Fission yields measurement in inverse kinematics at relativistic energies

The R3B/SOFIA experiments at the GSI/FRS facility

FIESTA Workshop

Los Alamos, USA

November 2024

A. Chatillon (CEA/DAM/DIF) for the R3B collaboration

The SOFIA project

1. Inverse kinematic at relativistic energies
   - Pros & cons
   - 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

1. Inverse kinematics at relativisitic energies

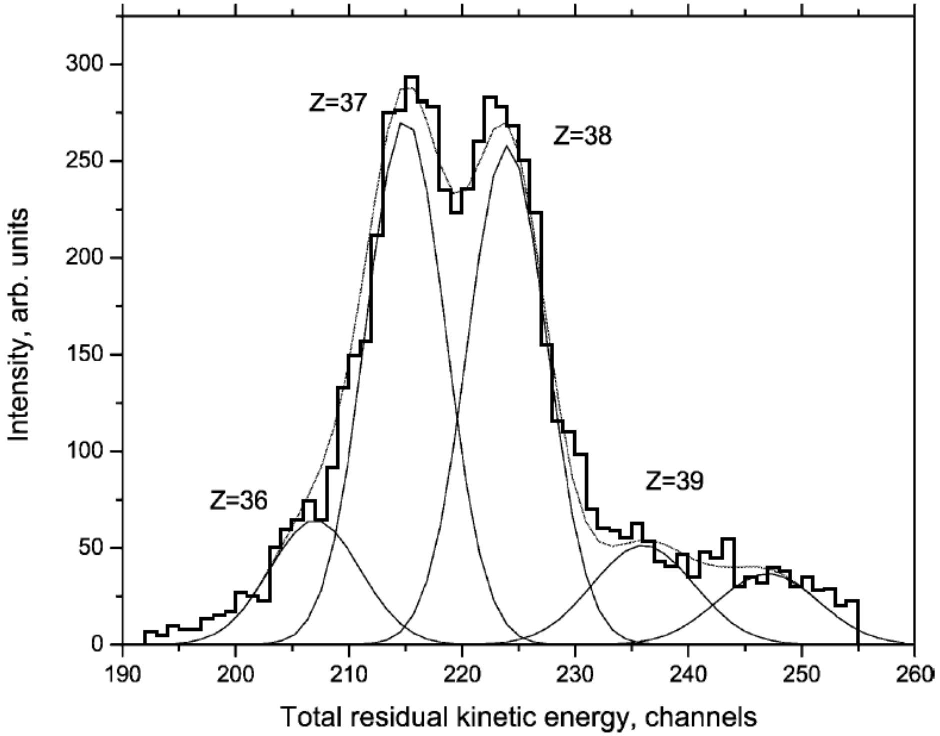
An alternative method for fission studies

Limitation of the direct kinematics for fission yields

Nuclear charge measurement limited to Z ≤ 40 in direct kinematics

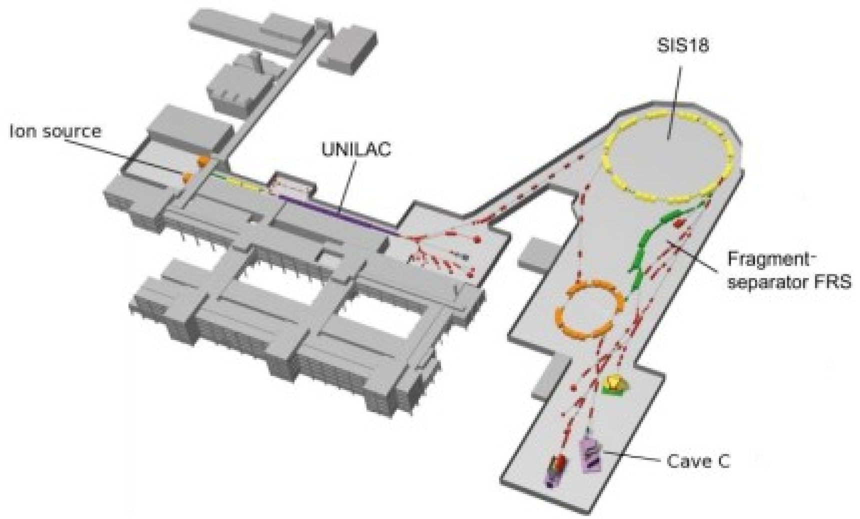
- DIRECT KINEMATICS: n-, p-, LCP-beam on an actinide target (at rest)
- FF are emitted with low energy in the lab frame: problem of ionic charge states
- FF are emitted in 4π: low geometrical efficiency
- Long-lived actinide targets only
- Availibility of actinide targets

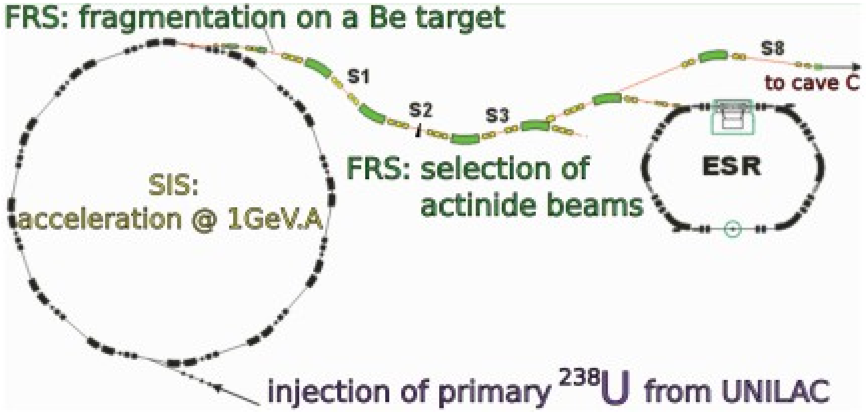
D. Rochman et al., Nucl. Phys. A 710 (2002) 3-28



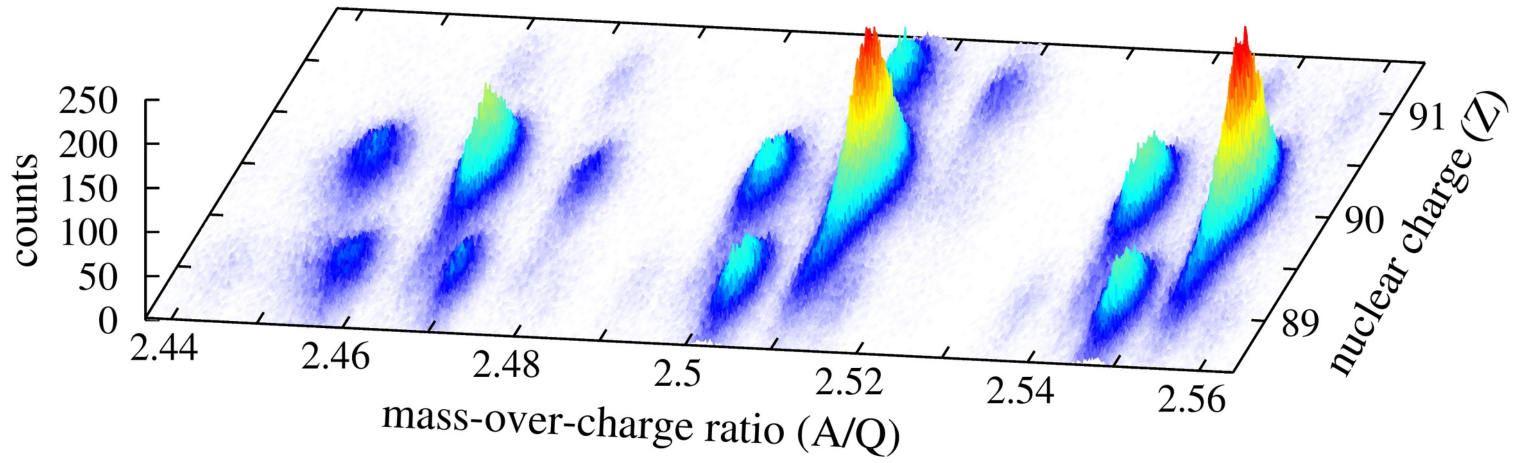
The inverse kinematics at **relativistic** energies (I)

Production of radioactive fissioning nuclei in-flight by fragmentation





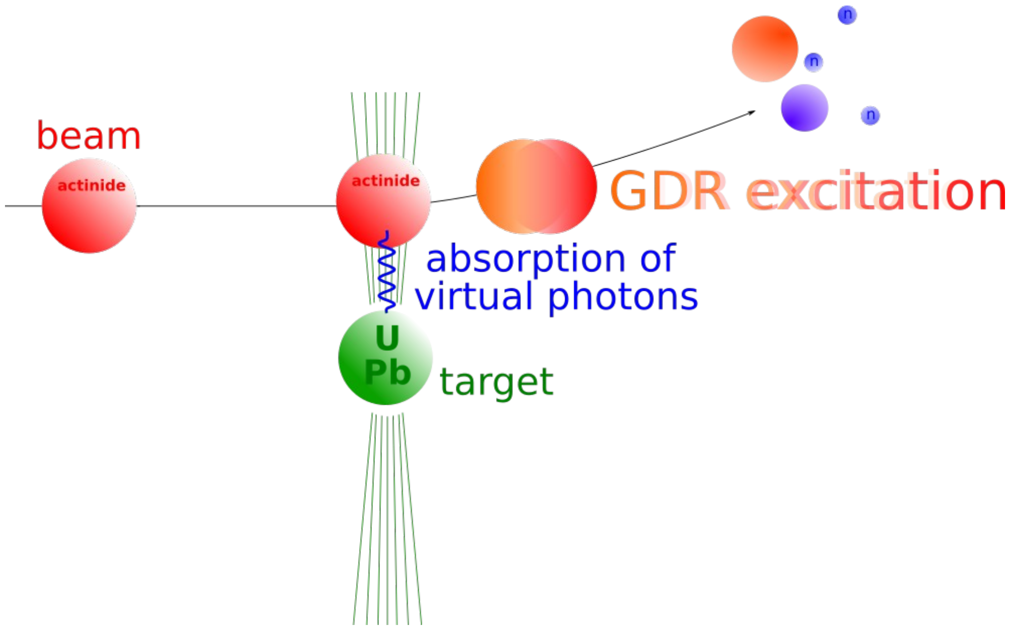
- @GSI, production of primary beam up to ^{238}U at 1 A.GeV
- @FRS, fragmentation of ^{238}U on a Be target and production of cocktail beams ~750 A.MeV with a selection in (Bρ,ΔE) around (A/Z , Z)

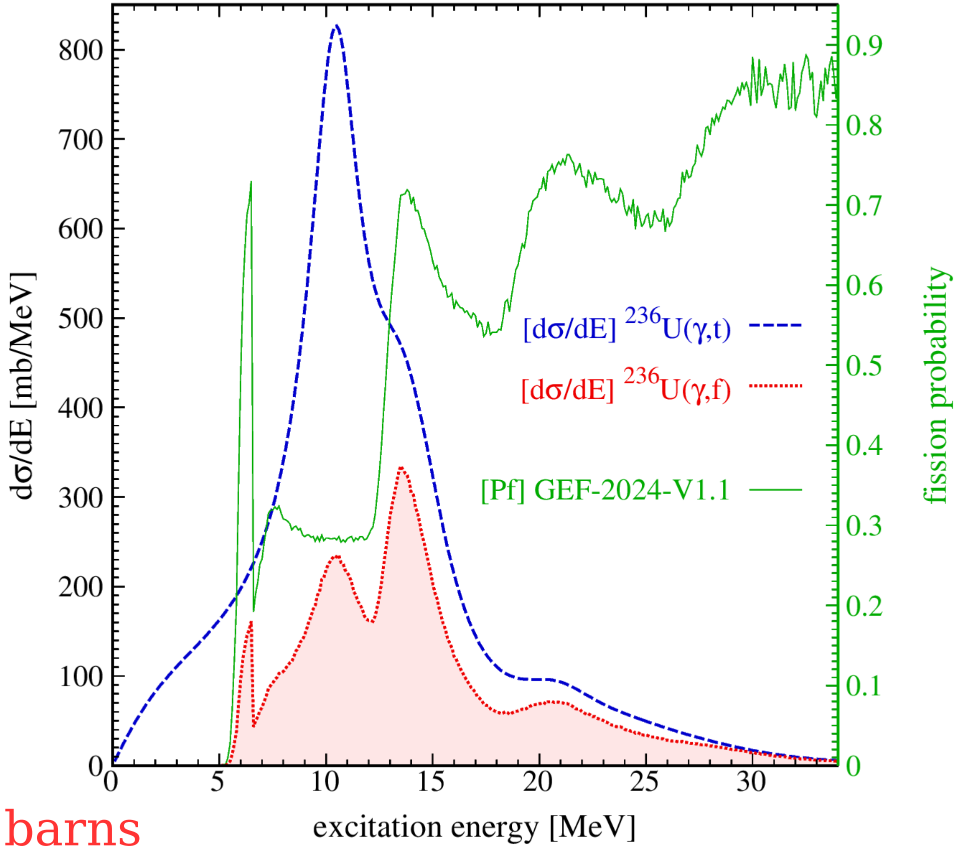


Identification plot for 3 different FRS settings around ^{222}Th, ^{226}Th and ^{230}Th

