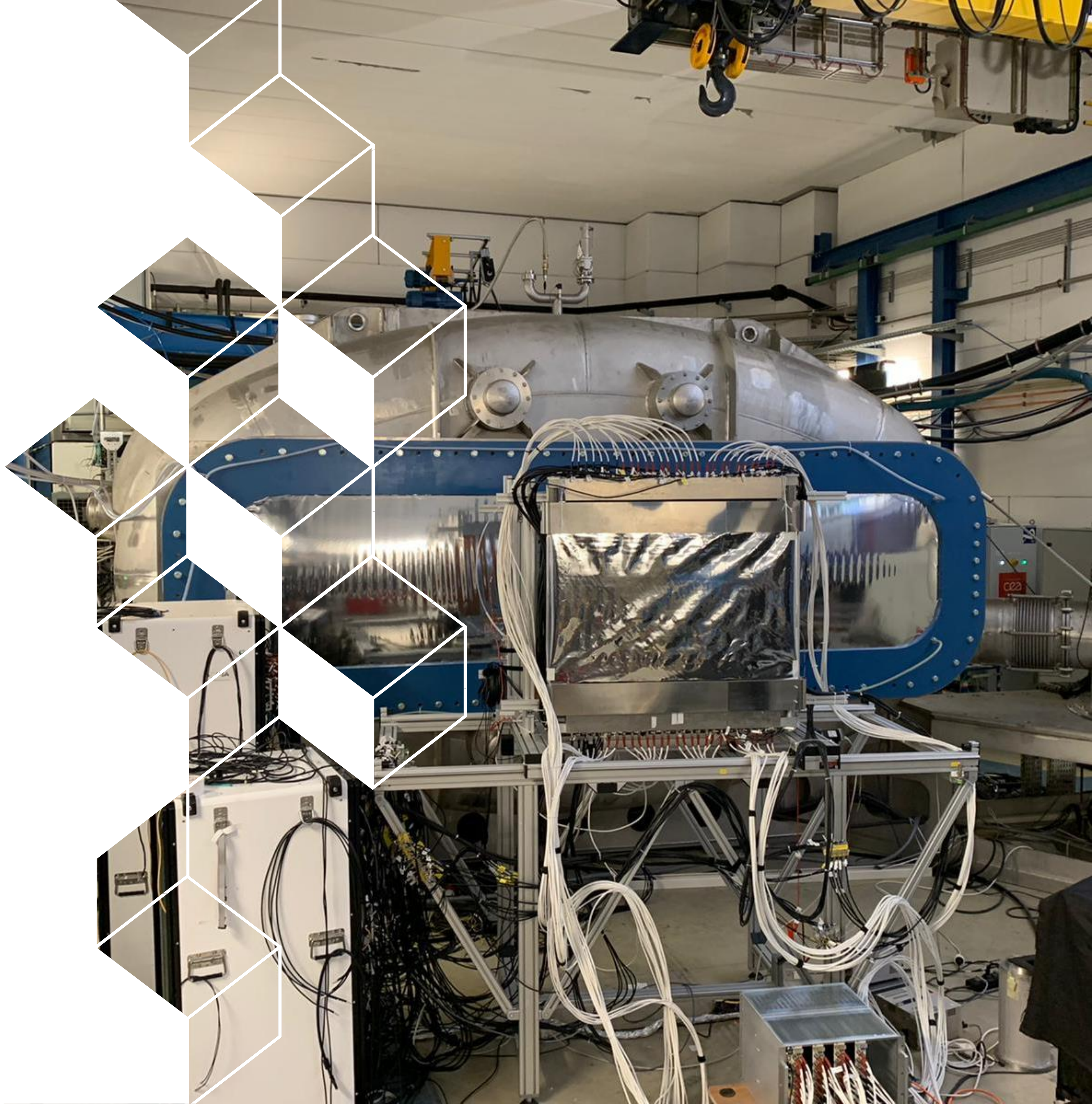
Fission yields measurements in inverse kinematics at relativitic energies

SOFIA : Studies On Fission with GLAD



PhyNuBE 3 – Fission and Astrophysics Workshop

October 2024 – CNRS center of Oleron

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

1/ Fission yields: influence of the nuclear structure in the yields

2/ Inverse kinematics at relativistic energy

3/ The SOFIA experiment

4/ Selection of results with SOFIA

1. Fission yields

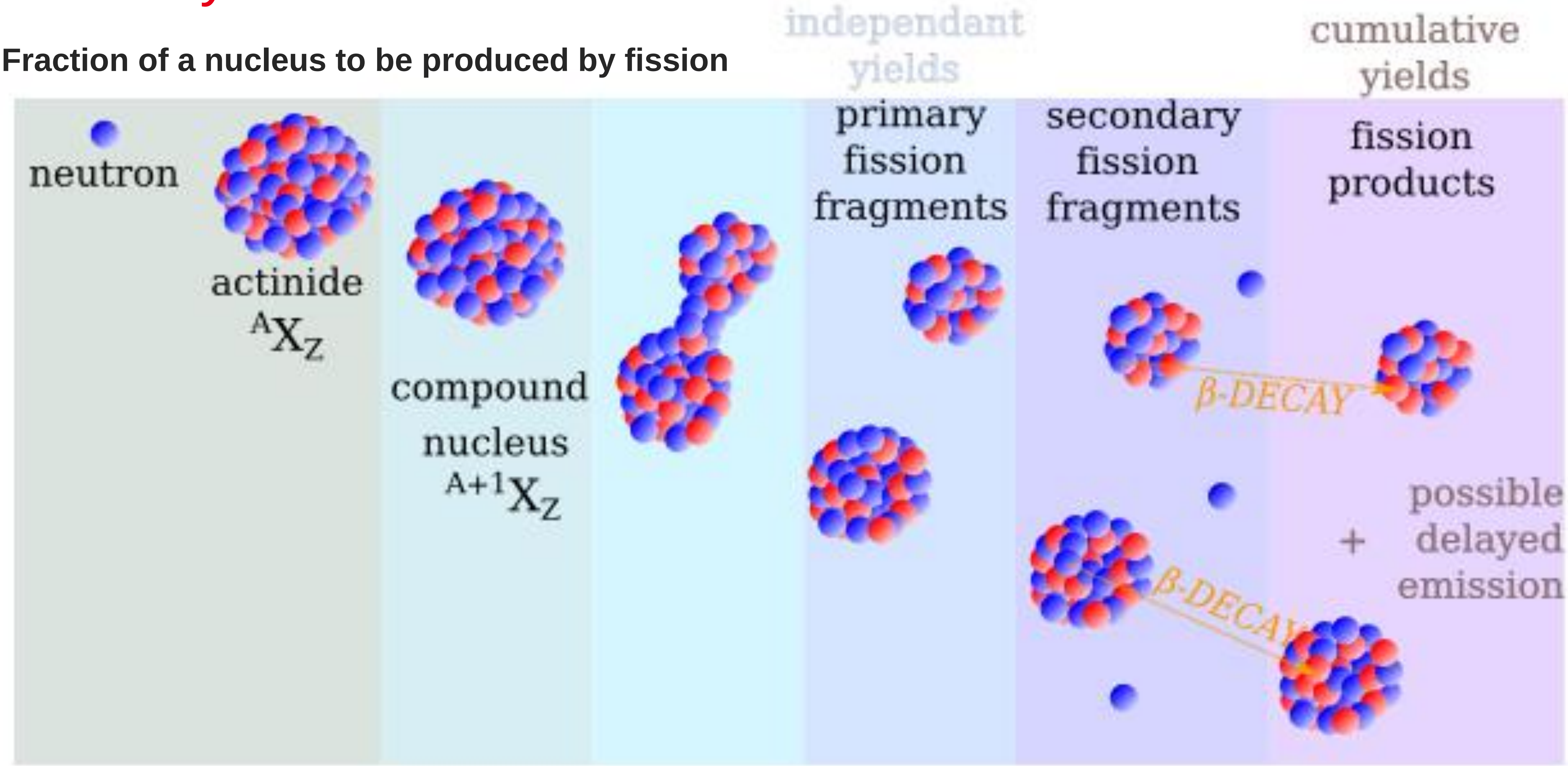
Basic definition

Nuclear structure effects in fission yields

Introduction to fission modes

Fission yields

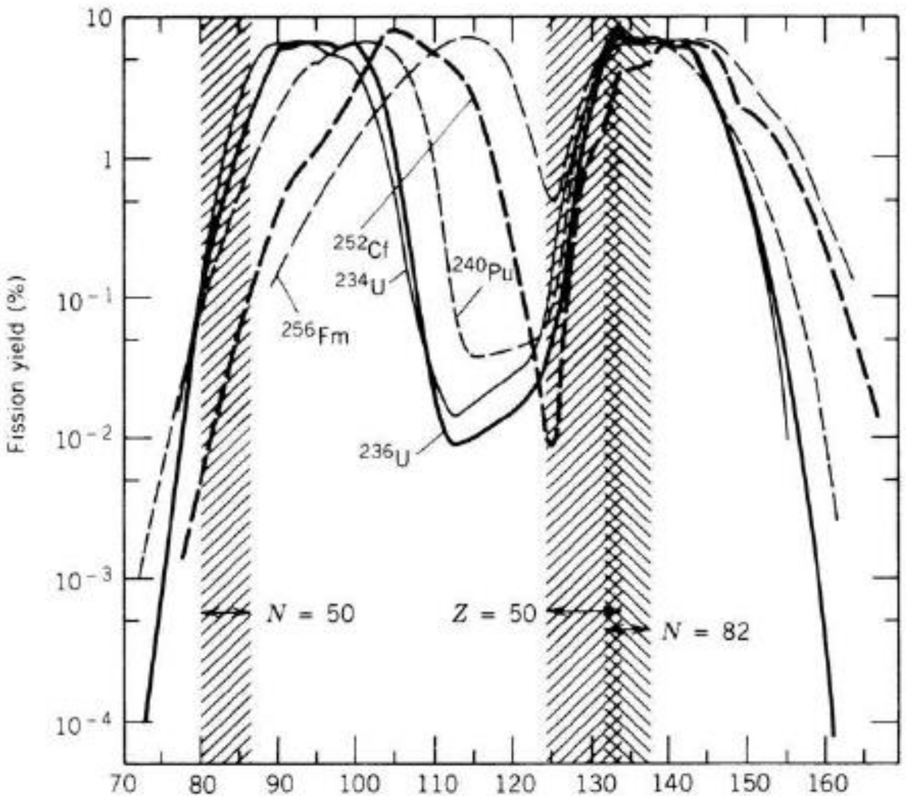
Fraction of a nucleus to be produced by fission



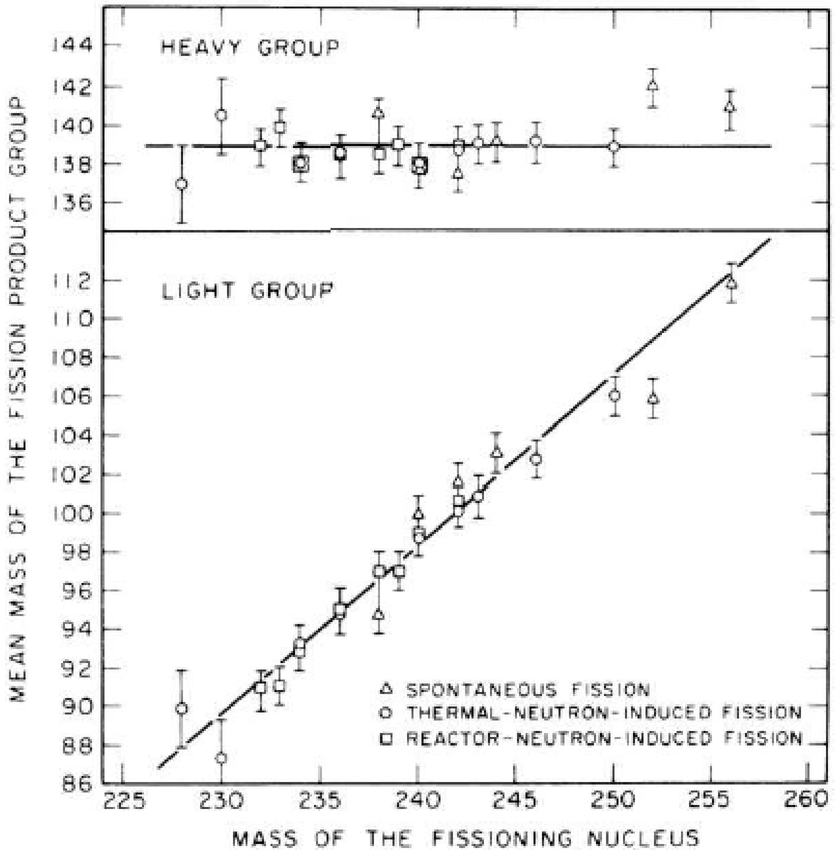
Fission yields

Some signatures of the underlying nuclear structure effects in the fission yields

- Fission is asymmetric: one of the first observation of shell effects of shell effects
- Heavy fission fragments mean mass stable for different actinides



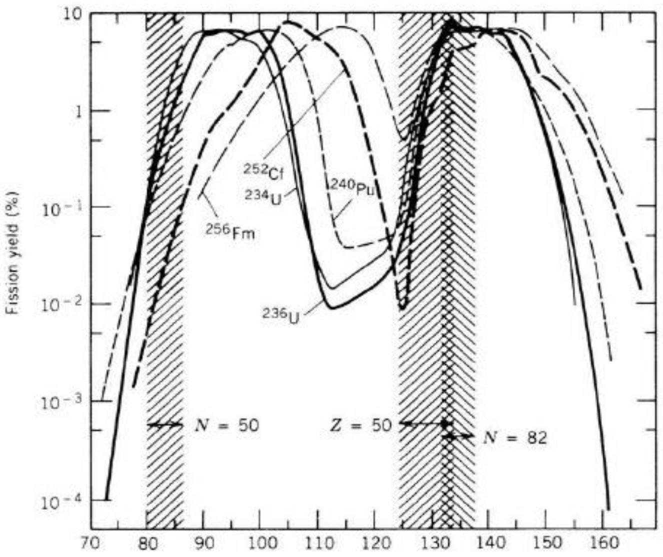
FLYNN *et al.*, PRC 5 (1972) 1725

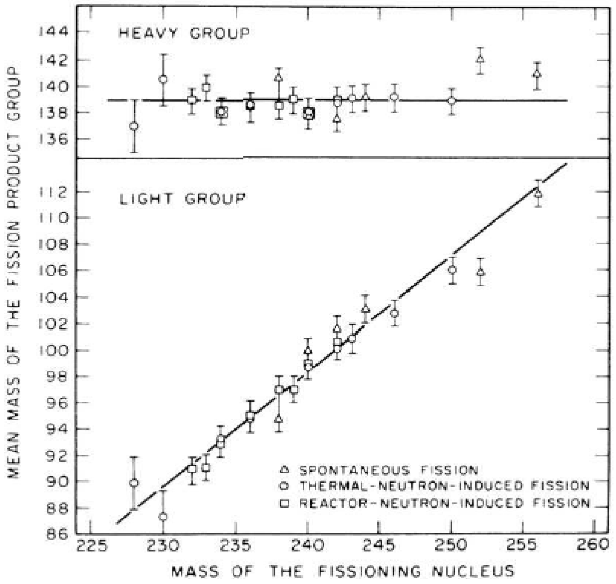


Fission yields

Some signatures of the underlying nuclear structure effects in the fission yields

- Fission is asymmetric: one of the first observation while studying the heavy actinides
- Heavy fission fragments mean mass stable for different actinides
- Proton even-odd staggering in even-Z fissioning system due to pairing
- Proton Evolution of the fission yields with the excitation energy





