Fission studies in Inverse Kinematics: recent results and perspectives

L. Audouin, L. Grente, A. Chatillon, J. Taieb

and the SOFIA collaboration

SOFIA

Studies On FIssion with ALADIN

Fission fragment yields : applied physics

- FF impact the dynamics of nuclear reactors
  - Delayed neutrons
  - Neutronic poisons
  - Increased influence with larger burn-ups
  - Criticality excursions : quick accumulation of FF
- FF are the main source of residual power and radioactivity
  - Shielding for used fuel handling and reprocessing
  - Loss Of Coolant Accident (LOCA)
  - Decay heat

- Fission is the termination of the r-process
  - Nucleosynthesis calculations depend on fission barriers

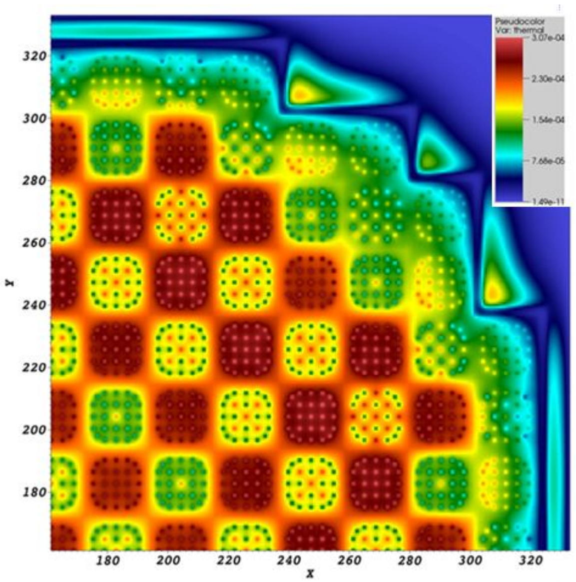
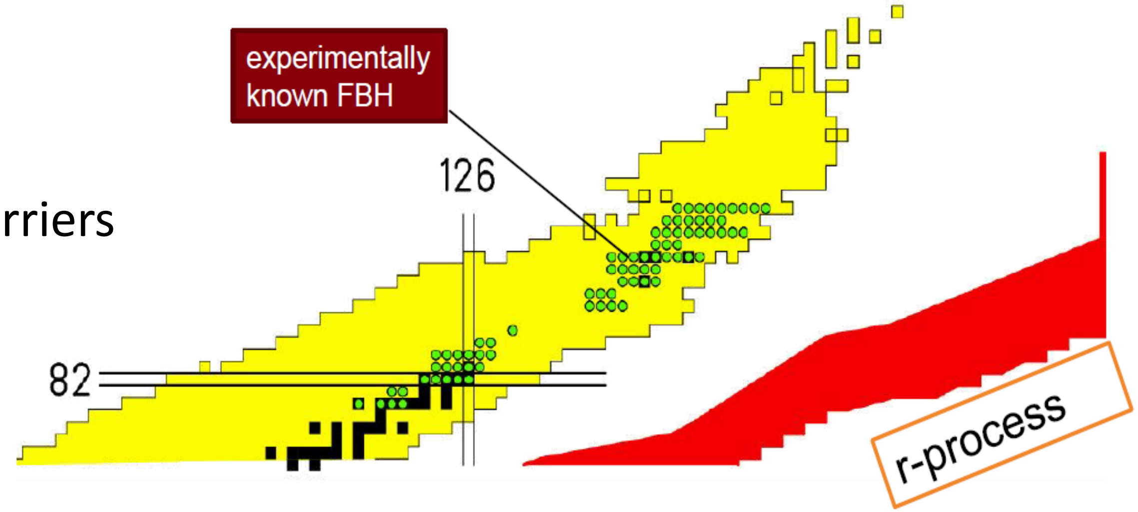
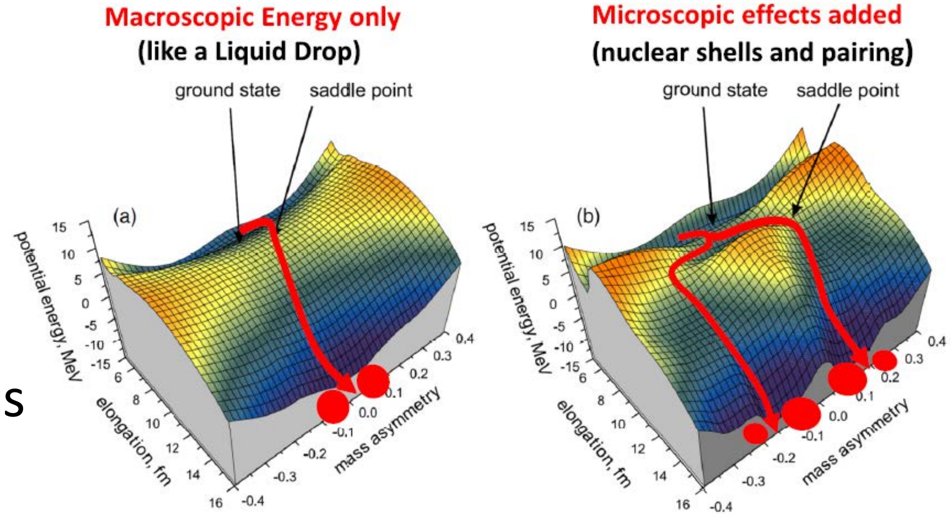


Figure 1 2D Slice of Thermal Flux Distribution near the Core Mid-plane

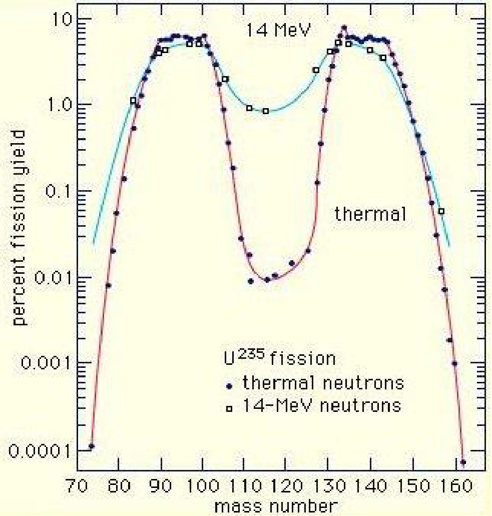


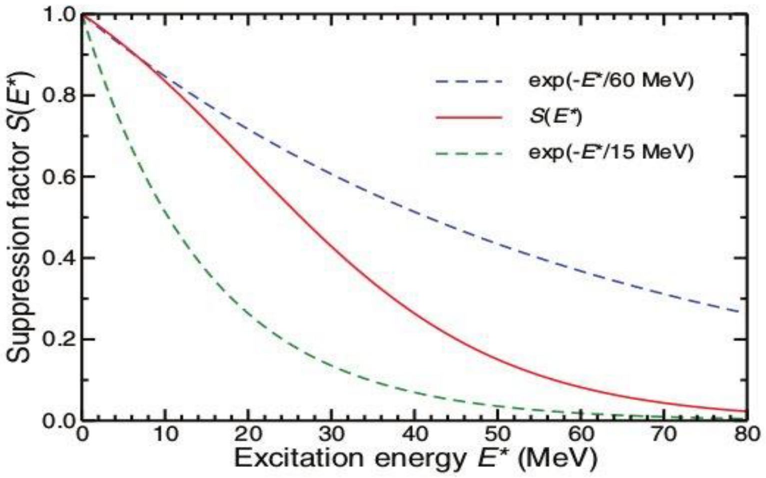
Fission yields : a unique probe for structure and dynamics

- How do shell effects constrain the yields ?
  - Do closed shells act as attractors ? N, Z, both ?
  - Dampening of shell effects with energy
  - Shell effects at large deformation ?
  - Are shell effects sole responsible for asymmetric fission ?
- Influence of the pairing : even-odd staggering in the yields
- Splitting of excitation energy among nascent fragments ?



Karpov A V et al. J. Phys. G: Nucl. Part. Phys. 35 035104





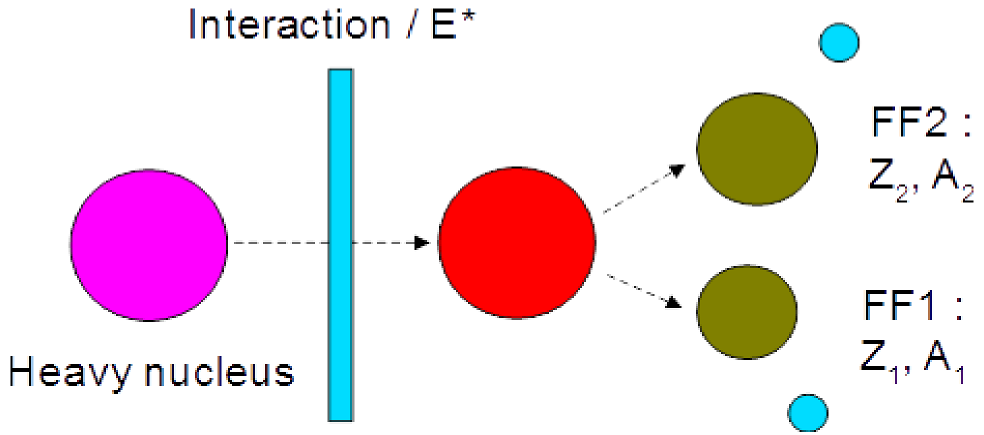
Several modelling of the damping of shell effects

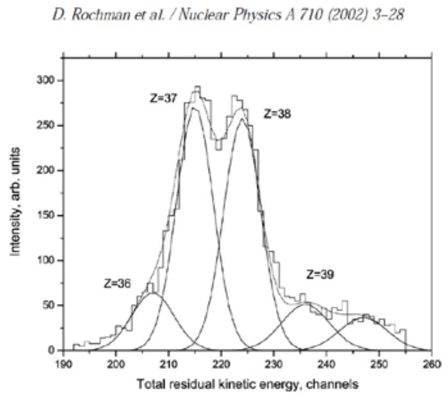
Ignatyuk et al Sov. J. Nucl. Phys 21 2555 (1975)

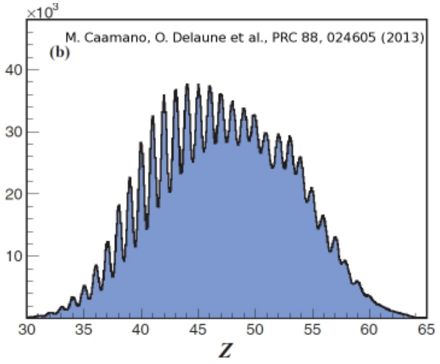
Randrup and Moeller, Phys. Rev. C 88 064606 (2013)

