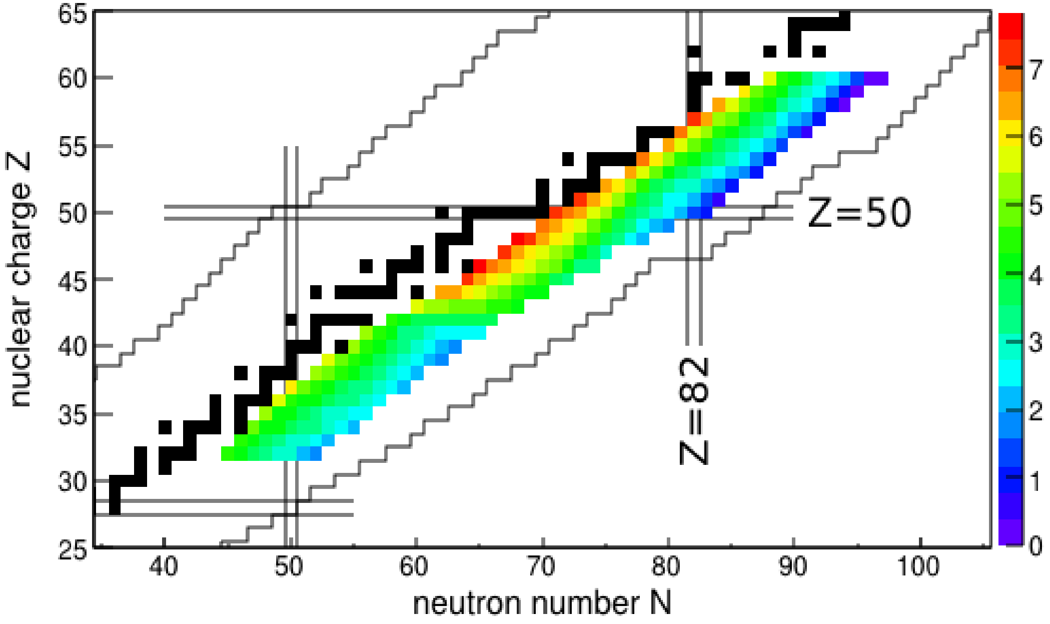
$^{236}U(\gamma,f)$ from SOFIA compared to $^{235}U(n,f)$ cumulative yields

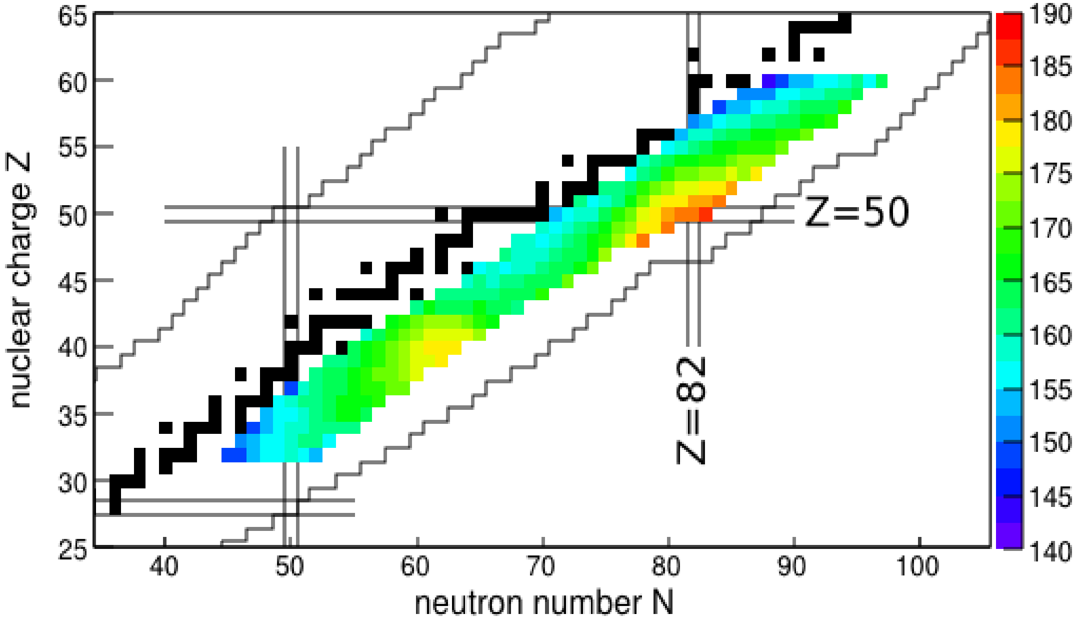




Analysis by L. Grente (CEA/DAM/DIF)

Beyond the yields: $\langle\nu_{tot}\rangle$ & TKE for $^{235}U(\gamma,f)$





2.2 Along the Th-chain

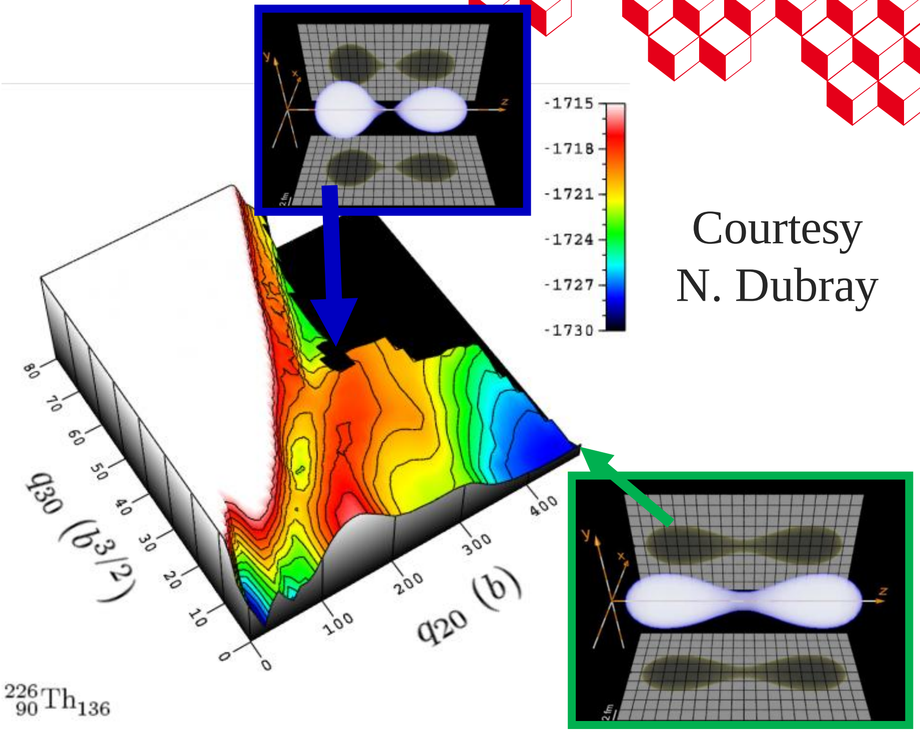
Correlated data to study microscopic effects