Electromagnetic induced fission

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



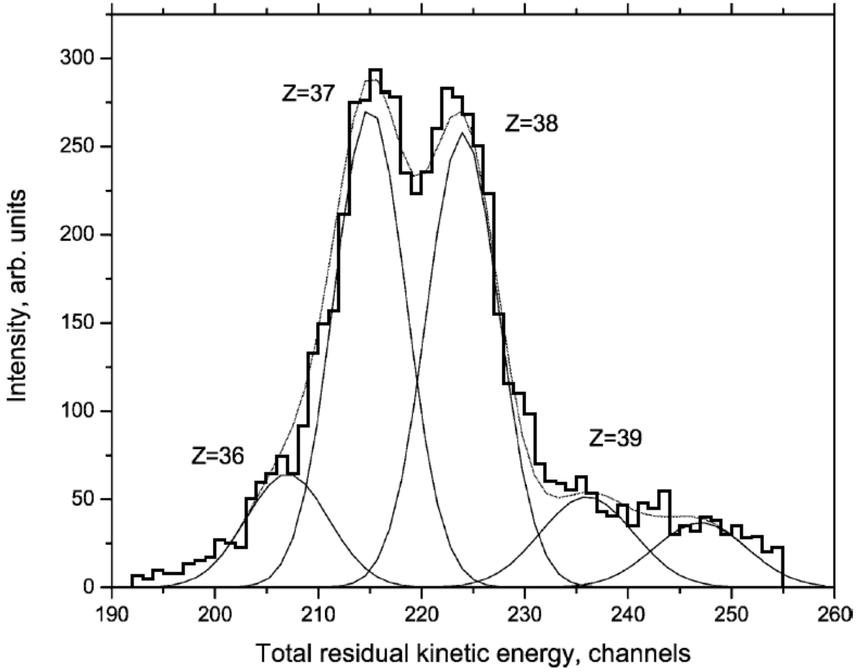


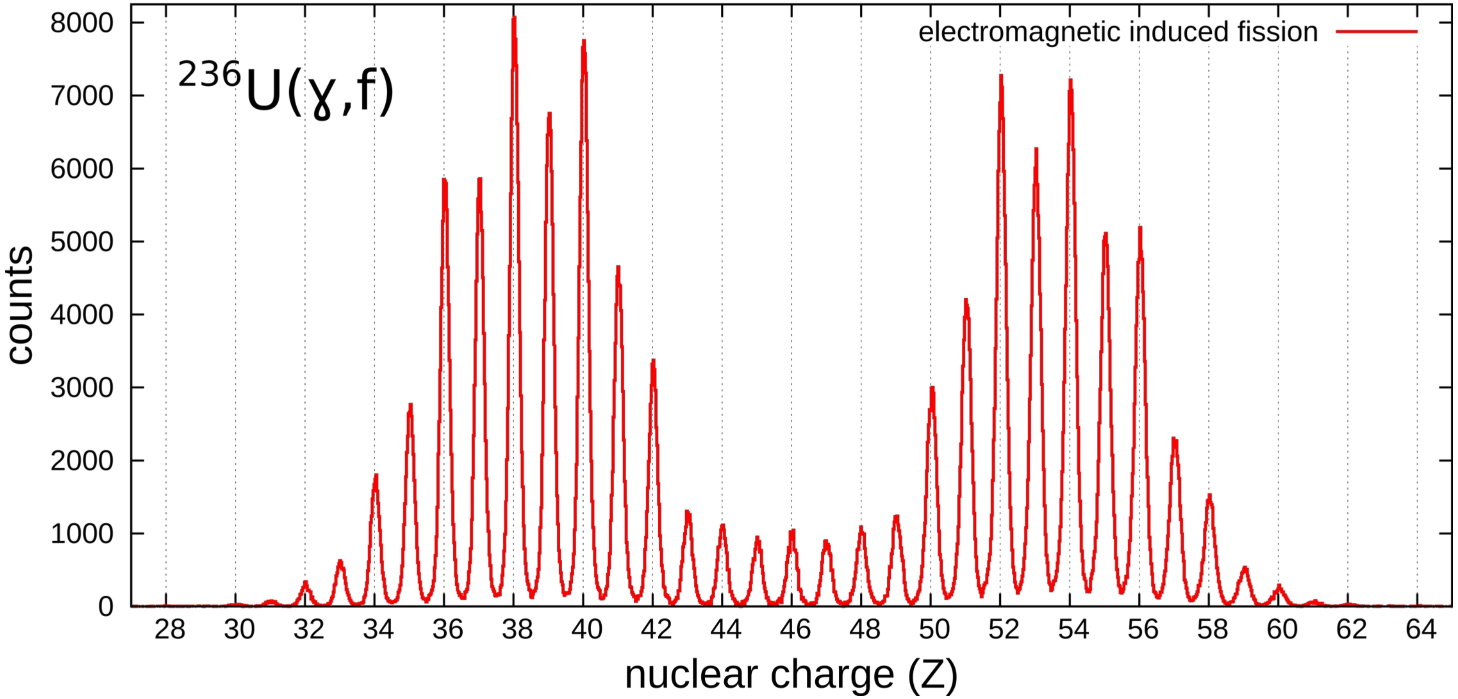
- Average excitation energy: $\langle E^* \rangle \sim 14.6$ MeV
- Average electromagnetic induced fission: $\sigma_{^{236}U(\gamma,f)} \sim 2.5$ barns
- Surrogate reaction: $^{236}U(\gamma,f) \Longleftrightarrow {}^{235}U(n_{8.2MeV},f)$

The inverse kinematics at relativistic energies (II)

A unique tool to get an absolute resolution in charge distribution on the full FF range

- At GSI, production of radioactive relativisic beam at FRS (~750 A.MeV)
- Ions are fully striped: Energy loss measurement directly gives the atomic number

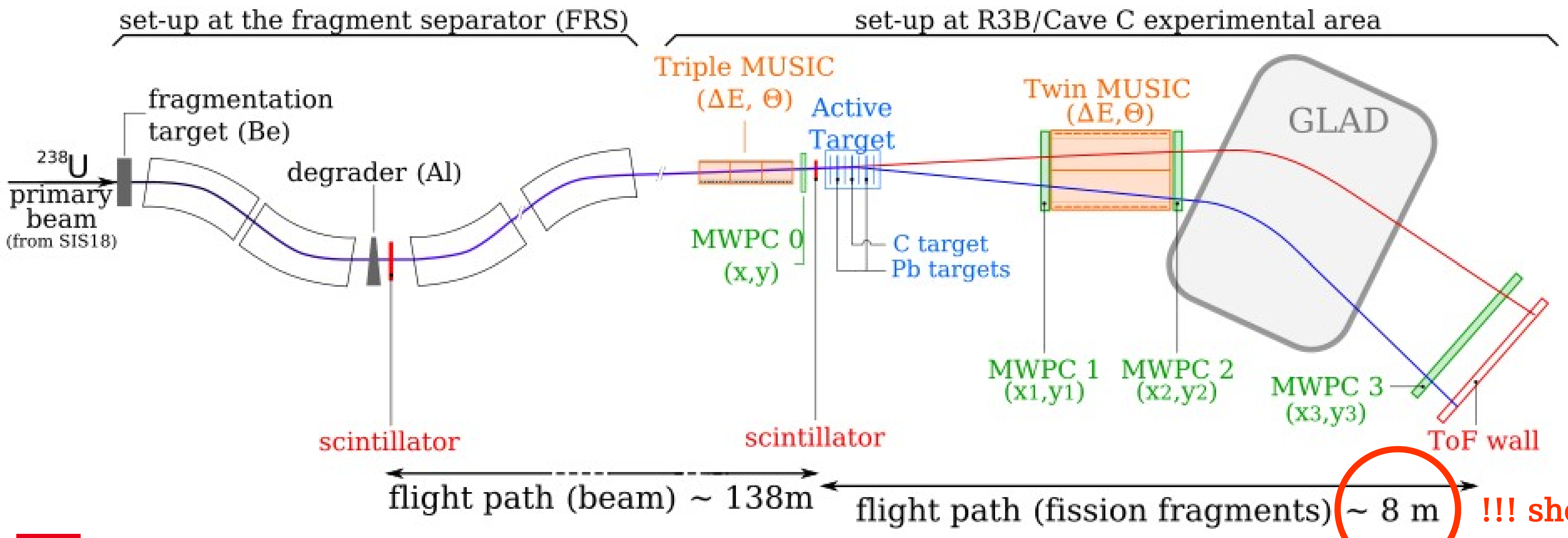




The inverse kinematics at relativistic energies (III)

Lorentz boost: all FF are emitted at forward angles ⇒ very high geometrical efficiency

- Nuclear charge and mass of both FF in coincidence
- Pionneer experiment with Z only at GSI by K.-H. Schmidt *et al.,* Nucl. Phys. A 665 (2000) 221
- Mass identification based on the ΔE – Bρ – ToF method with A/Z ~ Bρ / βγ



Both FF in coincidence !

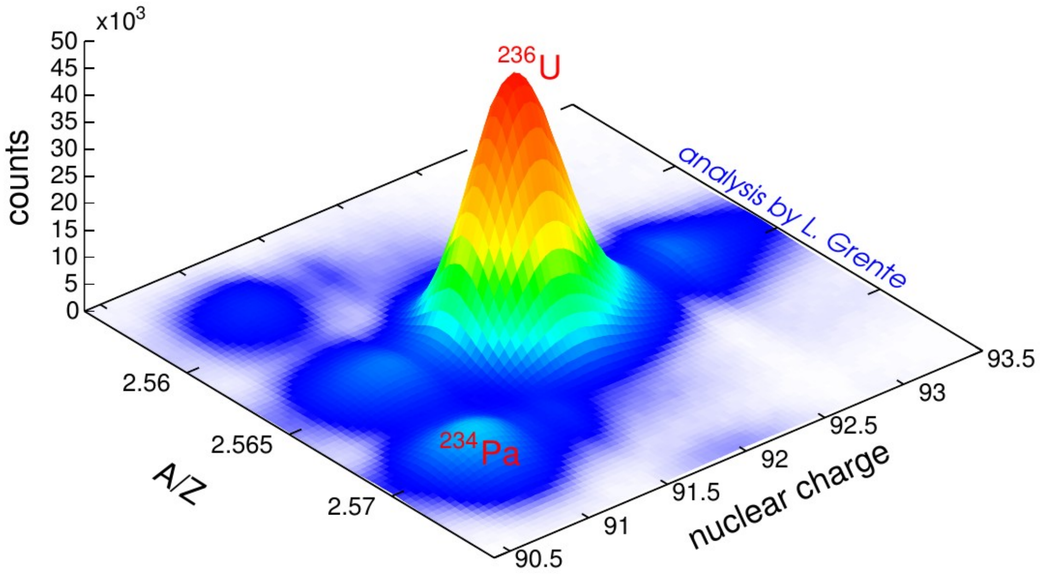
RESOLUTION [FWHM]

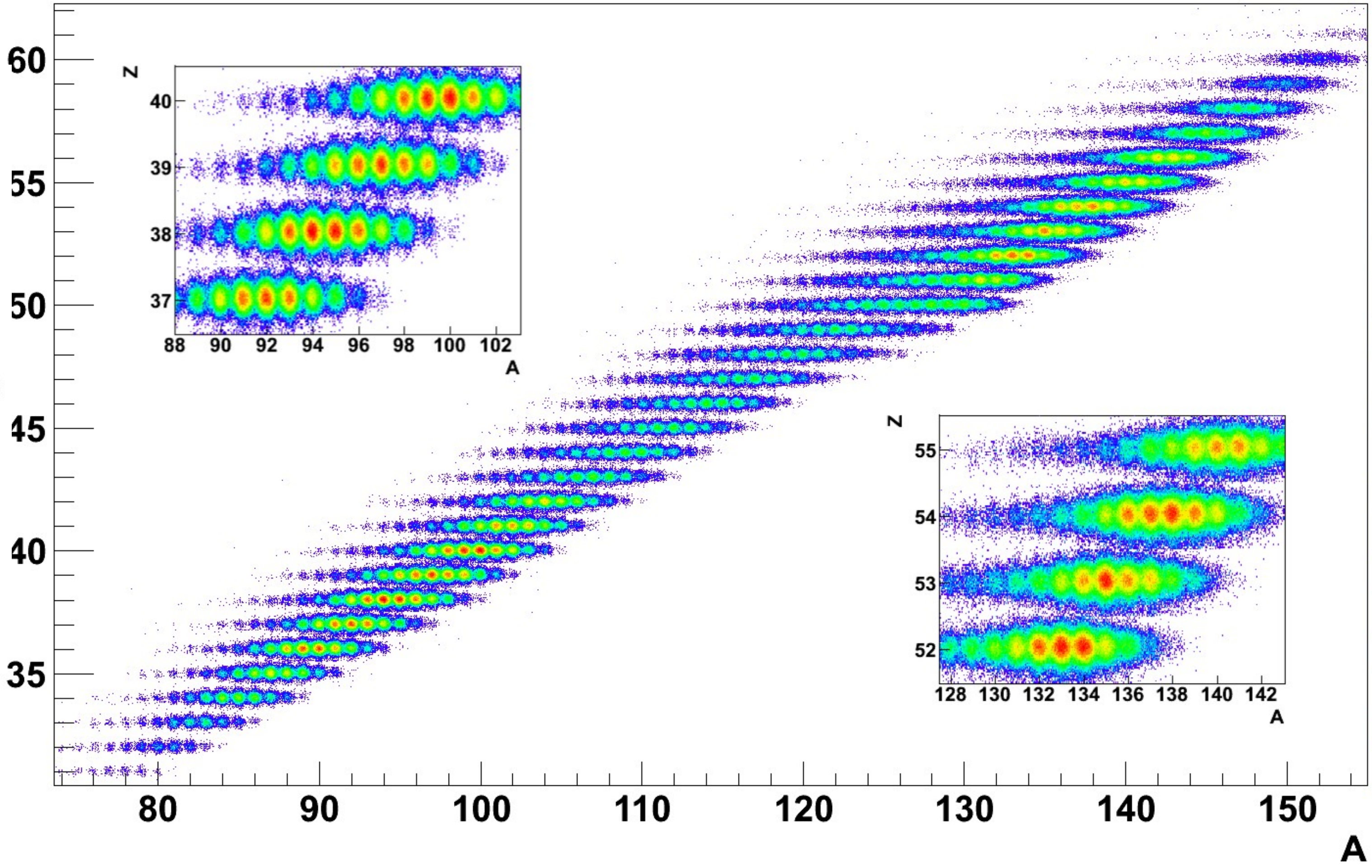
x = 100 to 300 µm

ToF = 35 ps

(Z,A) identification for the $^{236}U(\gamma,f)$ study

RESOLUTION [FWHM] : ΔZ = 0.31 to 0.34 charge unit & ΔA = 0.55 to 0.80 mass unit





Fission observables

Identification of both FF 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

  $\nu_{tot} = A_{beam} - A_{FF1} - A_{FF2}$

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

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 Editor's suggestion

2014 : ^{236}U [36 hours]