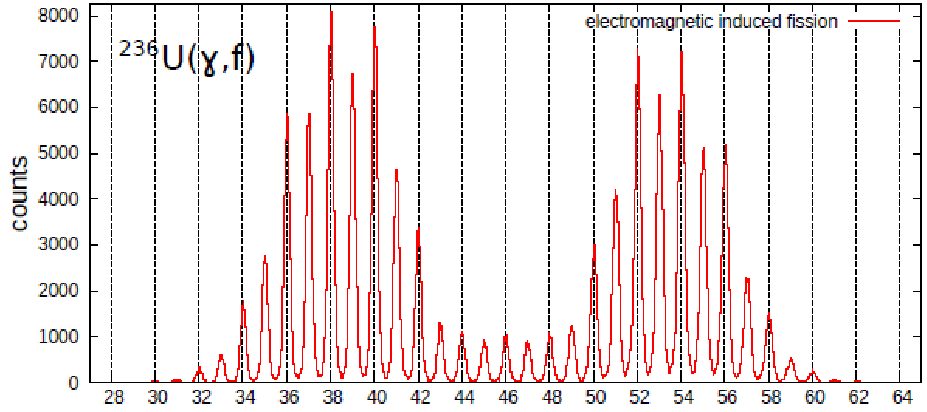
Interest of Inverse Kinematics

- Heavy partner (fissioning system) as projectile
- In-flight fission









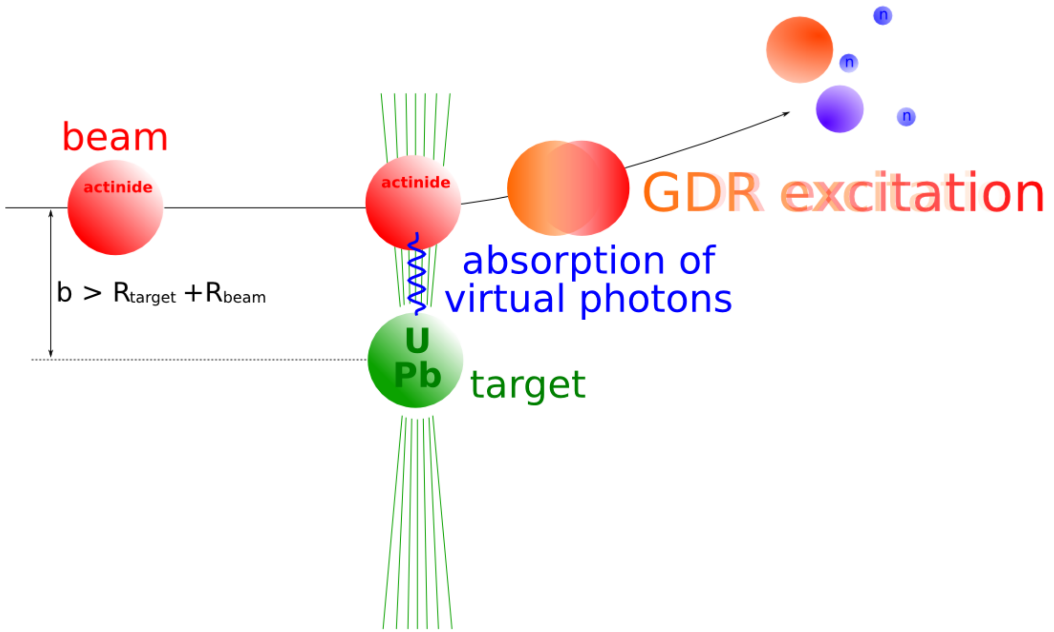
- Identification of the fragments: recoil spectrometer
- Measurement on short-lived nuclei
- High velocity FF : better (up to excellent) Z measurement

- Pioneer experiment : K.-H. Schmidt et al. (1996) : Z of both FFs
- 2010s : transfer@GANIL (see M. Camaano's talk), SOFIA@GSI

The SOFIA program

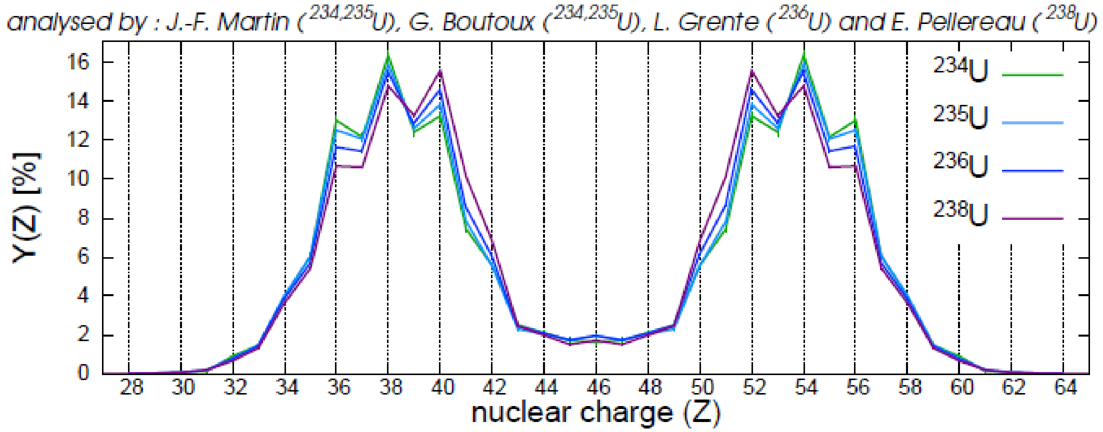
- High-precision measurement (~ % on isotopic yields)
- Simultaneous identification of <u>both</u> fission fragments : <u>A</u> & <u>Z</u>
  - Kinetic energy
  - Deduced total prompt neutron multiplicity
- “West-looking” : products of ^{238}U fragmentation (FRS)
  - Full identification of the fissioning system

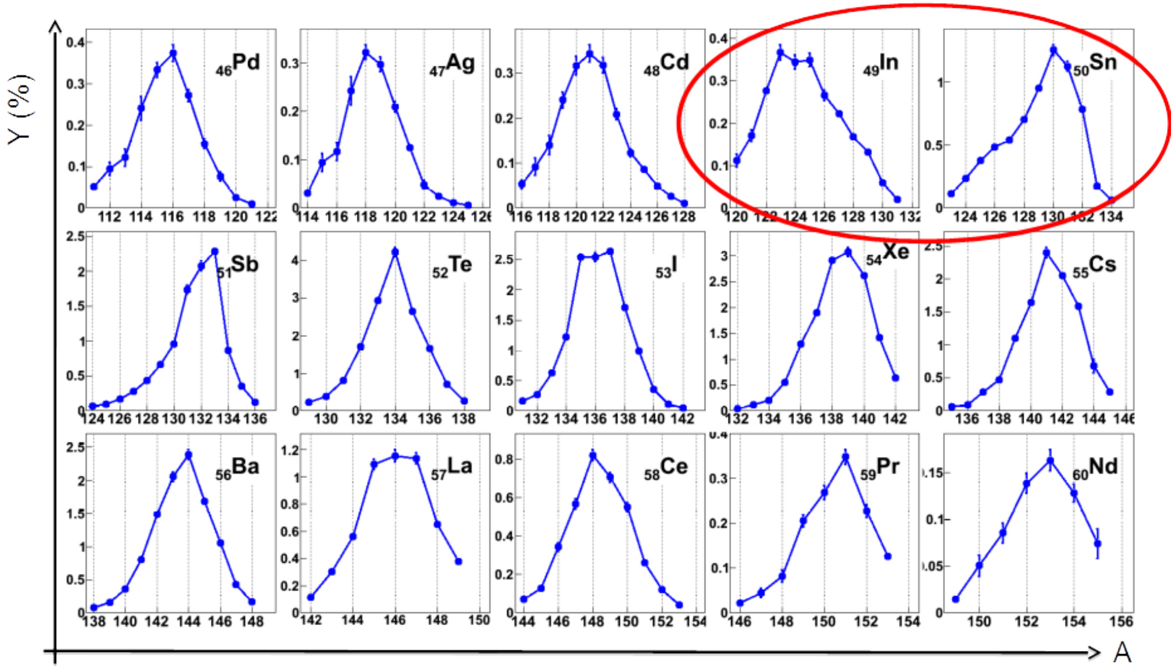
- Large-acceptance recoil spectrometer in cave C (GSI)
- Fission trigger : Coulomb interaction
  - Large cross section (~ b)
  - Small E* : excitation of the GDR (<E> ~ 14 MeV)
    - ^{236}U (γ,f) ~ ^{235}U (n,f) @ 8.2 MeV
    - 75% of first chance fission (23% 2nd chance)
  - Significant dispersion of E*: no info event-by-event



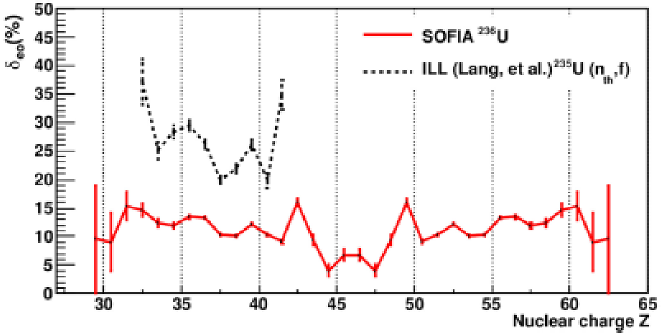
High-precision measurements

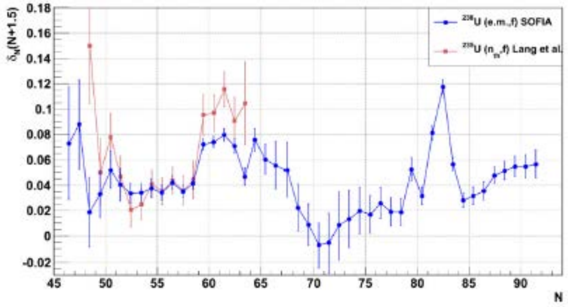
- High-precision indeed : σ < 1% for light and heavy fragments
- Lighter systems favor larger asymmetry