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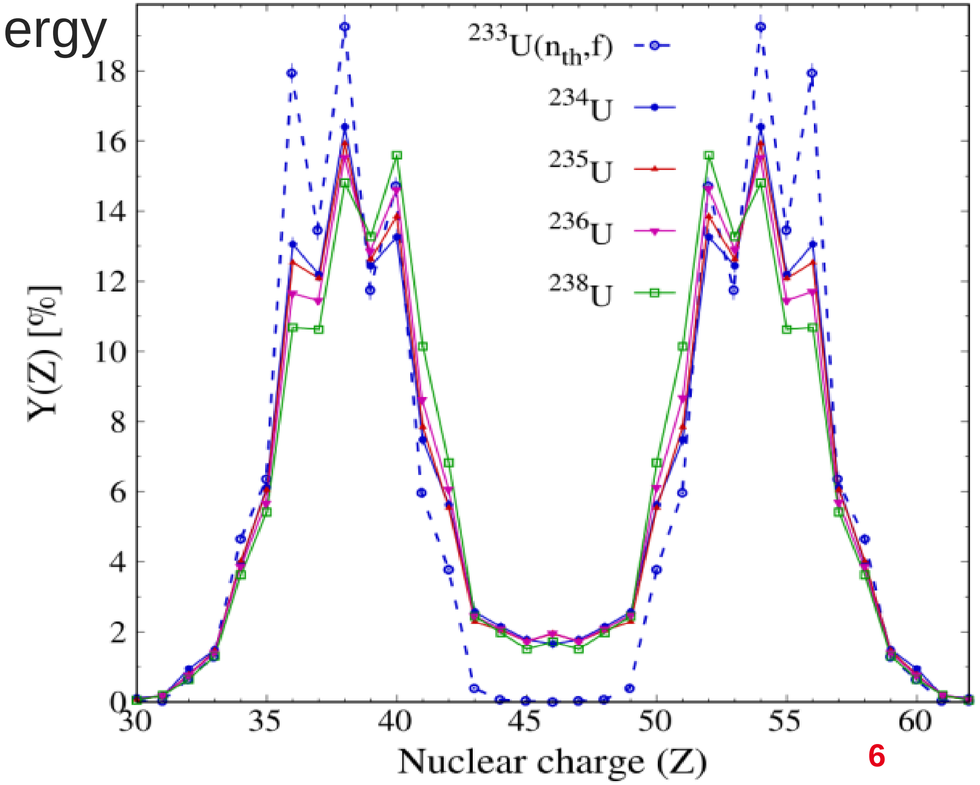
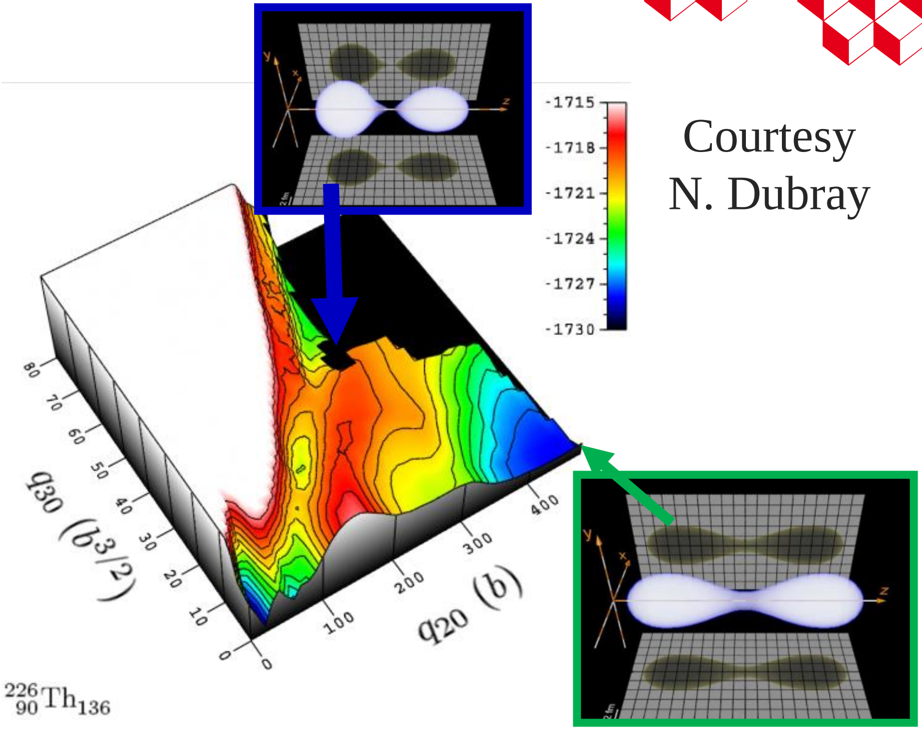


Fission modes around the U actinides

3 fission modes: 2 asymmetric modes and 1 symmetric mode

U. Brosa *et al.*, PRC 38 (1988) 1944

- One path on PES per mode
  - Valley from different underlying shell effects
  - Path reach the scission line at different (Q_{20},Q_{30})
  - Each mode has different configuration at scission



Courtesy N. Dubray

- STANDARD 1 (ST1)

  almost spherical FF_H
  ^{132}Sn spherical shells
  compact configuration

  high TKE, low ν

- STANDARD 2 (ST2) main

  deformed FF
  octupole shells Z=52, Z=56
  G. Scamps et al., Nature 564 (2018) 382

- SUPER-LONG (SL) with E*

  highly deformed FF
  shell effects washed-out
  deformed configuration

  low TKE, high ν

- **Importance of correlated data: yields, TKE, prompt neutrons, excitation energy, …**

2. Fission studies in inverse kinematics at relativistic energies

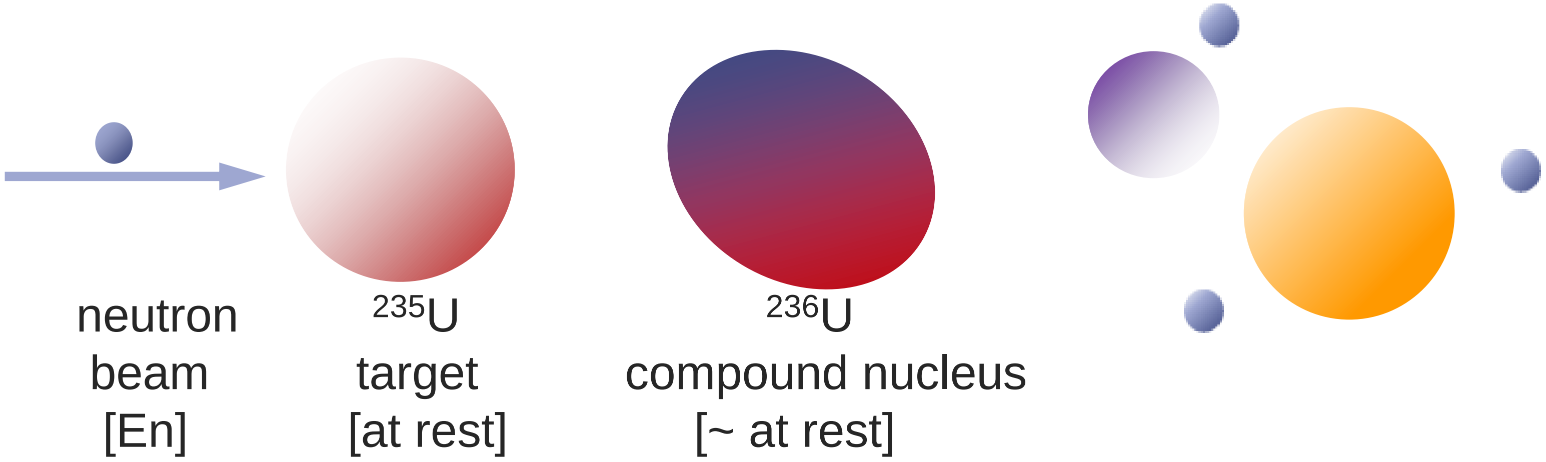
Why ?

How to induce low energy fission at relativistic energies ?

Experimental method at GSI: double - ΔE / $B\rho$ / ToF

Limitation of the direct kinematics

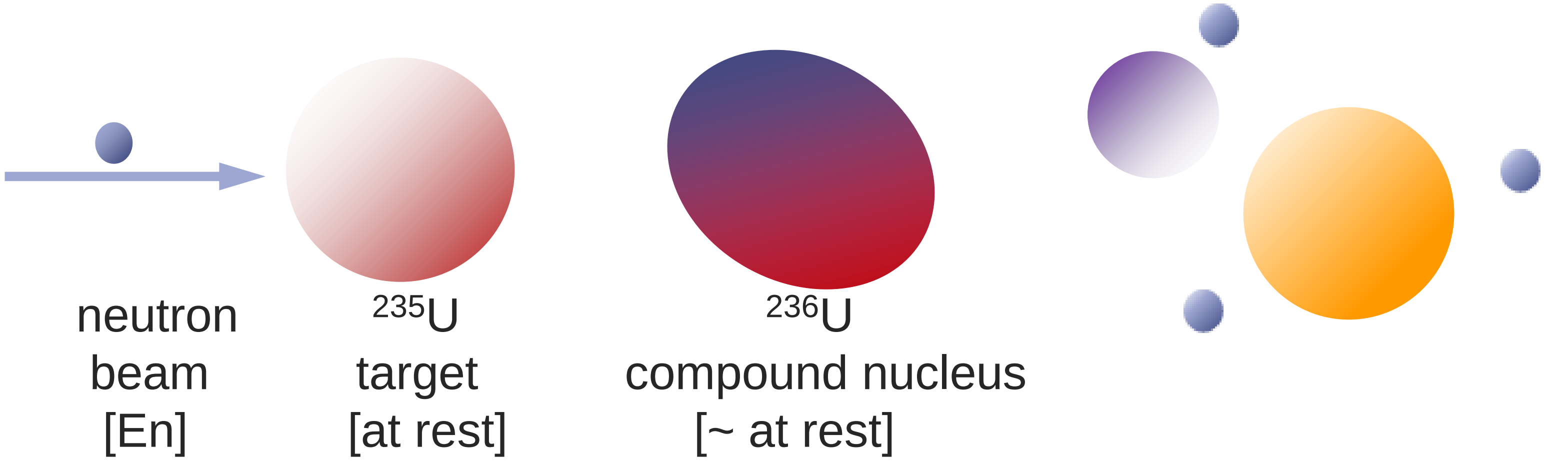
- Fission in direct kinematics:

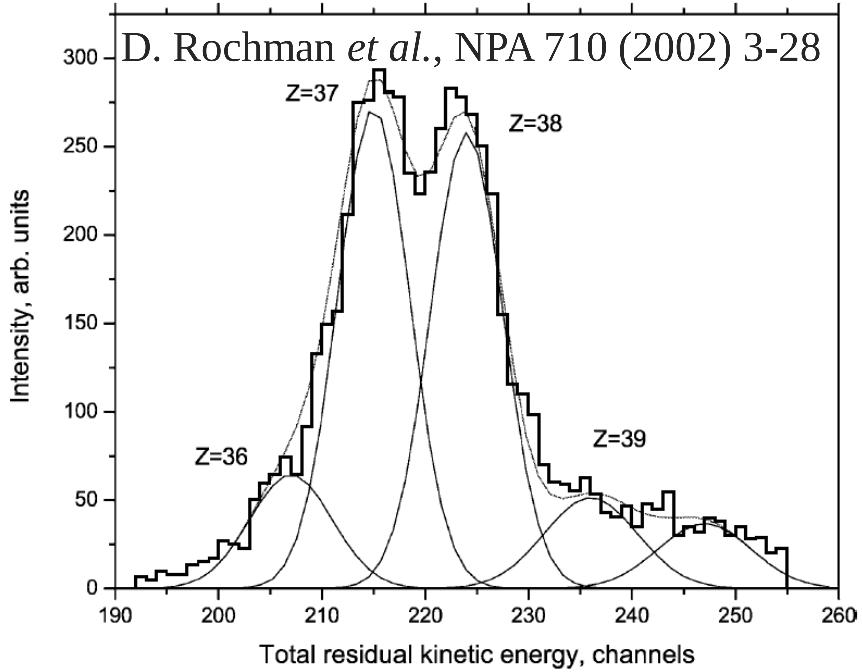


- A neutron-, proton- or light charged particle beam impinges on an actinide target
- Production of an excited compound nucleus which may de-excite by fission
- Fission fragments are emited with low energy in the lab frame

Limitation of the direct kinematics

- Fission in direct kinematics:





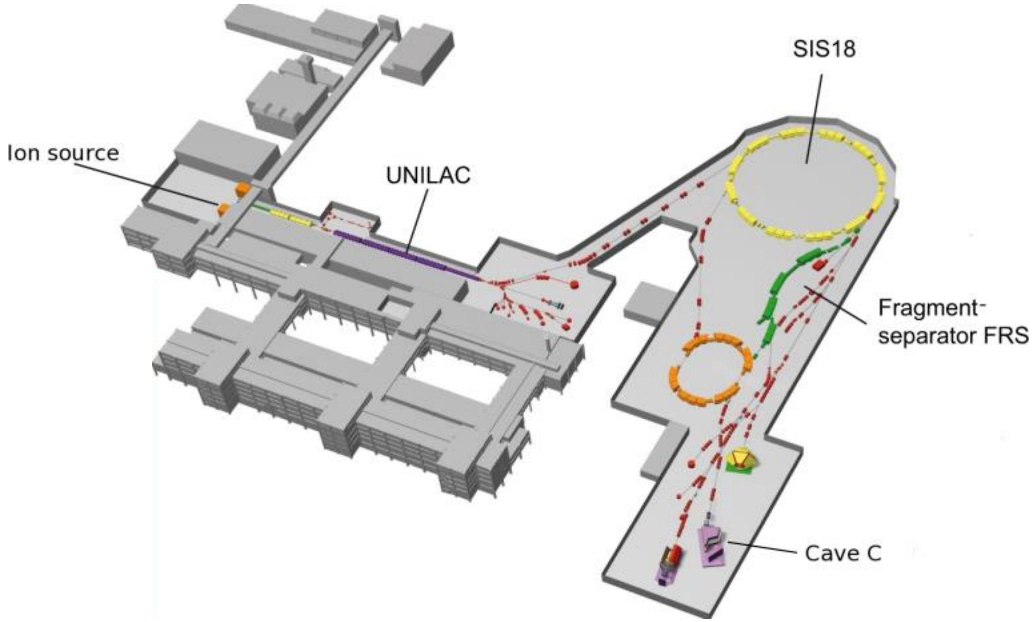
- Nuclear charge measurement limited to Z ≤ 40 due to ionic charge states