Asymmetric to symmetric transition study

2012: Ac, Th, Pa [12 hours]

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

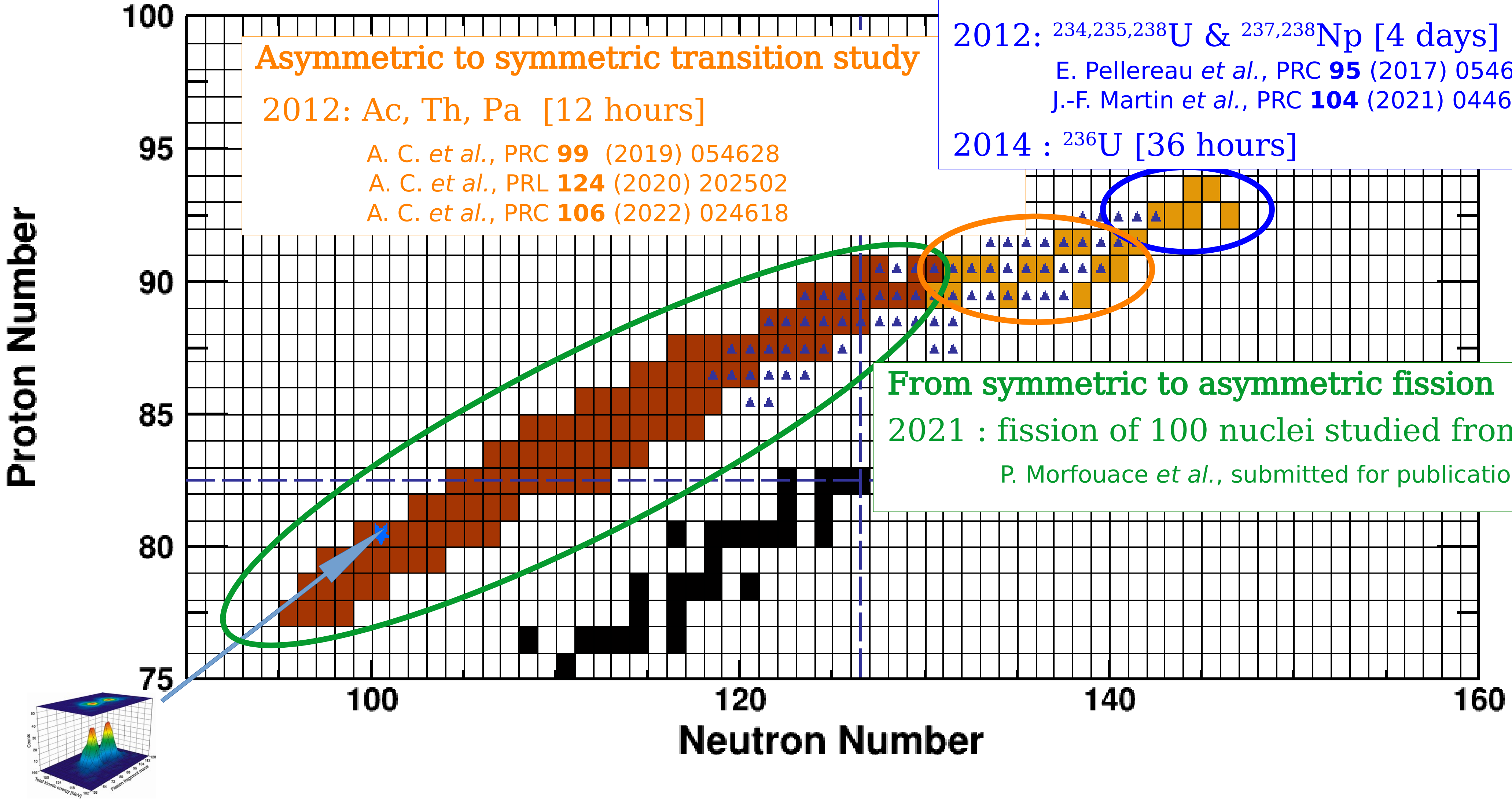
A. C. *et al.*, PRL **124** (2020) 202502

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

From symmetric to asymmetric fission

2021 : fission of 100 nuclei studied from Pb to Th [4 days]

P. Morfouace *et al.*, submitted for publication

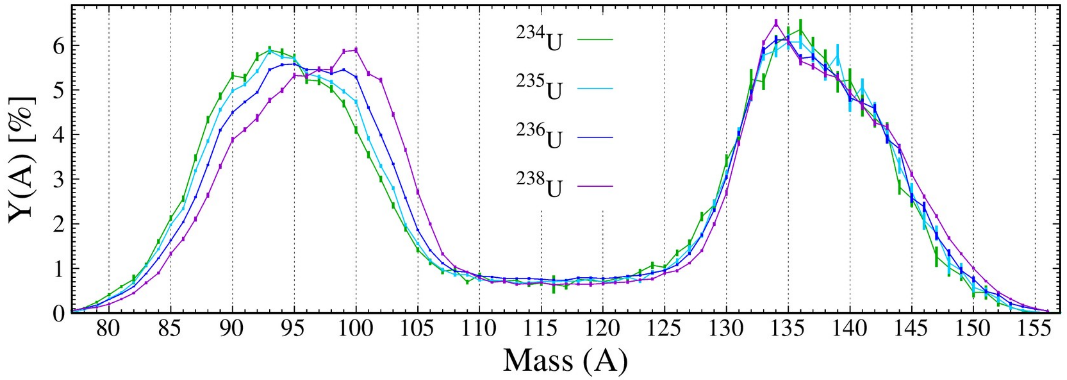


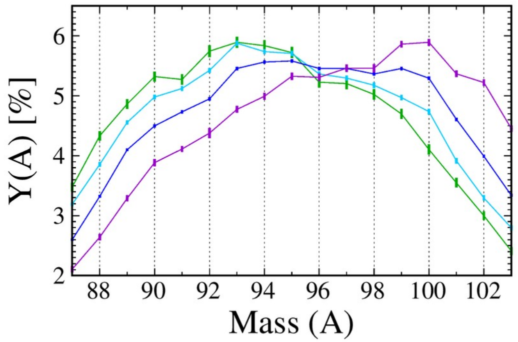
2.1 Along the U-chain

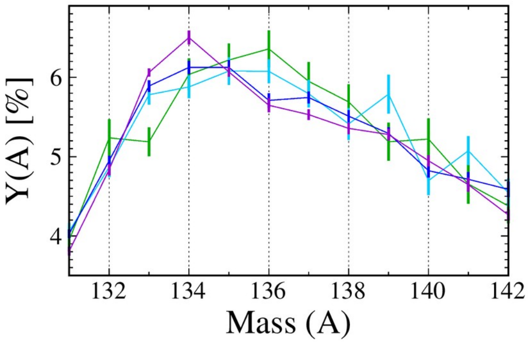
Accurate data for nuclear data need

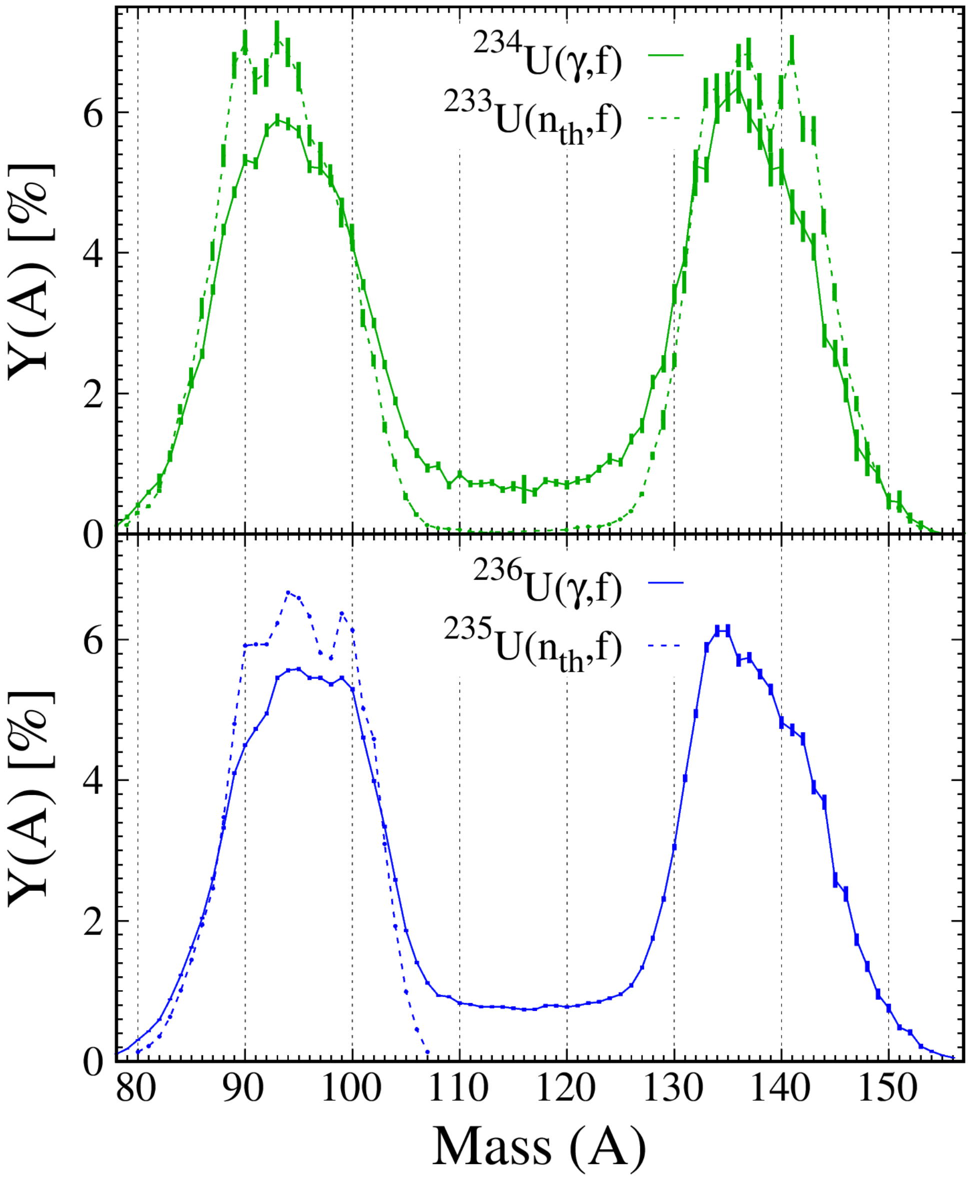
Isobaric yields

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





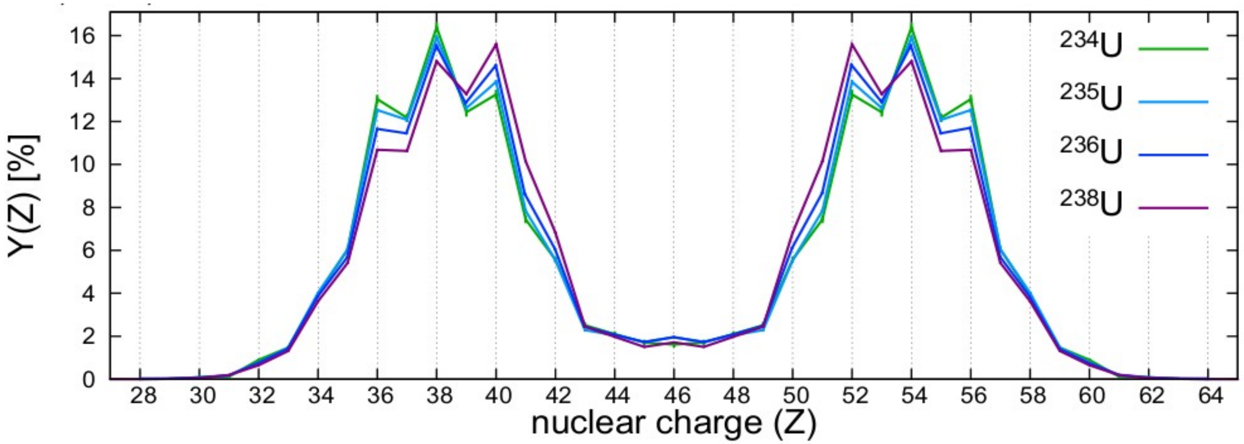


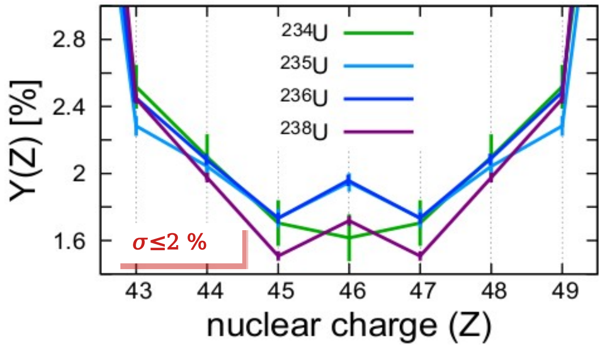


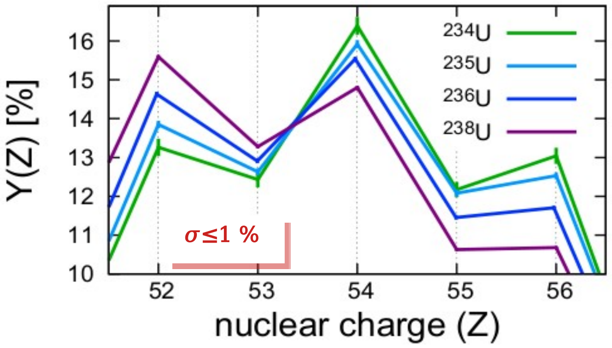
Analysis by L. Grente, J-F. Martin, E. Pellereau (CEA/DAM/DIF)