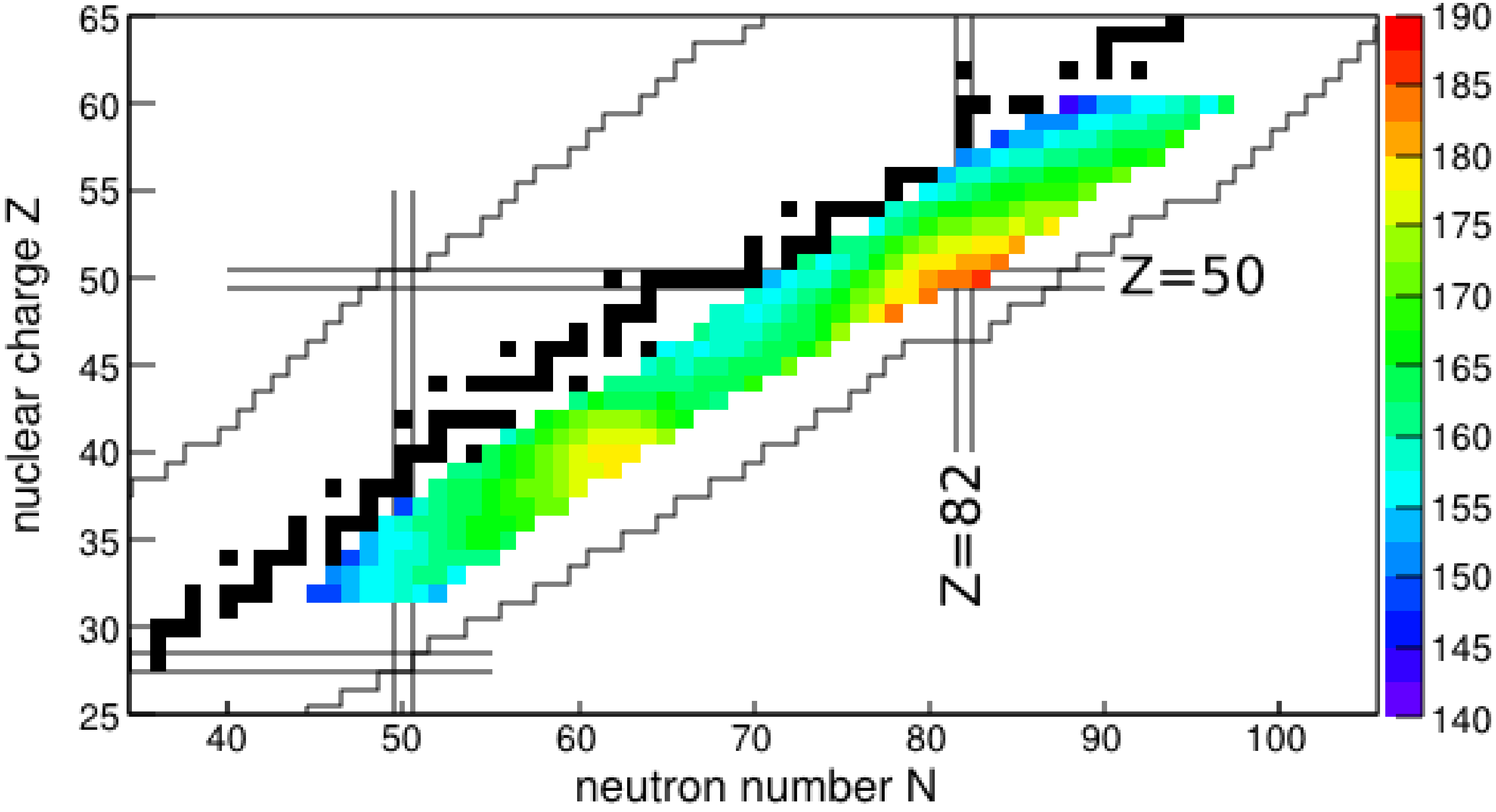
- Strong even-odd effect on Z
  - Fully decided at scission
  - Dampening due to E*
- Smaller even-odd effect on N
  - Decided by fluctuations of Sn
  - Insensitive to E*





An insight on the shape of fragments at scission

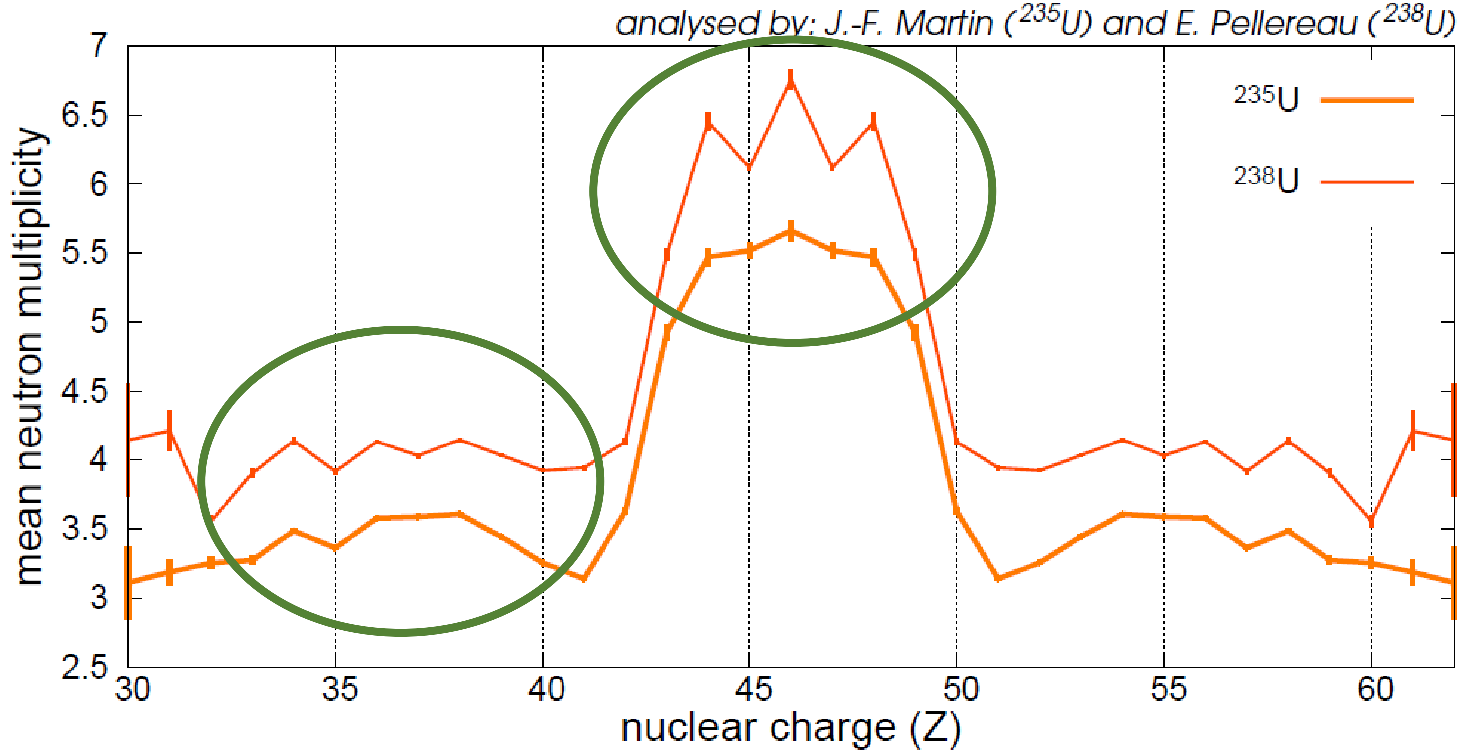
- Spherical prefragment : shorter distance at scission
- … Hence, larger kinetic energy

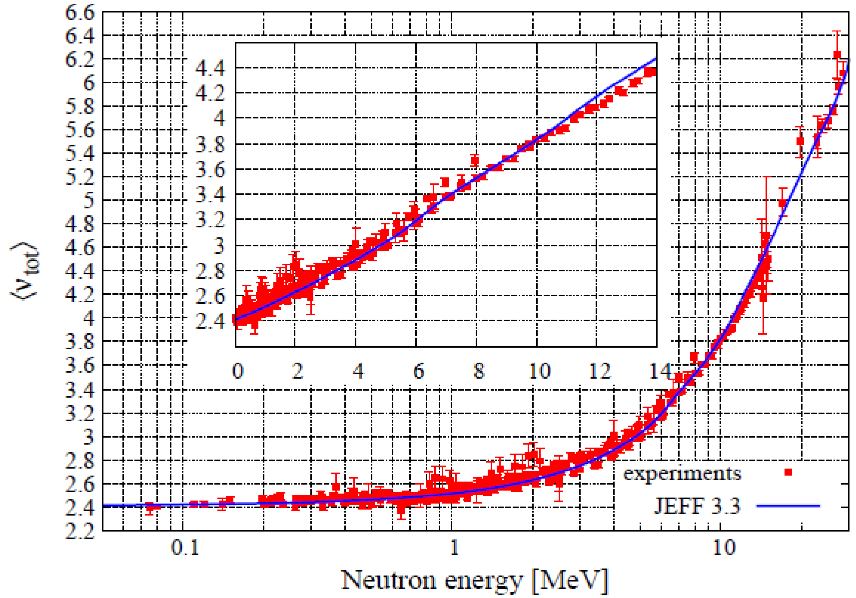


Prompt-neutrons: a probe of excitation energy

- $\upsilon = A_{CN} - A_{FF1} - A_{FF2}$ (measured event-by-event)
- Favored de-excitation channel : directly correlated to E*

- Deformation -> excitation -> neutrons
- Even-even split : larger Q





<E*> = 14,1 MeV

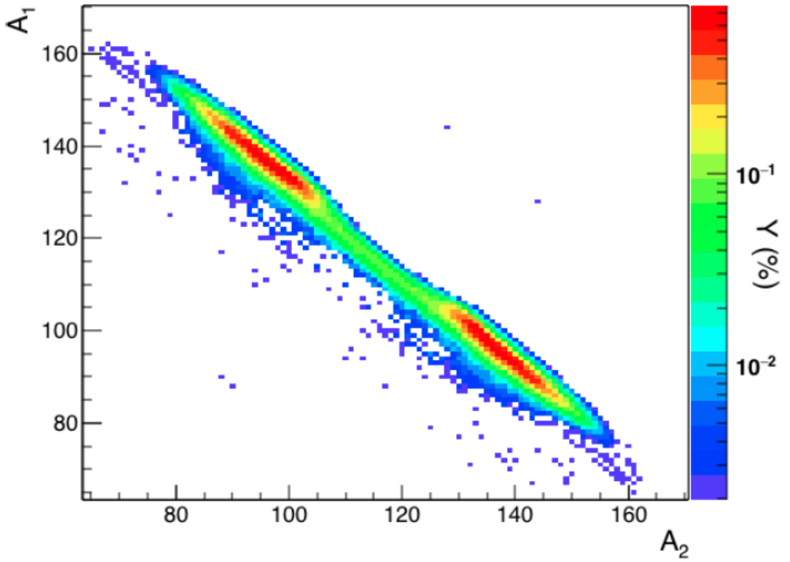
< υ > = 3,81 (^{236}U)

< υ >$_{th}$ = 2,45 (^{236}U)