⟨ν_{tot}⟩ to probe scission configuration

Three fission modes in the uranium region

- Proposed by Brosa *et al.*: 2 asymmetric, 1 symmetric
- One path on PES per mode due to different shell effects
- Each path reach the scission line at specific (Q_{20},Q_{30})

Importance of correlated data: Yields, TKE, ν, E*



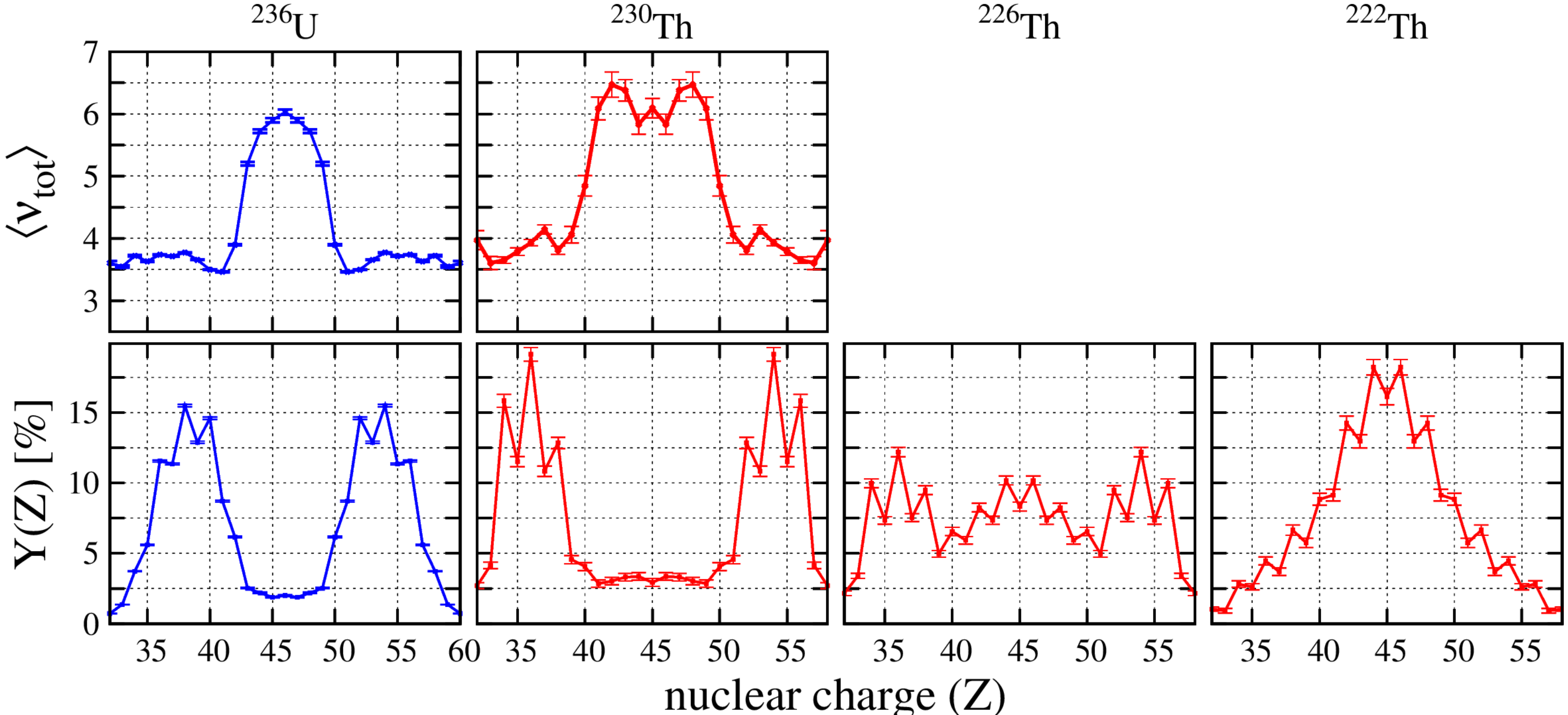
Courtesy N. Dubray

STANDARD 1	STANDARD 2	SUPER-LONG
ALMOST SPHERICAL HEAVY FF	interpreted as OCTUPOLE FF	HIGHLY DEFORMED FF
influence of (Z=50,N=82) shells	octupole p-shells in heavy FF	shell effects washed-out with E*
compact configuration	main mode	deformed configuration
High TKE, low ν		**LOW TKE, HIGH ν**

Correlation Y(Z) vs ⟨ν_{tot}⟩

For neutron deficient neutron isotopes ...