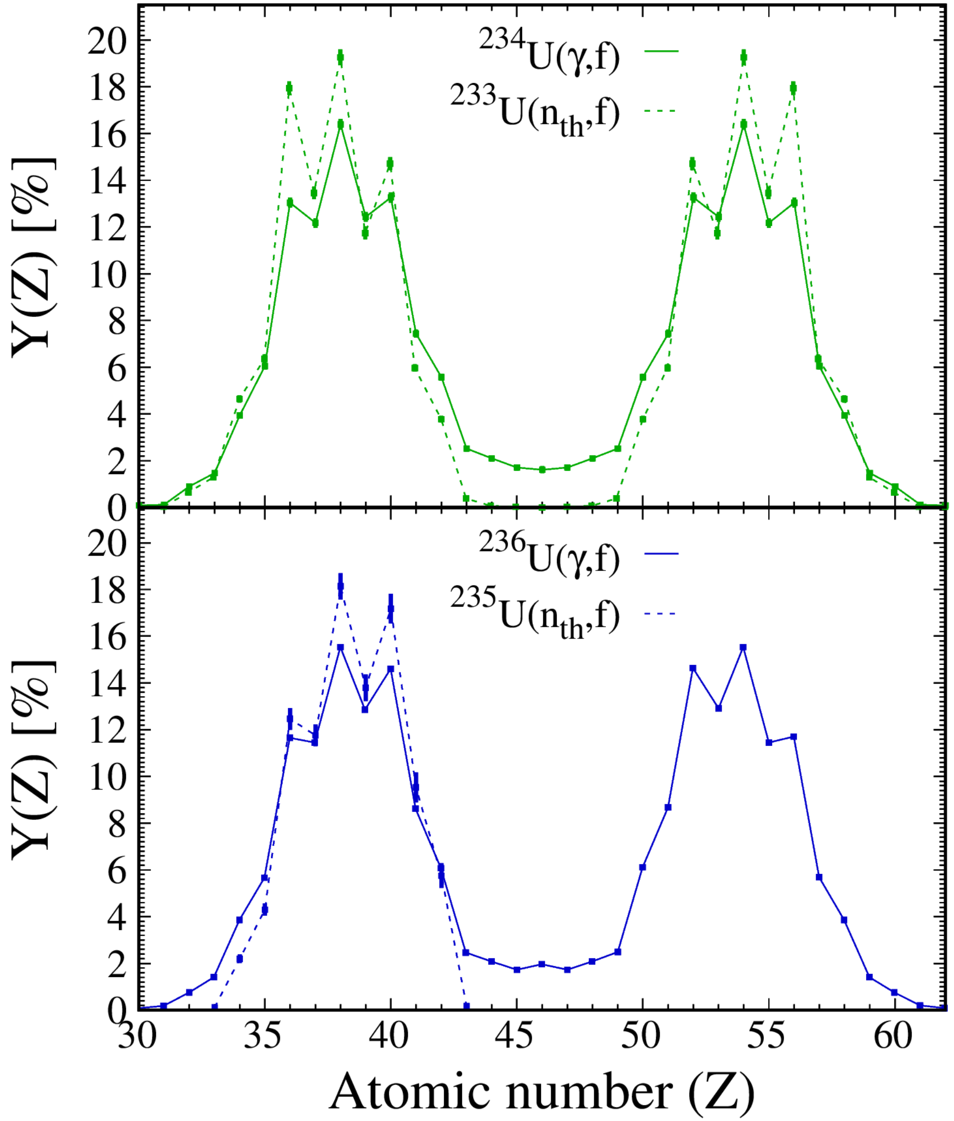
Elemental yields (I)

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









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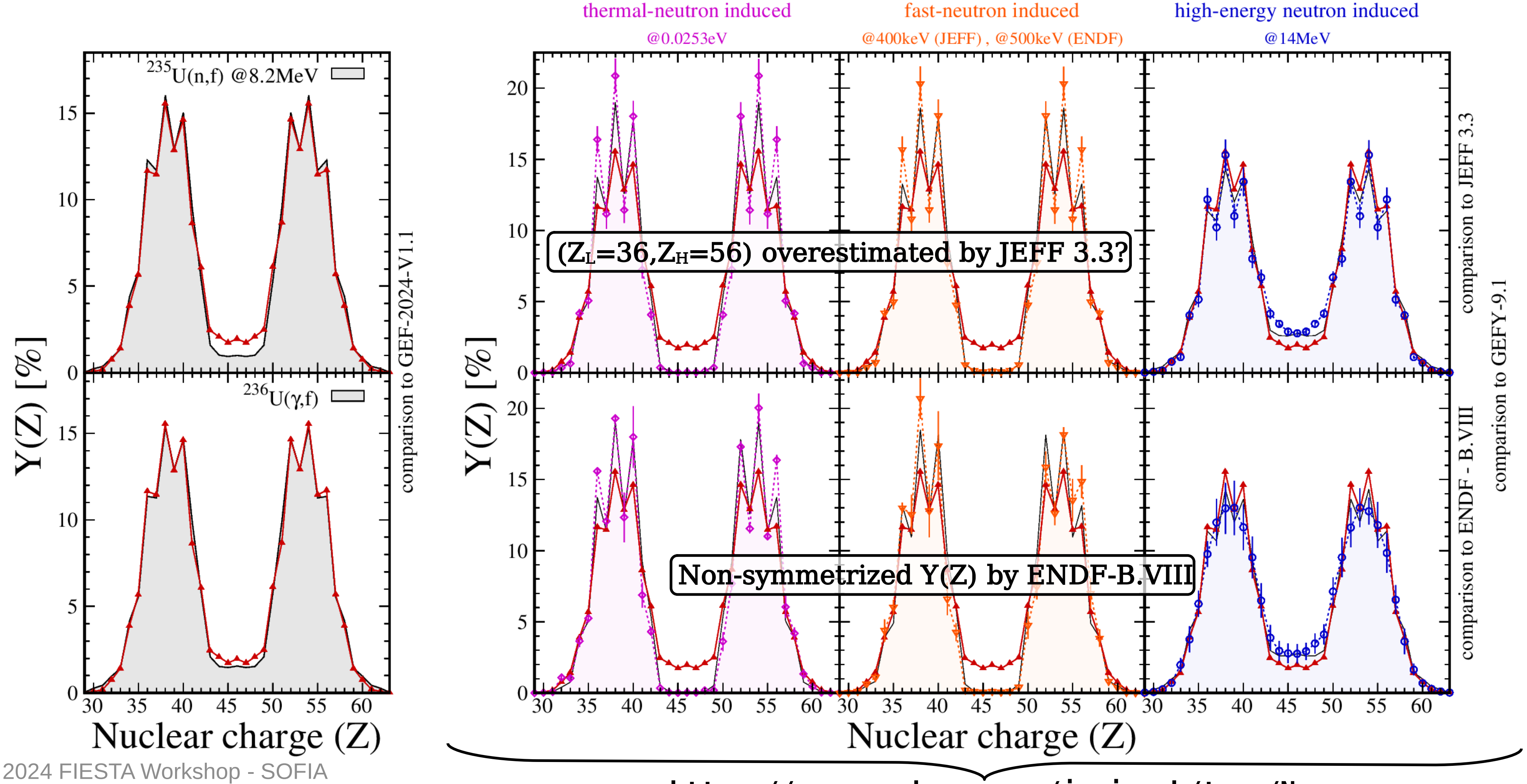
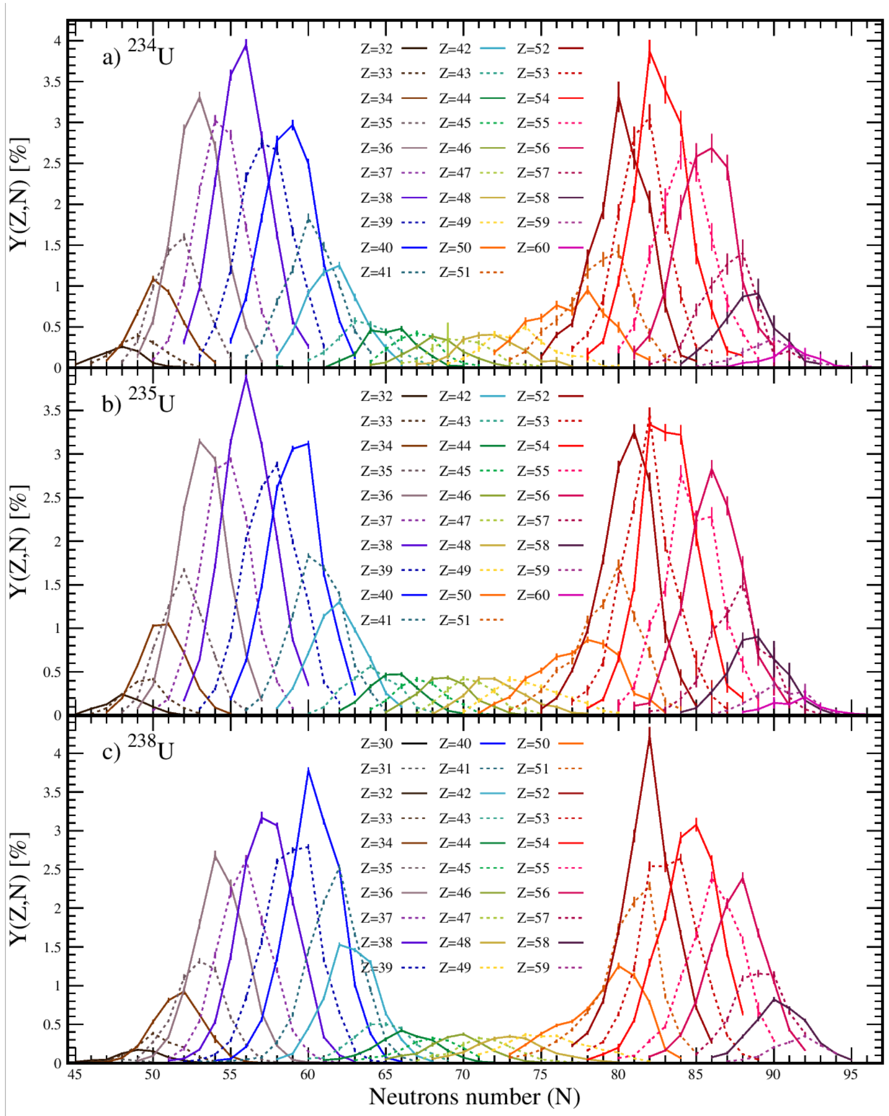
Elemental yields (II)

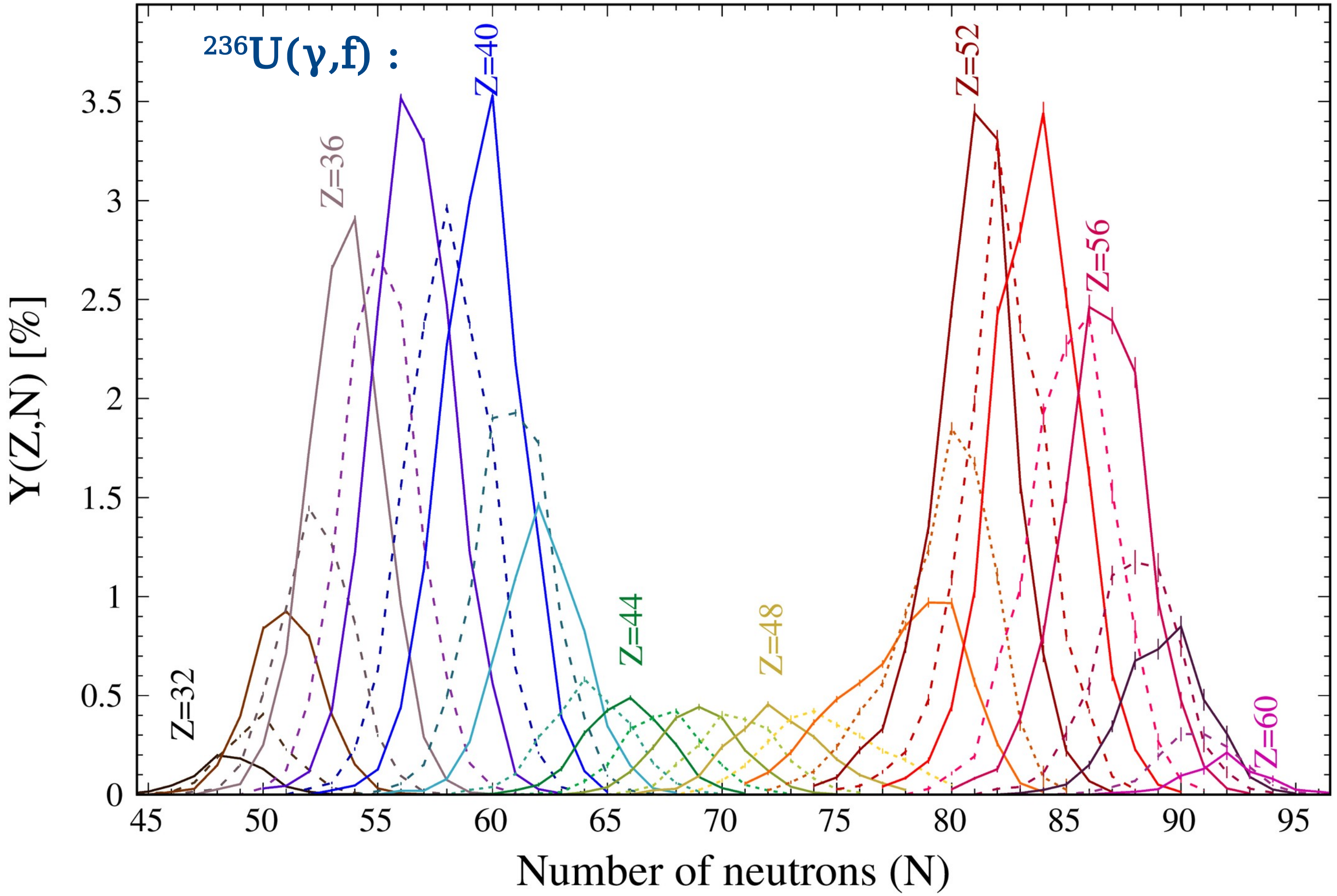
Comparison to GEF-2024-V1.1 and evaluations