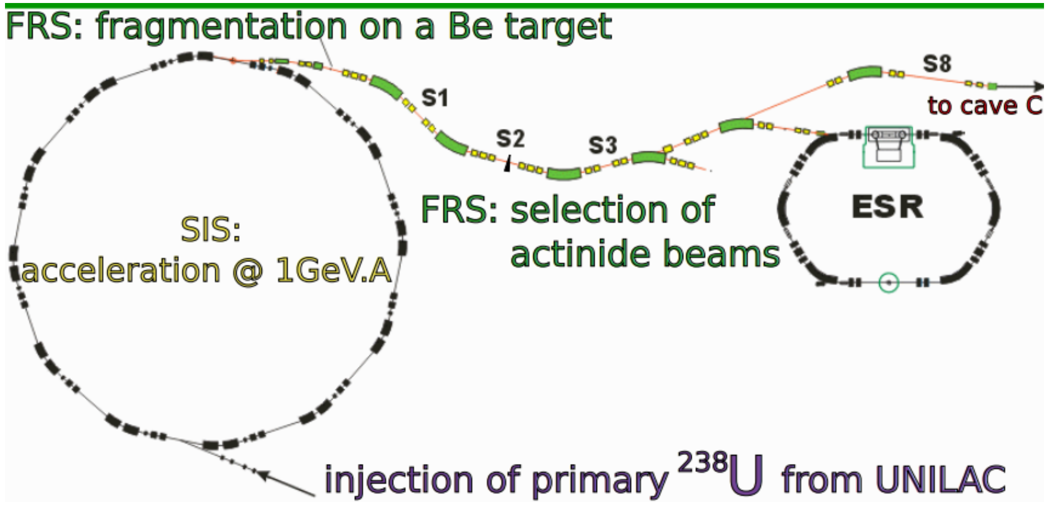
- Targets limited to long-lived actinides

- Very low efficiency due to 4π emission

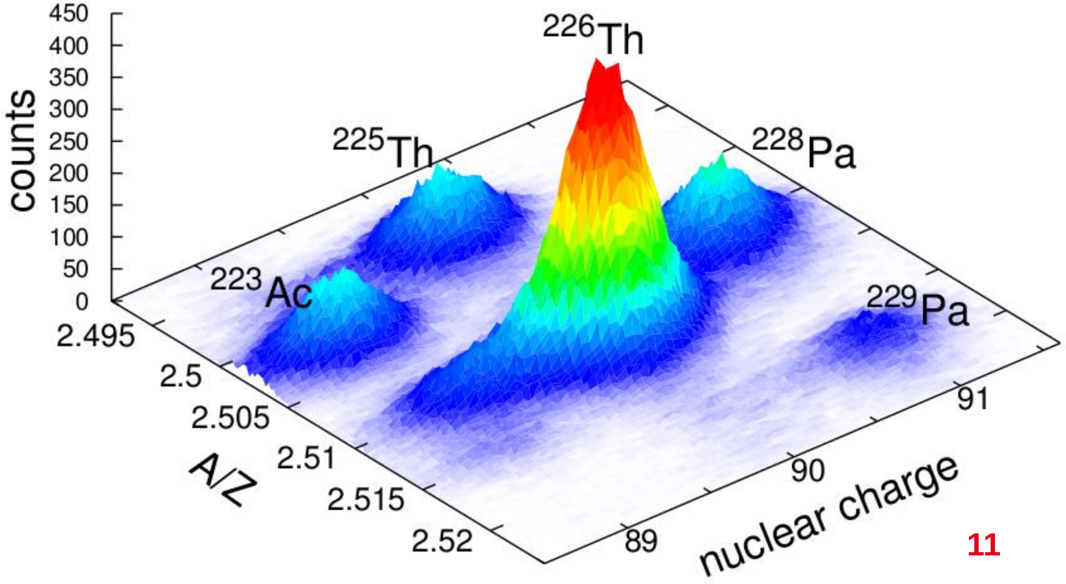
Inverse kinematics at **relativistic** energies (I)

GSI/FRS facility to produce radioactive relativistic beam





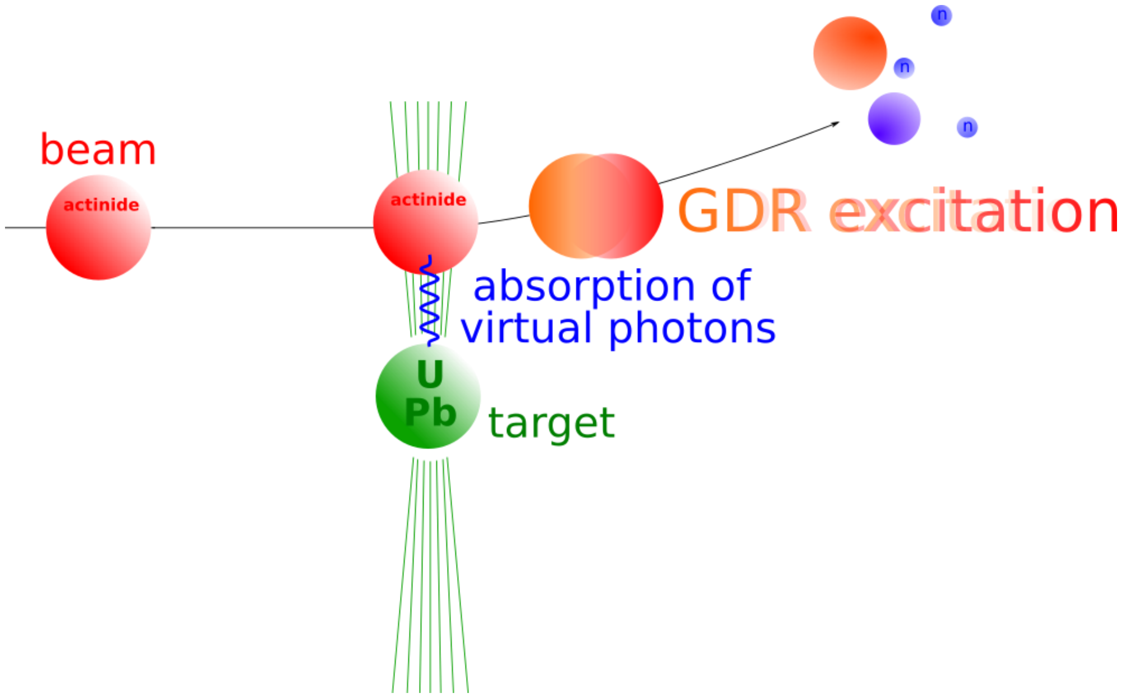
- @GSI: ^{238}U beam at 1 A.GeV
- @FRS: Fragmentation of 238U on a Be target and production of cocktail beams with a selection in **(Bρ,ΔE)** around **(A/Z , Z)** and sent to cave at ~750 A.MeV



Inverse kinematics at **relativistic** energies (II)

How to induce low energy fission at relativistic energies ?

- Fission is induced by coulomb excitation



Inverse kinematics at **relativistic** energies (II)

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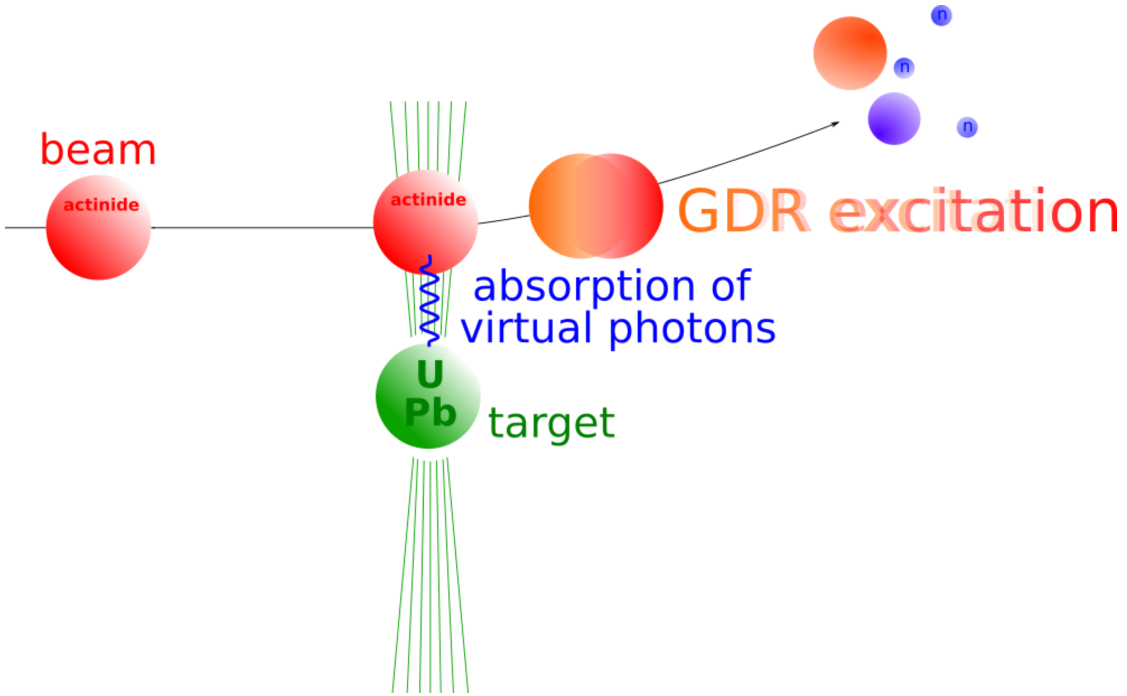
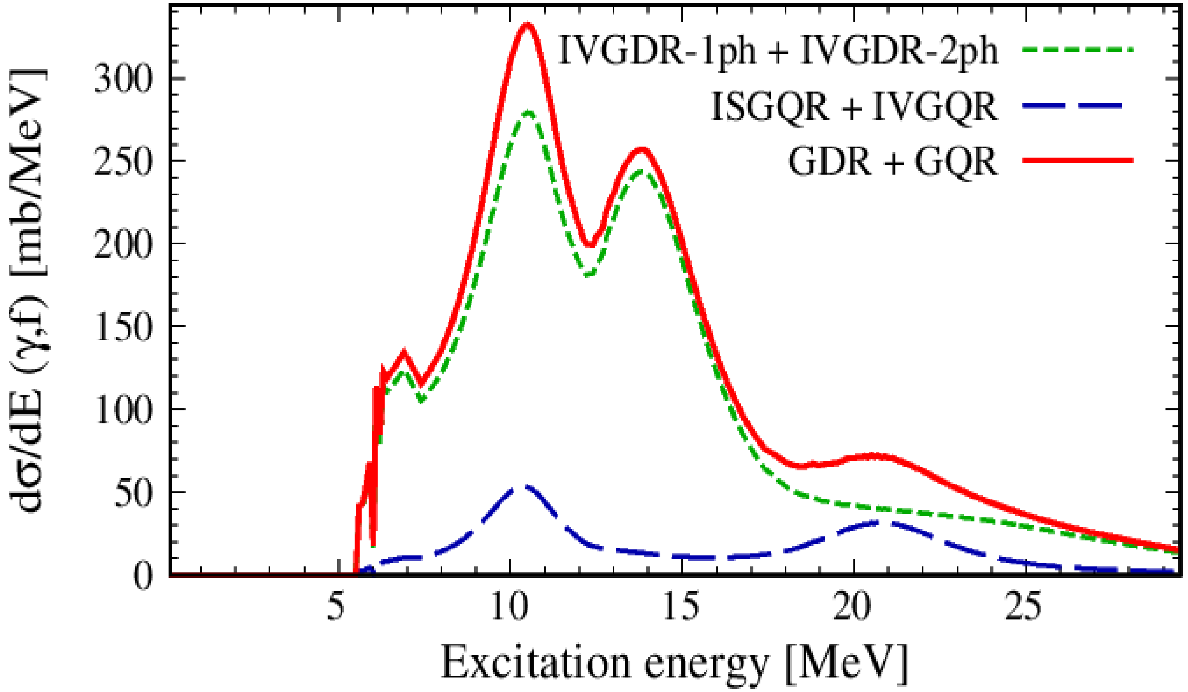


- Excitation energy: **⟨E*⟩ ~ 14MeV**



- Electromagnetic induced fission = surrogate reaction for 8 MeV neutron induced fission

$$\boxed{{}^{236}U_{750A.MeV}(\gamma,f) \leftrightarrow {}^{235}U(n_{8MeV},f)}$$

Inverse kinematics at **relativistic** energies (III)

Advantages compare to direct kinematics

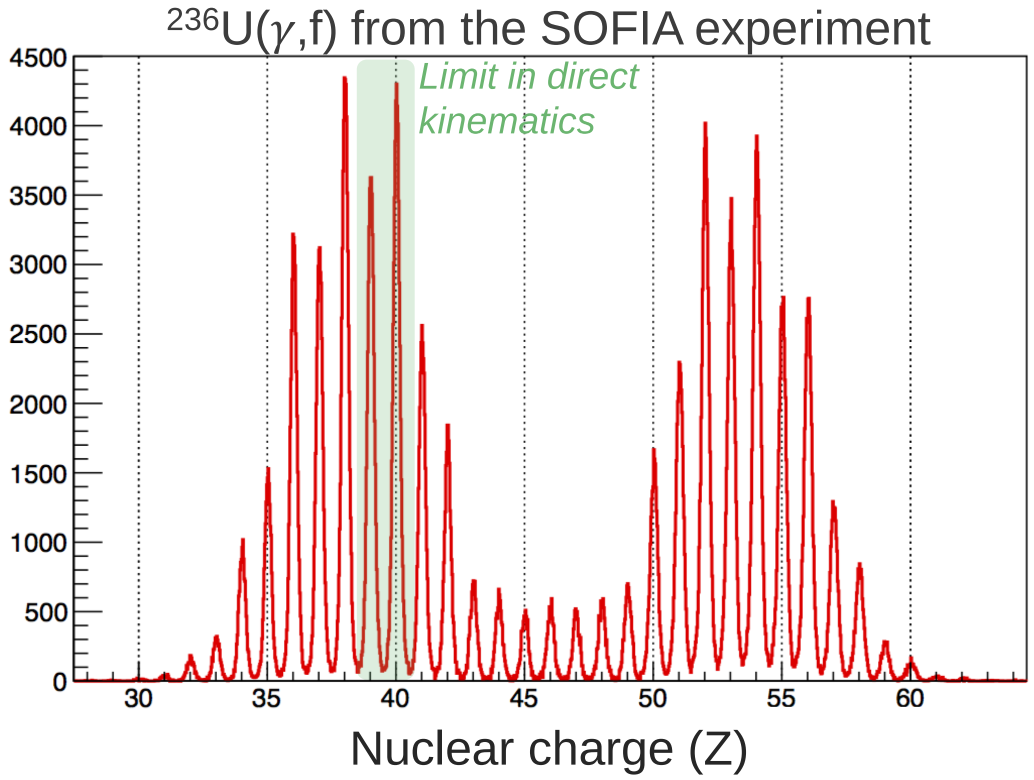
✓ Large cross section

- Example for $^{236}U(\gamma,f)$ **σ = 2 barns !!!!!**
- Accurate and large scale measurements

✓ Relativistic ions are fully stripped: Q=Z

- Q measurement from energy loss: $\Delta E \propto Q^2$
- More accurate measurement of Z
- **SOFIA resolution in charge :**