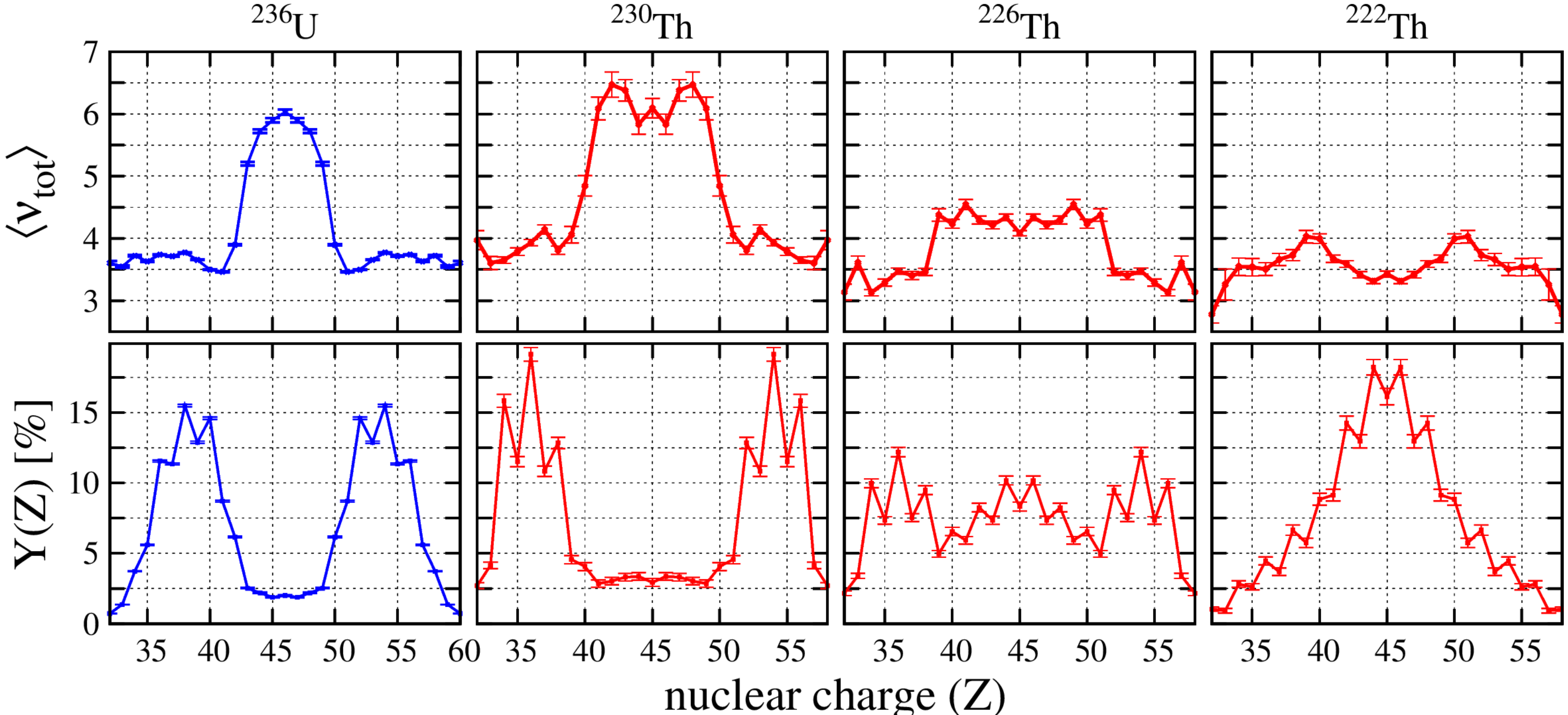
- Symmetric fission is becoming more and more important
- Odd-even staggering remains
- Correlated data helps to probe the scission configuration of the fission modes



Correlation Y(Z) vs ⟨ν_{tot}⟩

For neutron deficient neutron isotopes ...

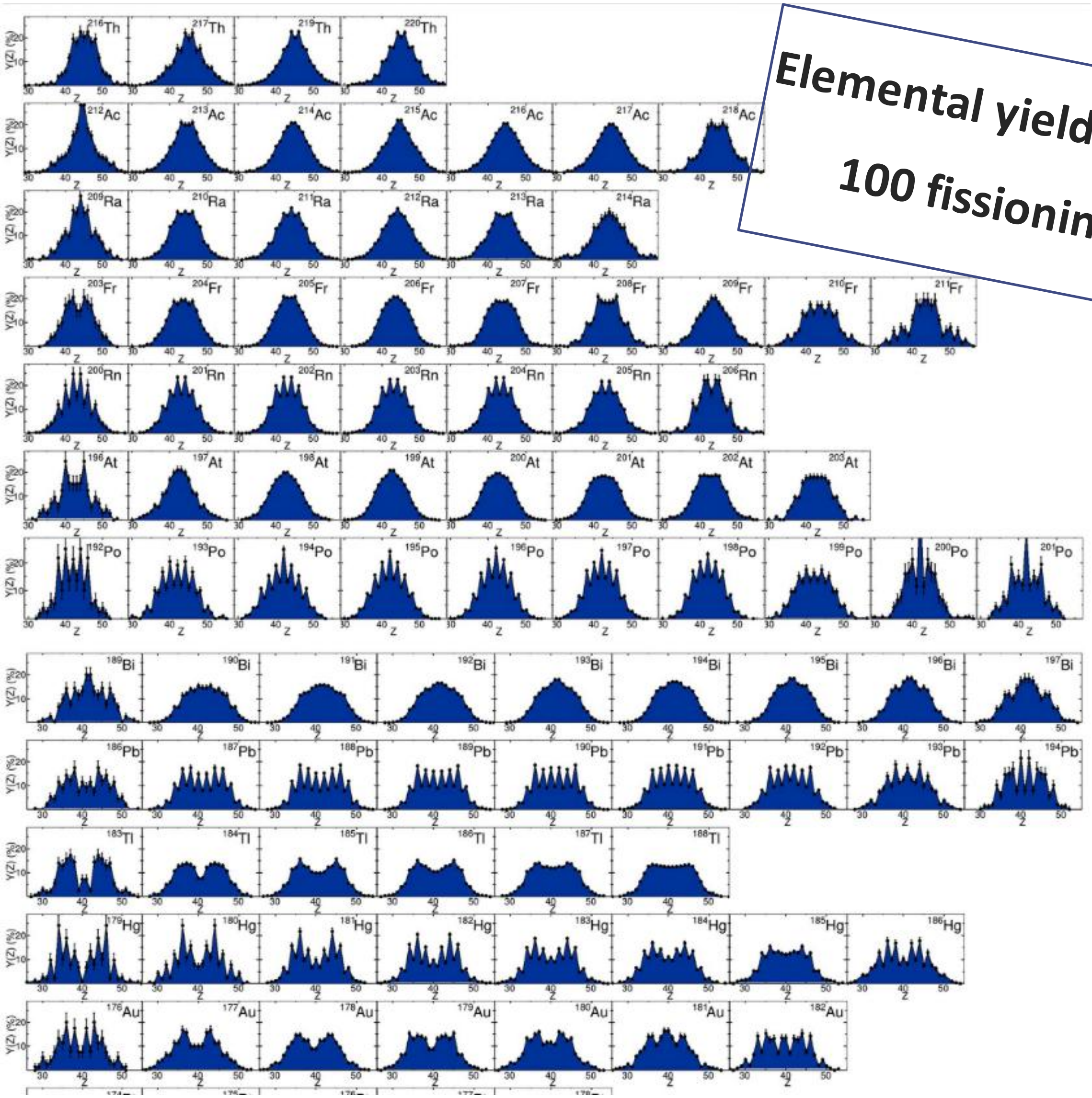
- Symmetric fission is becoming more and more important
- Odd-even staggering remains and ⟨ν_{tot}⟩ drop for symmetric fission of around 2.7 neutrons
- **New symmetric compact mode**