https://www.oecd-nea.org/janisweb/tree/N

Isotopic yields





0.5≤≤1.5 %

1.3≤≤3.5 %

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

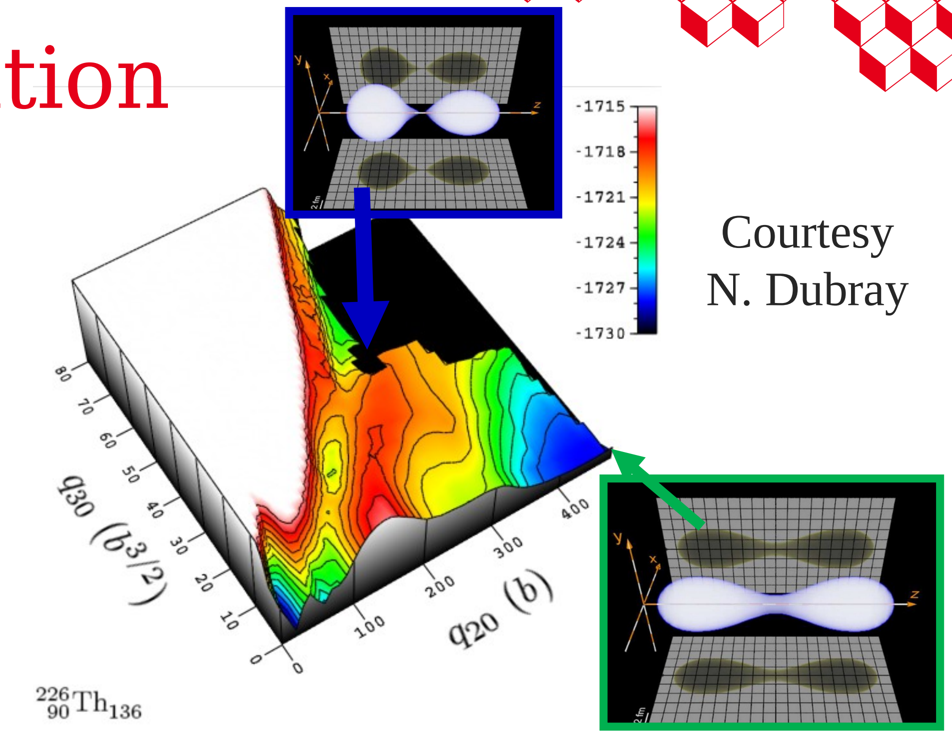
2.2 Along the Th-chain

Correlated data to study microscopic effects

⟨νtot⟩ 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})



Courtesy
N. Dubray

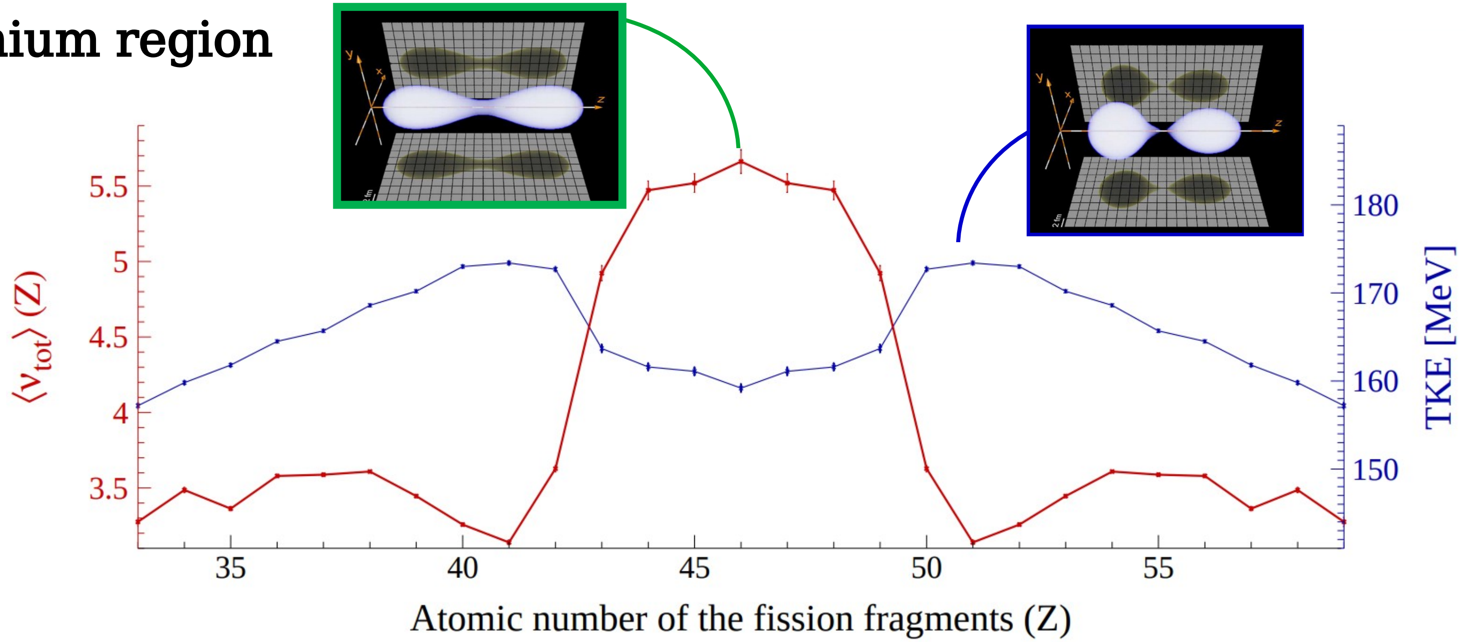
STANDARD 1	STANDARD 2	SUPER-LONG
ALMOST SPHERICAL HEAVY FF spherical (Z=50,N=82) shells compact configuration **High TKE, low ν**	OCTUPOLE FF octupole p-shells in heavy FF main mode	HIGHLY DEFORMED FF shell effects washed-out with E* deformed configuration **LOW TKE, HIGH ν**

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

⟨νtot⟩ to probe scission configuration

Three fission modes in the uranium region

- $^{235}U(\gamma,f)$ SOFIA results :



Analysis by J-F. Martin (CEA/DAM/DIF)

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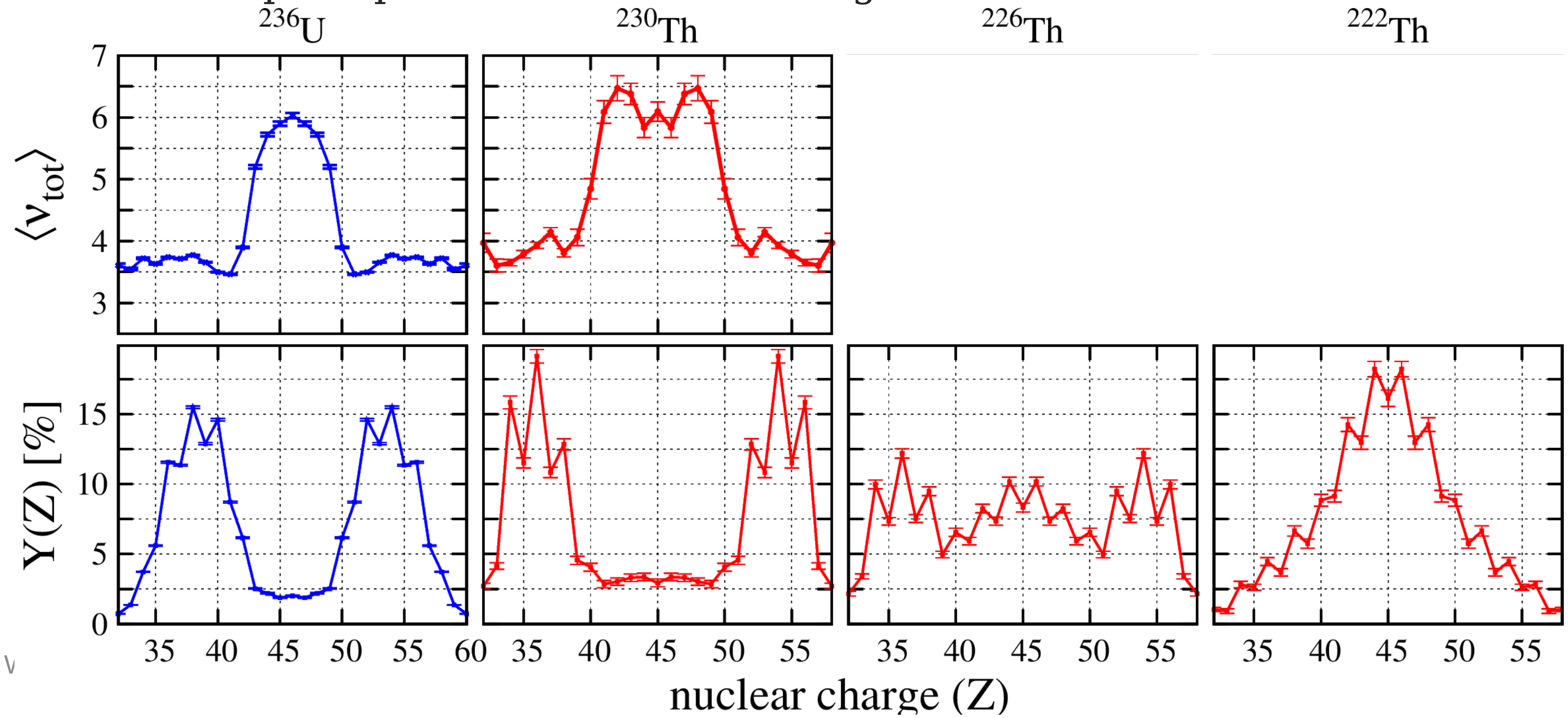
Importance of correlated data: Yields, TKE, ν, E*

Correlation Y(Z) vs $\langle \nu_{tot} \rangle$

For neutron deficient neutron isotopes …

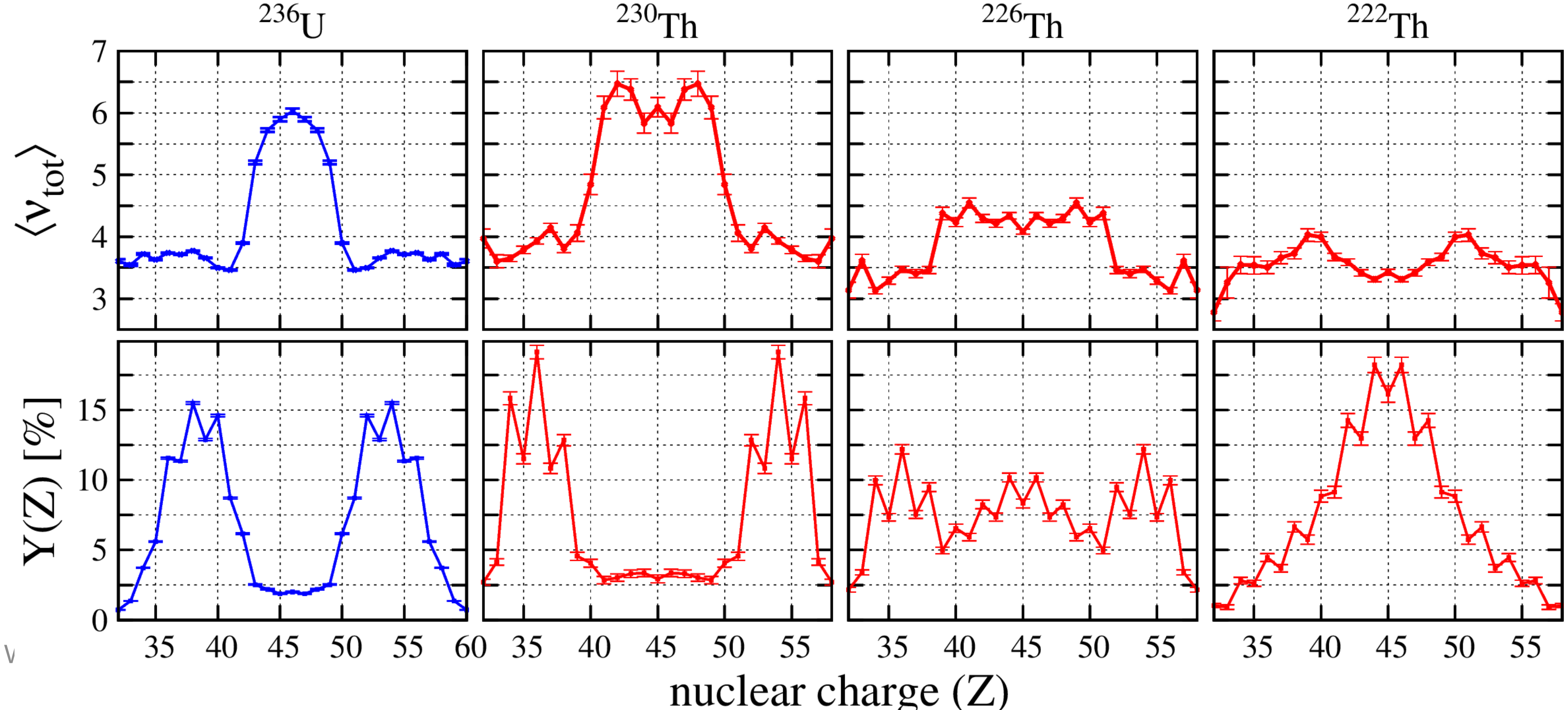
- Symmetric fission is becoming more and more important
- Odd-even staggering remains
- Correlated data helps to probe the scission configuration of the fission modes