ΔZ = 0.31 to 0.34 charge unit FWHM

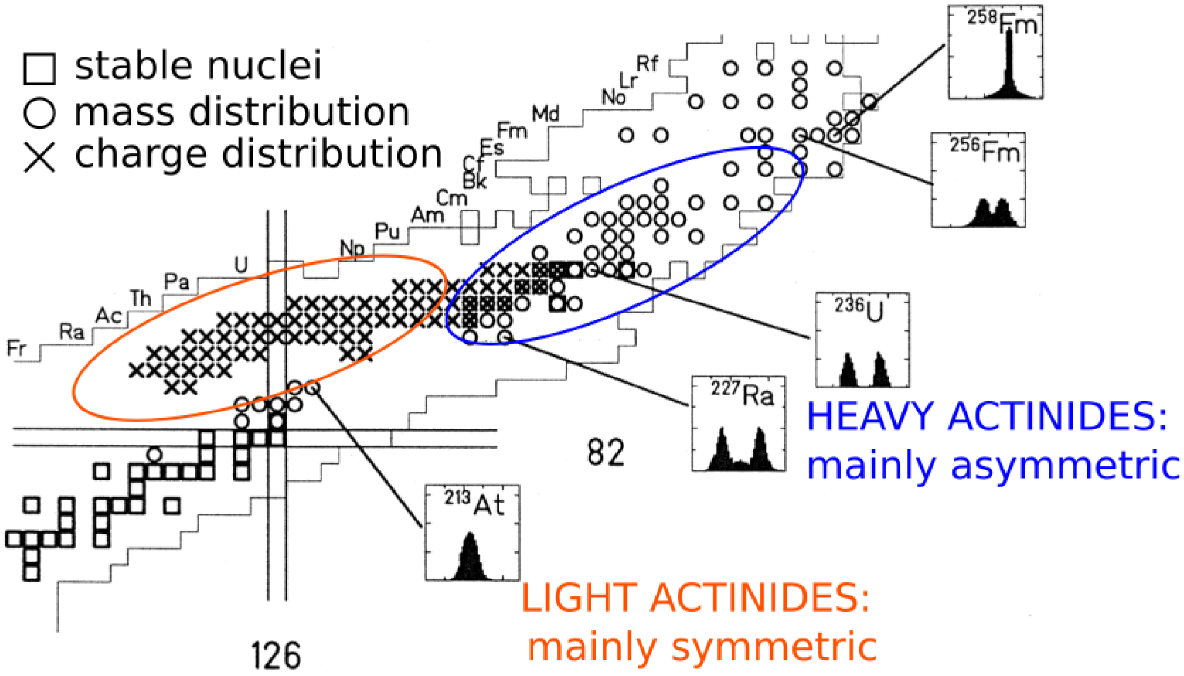


✓ Study of fission nuclei which can not be produced in direct kinematics

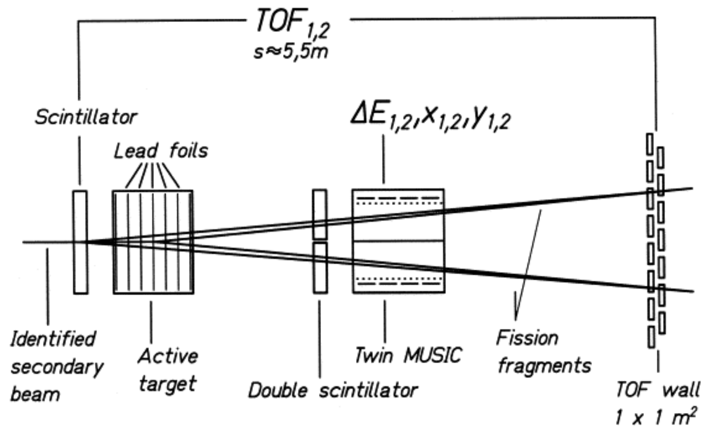
Pioneer experiment at GSI / FRS in inverse kinematics

K.-H. Schmidt *et al.*, Nucl. Phys. A 665 (2000) 221: measurement of the charge only

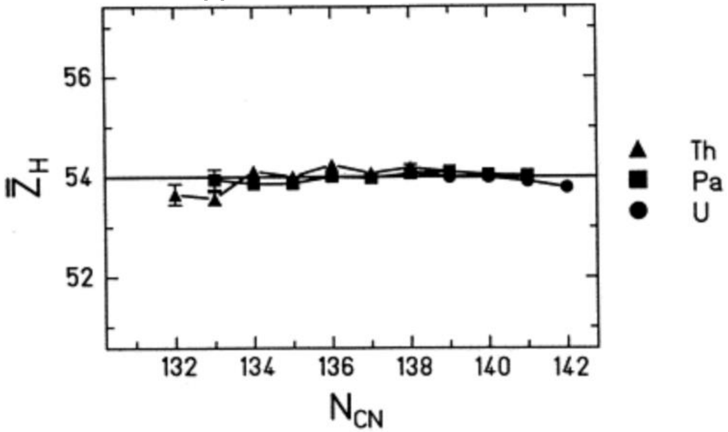
- Y(Z) measured for Rn to U fissioning isotopes



- Experimental setup: ΔE and ToF



- Important result: $\langle Z_H \rangle = 54$



2. The SOFIA experiment

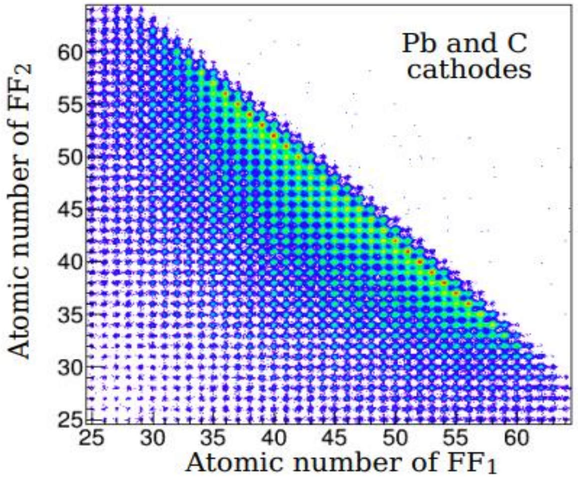
A dedicated spectrometer for fission studies @ GSI

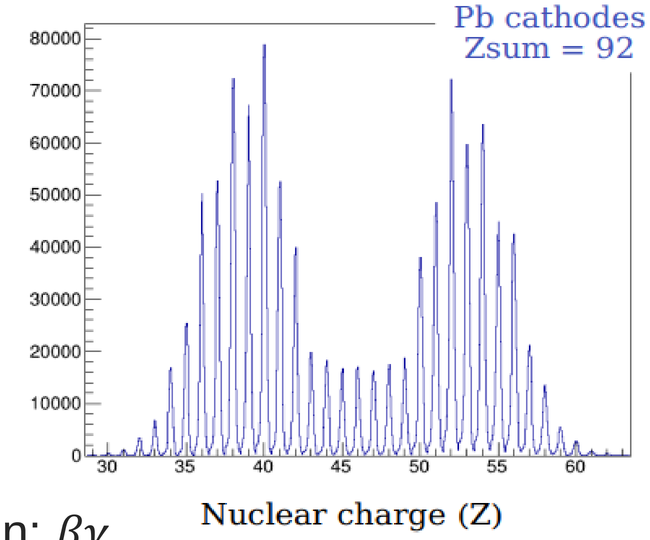
Experimental program

SOFIA: (Z,A) identification

ΔE – Bρ – ToF method after prompt emission and before any β-decay

- **Nuclear charge Z**
  - Energy loss (ΔE) ~ $Q^2 = Z^2$
  - Z is « easy » to obtain





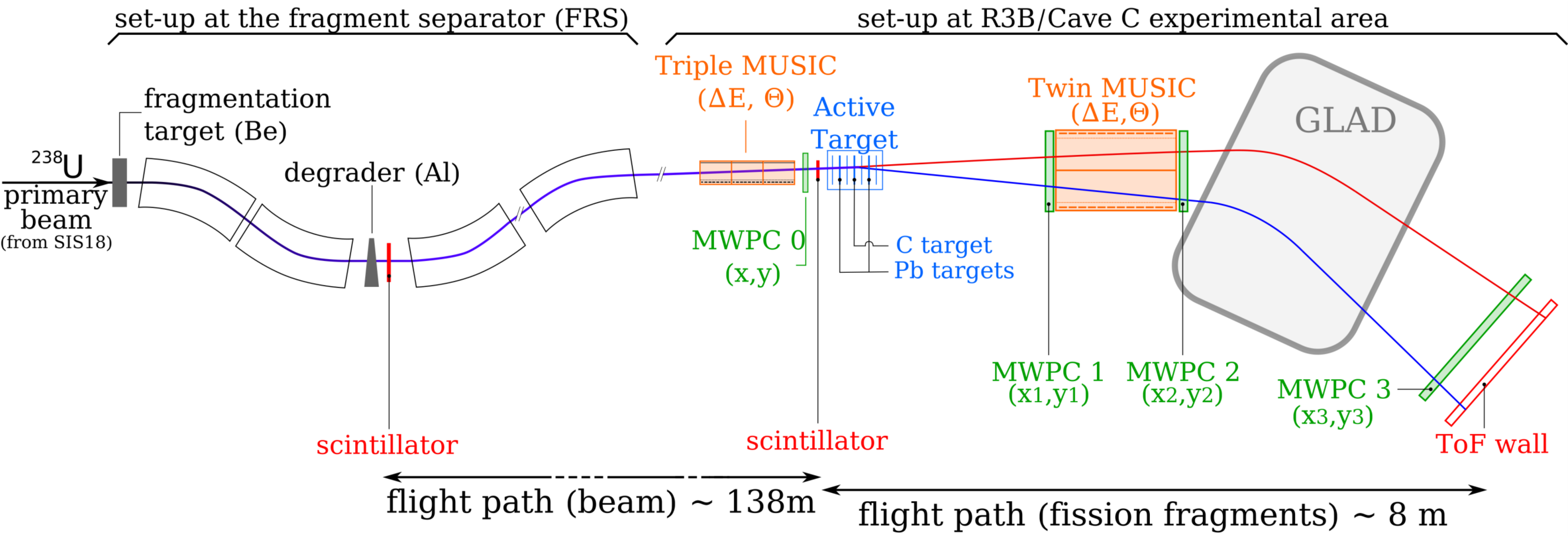
- **Mass A**
  - Time-of-flight measurement (ToF) combined with flight path reconstruction: $\beta\gamma$
  - Tracking of the ions in a magnetic field (Bρ)
  - A/Q ~ Bρ / $\beta\gamma$

CHALLENGING RESOLUTION
Δx = 100 to 300 µm
ΔToF = 35 ps
FWHM

- **Total prompt-neutron multiplicity ν_{tot}**
  - Method at FRS for (Z,A) identification of beam
  - Method at cave C for (Z,A) identification of both fission fragments in coincidence

SOFIA spectrometer

3 types of detectors : **MUSIC** **MWPC** **scintillators**



Identification of the fission fragments in $^{236}U(\gamma,f)$

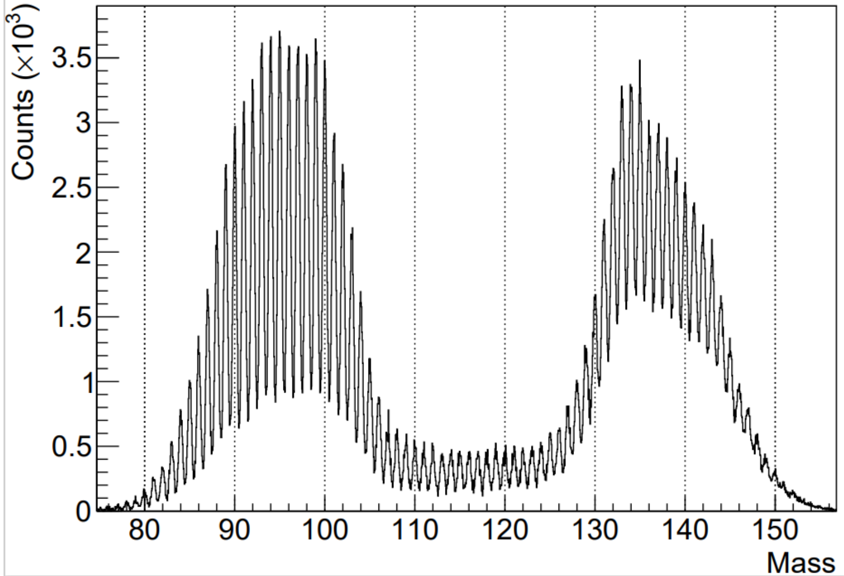
RESOLUTIONS [FWHM]:

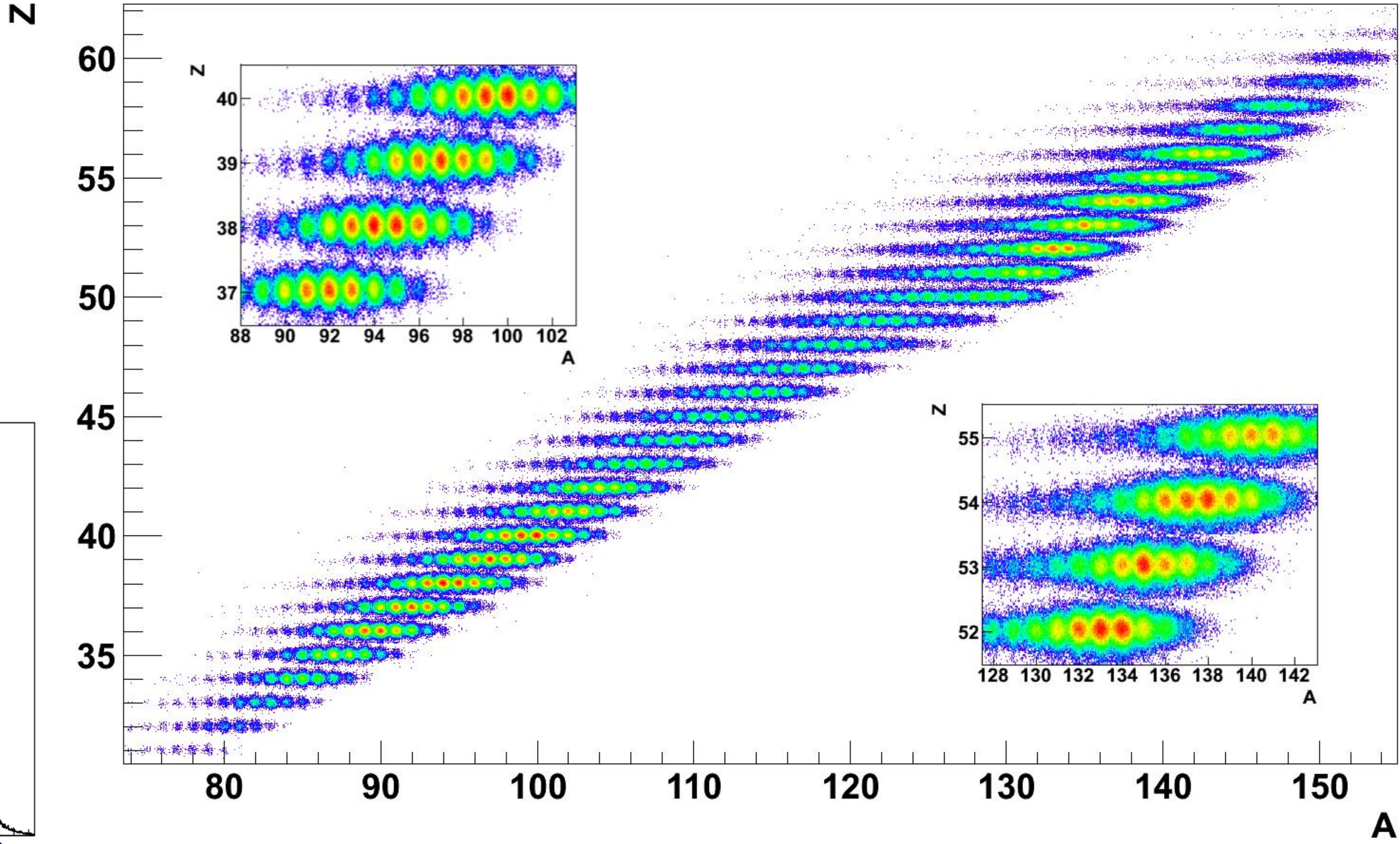
ΔZ = 0.31 to 0.34 charge unit

ΔA = 0.55 to 0.80 mass unit

Δx = 100 to 300 μm

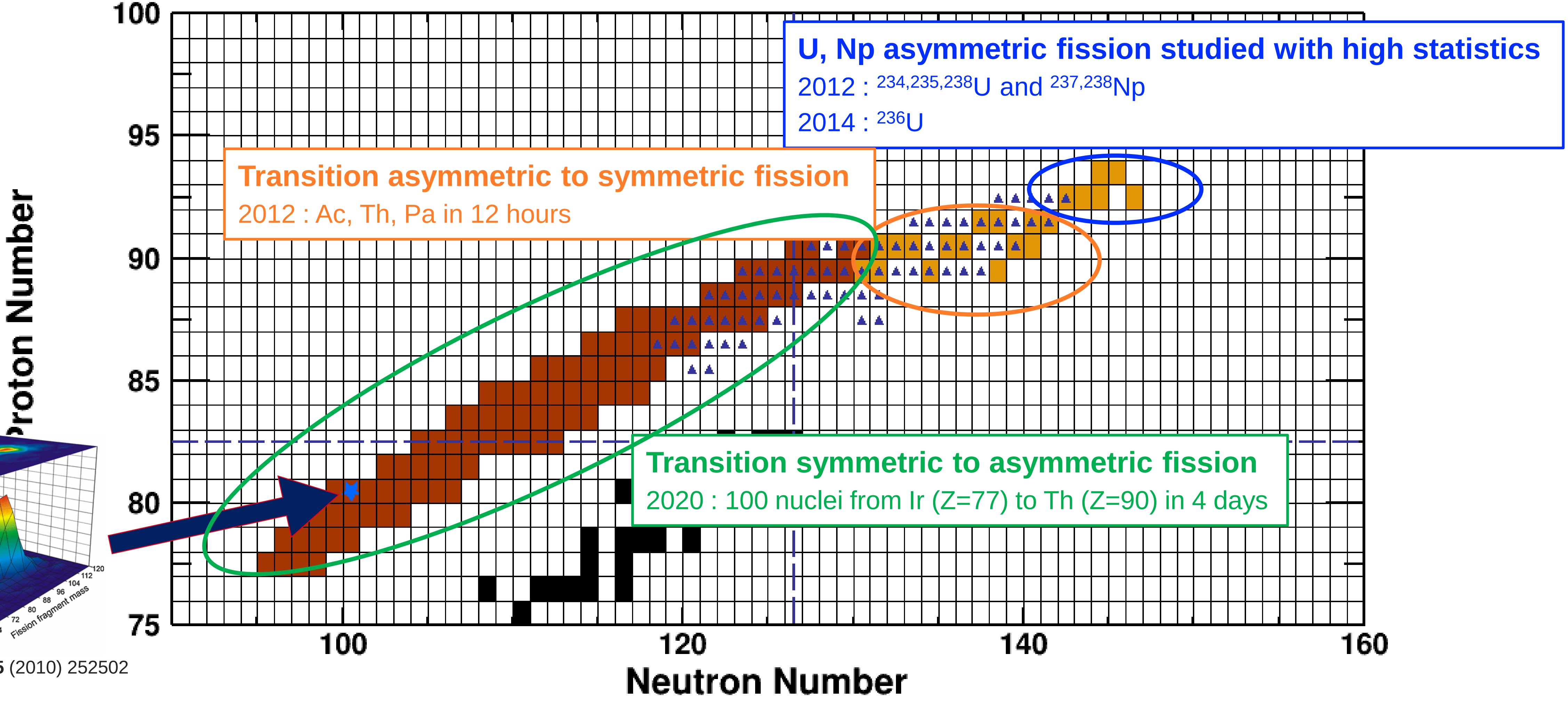
ΔToF = 35 ps

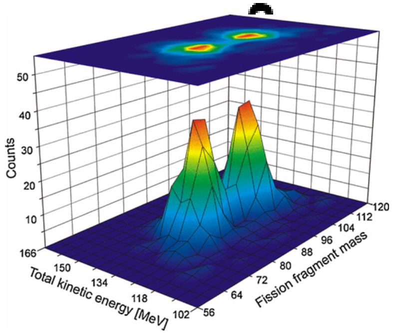




Analysis by L. Grente (CEA,DAM,DIF)

SOFIA experiments





A. Andreyev, PRL **105** (2010) 252502

3. Results

Accurate measurement: Isotopic yields and isobaric yields

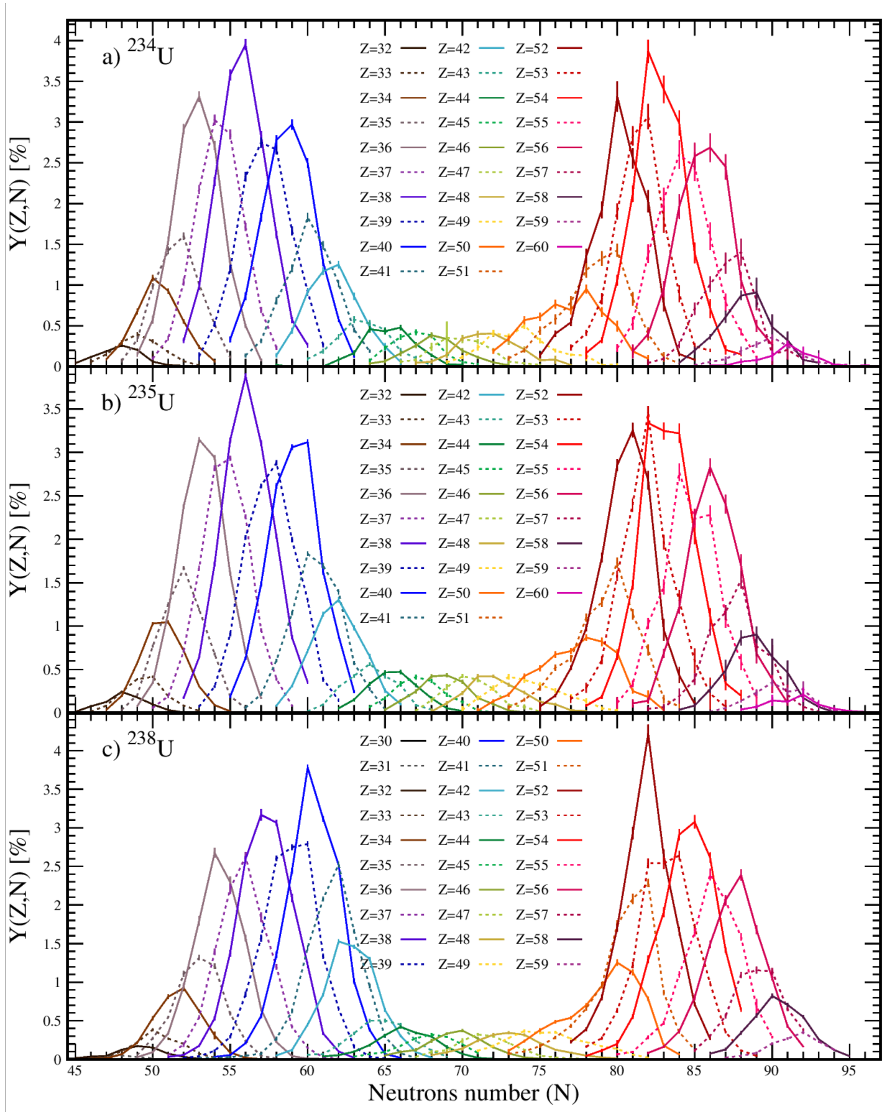
TKE and ν_{tot}: a probe of scission configuration

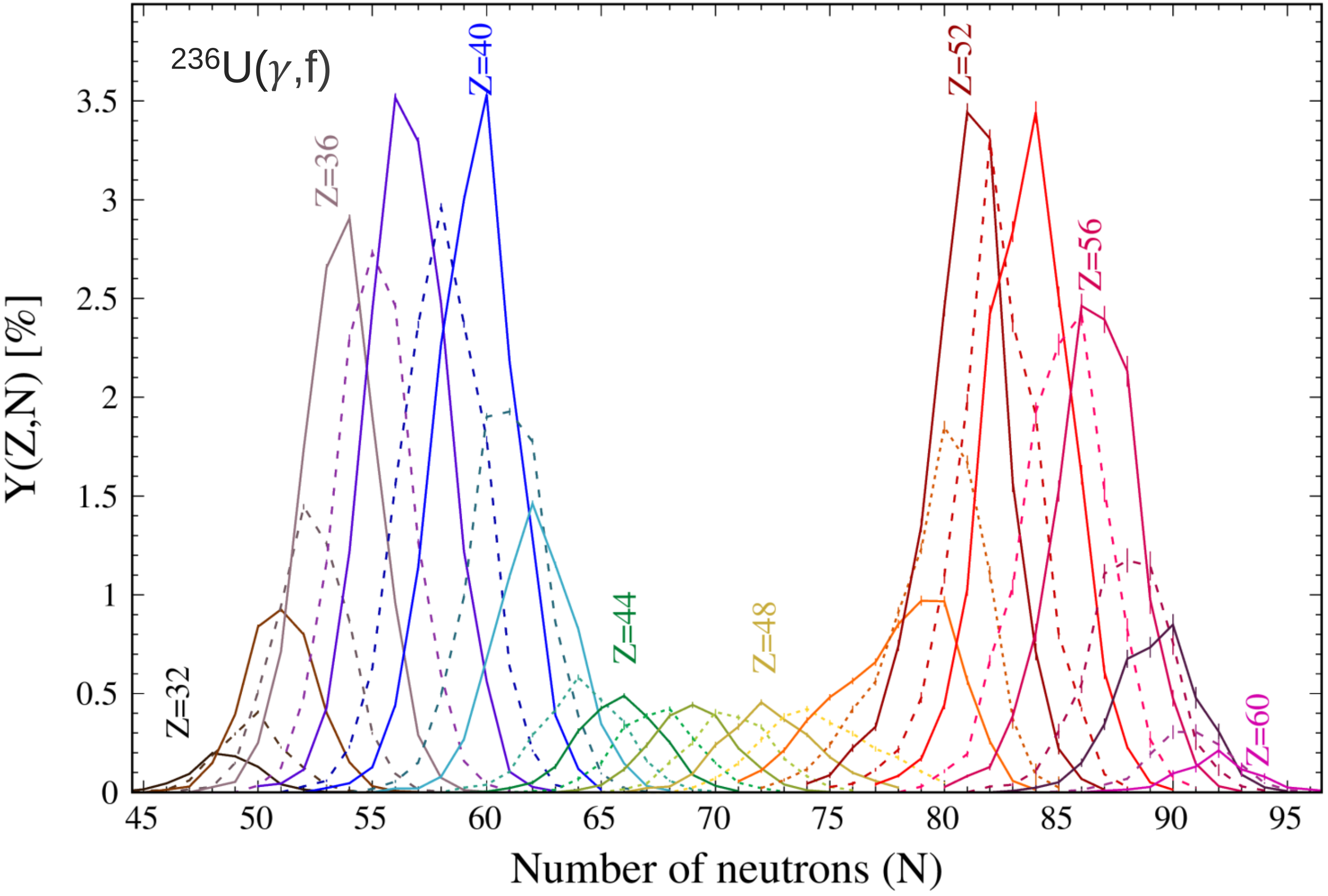
Signatures of energy sorting: ν(A) and even-odd staggering

