Isotopic fission yields: a unique tool to study fission dynamics and nuclear structure

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and the SOFIA collaboration

SOFIA

STUDIES ON FISSION WITH ALADIN

Fission fragment yields : applied physics

- Nuclear reactors: core dynamics
  - Delayed neutrons
  - Neutronic poisons
  - Increased influence with larger burn-ups
- Nuclear fuel: inventory
  - Used fuel handling and reprocessing
  - Residual (decay) heat

Talk by P. Demetrious (Fri. 11:25)

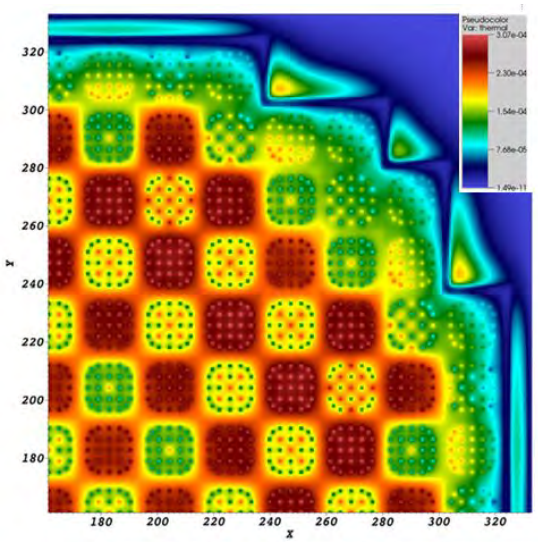
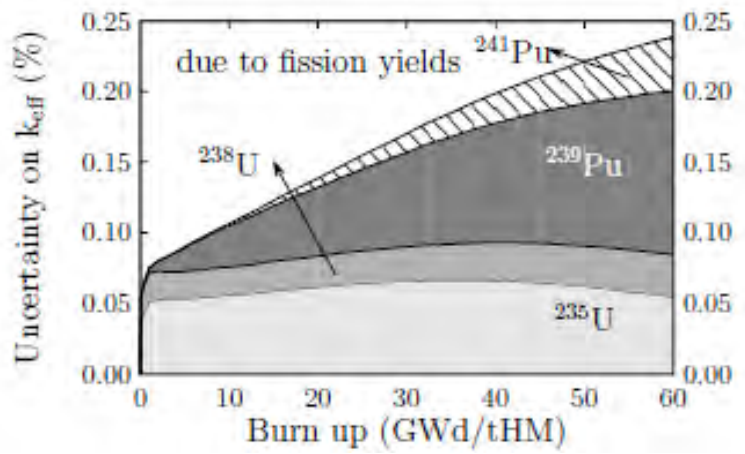
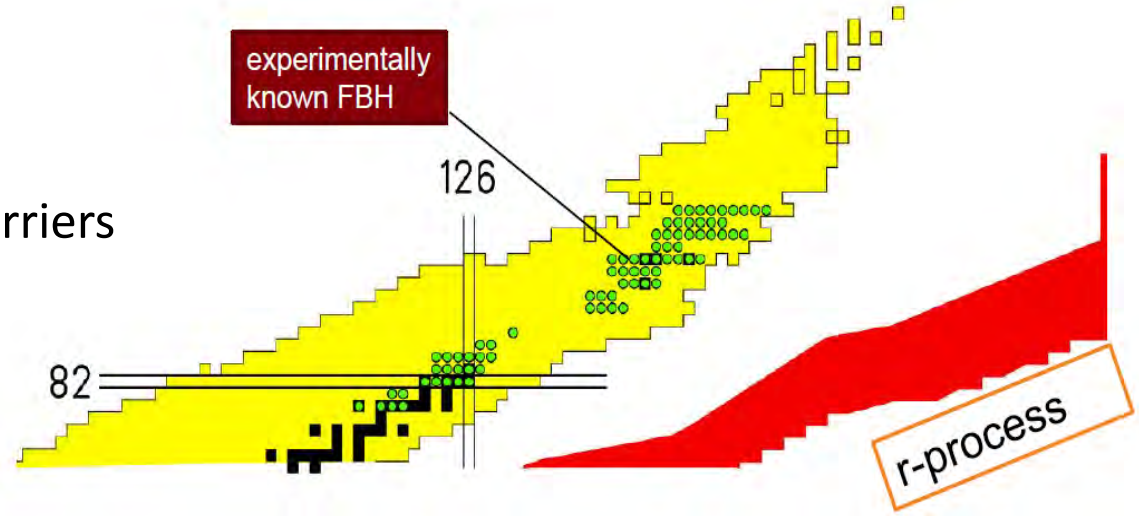