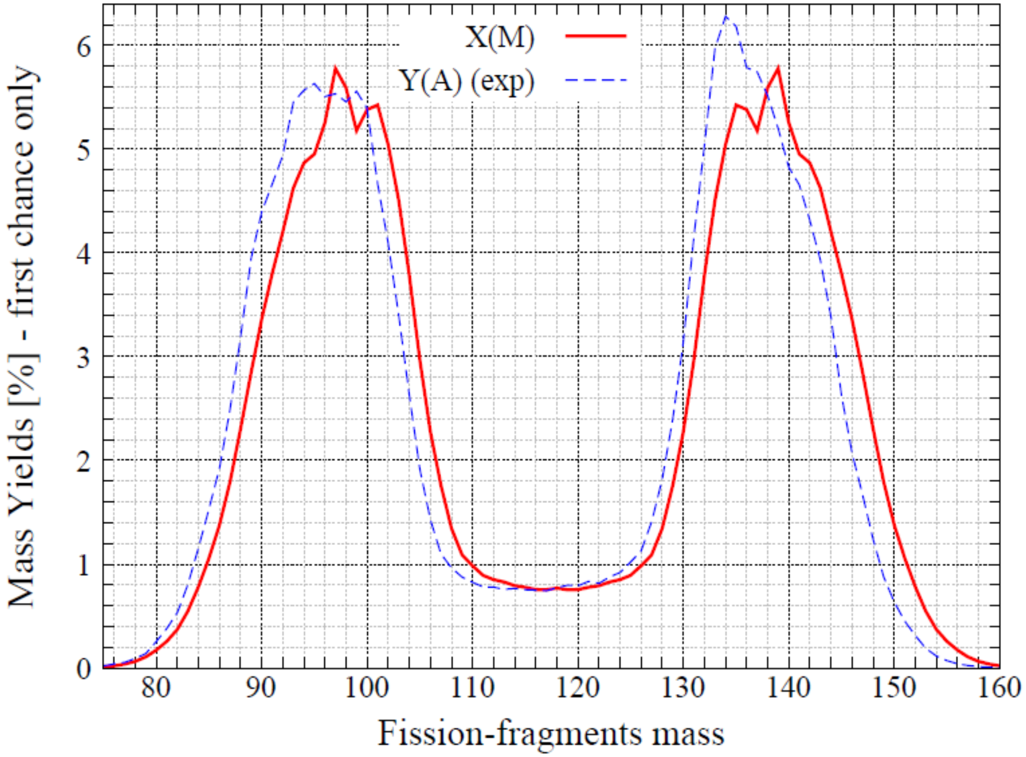
Pre and post neutron emission mass yields

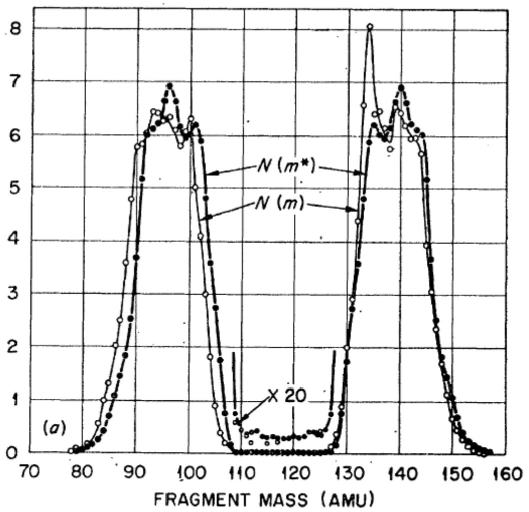
- Subtraction of higher-chance fission
- Yields are correlated: $Y(A_i) = 236 - \upsilon(i,j) - Y(A_j)$

$$Y(A_1, A_2) = \sum_{\nu_1=0}^{236-A_1-A_2} P^{M_1}(\nu_1) P^{M_2}(\nu_2) X(M_1)$$



Calculations by L. Grente and J. Taieb



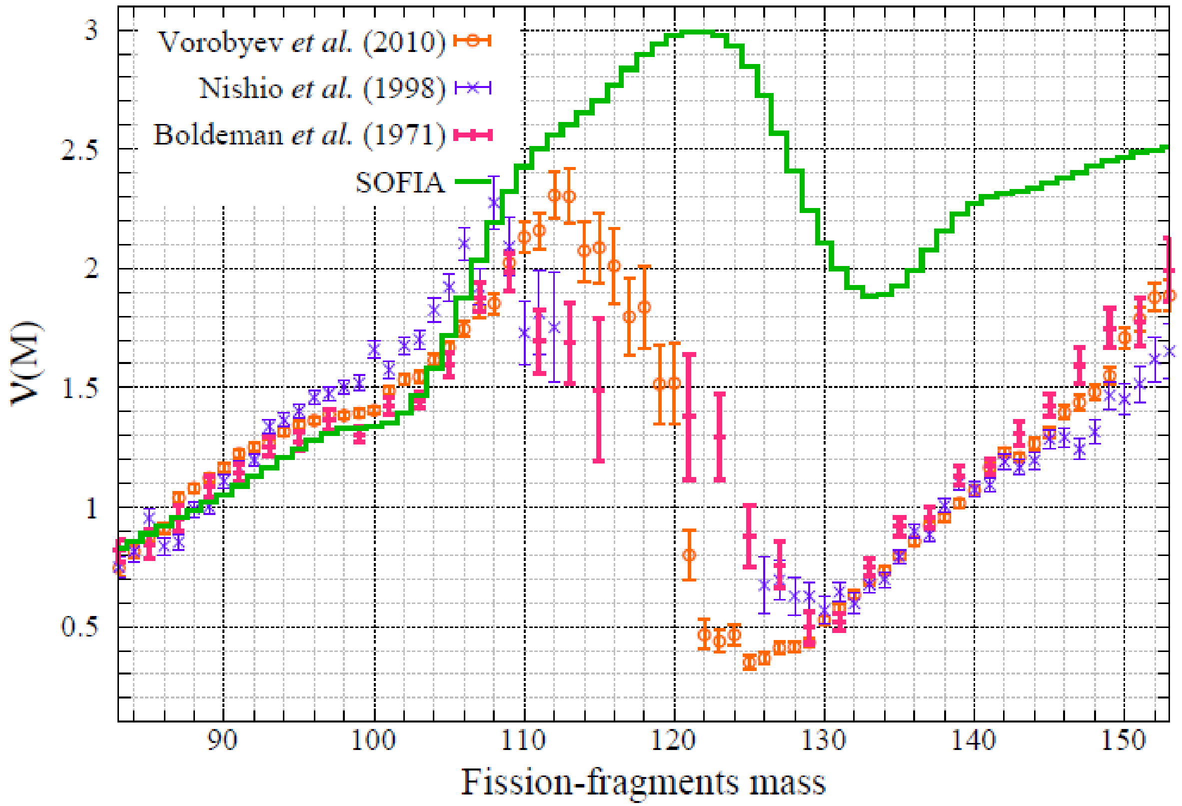


H. W. Schmitt *et al.*, Phys. Rev. 141, 1146 (1966)

Energy-sorting study through prompt-neutrons yields

SOFIA data: $\langle\nu\rangle_{LIGHT}$=1.40, $\langle\nu\rangle_{HEAVY}$=2.26 $\langle E^*\rangle_{1^{st}\,chance}$=12.4 MeV

Nishio *et al.*: $\langle\nu\rangle_{LIGHT}$=1.42, $\langle\nu\rangle_{HEAVY}$=1.01 thermal neutrons



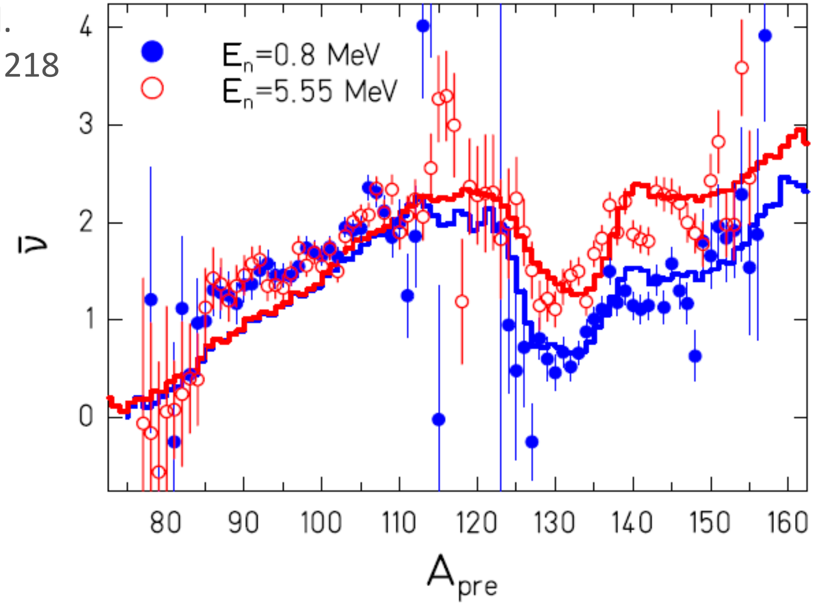
Additional excitation goes *entirely* into the heavy fragment

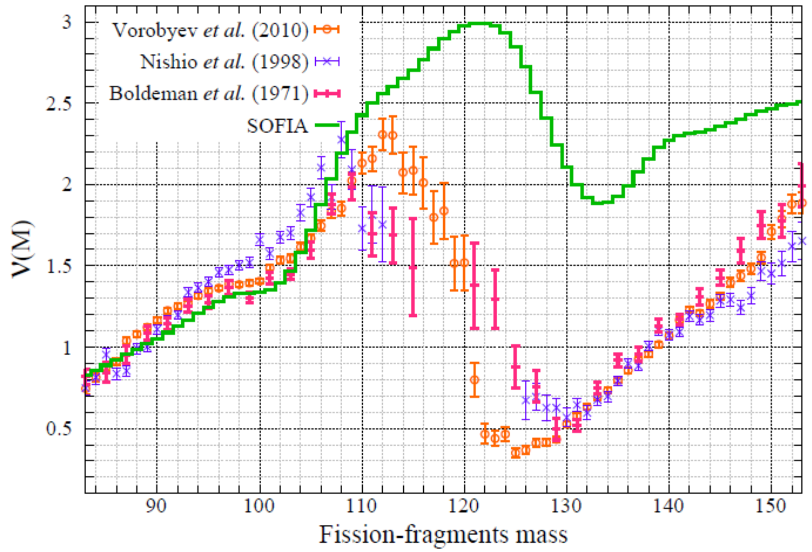
Energy sorting: an explanation

- K. H. Schmidt and B. Jurado
  - Phys. Rev. Lett. 104 212501 (2010)
  - Phys. Rev. C 83 061601(R) (2011)
  - Phys. Rev. C 84 059906(E) (2011)
  - Phys. Rev. C 83 014607 (2011)

- The scissioning system behaves as coupled thermostats
- At low energy (superfluid regime) $T \propto A^{-2/3}$
- Energy flows toward the heavy fragment