2.3 From Pb to Th

Origin of the asymmetric fission island

Th→ Pb : asymmetric to symmetric fission



Elemental yields of more than 100 fissioning systems

Nature volume 641, pages 339–344 (2025)

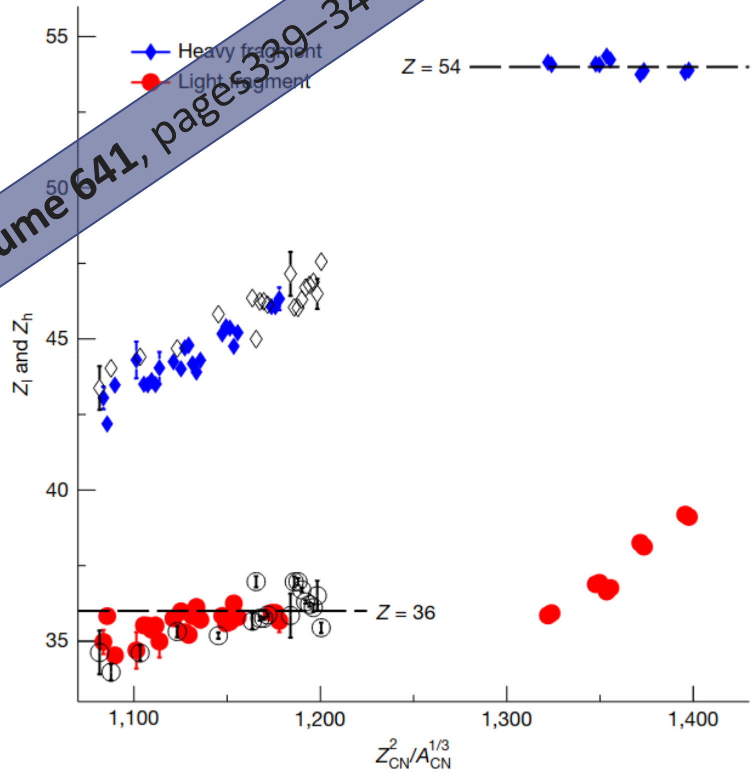
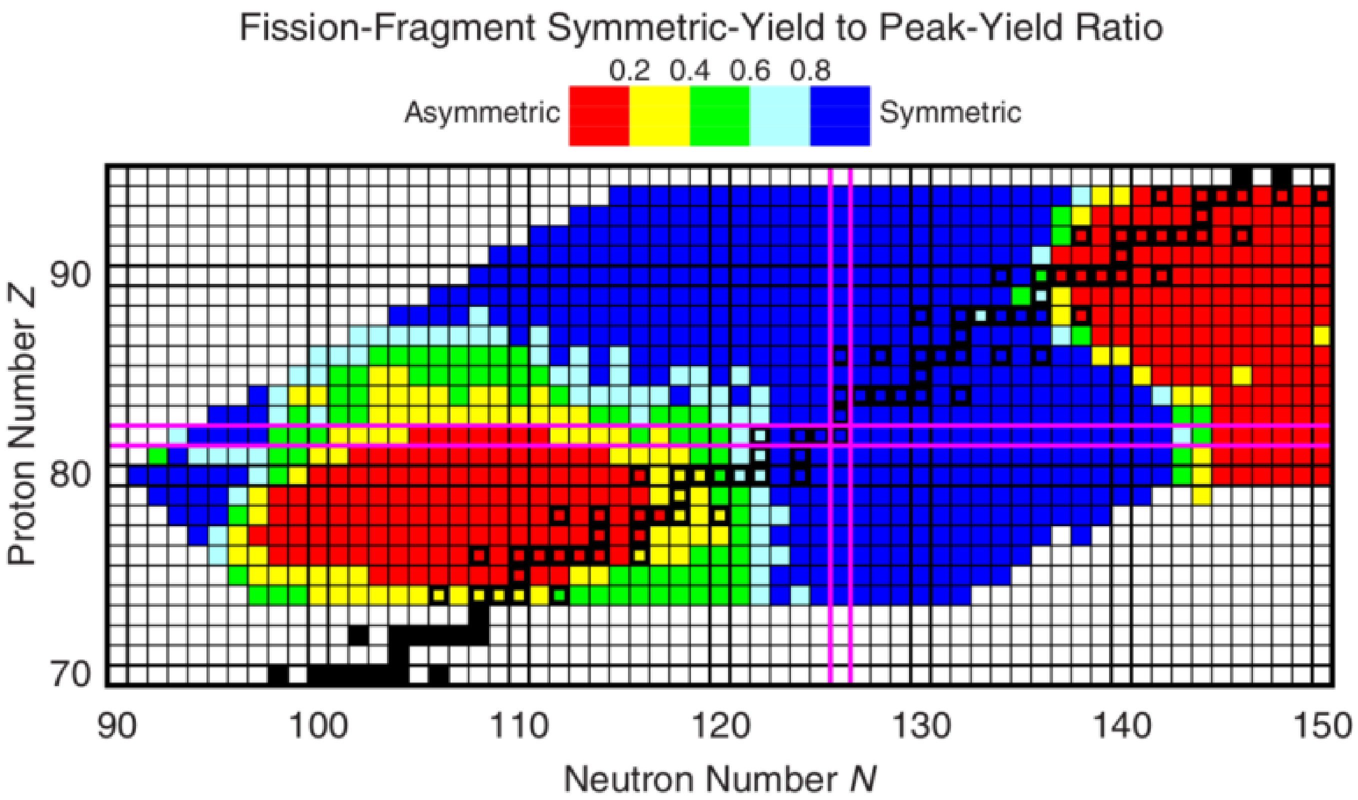