Large scale measurement: investigating new fission modes

Isotopic yields along the uranium chain

E. Pellereau *et al.*, PRC 95 (2017) 054603
J. F. Martin *et al.*, PRC 104 (2021) 044602



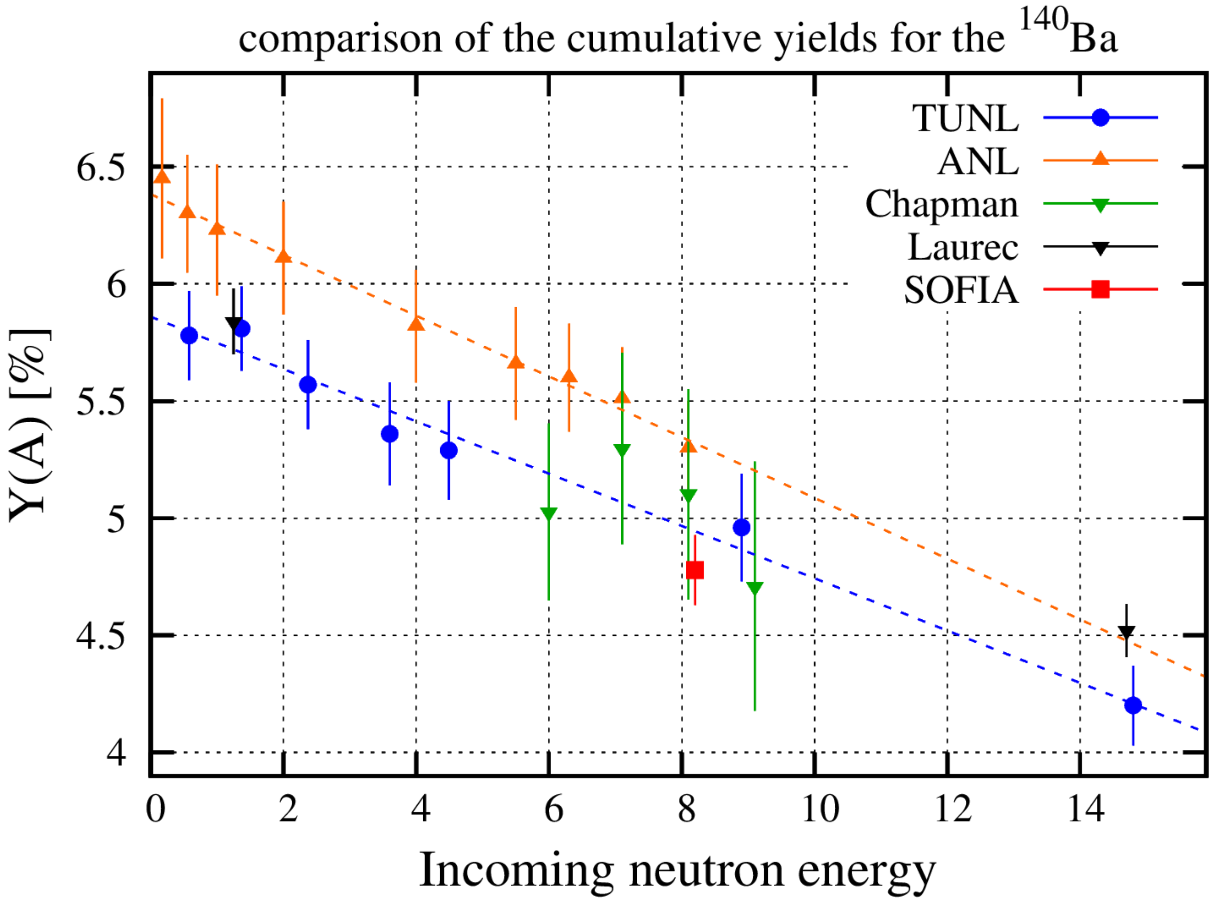


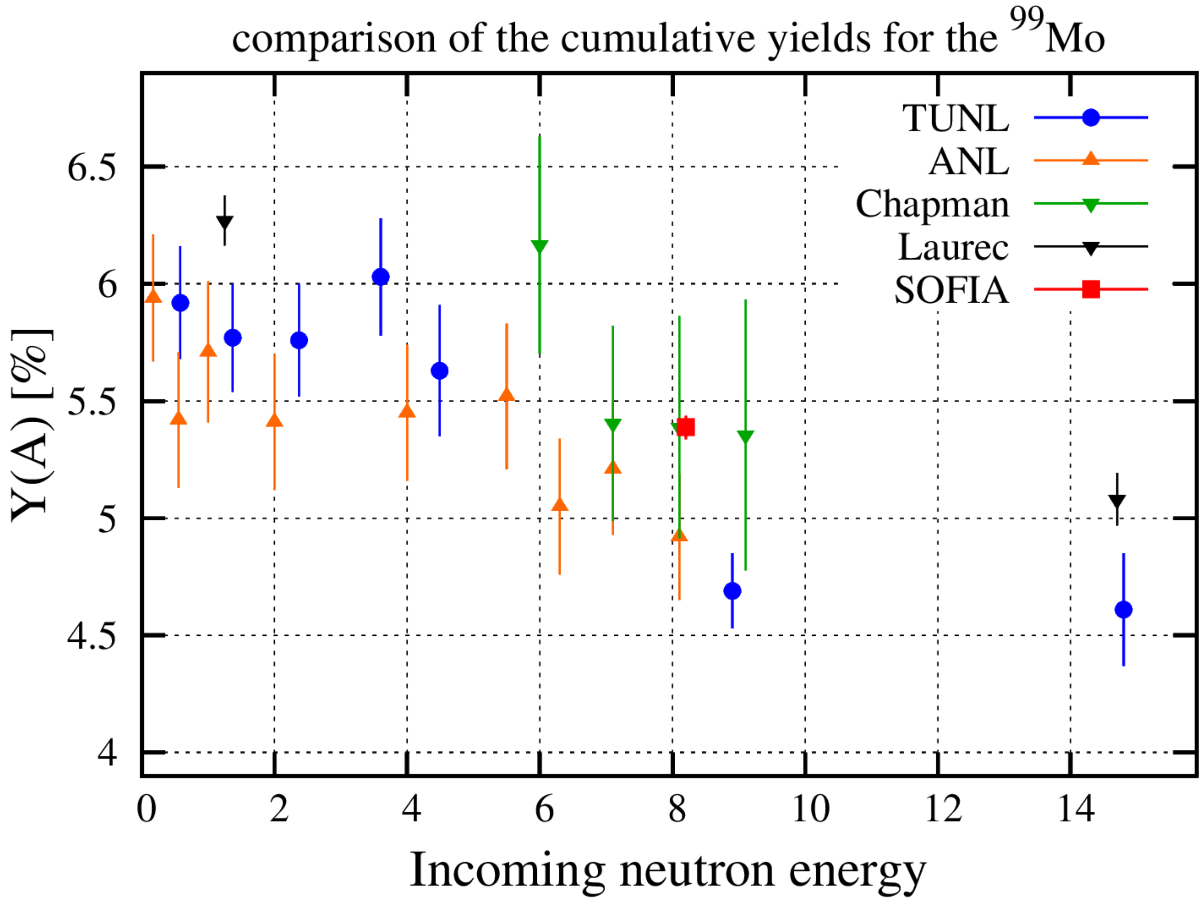
0.5% ≤ σ ≤ 1.5%

1.3% ≤ σ ≤ 3.5%

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

Cumulative yields: $^{236}U(\gamma,f)$ vs $^{235}U(n,f)$ cumulative yields

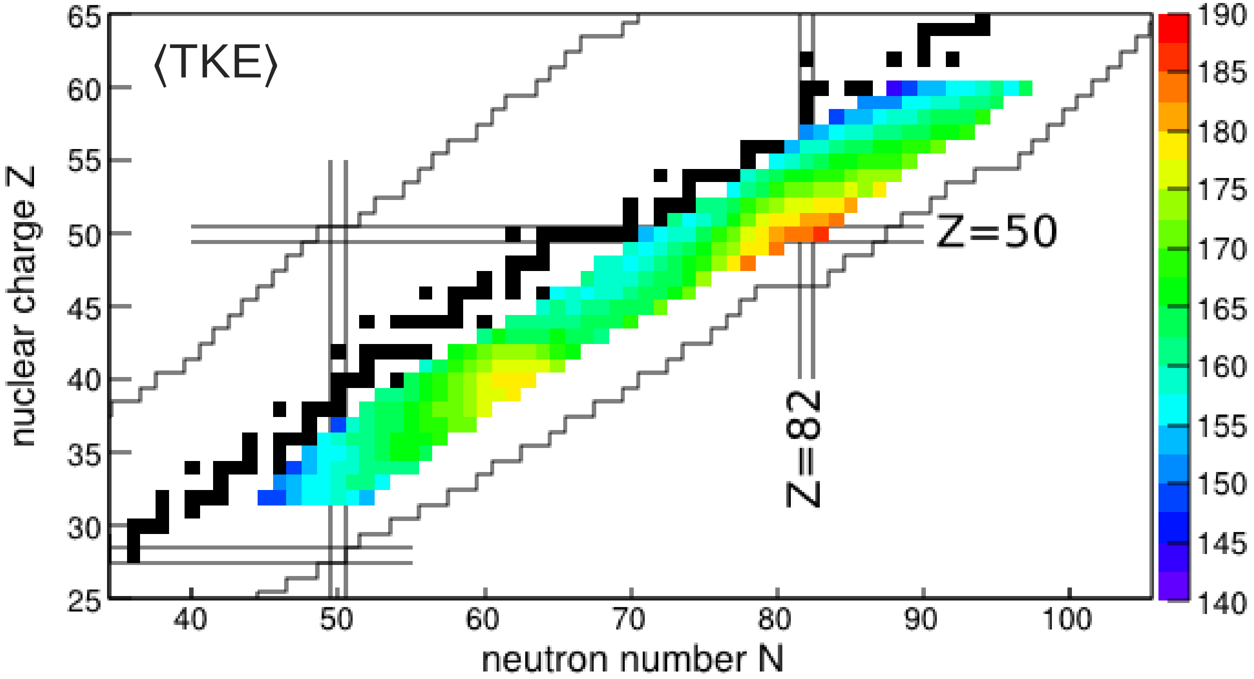


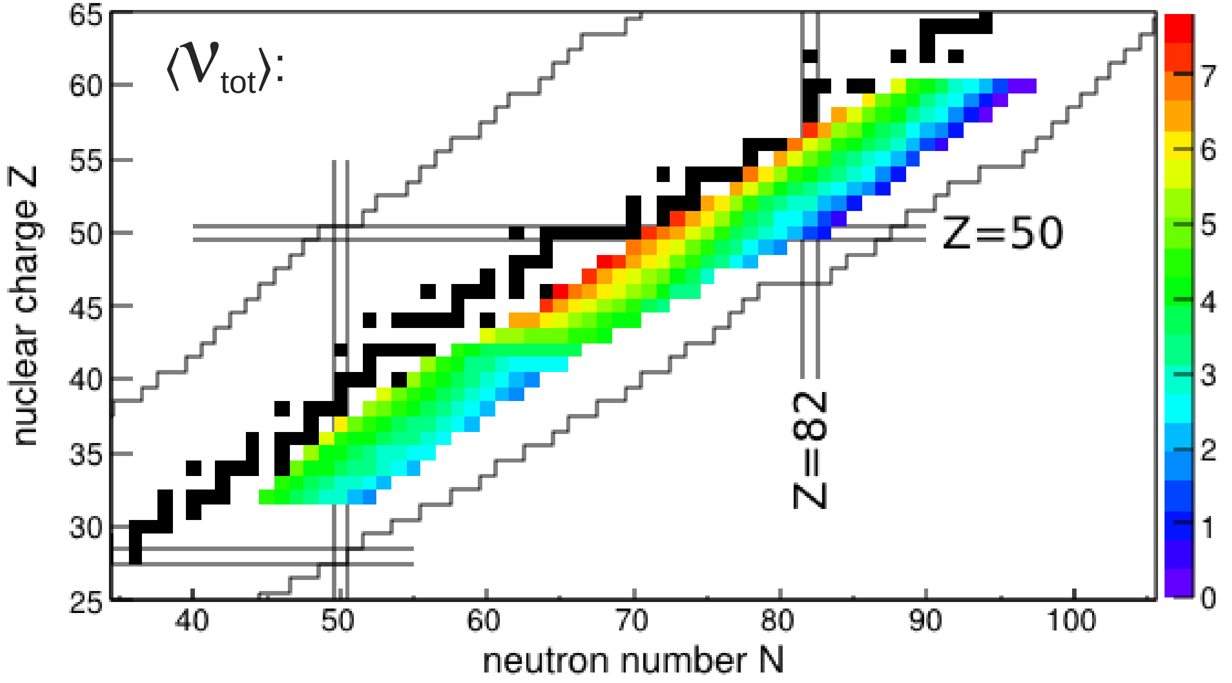


Analysis by L. Grente (CEA,DAM,DIF)

$\langle$TKE$\rangle$ vs $\langle\nu_{tot}\rangle$: $^{235}U(\gamma,f)$

- Both observables probe the scission configuration
- Large deformation: high ν_{tot}, but low TKE
- Highly deformed symmetric mode compared to compact asymetric mode





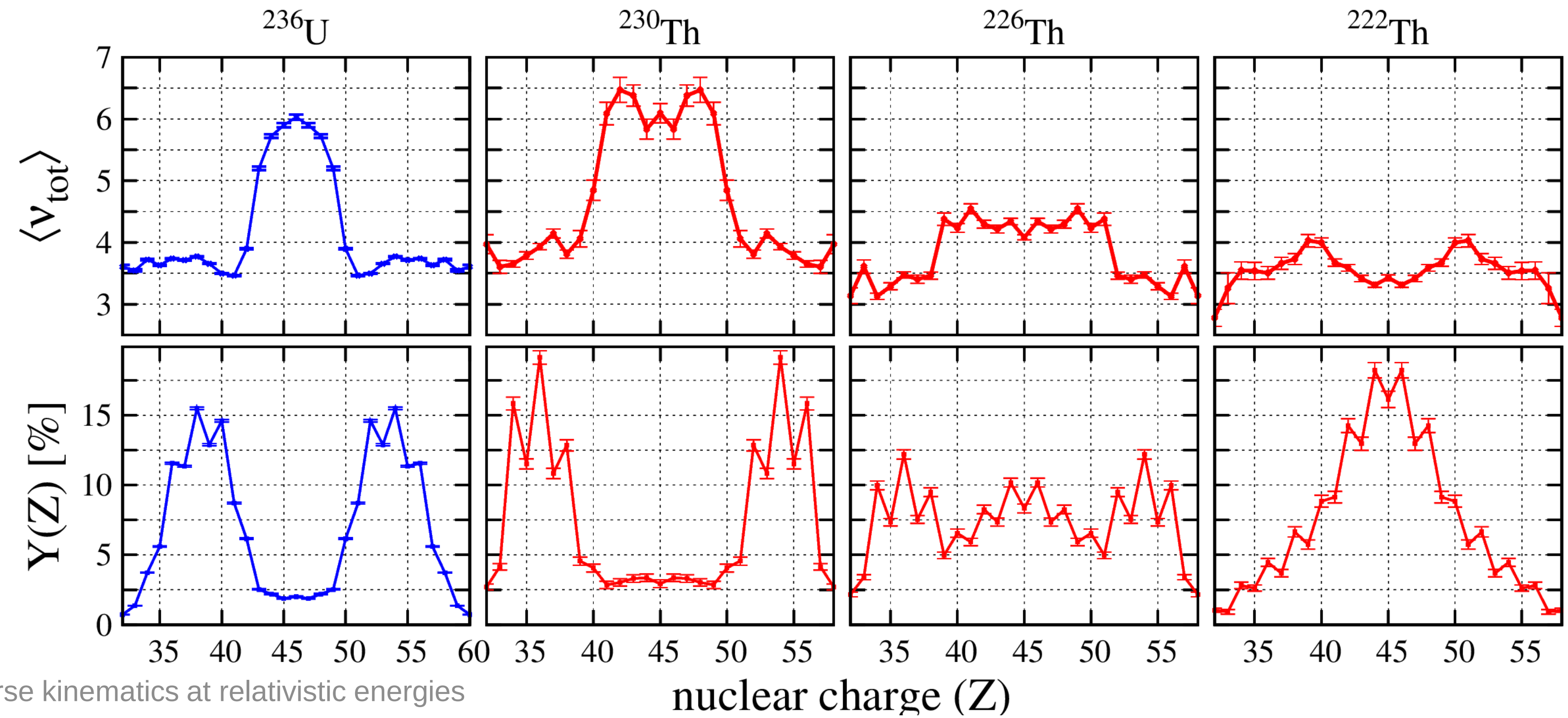
Analysis by J.-F. Martin (CEA,DAM,DIF)

Y(Z) vs ν_{tot}: ^{222,226,230}Th(γ,f) and ^{236}U(γ,f)

For neutron-deficient thorium isotopes

- Symmetric fission becomes the main fission mode
- Even-odd staggering remains , but ν_{tot} drops around 2.7 MeV (effect of 19 MeV)
- New symmetric fission mode observed with a compact configuration at scission

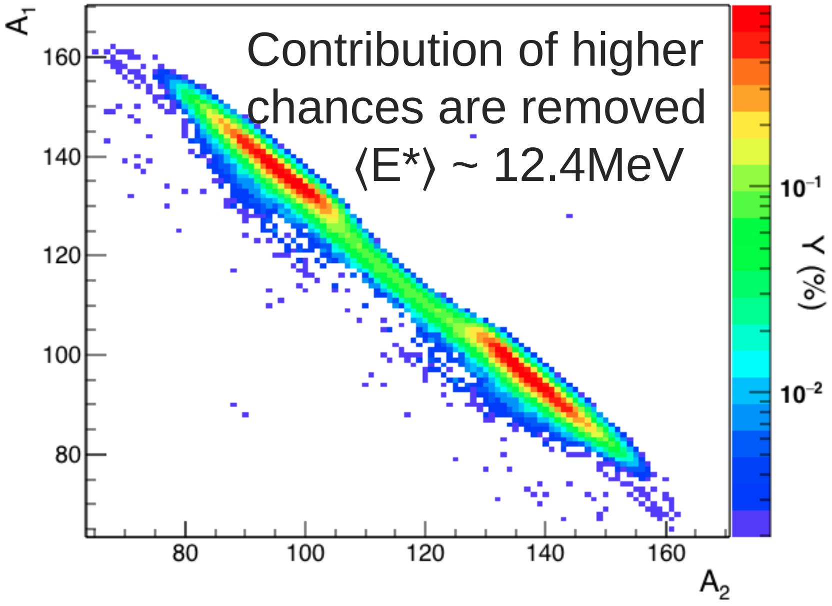
A. Chatillon *et al*. PRC 99 (2019) 054628
B. PRL 124 (2020) 202402



^{236}U(γ,f): Prompt neutron multiplicity per fission fragment

From the correlated mass yield Y(A1,A2) to $\langle\nu\rangle$(M)

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



$$Y(A_1, A_2) = \sum_{\nu_1=0}^{A_B-A_1-A_2} P^{M_1}(\nu_1)P^{M_2}(\nu_2)X(M_1)$$