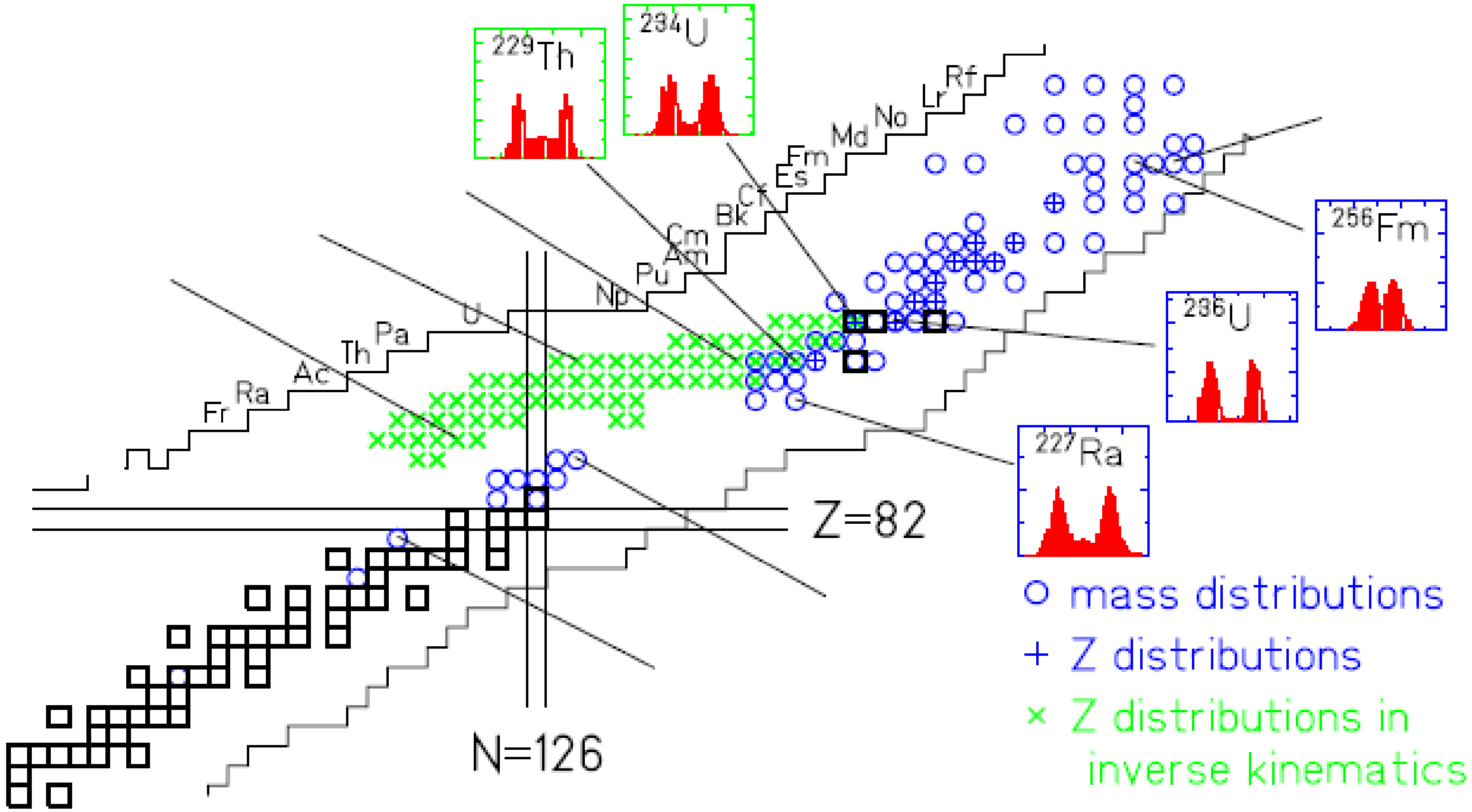
A. A. Naqvi et al.
Phys. Rev. C **34**, 218





Fission along the nuclear chart

- Asymmetric fission is understood as a consequence of spherical/deformed shells



Courtesy K.H. Schmidt

Fission along the nuclear chart

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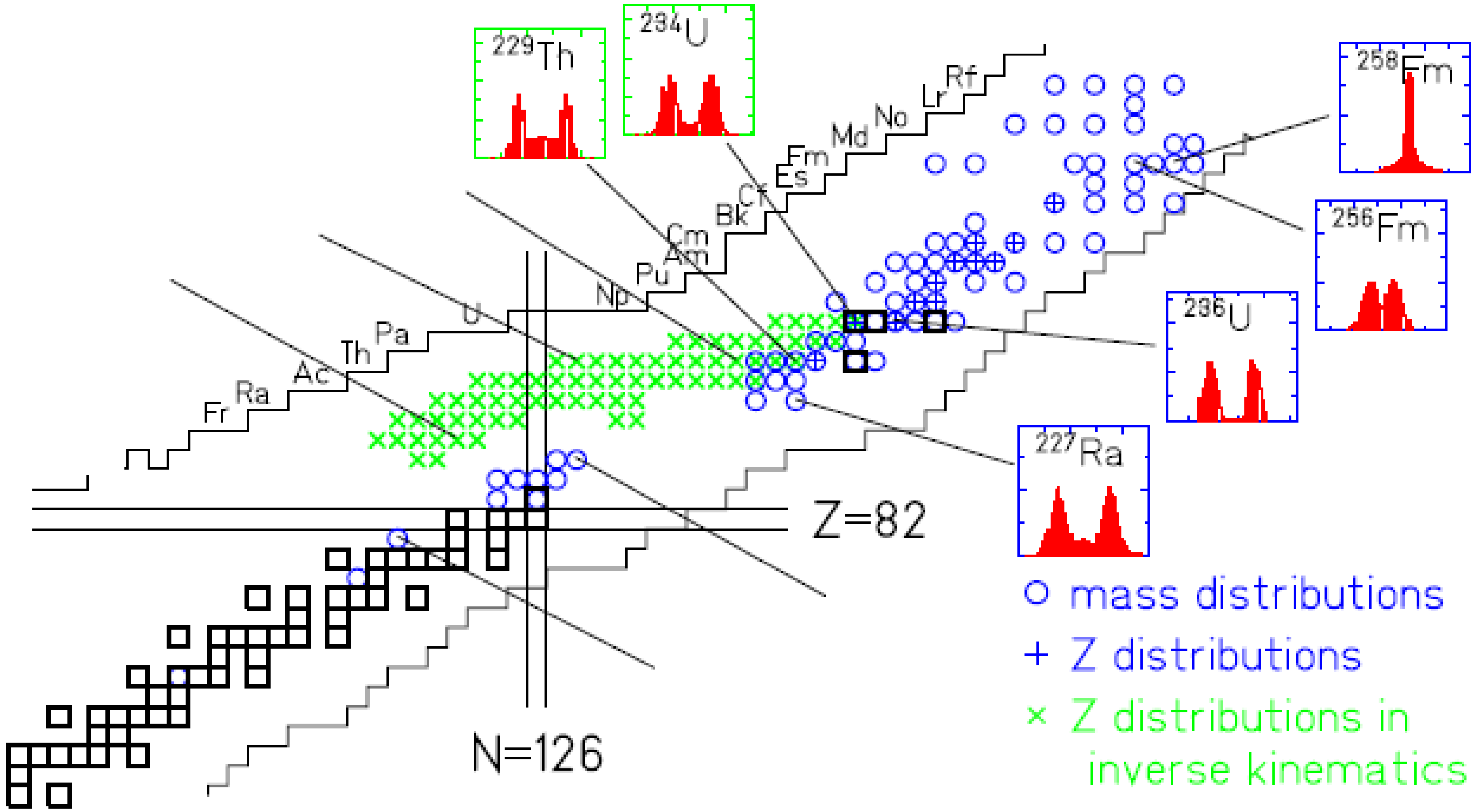
- Heavier systems tend toward double ^{132}Sn-like nuclei (symmetric)



Courtesy K.H. Schmidt

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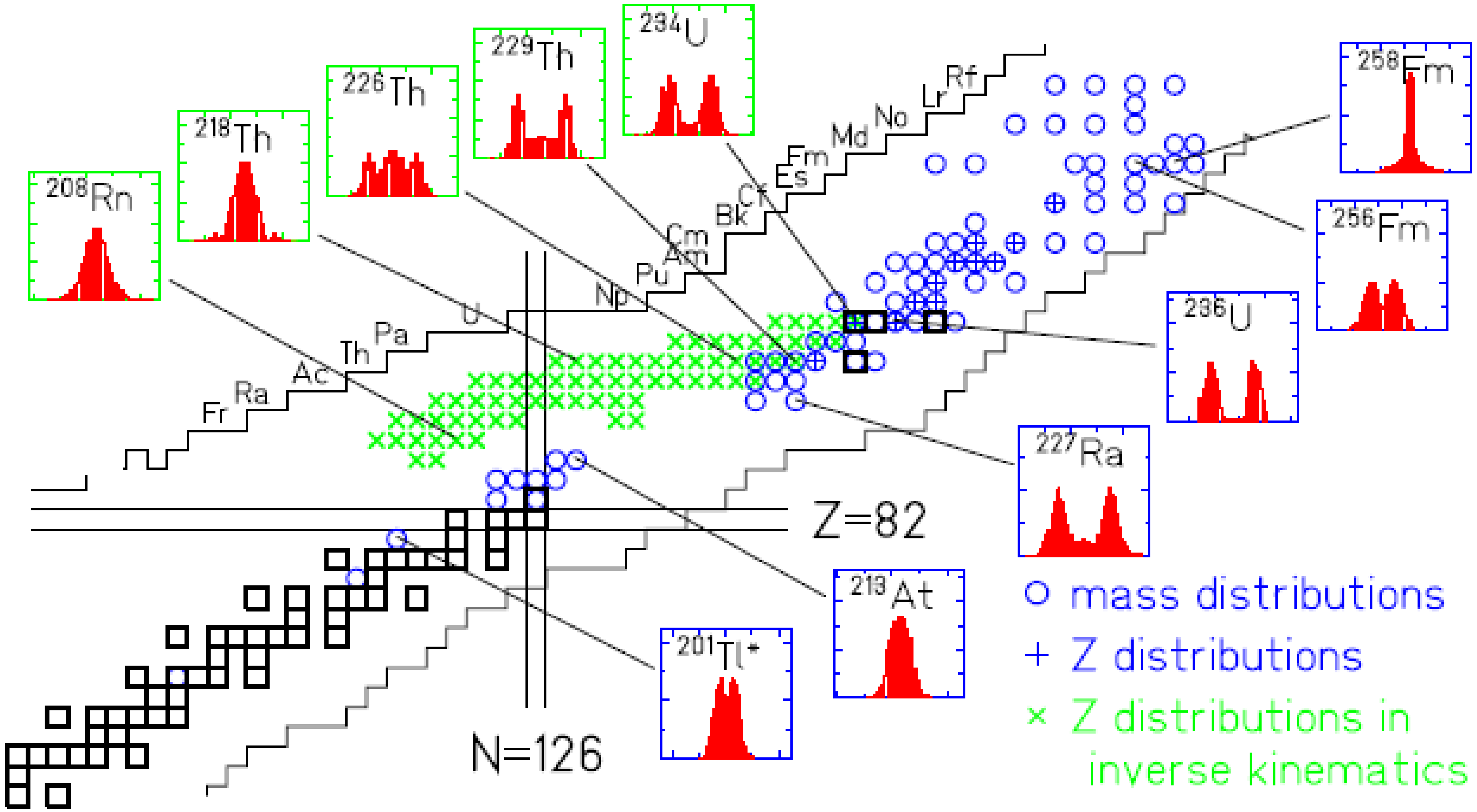
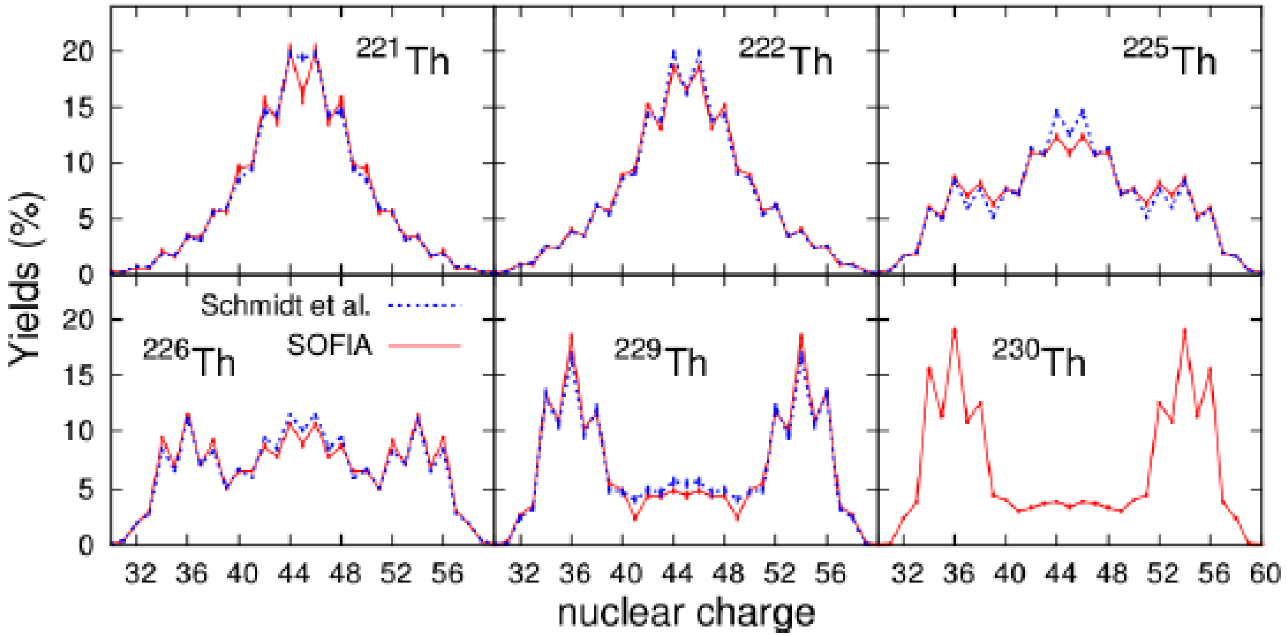