Fig. 4 | Evidence of $Z = 36$ stabilization of the light fragments. Light (red filled circle) and heavy (blue filled diamonds) charge fragments from the asymmetric fission islands as a function of the Coulomb parameter of the compound nucleus when $A_{Gauss} > 1$. The open symbols represent the asymmetric fission mode for symmetric fission when $A_{Gauss} < 1$. These have distinctly asymmetric tails. The data clearly display the well-known $Z_h \approx 54$ stabilization for heavy fissioning systems as well as new $Z_l \approx 36$ stabilization for pre-actinides in the new island of asymmetric fission. Z_{CN} and A_{CN} correspond, respectively, to the charge and mass of the fissioning system. When the error bars (1σ) do not appear, they are smaller than the data points.

Analysis by P. Morfouace (CEA/DAM/DIF)

Th→ Pb : asymmetric to symmetric fission

P. Moller J. Randrup., PRC **91** (2015) 044316



SOFIA (2021)

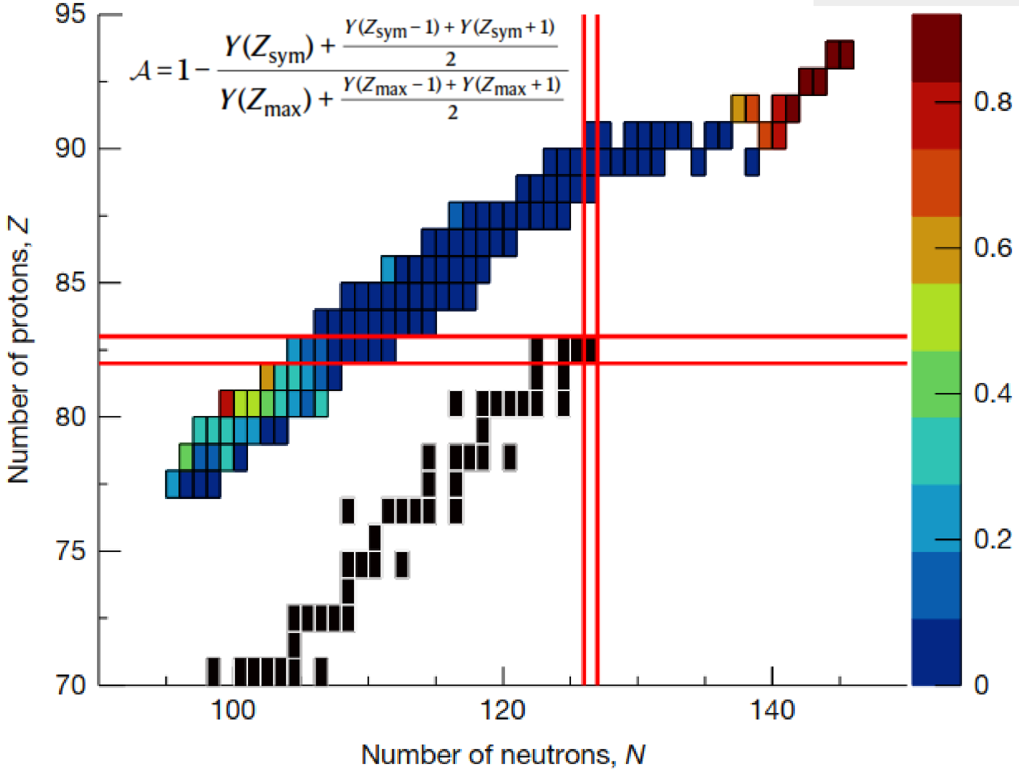


Fig. 2 | Map of the evolution of asymmetric fission. Experimental asymmetry as defined in equation (1). The data showing the asymmetric fission island in the actinide region are taken from previous experimental data with the SOFIA set-up (see text for details)[39,40]. All other nuclei are from the current dataset, and their charge yields are displayed in Extended Data Fig. 4. The black squares represent the valley of stability, and the red lines show the magic numbers $Z = 82$ and $N = 126$.