Figure 1 2D Slice of Thermal Flux Distribution near the Core Mid-plane

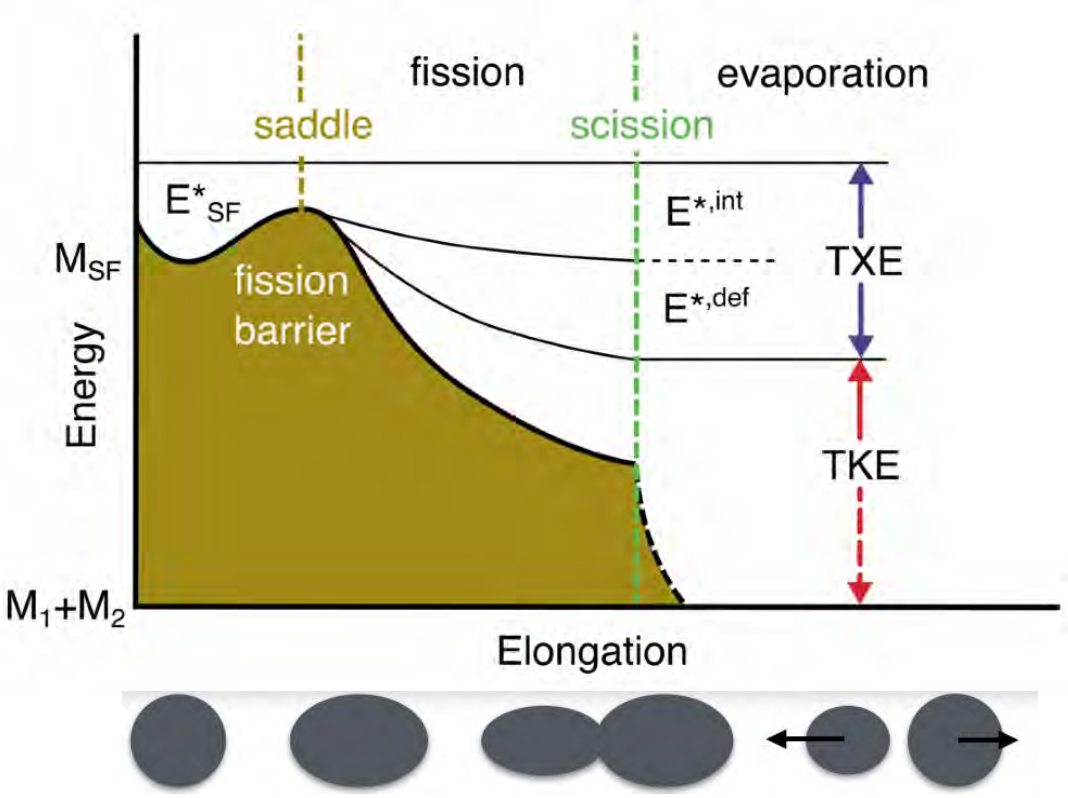


- Nuclear astrophysics: material cycling
  - Fission is the termination of the r-process
  - Nucleosynthesis calculations depend on fission barriers

Talk by T. Kajino (Fri. 11:40)