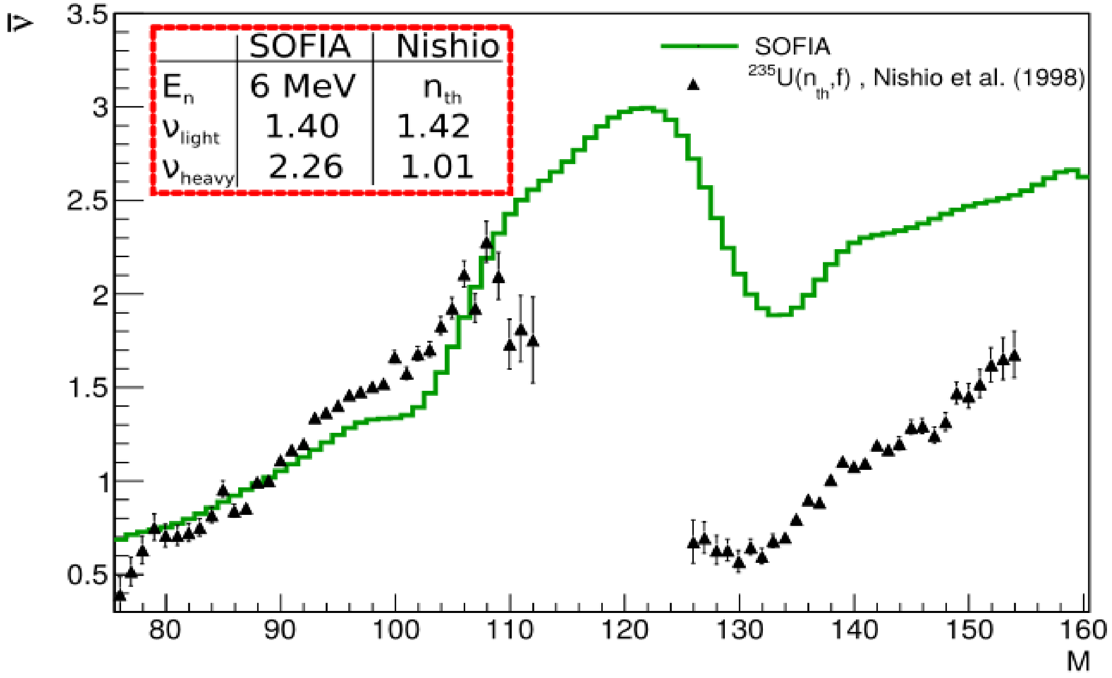
A_i: mass of the fragment after neutron emission

$X(M_i)$: mass yields before neutron emission

$Y(A_i)$: mass yields after neutron emission

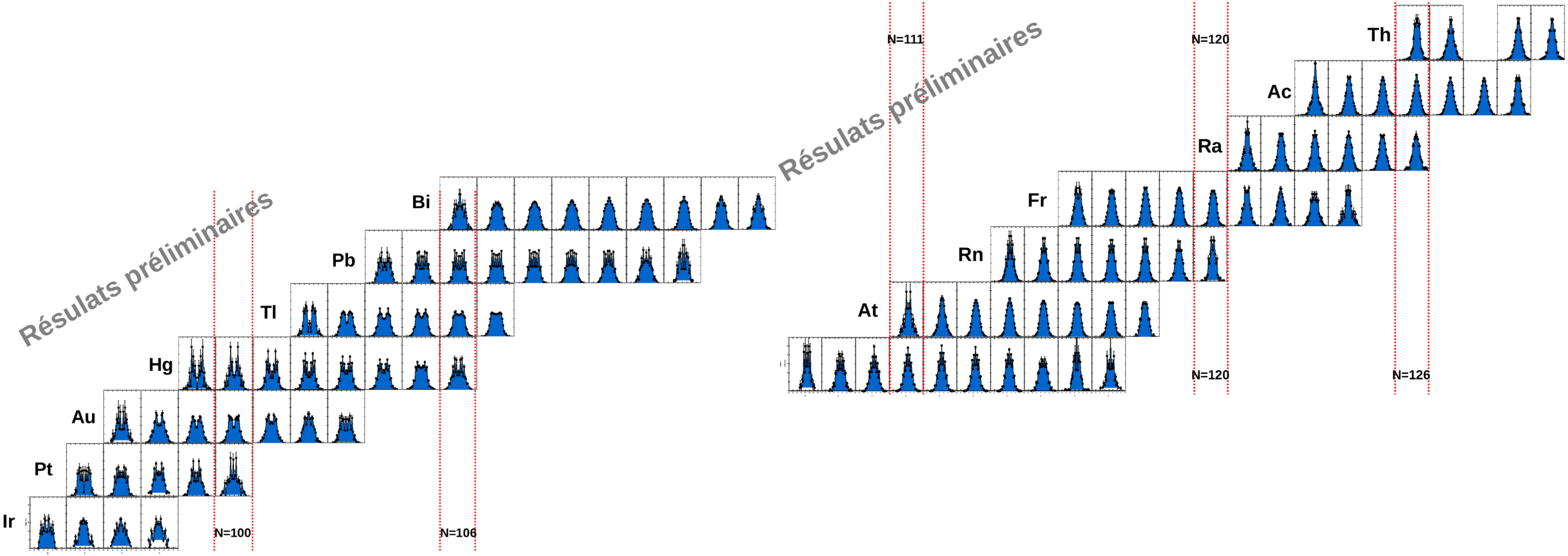
$P^{M_i}(\nu_i)$: probability for a primary fragment of mass M, to emit ν neutrons

- **hyp 1:** $\mathbf{P^{M_i}(\nu_i)}$ **gaussian**
  $\Rightarrow$ 3 sets of independant parameters
  $\langle\nu\rangle$(M), σ(M), X(M$_i$)
- **hyp 2:** $\langle\nu\rangle$**(M),** σ**(M) Fourier series**
  $\Rightarrow$ cut in the high frequency domain
- χ^2 **minimization using MIGRAD**
  $\Rightarrow$ from the CERN library MINUIT



Study of the new island of asymmetry

Fission study of more than 100 nuclei in 4 days of beam time



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

Conclusions

Inverse kinematics at relativistic energy for accurate fission yields and ν_{tot}

Fission study of exotic nuclei with the underlying microscopic effect

Few limitation: no E* measurement

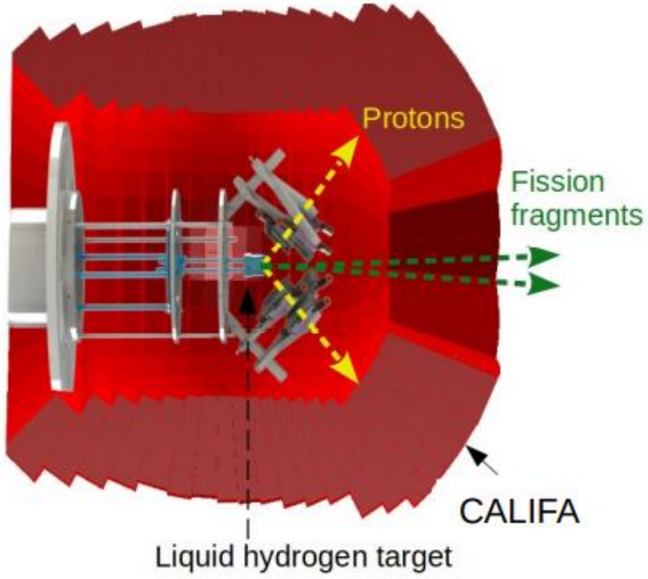
→ (p,2p) reaction to get E instead of Coulex but with lower statistics*

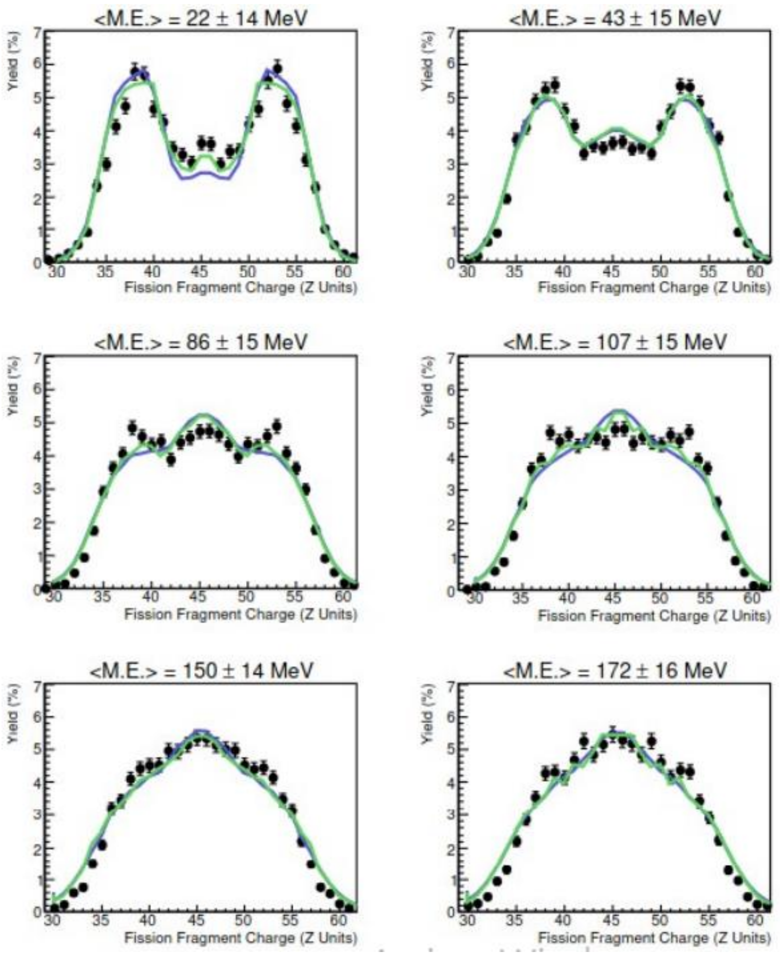
Fission induced by quasi-free nucleon-knockout collisions

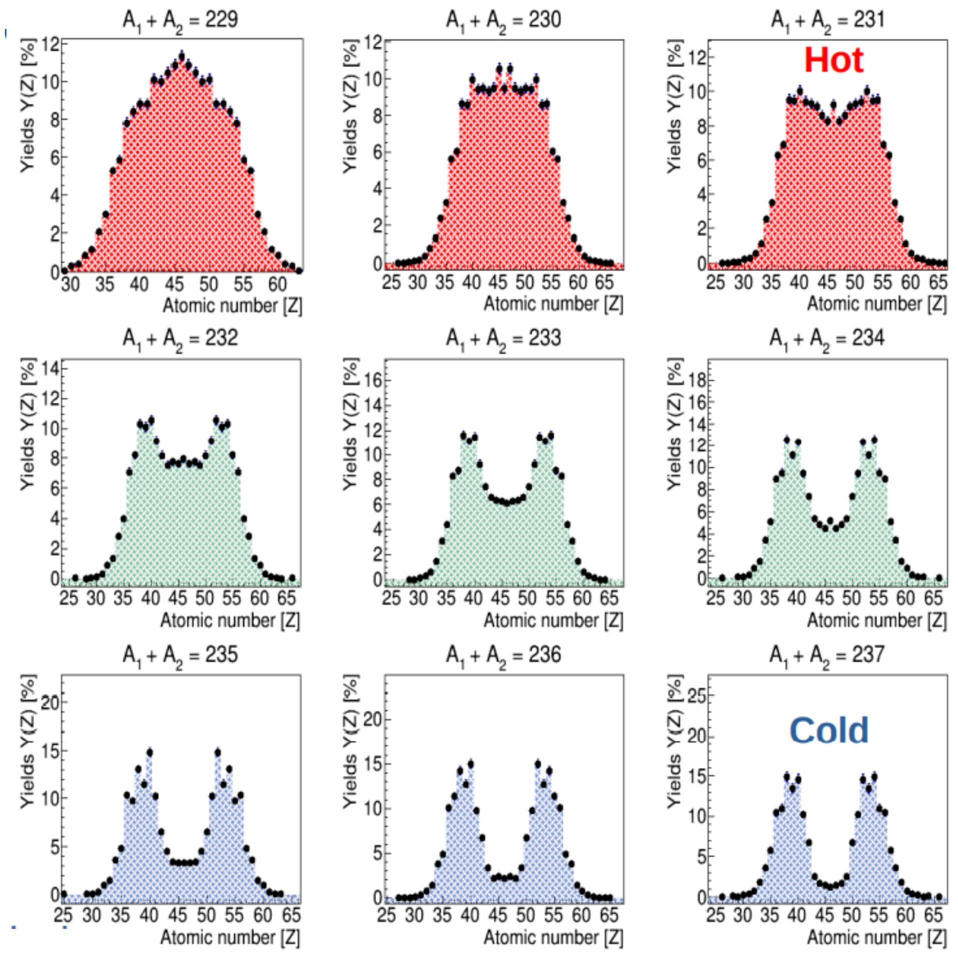
$^{238}U(p,2p)^{237}Pa$ in inverse kinematics used to induce fission and measure E*

Analysis by G. Garcia and A. Grana (Univ. Santiago de Compostella) supervised by J. L. Rodríguez-Sánchez (Univ. Coruña)

Same set-up but liquid H target surrounded by Si array and the CALIFA calorimeter







Conclusions

Inverse kinematics at relativistic energy for accurate fission yields and ν_{tot}

Fission study of exotic nuclei with the underlying microscopic effect

Few limitation: no E* measurement, A_{CN} ≤ 238

→ *(p,2p) reaction to get E* instead of Coulex but with lower statistics*

→ *complementary to measurement at GANIL/VAMOS (see Diego's talk)*

4. More info

Set-up

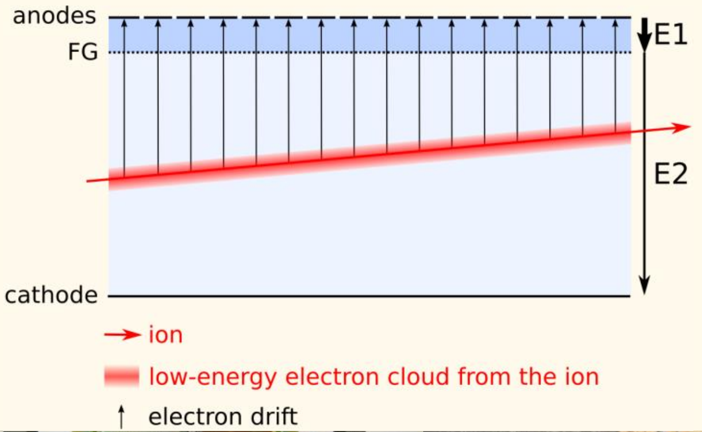
Analysis: nuclear component subtraction

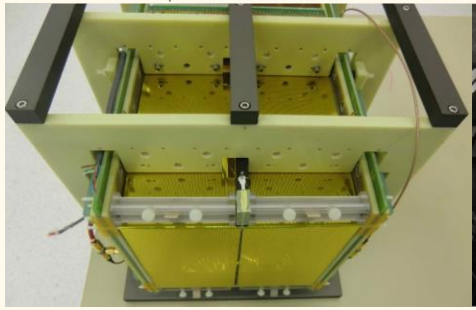
Fission modes

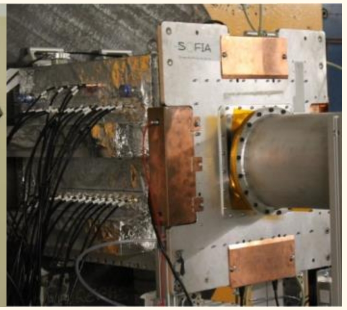
SOFIA spectrometer

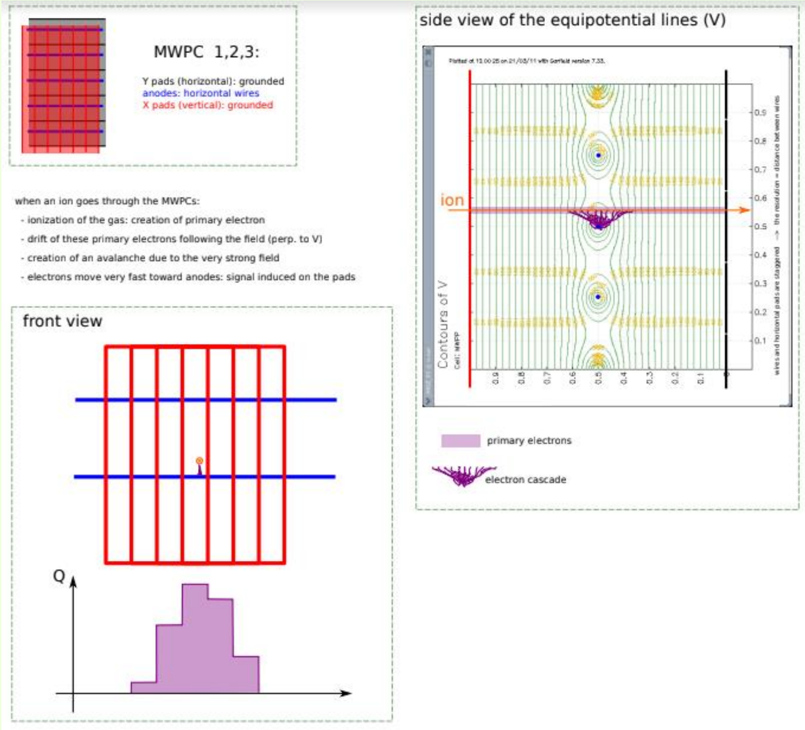
3 types of detectors : MUSIC, MWPC, scintillators