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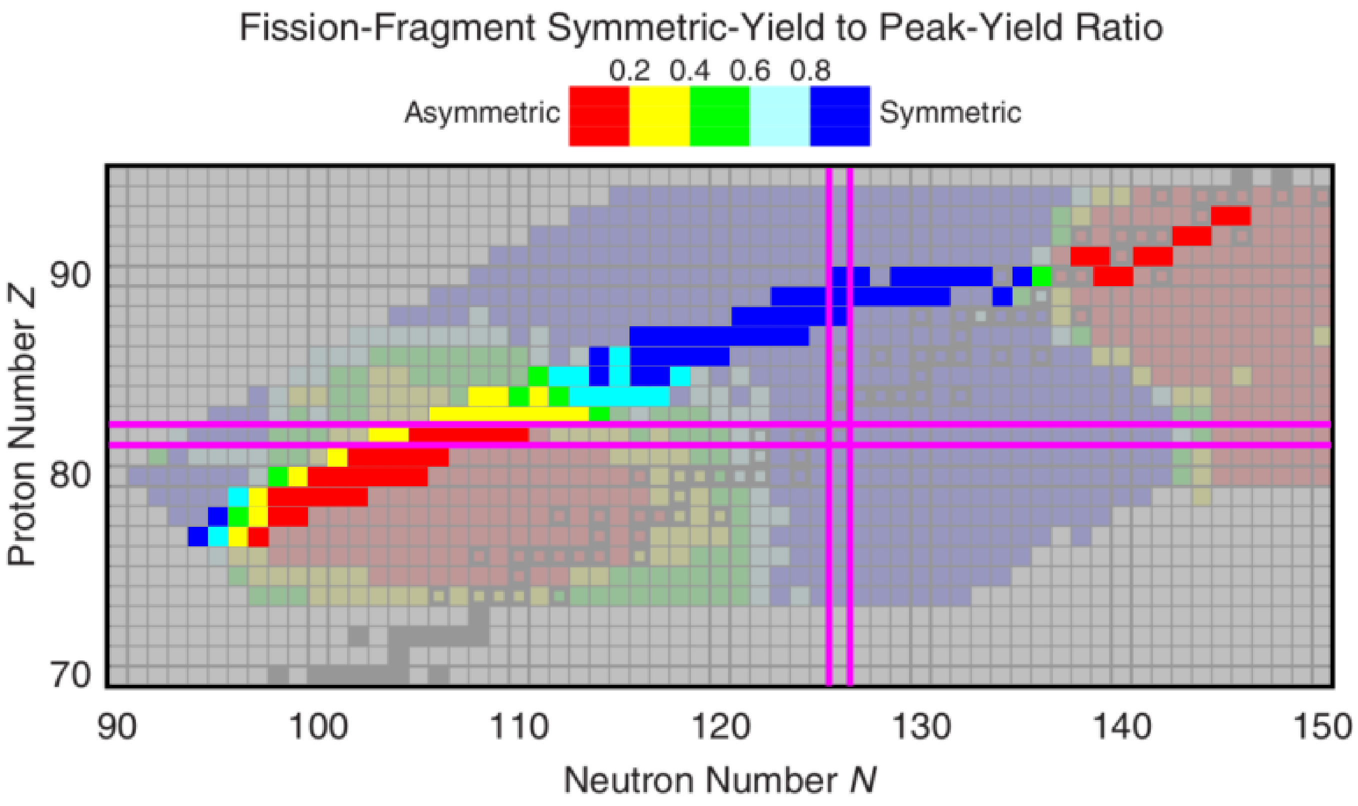

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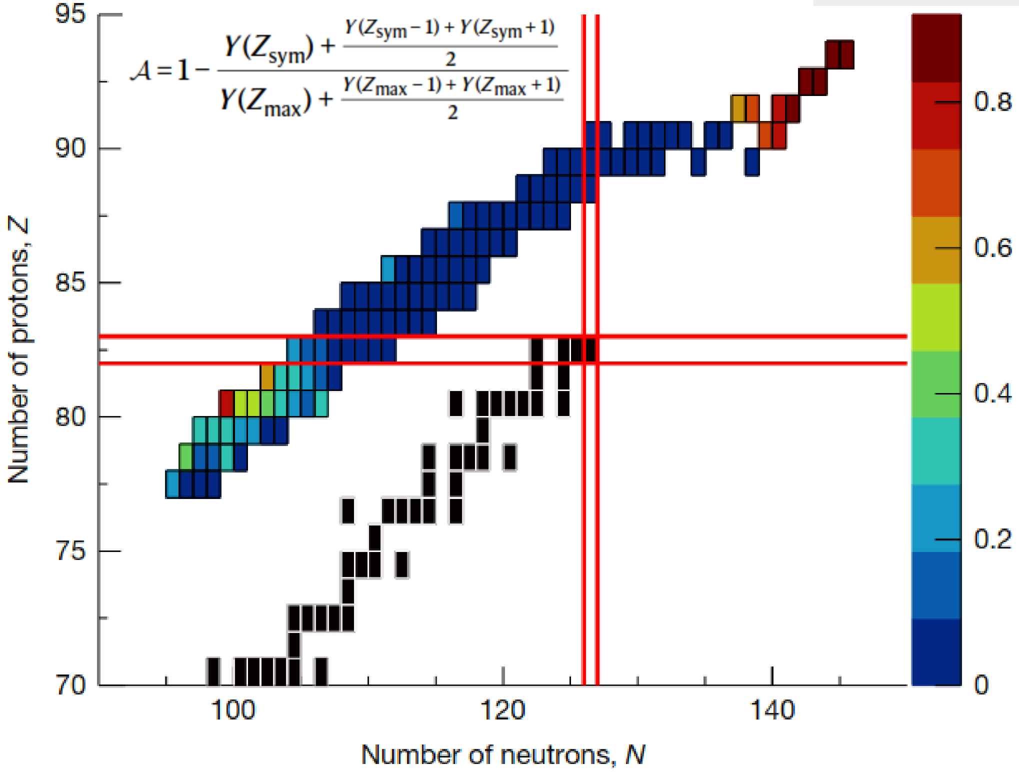

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Analysis by P. Morfouace (CEA/DAM/DIF)

Fission yields measurement with SOFIA

Inverse kinematics at relativistic energies

Isotopic identification of both fission fragments in coincidence

High statistics data for accurate measurement

BUT : Excitation energy distribution is not measured

Mass of the compound nucleus limited to 238

Set-up: SOFIA set up combined with the FRS spectrometer

ΔE – $B\rho$ – ToF method to identify in (Z,A) beam and **both FF**

Observables:

$Y(Z)$, $Y(A_{post})$, $Y(N_{post})$, $Y(Z,A_{post})$, $\langle \nu_{tot} \rangle$, $\langle TKE \rangle$

Physics cases:

for nuclear data need & basic science

Setup for the inverse kinematics at relativistic energies

Production of radioactive relativistic beams at GSI/FRS

Study of low energy fission (E*~14 MeV) induced by Coulomb excitation

(Z,A) identification of incoming beam + 2 FF in coinc

Fission yields $Y(Z)$, $Y(N_{post})$, $Y(A_{post})$, $Y(Z,A_{post})$

Total prompt-neutron multiplicity + TKE

In the following, selection of few results

Fission observables

Measurement after the prompt neutron emission and prior to any β-decay

- **Fission yields** from the isotopic identification fission fragments

  Y(Z), Y(Apost), Y(Npost), Y(Z,Apost)