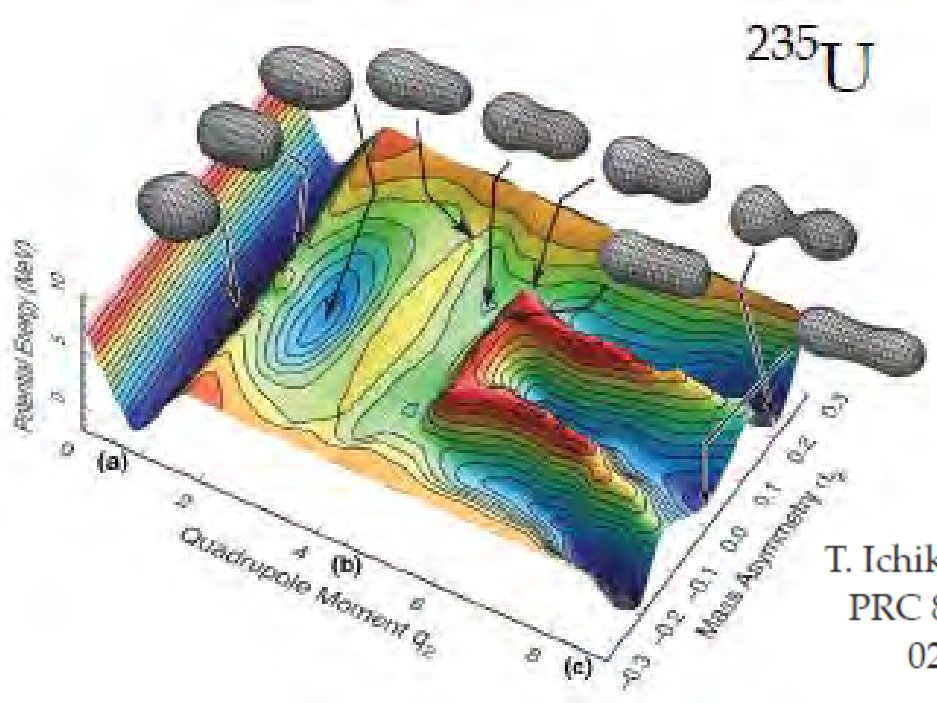
The fission process



- Energy carried by fragments
  - Excitation
  - Deformation at scission
  - Kinetic

- Collective motion of nucleons
- Largely-deformed nuclei
- Shell structure of nascent fragments

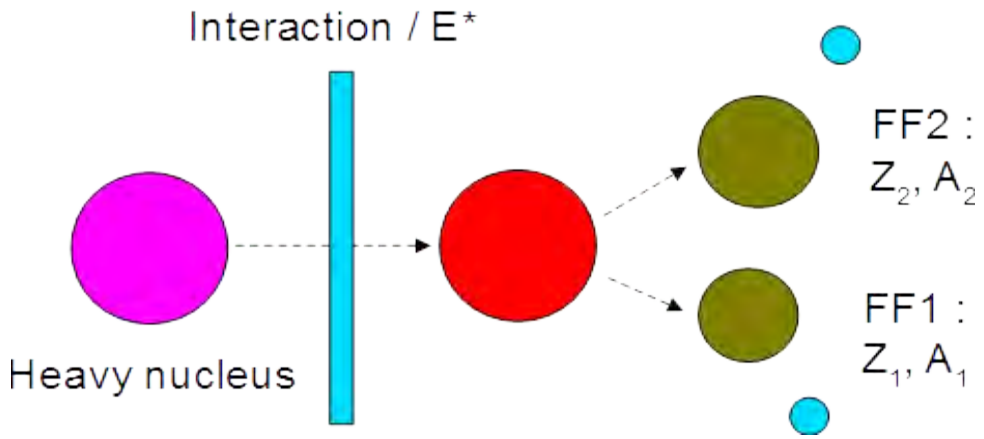
- Complex potential-energy surface
- Excitation energy smooths out structure effects