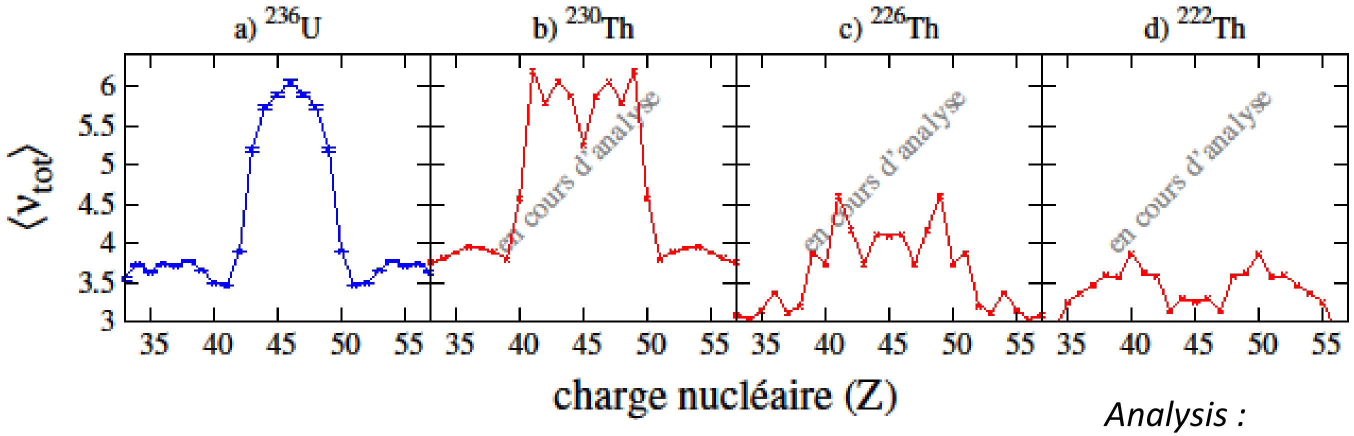
Courtesy K.H. Schmidt

Transition to symmetry in Th isotopes

- The heavy peak sticks around Z = 54
- With lighter systems, such partition gets costly in asymmetry energy
- Coexistence and finally symmetry



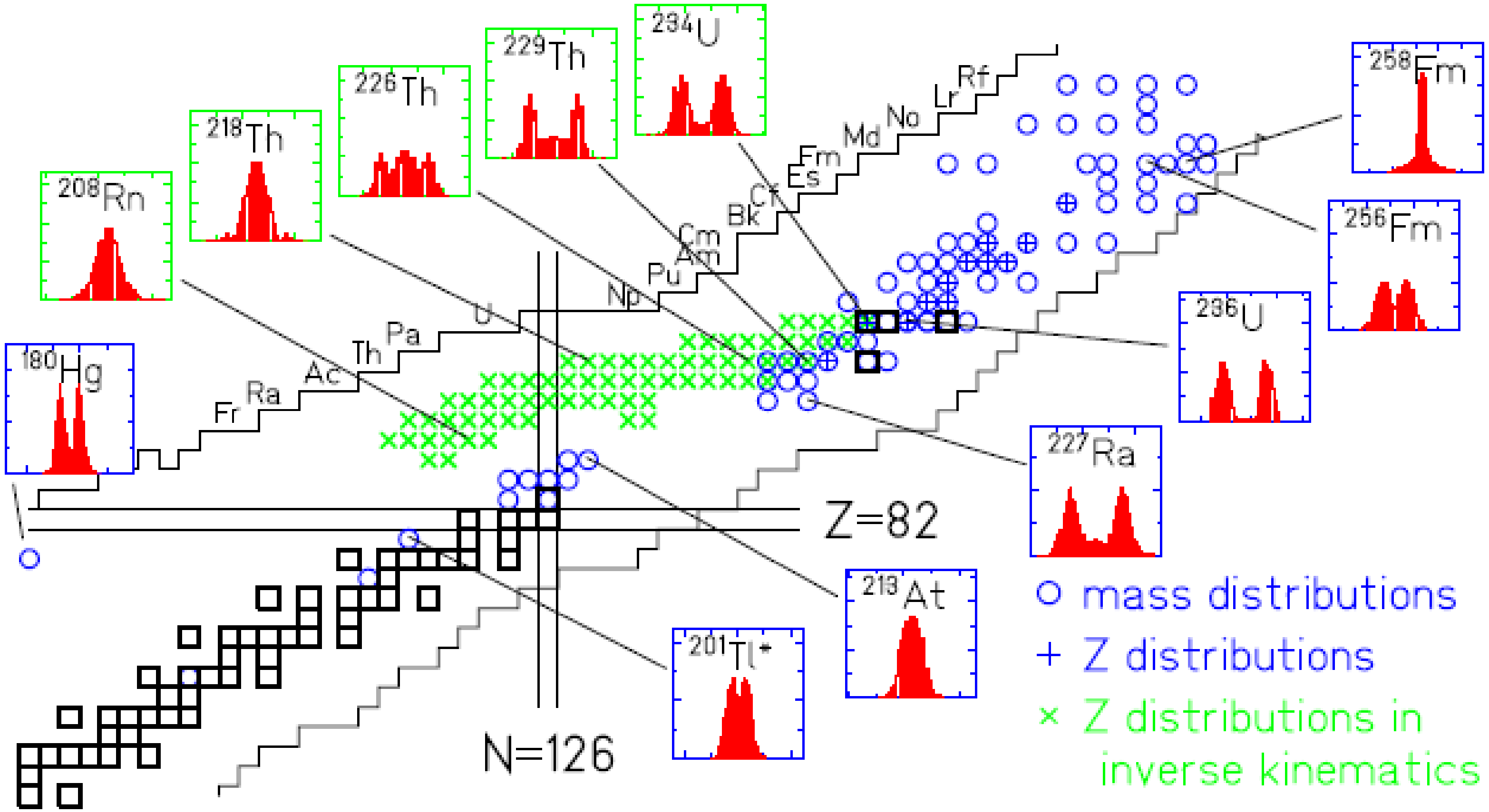
- First-ever results on neutrons for light Th isotopes !
- Large reduction of the excitation energy for the symmetric fission
- Colder fissionning system ?



Analysis : Audrey Chatillon

Fission along the nuclear chart

- Asymmetric fission is understood as a consequence of spherical/deformed shells
- Heavier systems tend toward double ^{132}Sn-like nuclei (symmetric)
- For pre-actinides, closed-shell fragments lead to too large asymmetry: symmetry takes precedence
- Asymmetry appears again for very light, neutron-deficient systems ?!