  ⇨ Z : direct measurement of the number of proton per fragment at scission

  ⇨ Npost : should be interpreted taking into account the evaporation phase

- **Total prompt-neutron multiplicity** from the mass measurement of beam and FF

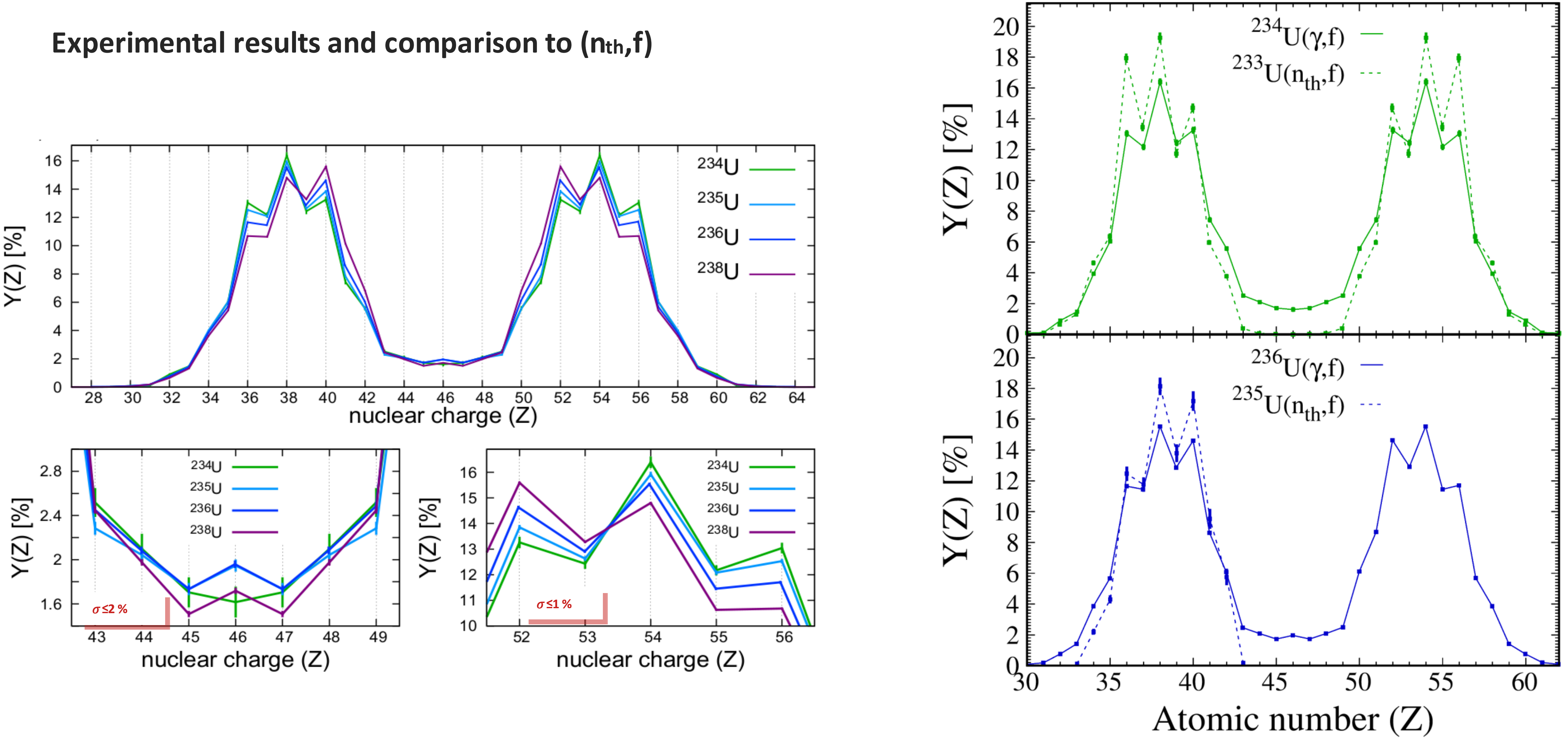
  $\mathbf{V}_{tot} = A_{beam} - A_{FF1} - A_{FF2}$

- **Total kinetic energy** from the velocity vectors reconstruction

  Need assumption of **V**(A) + energy loss estimation in material

Elemental yields

Experimental results and comparison to (n_{th},f)