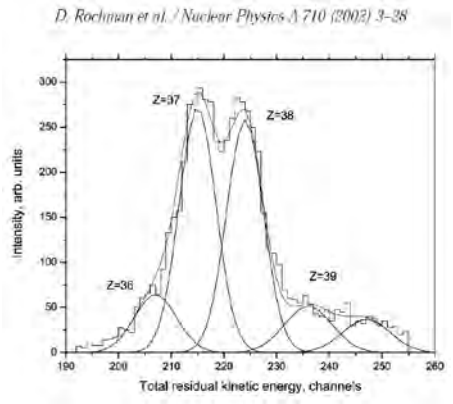


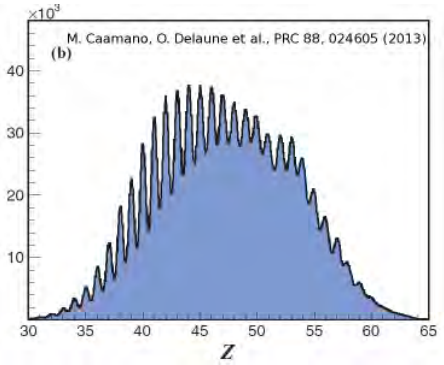
T. Ichikawa et al.
PRC 86 (2012)
024610

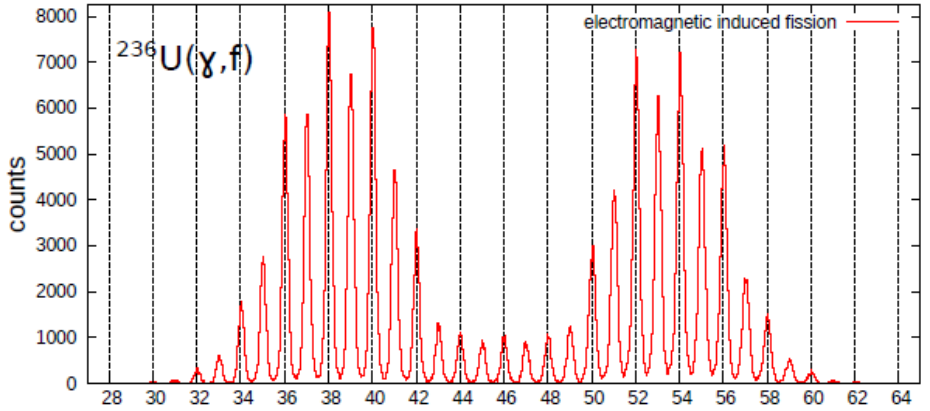
Interest of Inverse Kinematics

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









✓ **Access to very short-lived nuclei**
✓ **Direct, precise Z measurement (A as well, TKE…)**

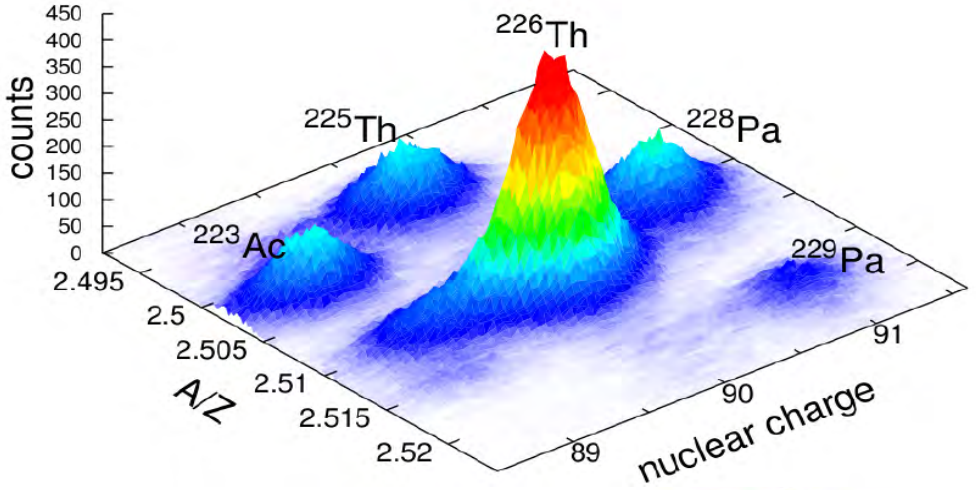
- Identification of the fragments: recoil spectrometer
- Pioneer experiment : K.-H. Schmidt et al. (1996) : Z of both FFs
- 2010s : SOFIA@GSI, transfer@GANIL, RIKEN