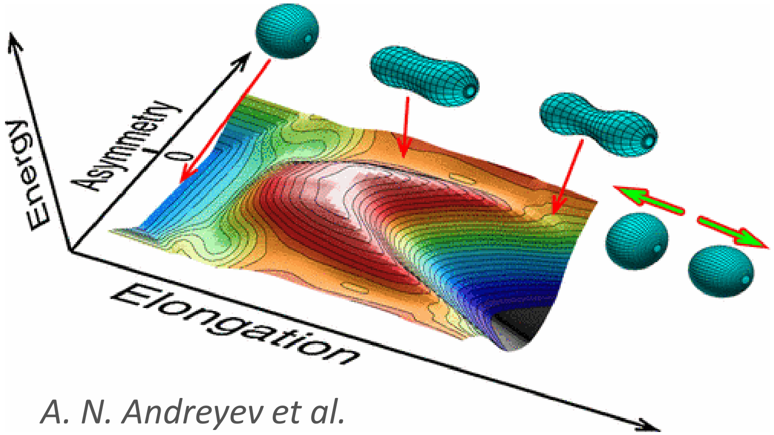
A. N. Andreyev et al.
Phys. Rev. Lett. ***105****, 252502*

Courtesy K.H. Schmidt

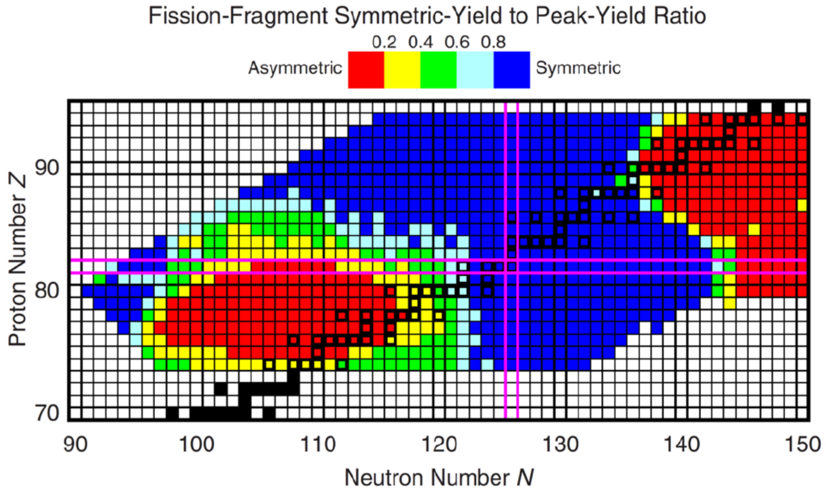
Fission modes in neutron-deficient pre-actinides

- β-delayed fission at ISOLDE

- Intense theory work !
- Complex potential landscape
  no shell effects
- 5D calculations of Möller

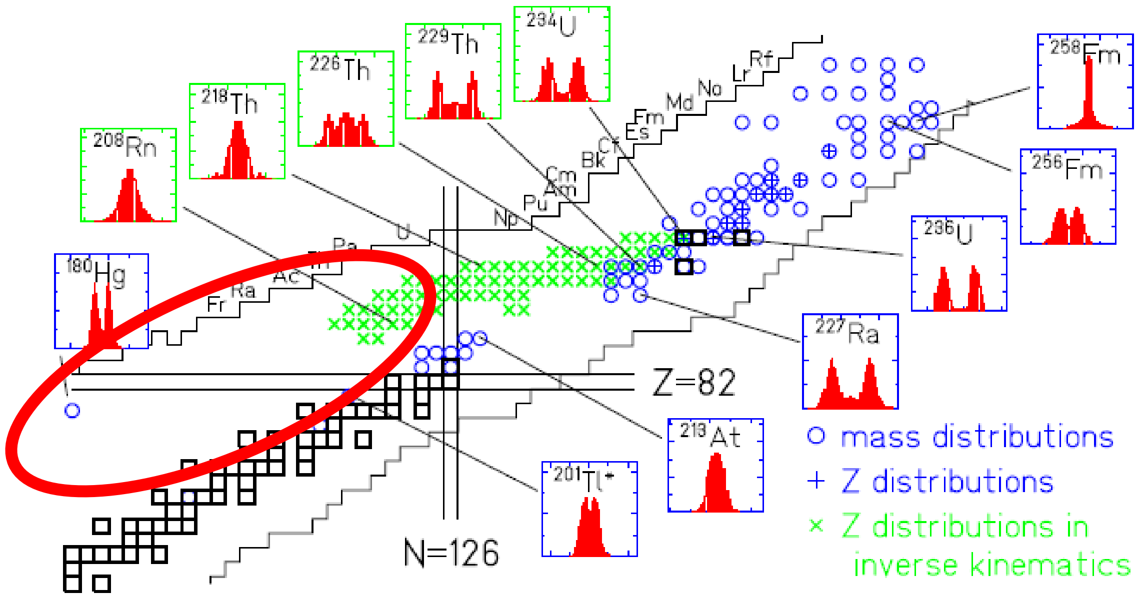


A. N. Andreyev et al.
Phys. Rev. Lett. ***105****, 252502*



Moller P and Randrup J 2015 *Phys. Rev.* C **91** 044316

- Objective of the next SOFIA measurement (2019)



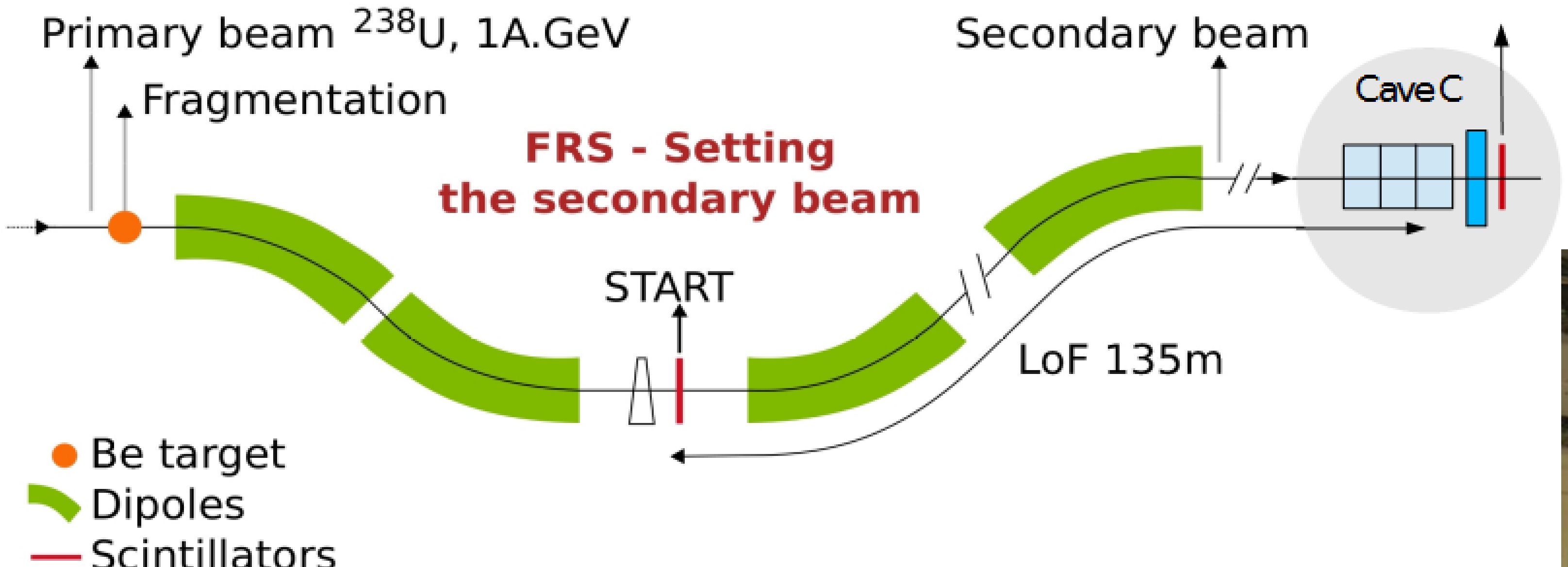
Summary and outlook

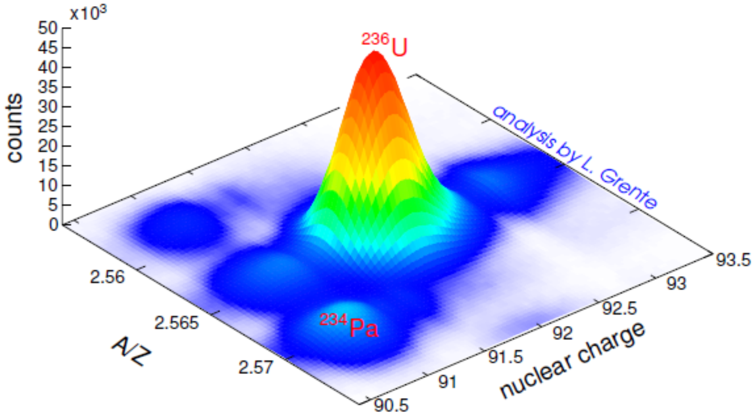
- New generation of fission experiments
  - High-resolution measurements
  - Exploration of the complete isotopic space of fragments
  - Wide range of fissioning systems
  - Increased number of combined observables
    - SOFIA coupling with NeuLAND : neutron tagging
    - SOFIA coupling with CALIFA : gamma multiplicity
- Measurement of the U-Pu region : ^{242}Pu primary beam
- Exclusive experiments : (e,f) or surrogate reactions at storage ring
- Neutron-rich systems : Super-FRS exotic beams

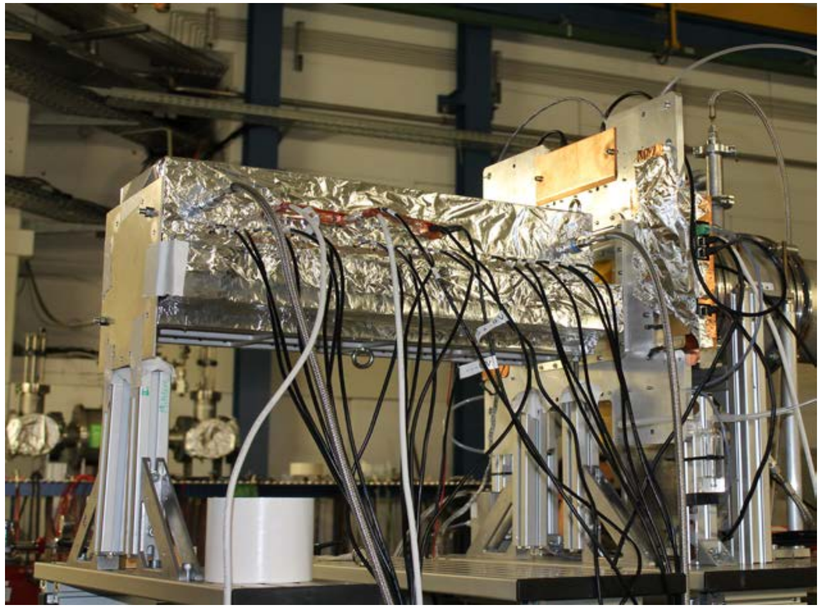
- *Detailed studies of trans-actinides*
- *Origin of angular momentum from fragments ?*
- *Fission time ?*

Secondary beam identification

- Standard Bρ – ΔE – ToF method
- High-Z fragments have a large probability to carry electron(s)