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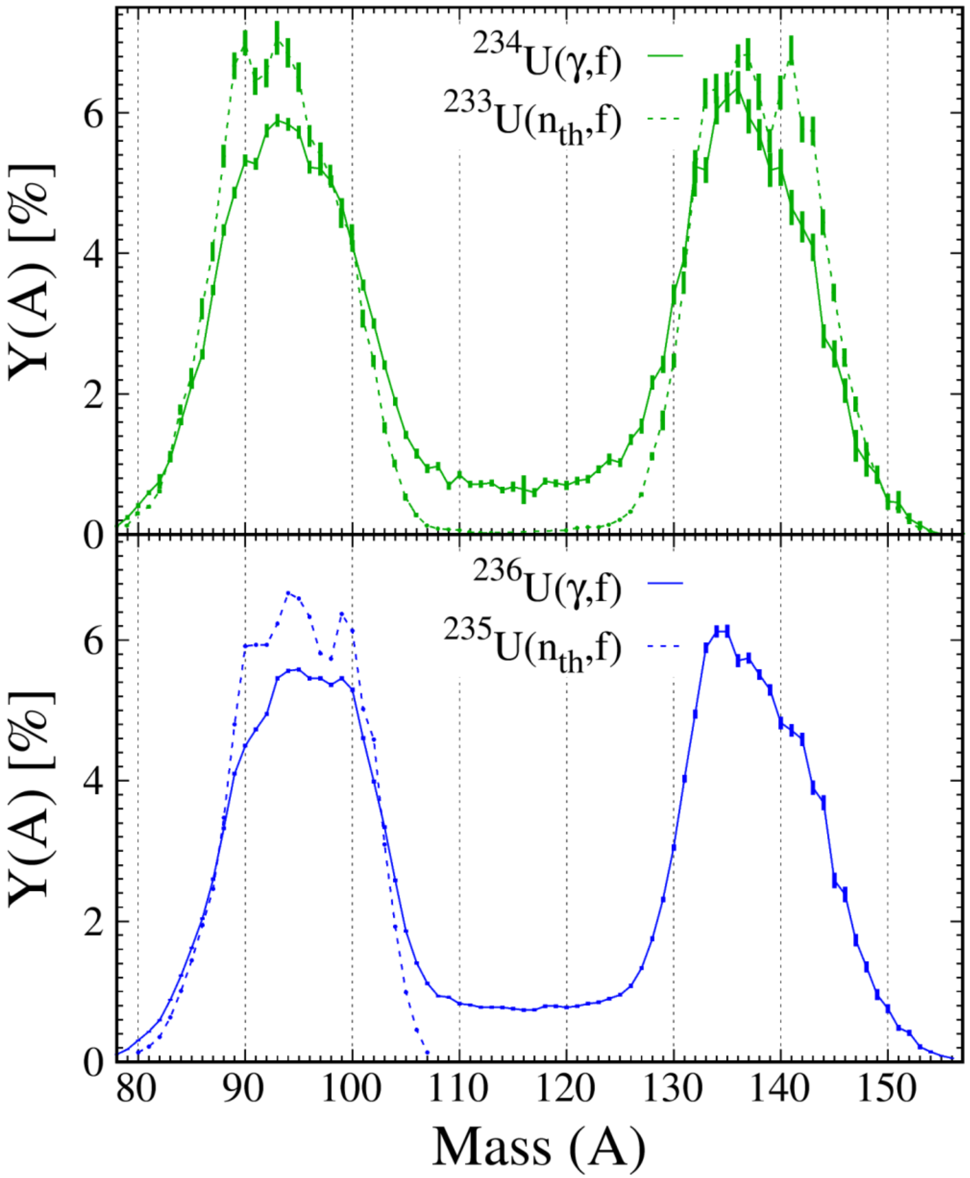
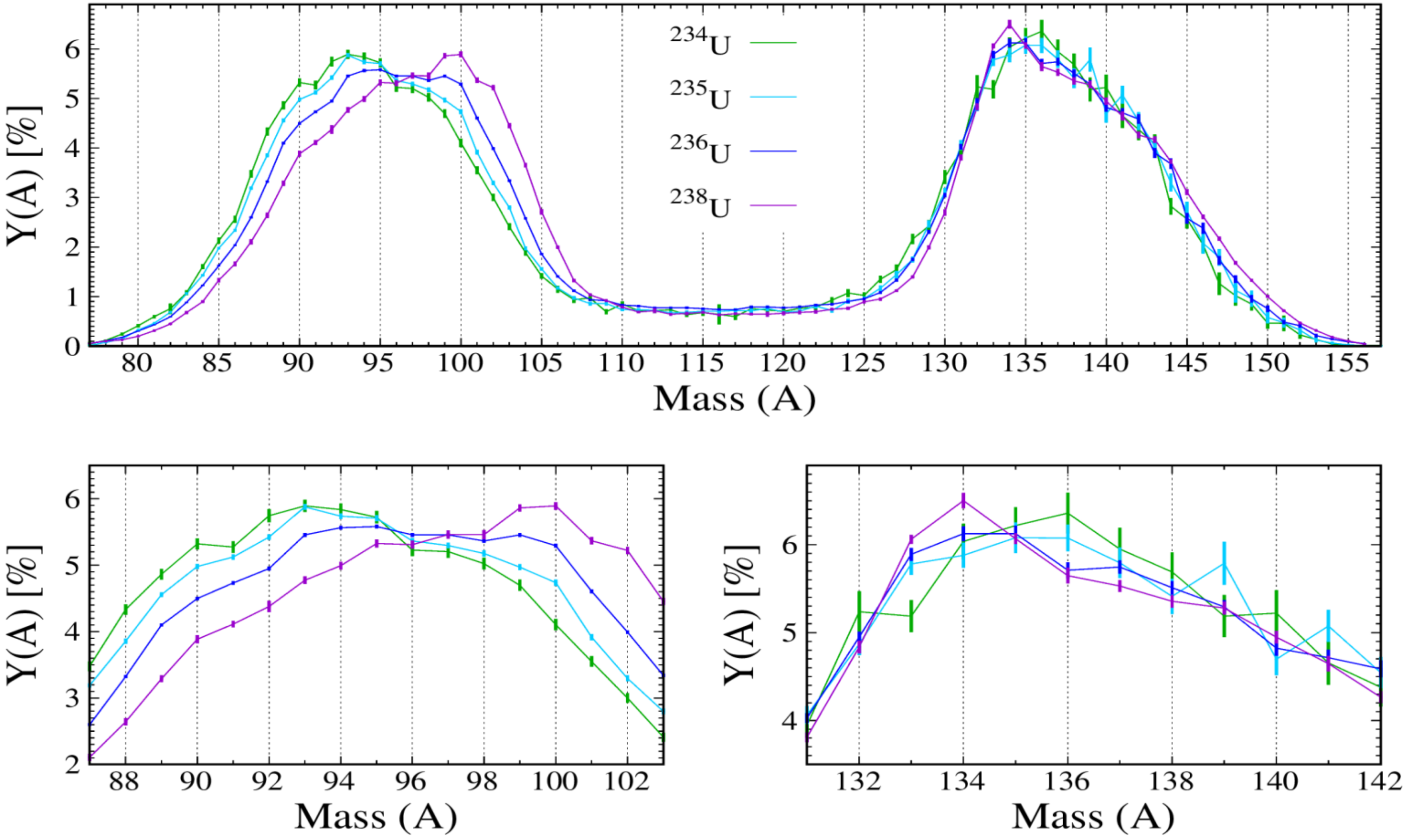


^{234}U(γ,f)
^{233}U(n$_{th}$,f)
^{236}U(γ,f)
^{235}U(n$_{th}$,f)
Y(A) [%]
Mass (A)

Isobaric yields (I)

Experimental results and comparison to (n_{th},f)



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