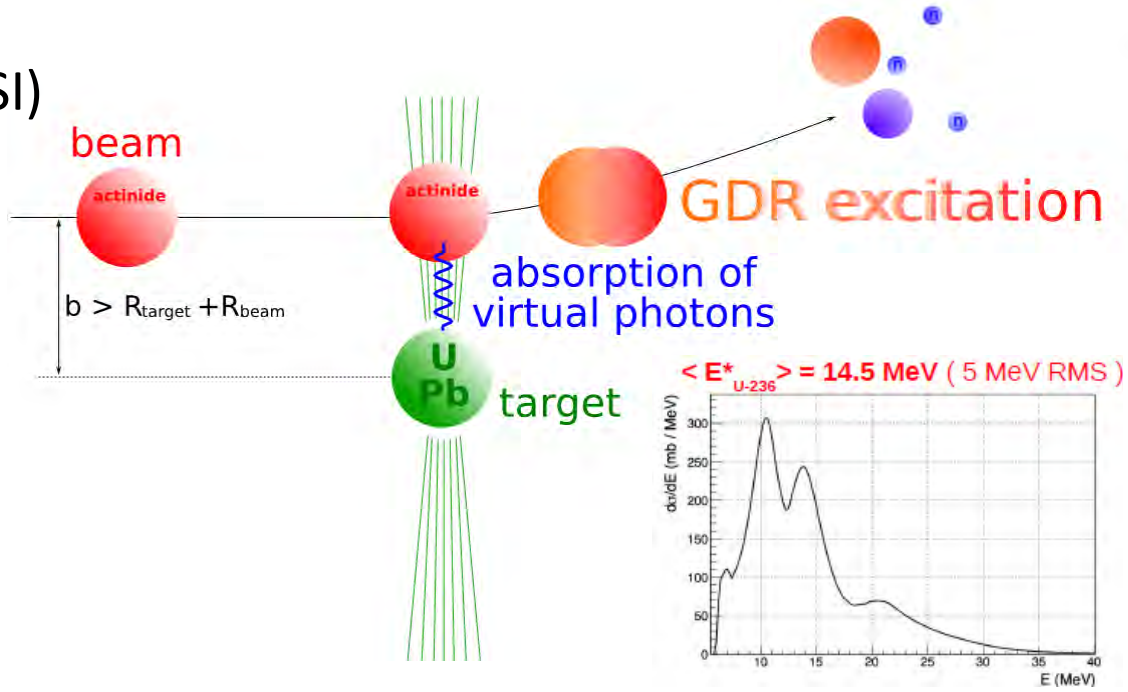
The SOFIA program

- Radioactive beam
  - Fully-identified fragments of ^{238}U (FRS)
- Direct identification of <u>both</u> fission fragments : <u>A</u> & <u>Z</u>
  + Kinetic energy (fragments shapes)
  + Total prompt neutron multiplicity (fragments excitation)
- High-precision measurement (~ % on isotopic yields)

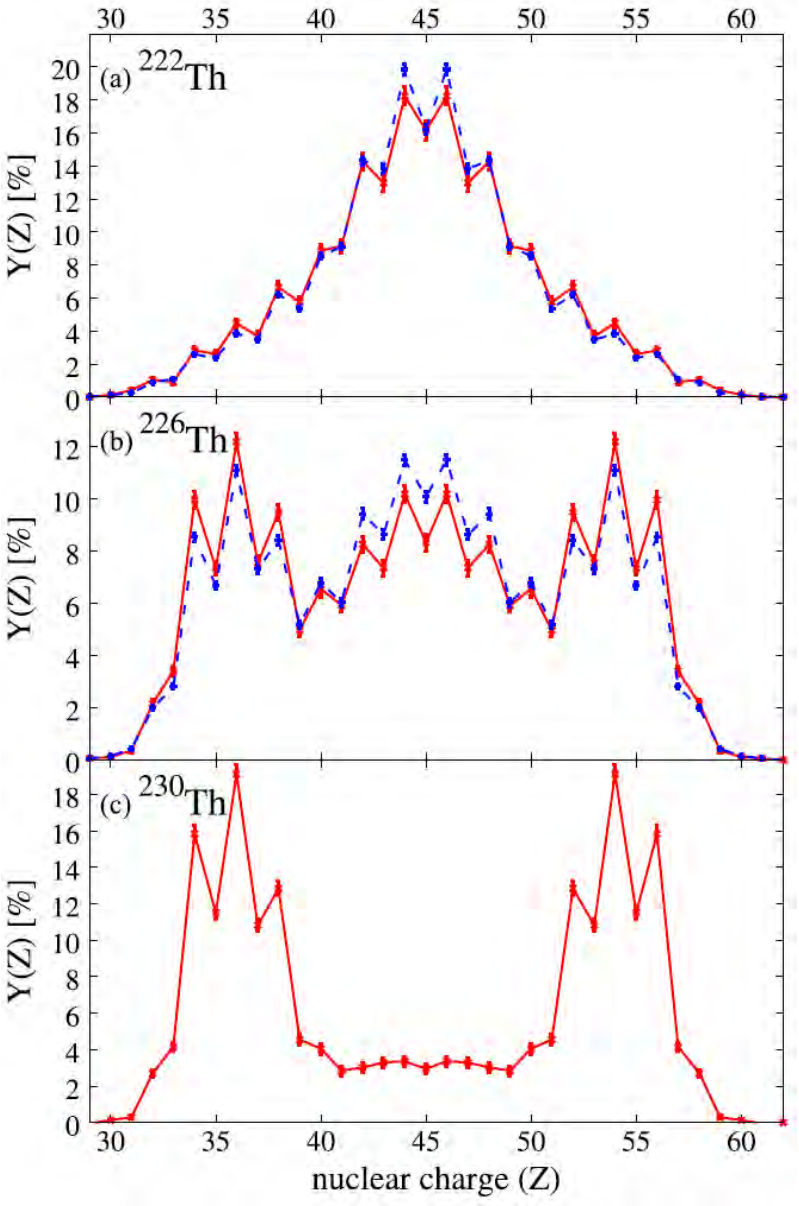
- Large-acceptance recoil spectrometer in cave C (GSI)