Correlation Y(Z) vs $\langle \nu_{tot} \rangle$

For neutron deficient neutron isotopes …

- Symmetric fission is becoming more and more important
- Odd-even staggering remains and $\langle \nu_{tot} \rangle$ drop for symmetric fission of around 2.7 neutrons
- **New symmetric compact mode**



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 spectrometer combined with the FRS spectrometer

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

Observables:

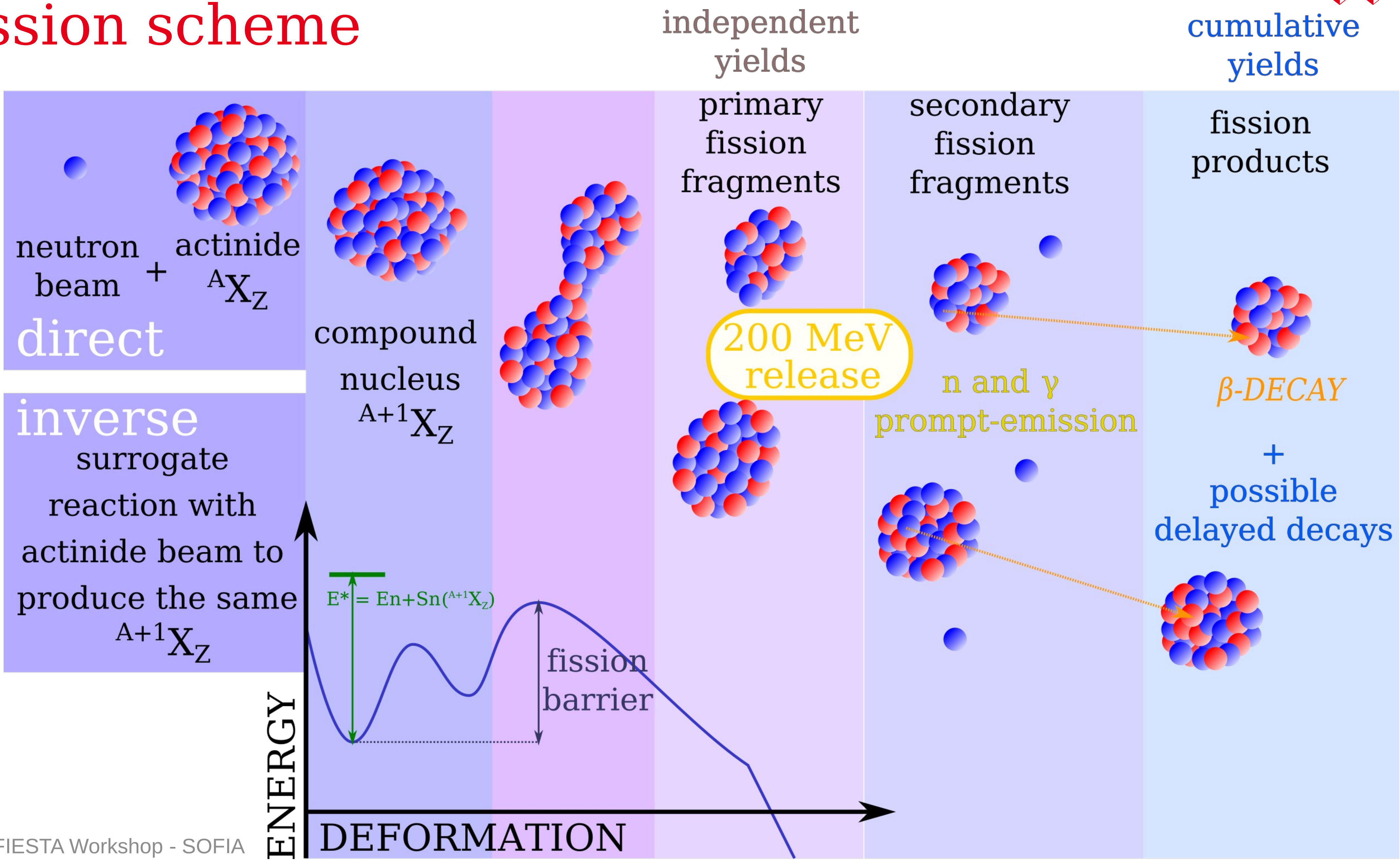
$Y(Z)$, $Y(A_{post})$, $Y(N_{post})$, $Y(Z,A_{post})$, $\langle \nu_{tot} \rangle$, $\langle TKE \rangle$

Physics cases:

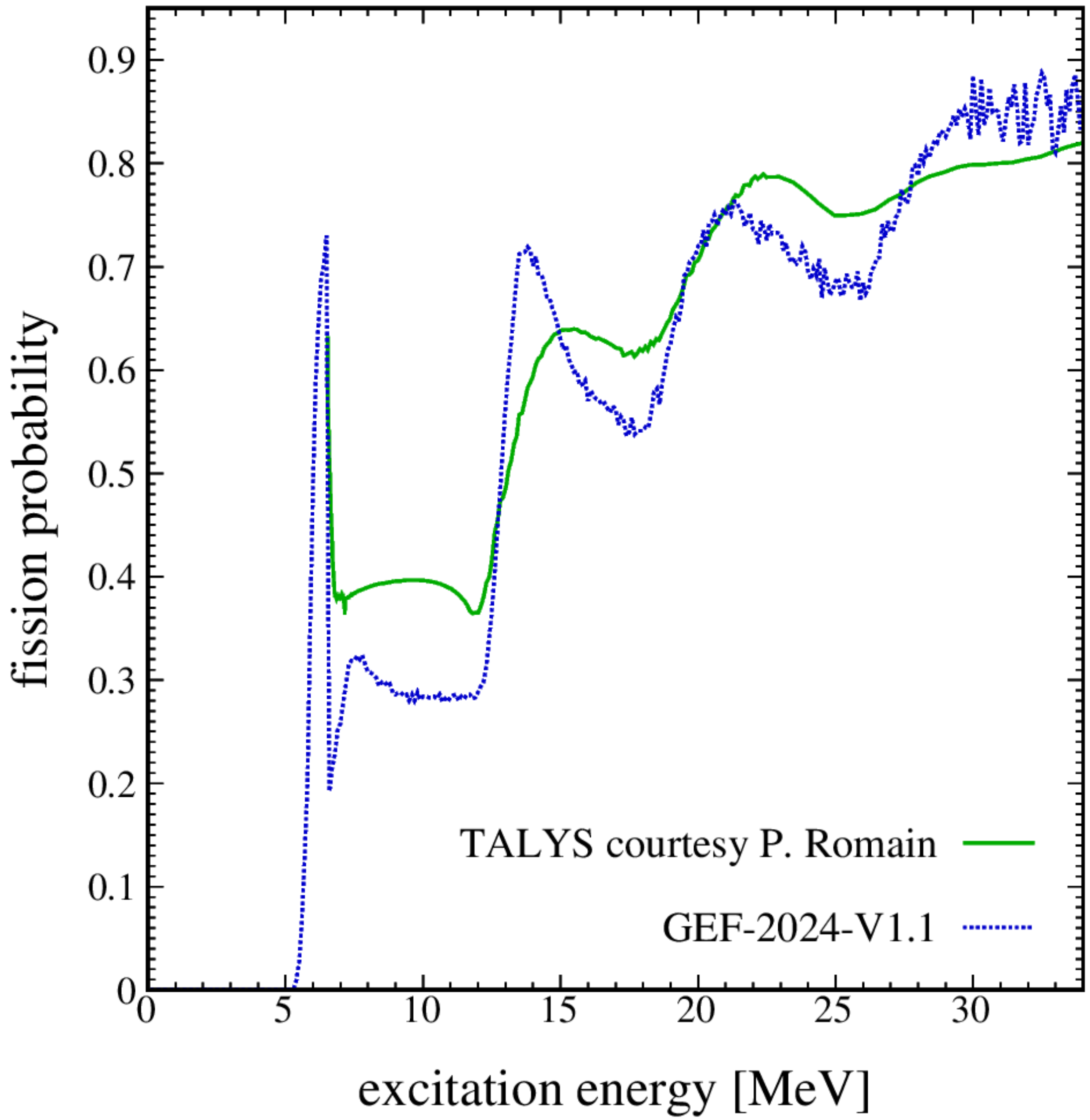
for nuclear data need & basic science

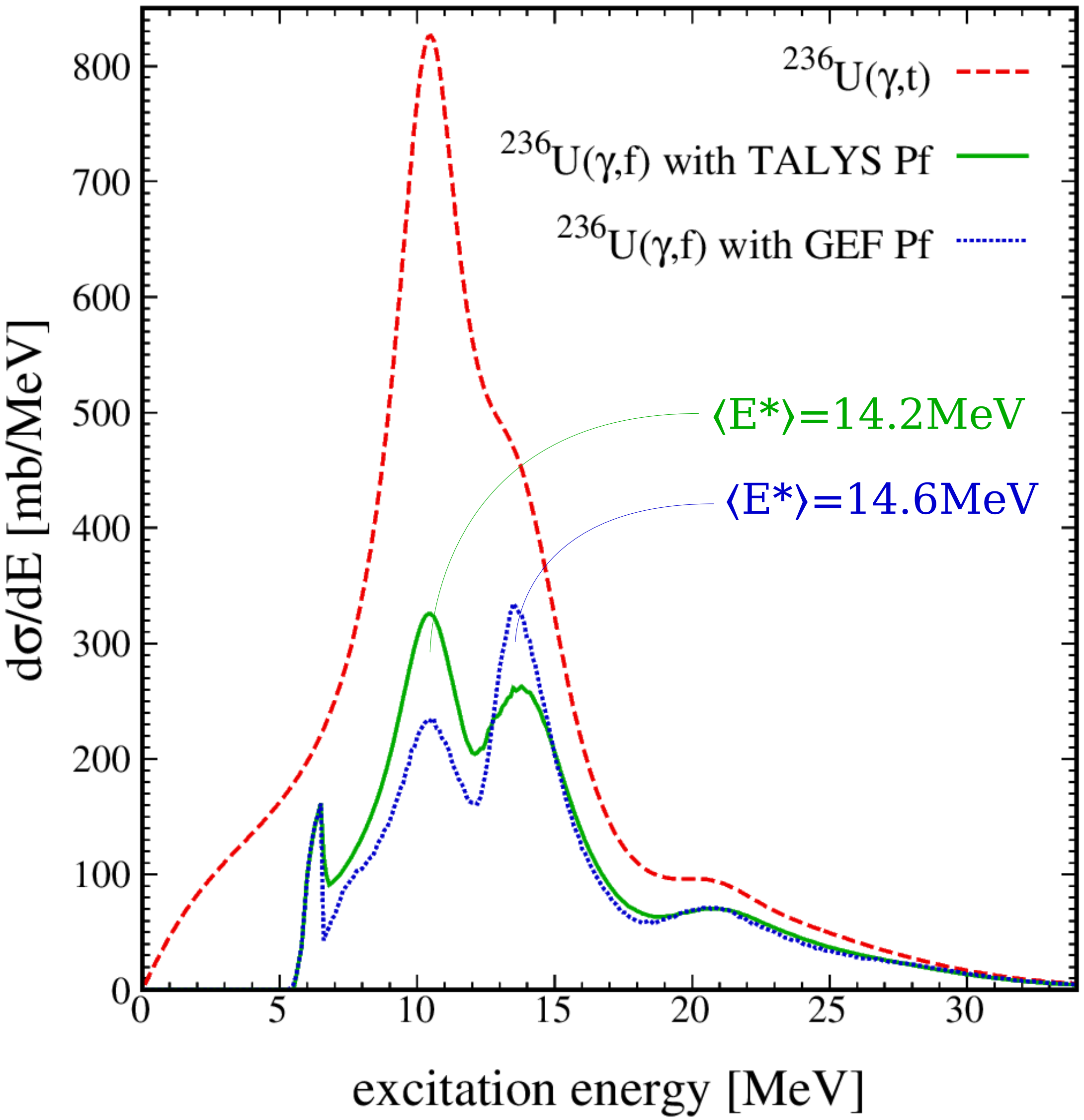
3. Extra slides

Fission scheme



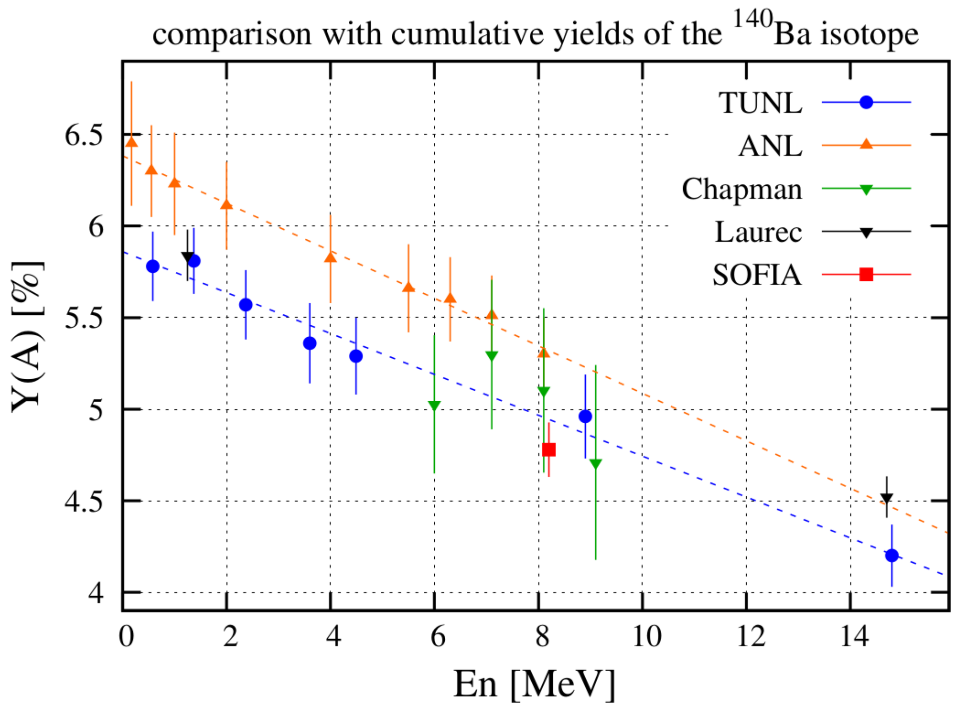
Excitation energy distribution for $^{236}U(\gamma,f)$