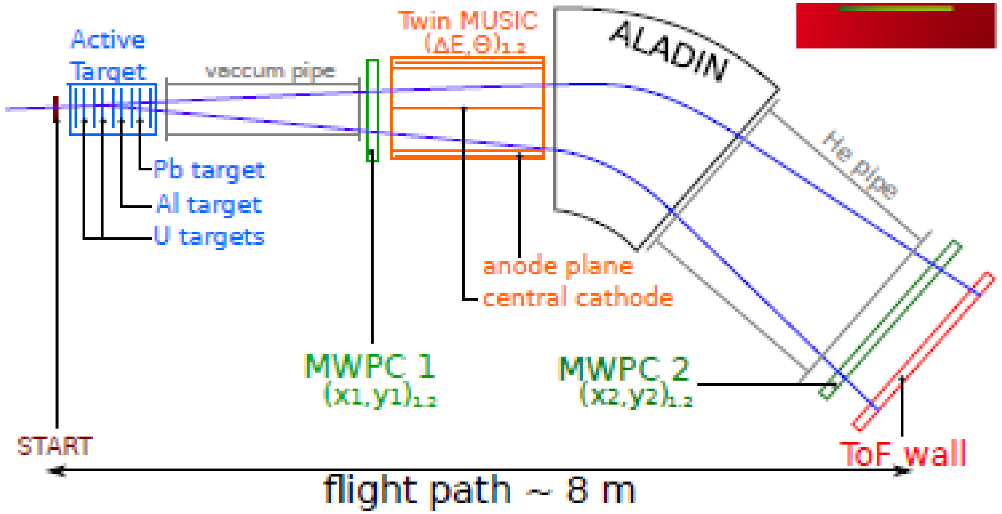
Fission fragments identification

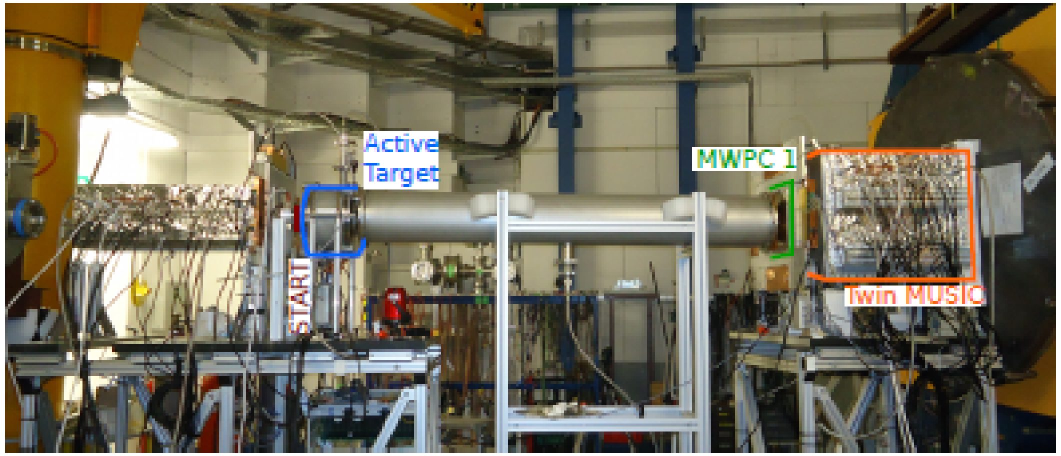
ΔE - Bρ - ToF method
$A/Z = B\rho / \beta\gamma$

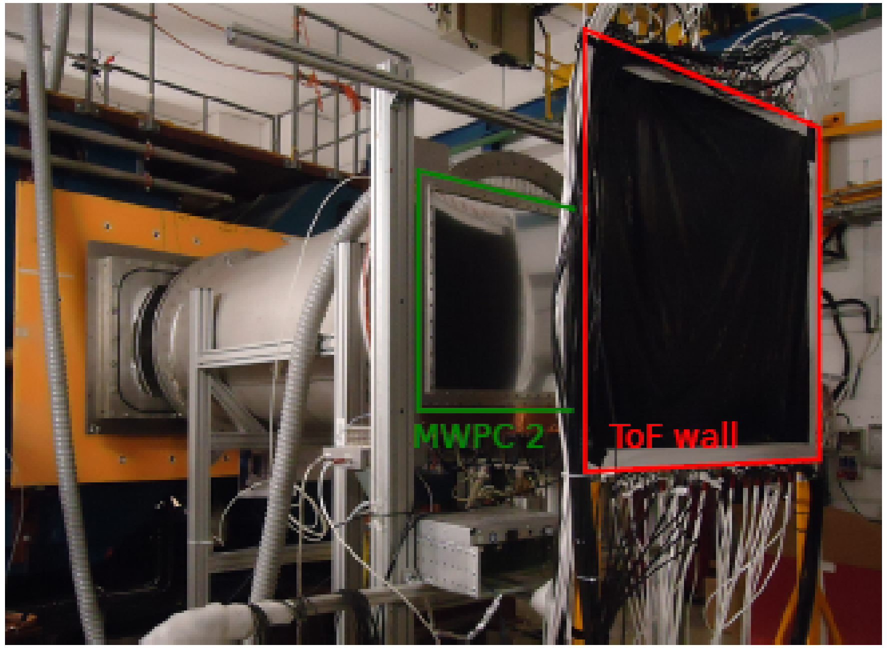
Bρ: position from MWPCs
Θ from the Twin-MUSIC

ΔE: from the Twin-MUSIC

ToF: between START and ToF-wall

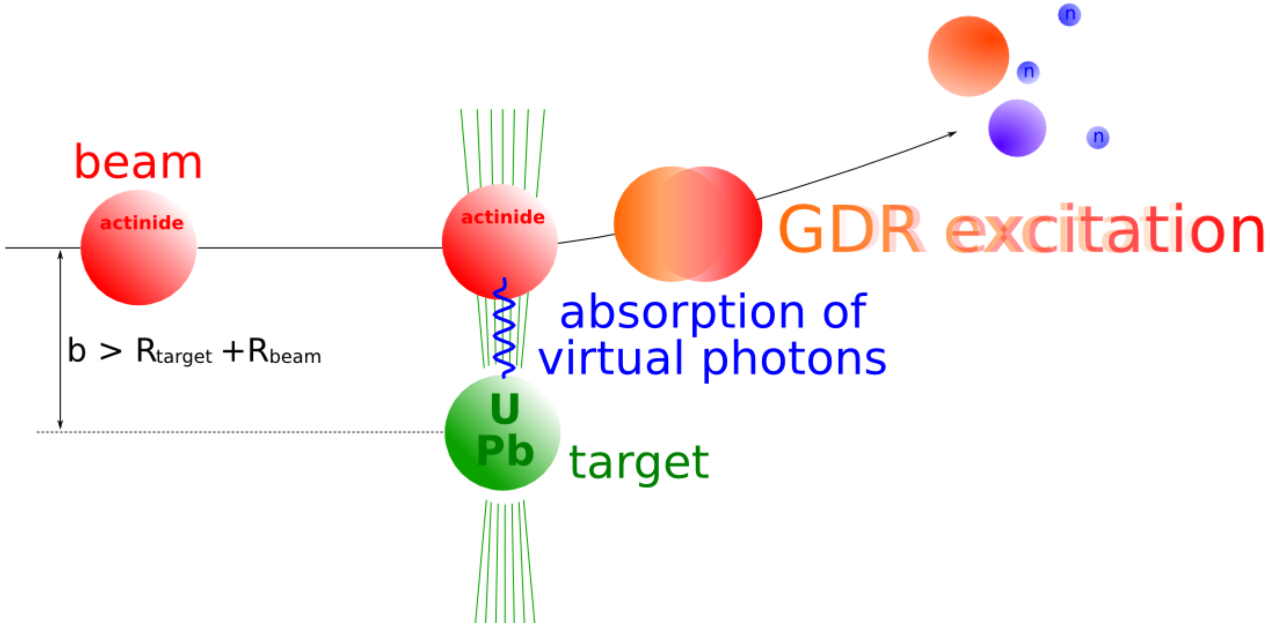


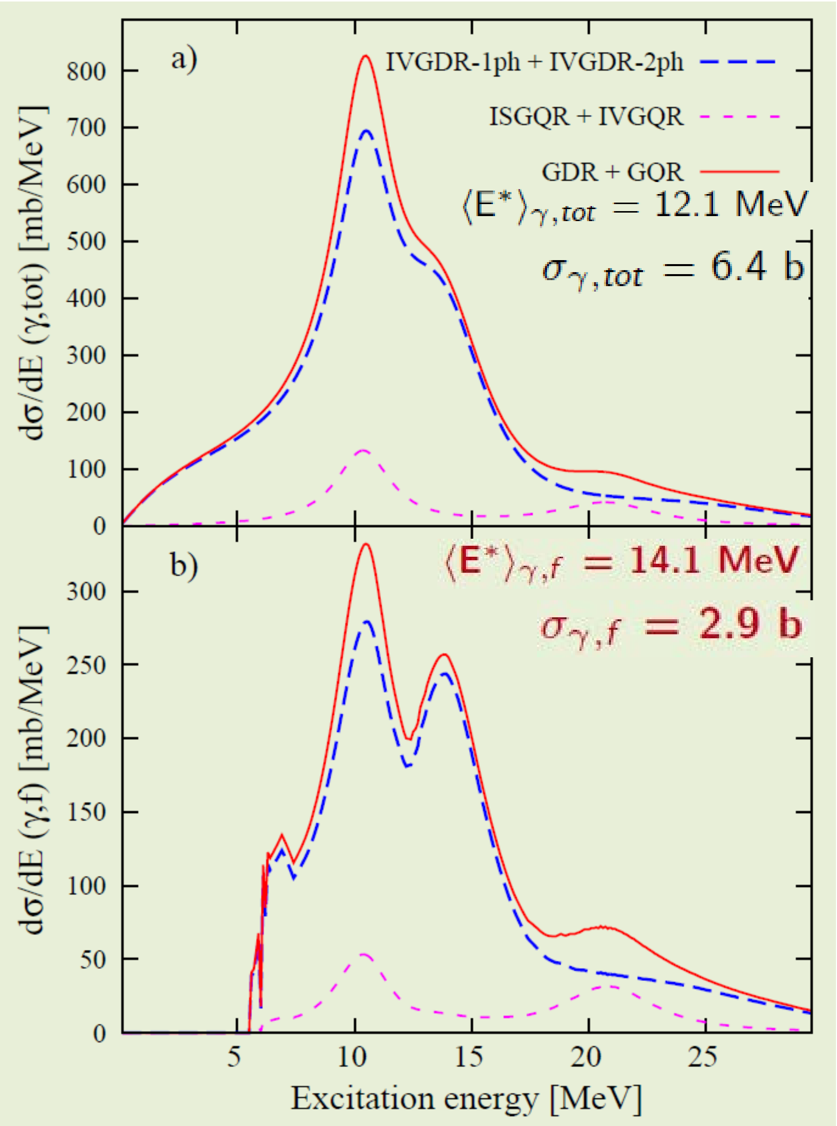




Coulomb-induced fission

- Large cross section (~ b)
- Small E* : excitation of the GDR (<E> ~ 14 MeV)
  - ^{236}U (γ,f) ~ ^{235}U (n,f) @ 8.2 MeV
  - 75% of first chance fission (23% 2nd chance)
- Significant dispersion of E*: no info event-by-event
- Need to subtract nuclear contribution





Rejection of the nuclear contribution

- Selection of events $Z_1+Z_2 = Z_{beam}$
- Limiting fragmentation regime :
  - The reaction mechanism does not depend on the target
  - Subtraction of yields obtained on Al target (renormalization)