- 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





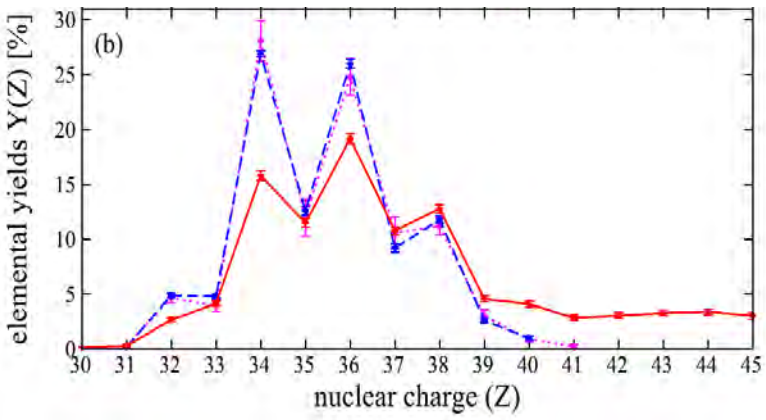
Th-chain measurement : Z yields

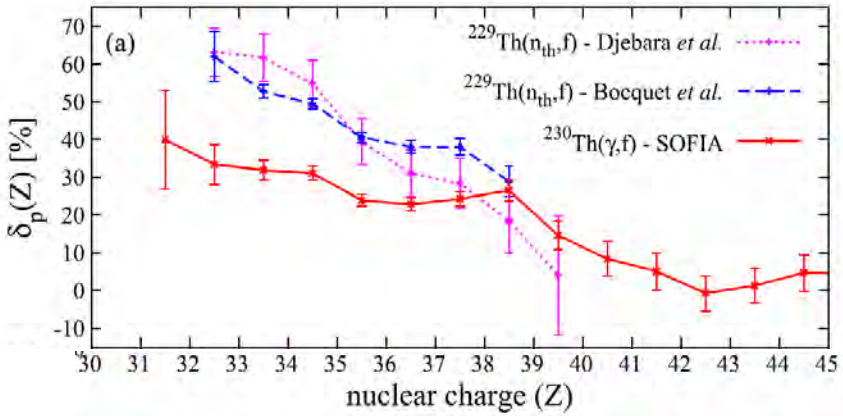


- Fully consistent with Schmidt et al. measurement
  - Better evaluation of the nuclear contribution (Al vs H)
  - Better Z resolution