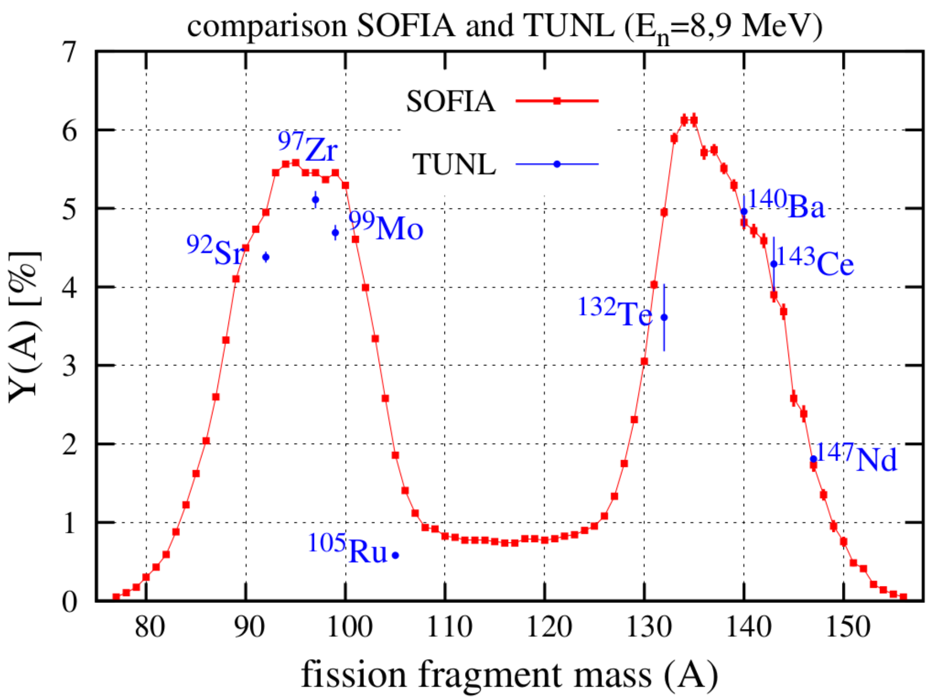




Isobaric yields (II)

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





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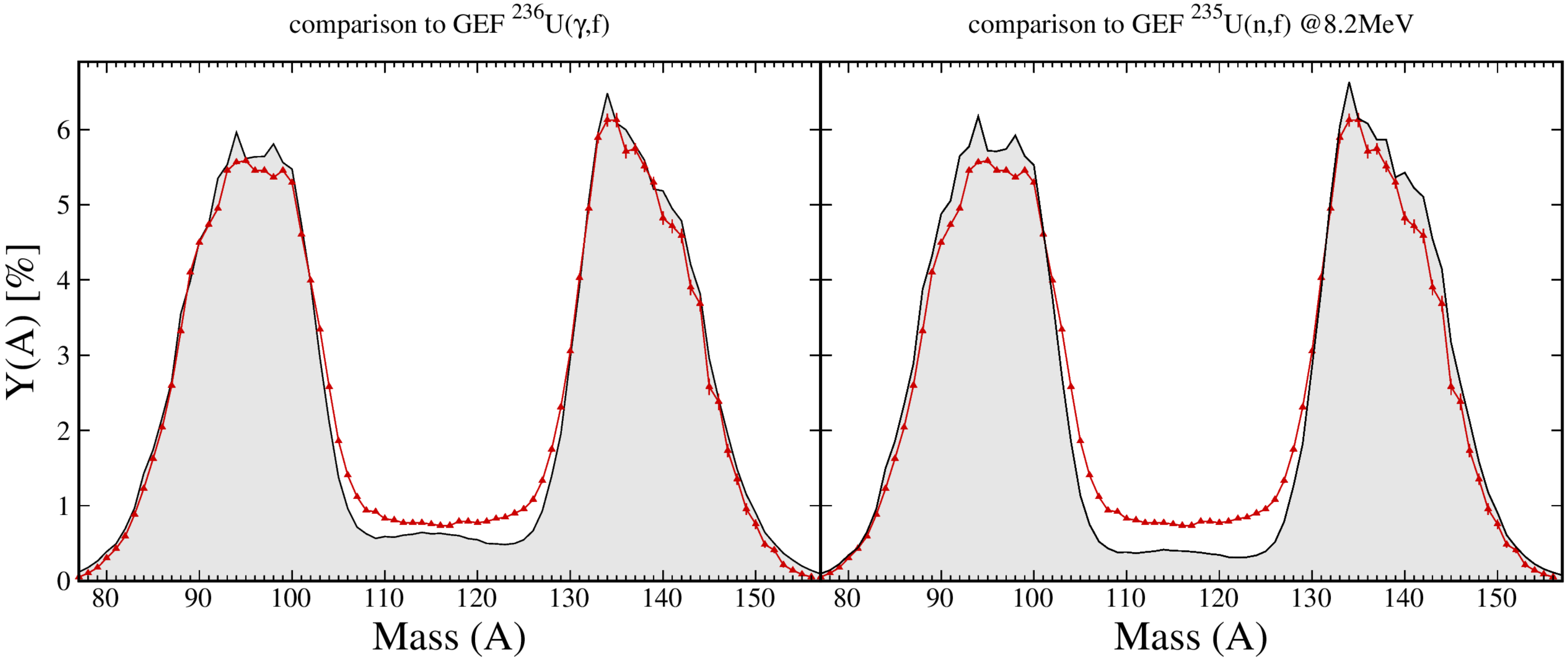
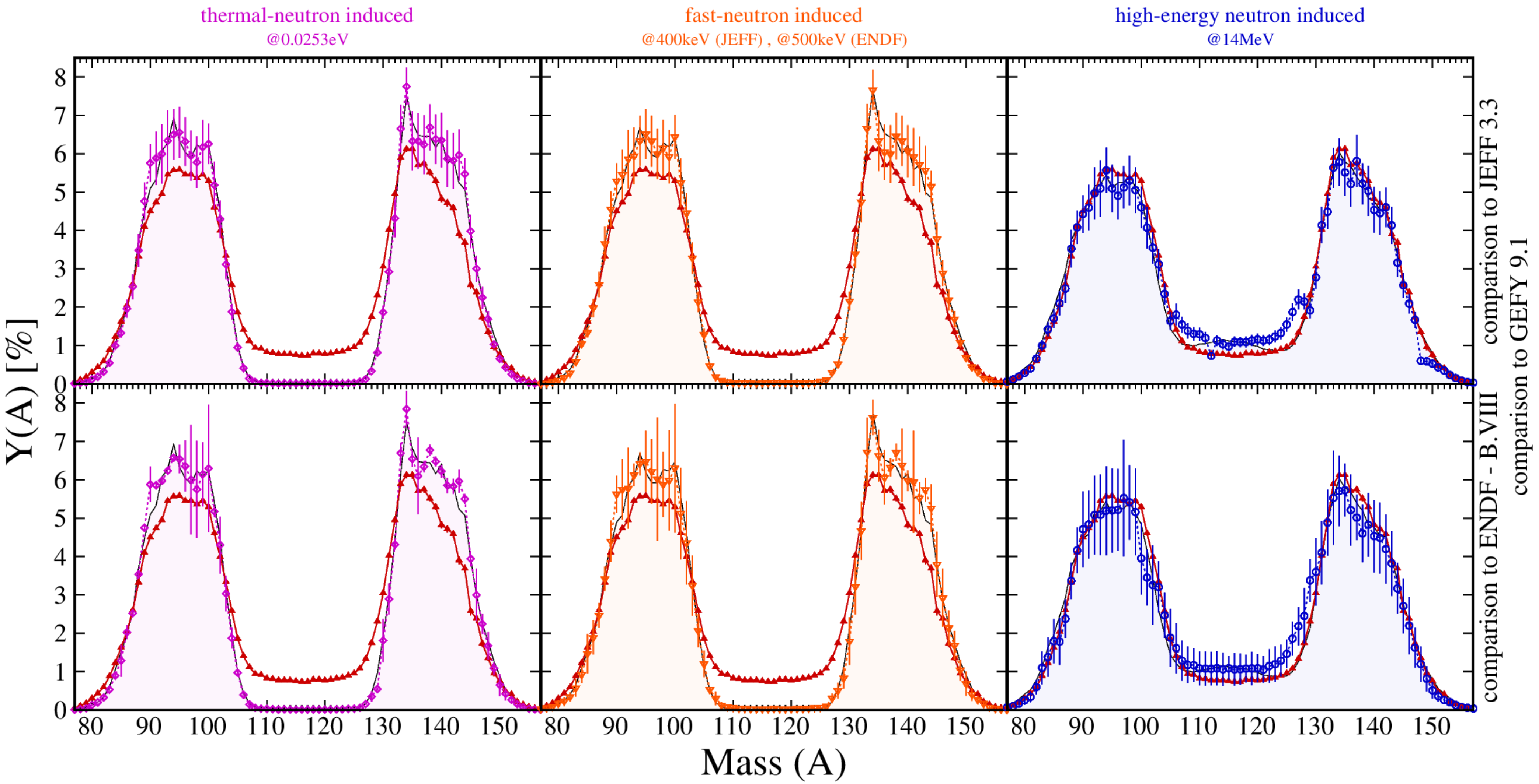
Isobaric yields (III)

$^{236}U(\gamma,f)$ from SOFIA compared to GEF-2024-V1.1 with Pf from GEF



Isobaric yields (IV)

$^{236}U(\gamma,f)$ from SOFIA compared to evaluations : JEFF3.3, ENDF-B.VIII, GEFY 9.1



https://www.oecd-nea.org/janisweb/tree/N

Th chain: $\langle \nu_{tot} \rangle$ sharing to extract $\langle N_{pre} \rangle_{L,H}$

How to share $\langle \nu_{tot} \rangle$ between light fragment and heavy fragment ?

$$\langle N_{pre} \rangle_{L,H} = \langle N_{post} \rangle_{L,H} + \langle \nu \rangle_{L,H}$$

- **Method 1: Fission consider as an adiabatic process in a Fermi gas**

→ $\langle A_{pre,L} \rangle / \langle A_{pre,H} \rangle = \langle E^*_L \rangle / \langle E^*_H \rangle \sim \langle \nu_L \rangle / \langle \nu_H \rangle$

→ $\langle \nu_{L,H} \rangle = \langle \nu_{tot} \rangle (Z_L, Z_H) * \langle A_{post,L,H} \rangle / (\langle A_{post,L} \rangle + \langle A_{post,H} \rangle)$

→ this method can be applied to all compound systems studied with SOFIA

- **Method 2: Based on combination of experimental data only**

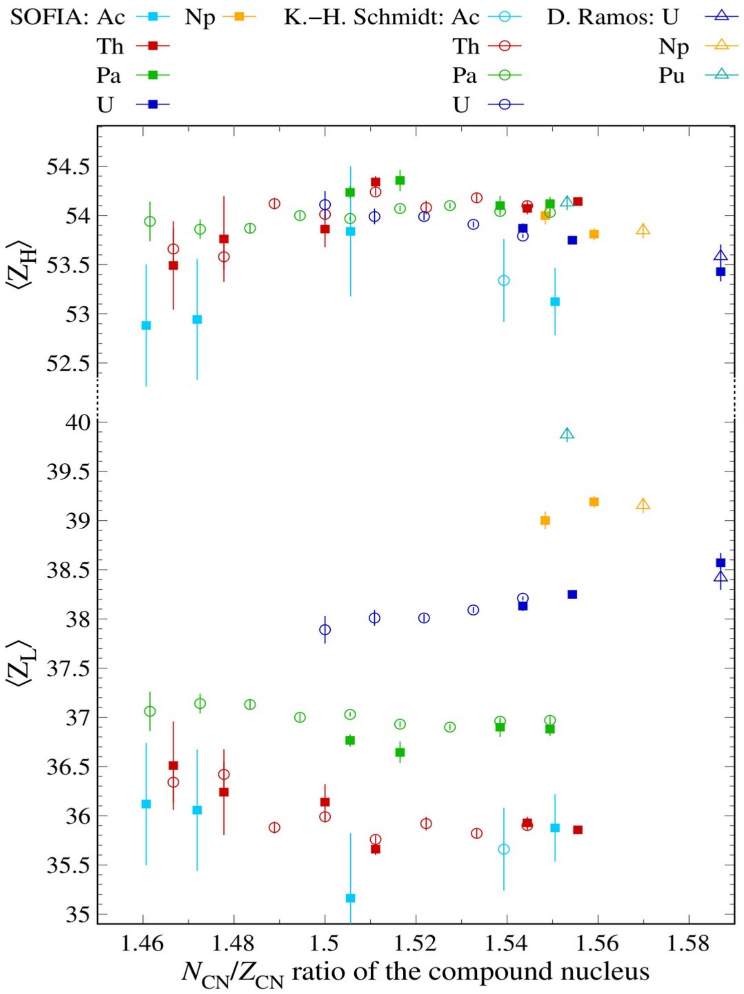
→ No model : combination of results from SOFIA and previous experiments in neutron-induced