MUltiple Sample Ionisation Chamber **ENERGY LOSS: Z & DRIFT TIME: x , θ**	Multi Wire Proportional Counter **Q DISTRIBUTION ON PADS: x , y**	scintillator readout by 2 PMTs **TIME PER PMT: x , Tof**
Triple-MUSIC for incoming beam Twin-MUSIC for fission fragments	MWPC0 for incoming beam MWPC1, MWPC2, MWPC3 for fission fragments	2 scintillators for incoming beam scintillator + ToF wall for fission fragments



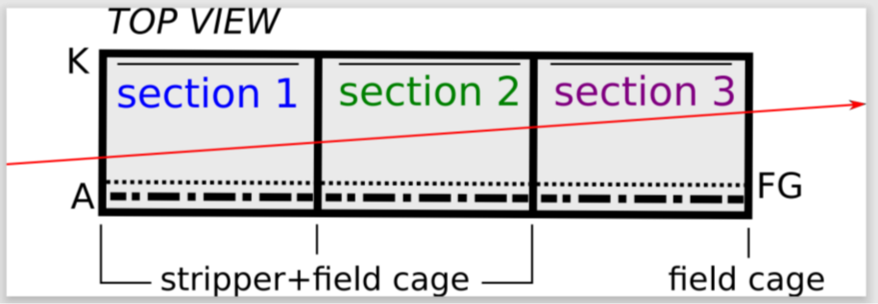


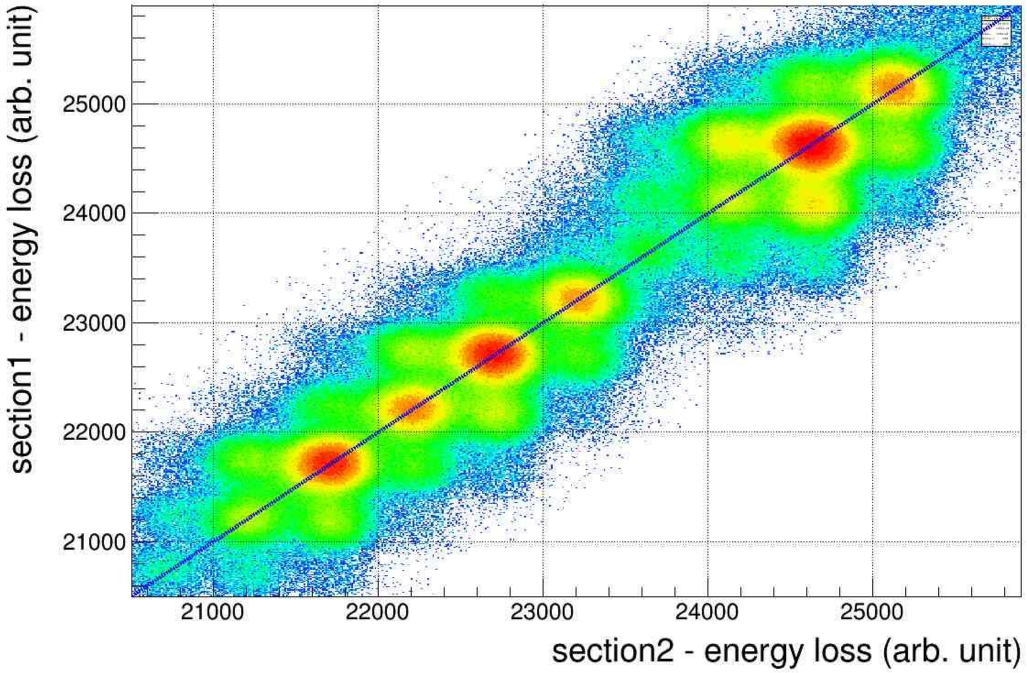


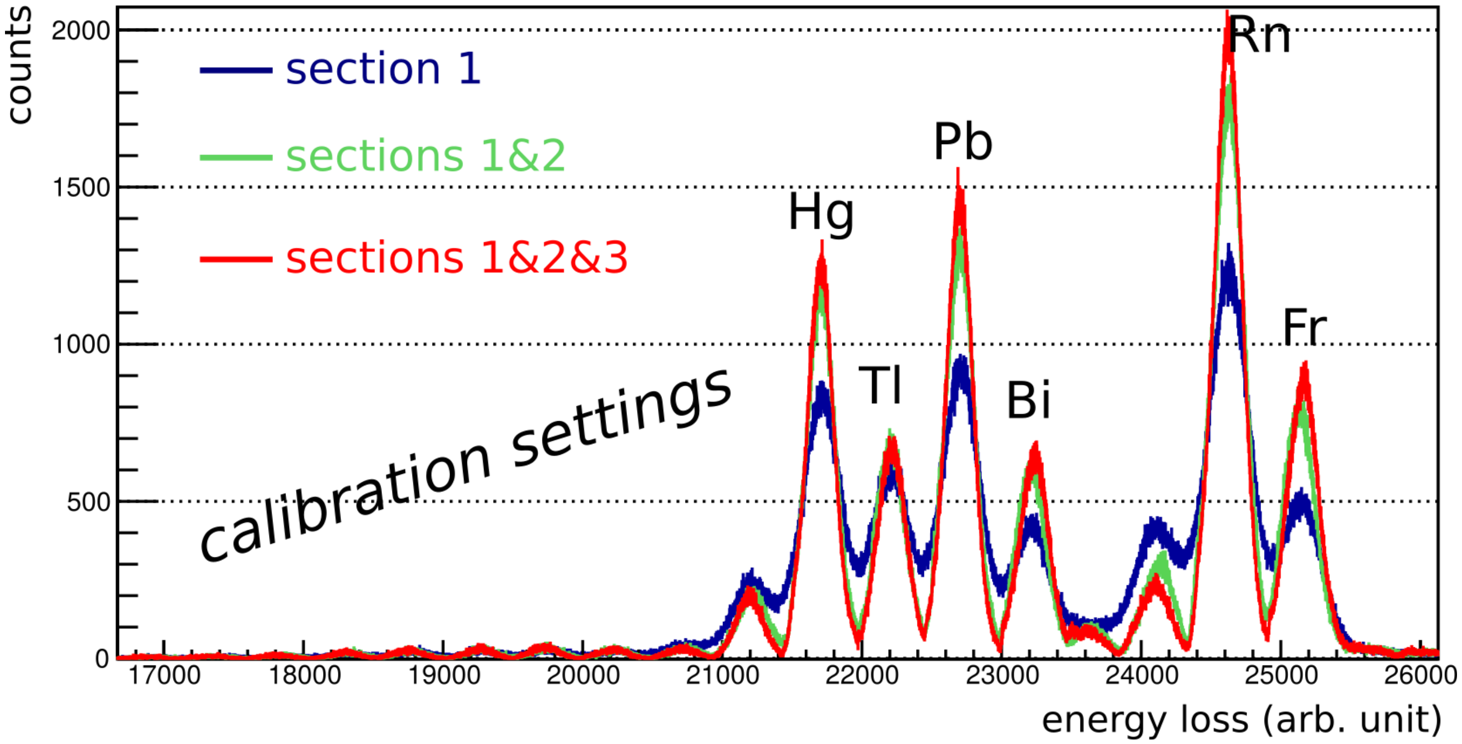


Specificities of the detection of beam vs fission fragment

Beam with ionic charge states, even at 750 A.MeV: Triple-MUSIC

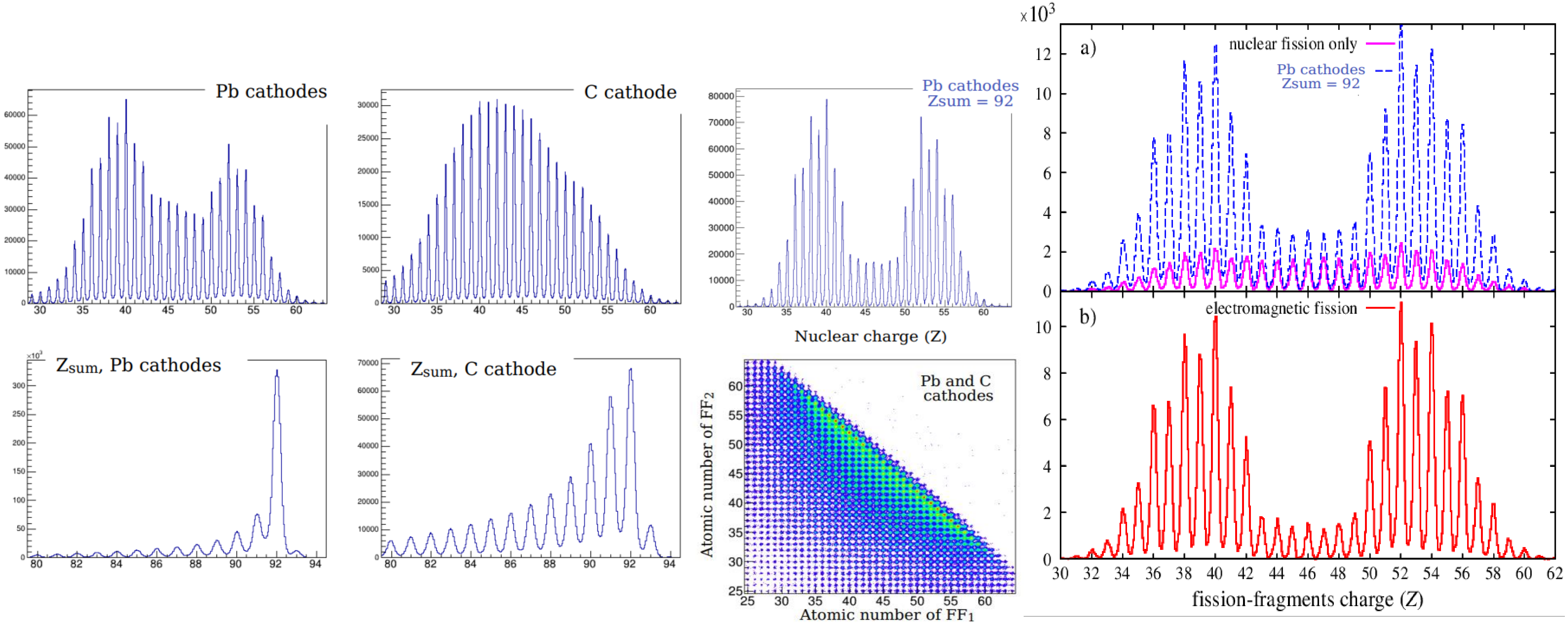






Analysis: Nuclear reaction subtraction

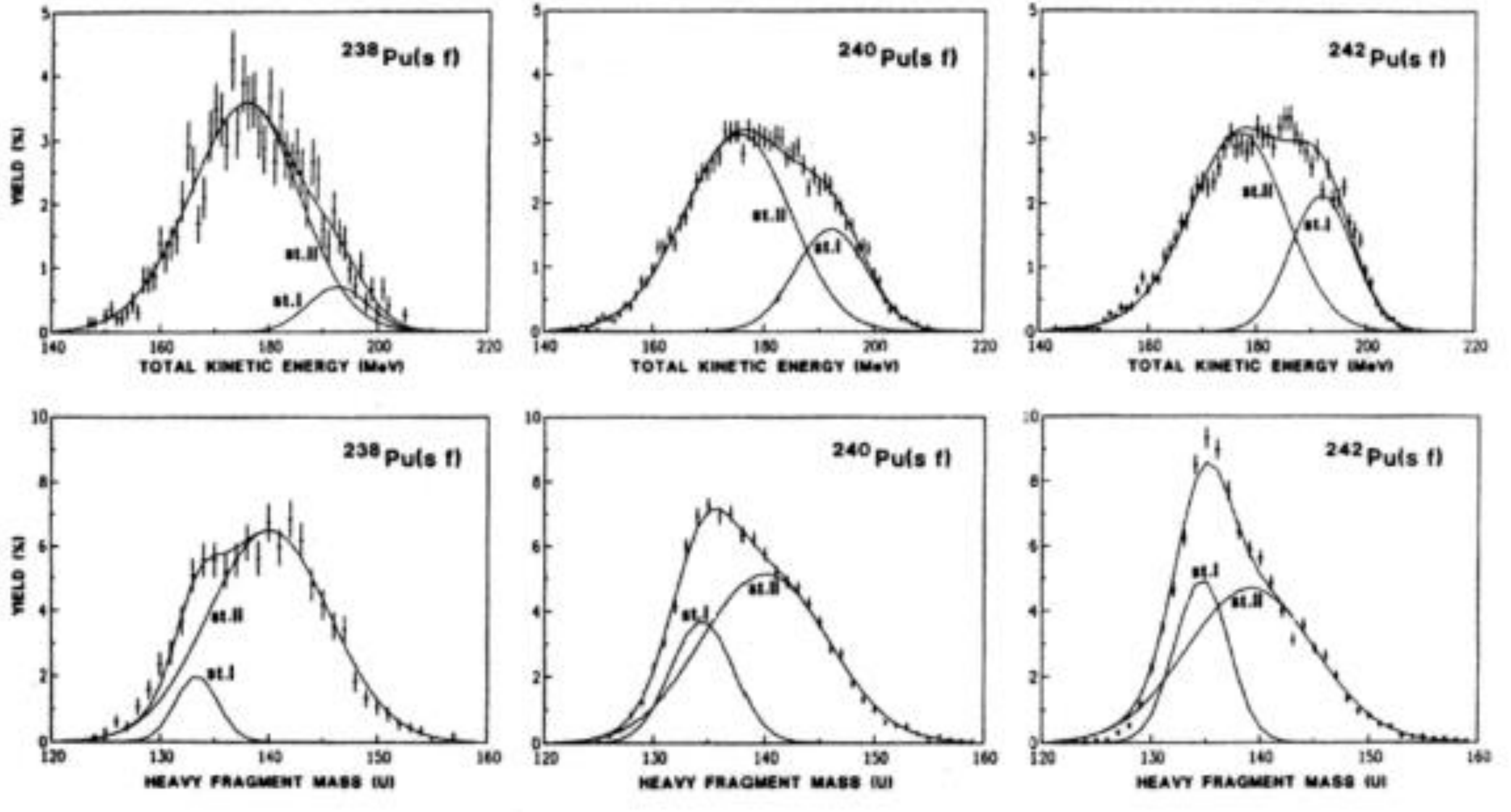
How to select coulomb induced fission only ?



Standard 1 and standard 2 asymmetric modes in Pu (sf)

TKE

Mass (A)



Asymmetric to symmetric fission in Fm isotopes