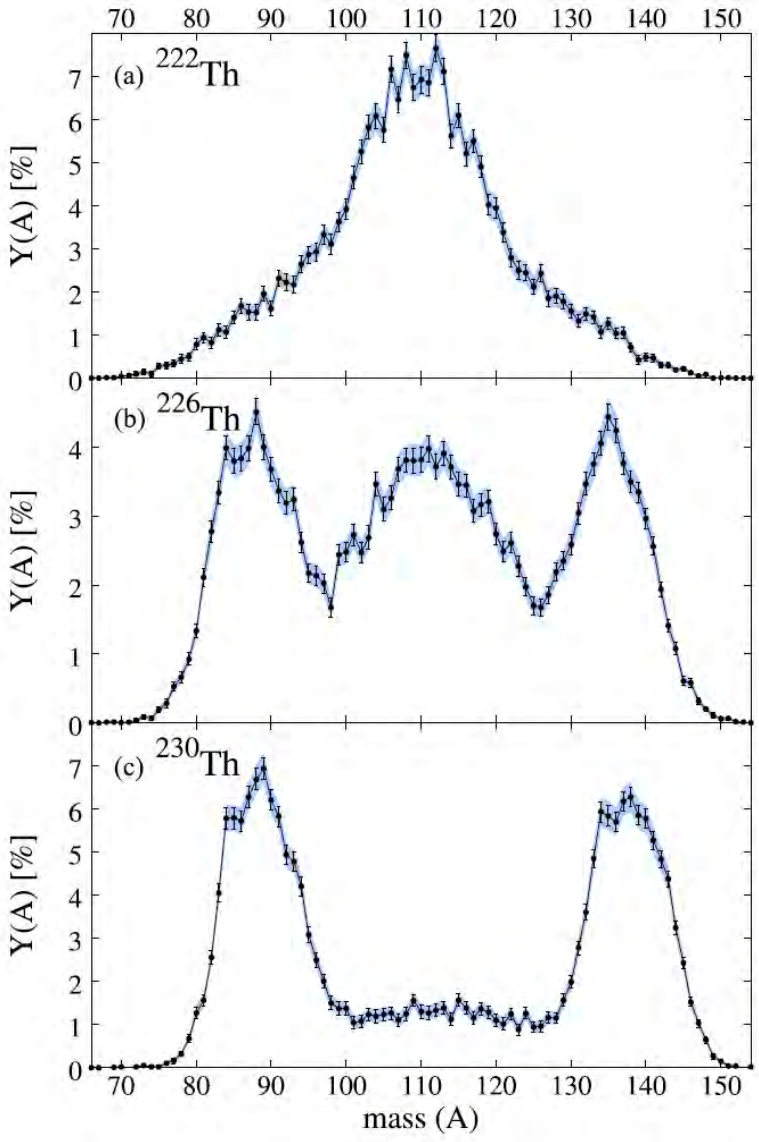
- Comparison to neutron-induced fission
  - 14.6 MeV vs 6.8 MeV
  - Symmetry favored
  - Even-odd staggering dampened

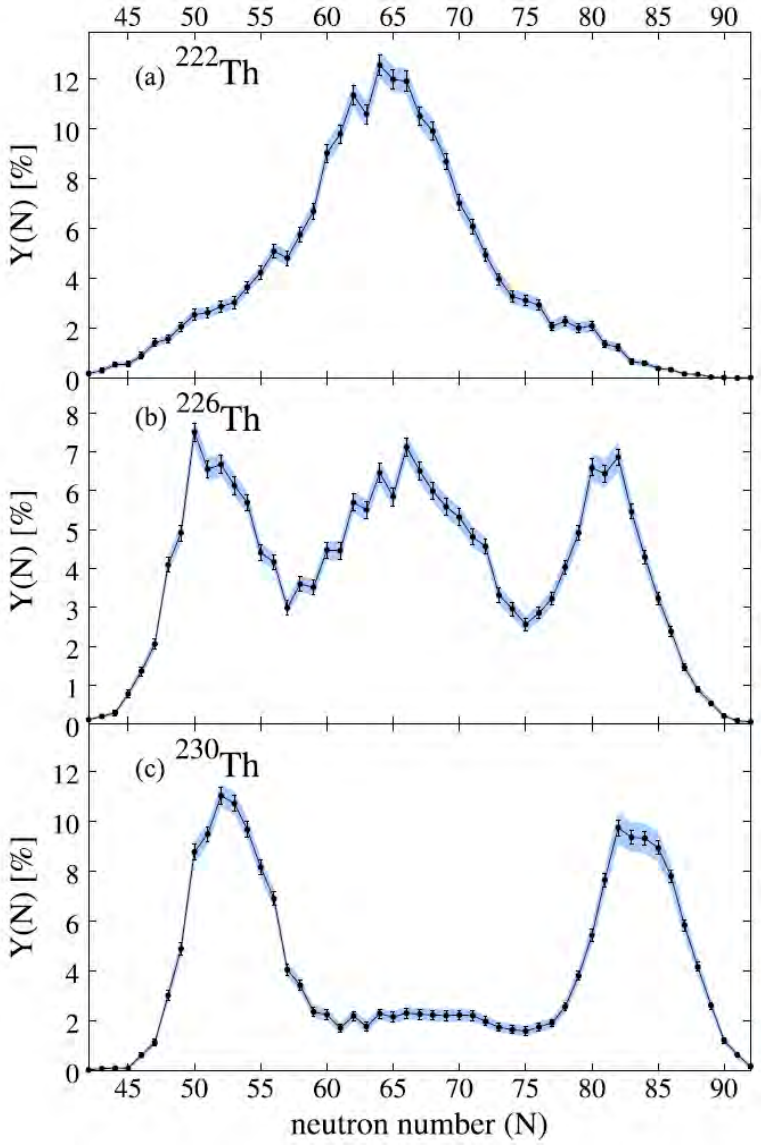
Chatillon et al., PRC 99, 054628 (2019)