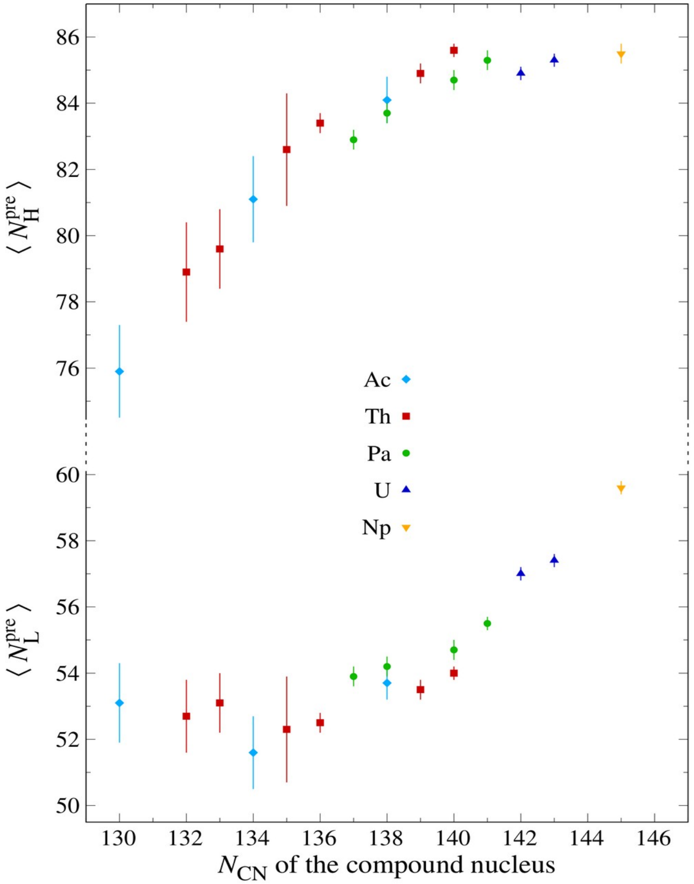
→ Can be applied only to the specific cases with existing and precise n-induced data

→ Used for the validation of method 1

- More information in references: PRC 104 044602 (2021) and PRC 024618 106 (2022)

$\langle Z_{pre} \rangle_{L,H}$ & $\langle N_{pre} \rangle_{L,H}$





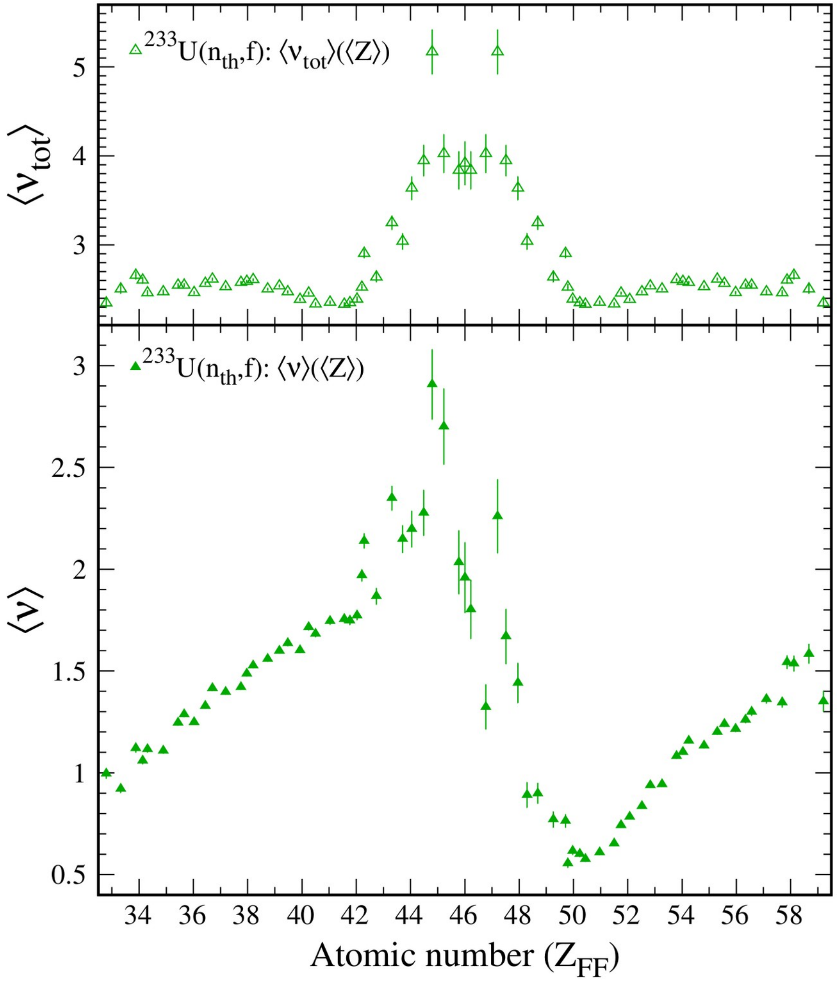
- From Th (Z=90) to Pu (Z=94)
  $\langle Z_H \rangle \sim 54$
- This effect becomes weak for Ac isotopes(Z=89)
- **For neutron deficient isotopes, stabilisation around $\langle N_L \rangle \sim 54$**

Th chain: $\langle \nu_{tot} \rangle$ sharing to extract $\langle N_{pre} \rangle_{L,H}$

- **Method 2: Based on combination of experimental data only**

  1/ Neutron-induced fission data $^{233}U(n_{th},f)$

  K. Nishio *et al. j. Nucl. Sci. Technol. 35, 631 (1998)*



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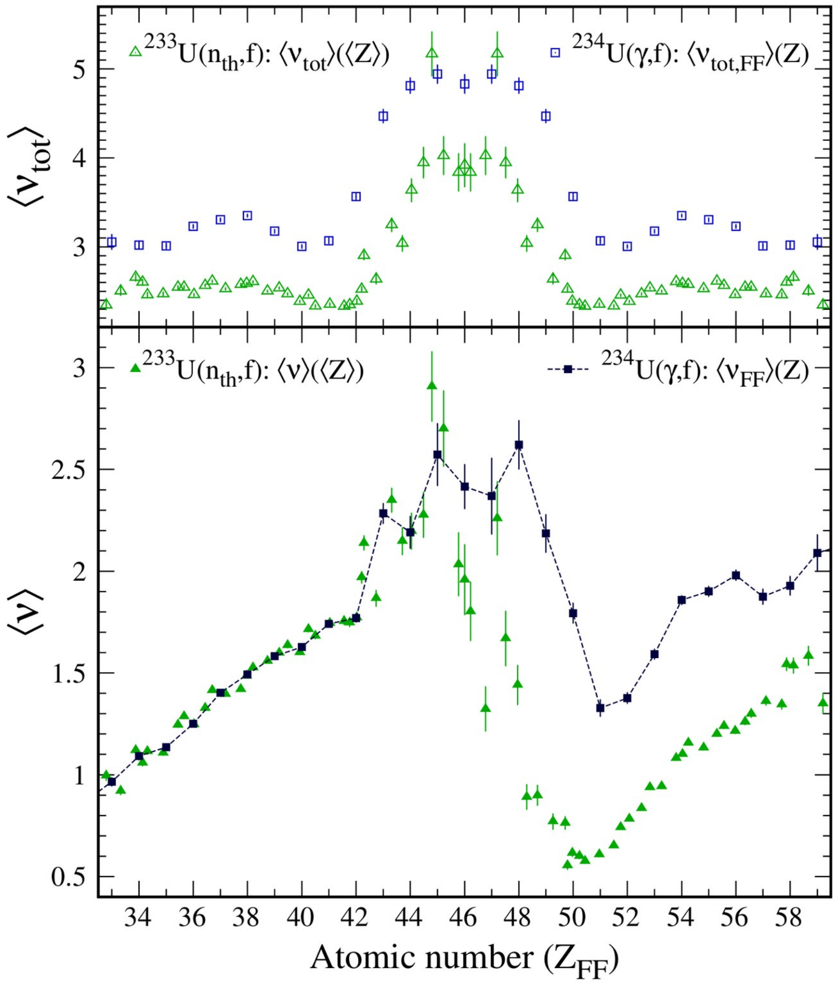
  2/ SOFIA : Coulomb-induced fission of ^{234}U

  3/ Any increase of E* translates into additional neutron emission in the heavy fission fragment only

  R. Müller *et al.*, PRC 29, 885 (1984)
  A. A. Naqvi *et al.*, PRC 34, 218 (1986)
  V. A. Rubchenya *et al.*, NPA 734, 253 (2004)



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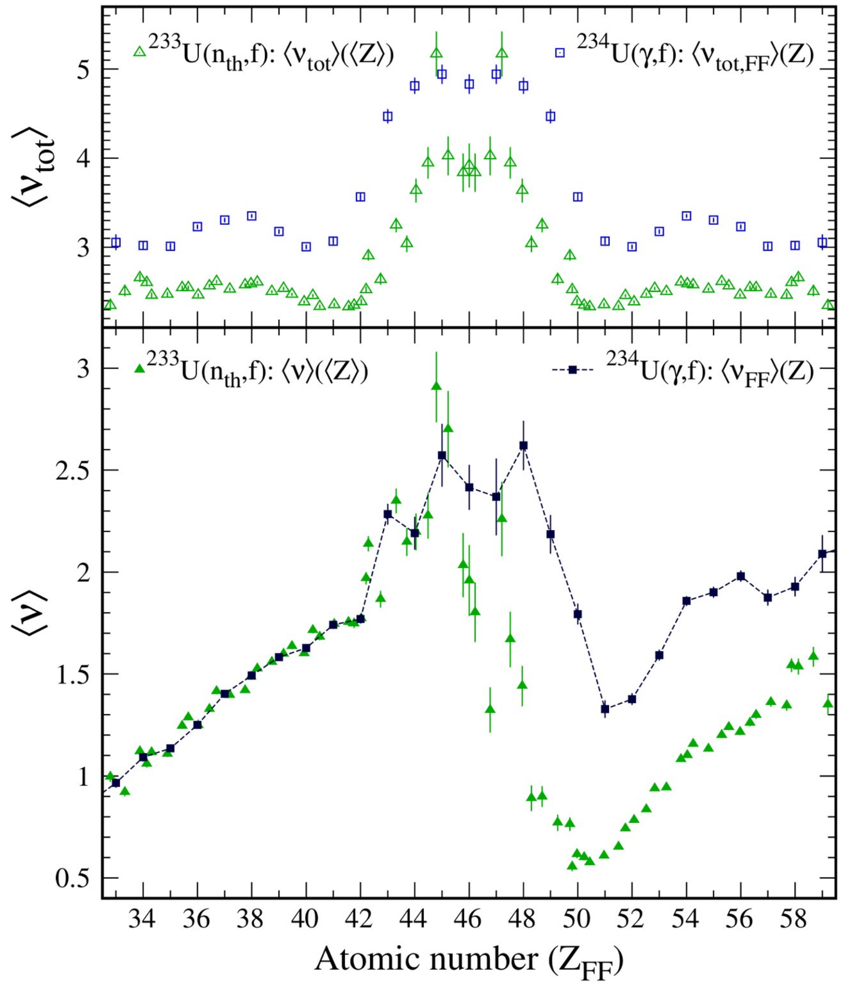
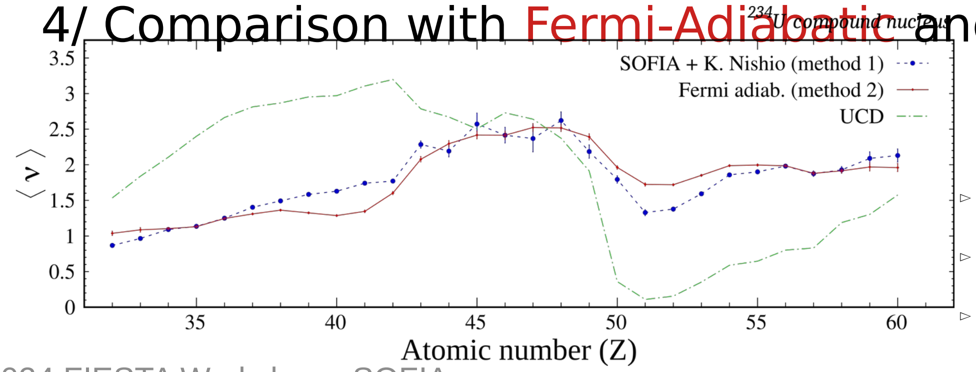


4/ Comparison with Fermi-Adiabatic and UCD



- Excellent agreement between both methods
- Maximum discrepency of 0.4 neutrons around st1 mode
- UCD introduces a significant bias in the neutron emission