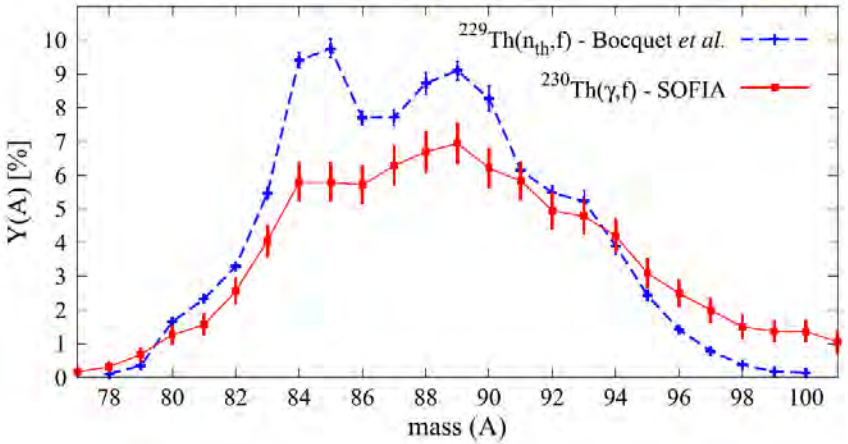


Th-chain measurement : A and N yields



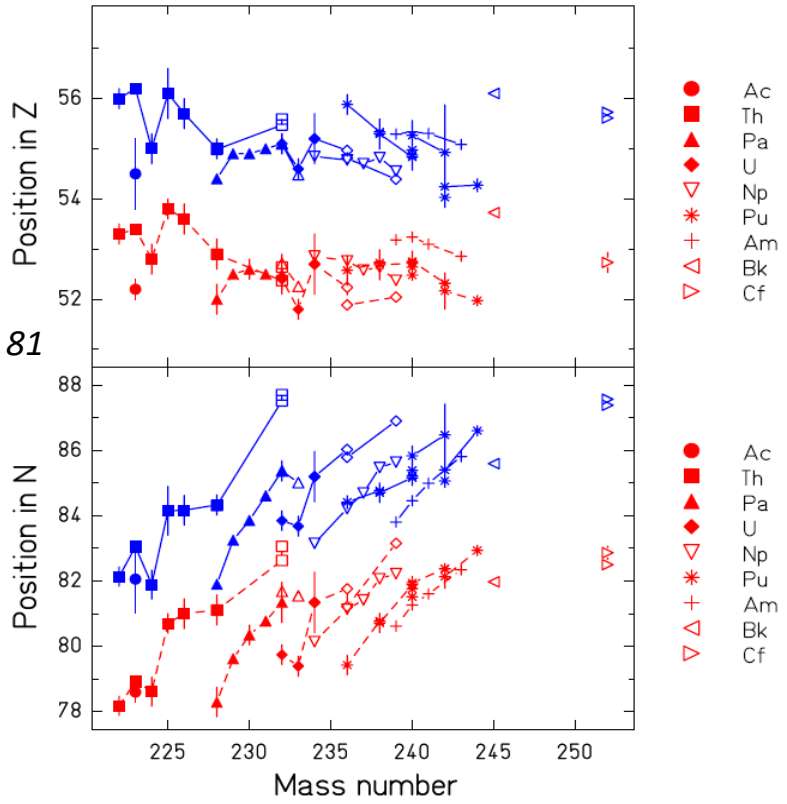


- Neutron even-odd staggering
  - Driven by evaporation
- Influence of N=50 and N=82
  - Clearly visible…
  - … but not striking

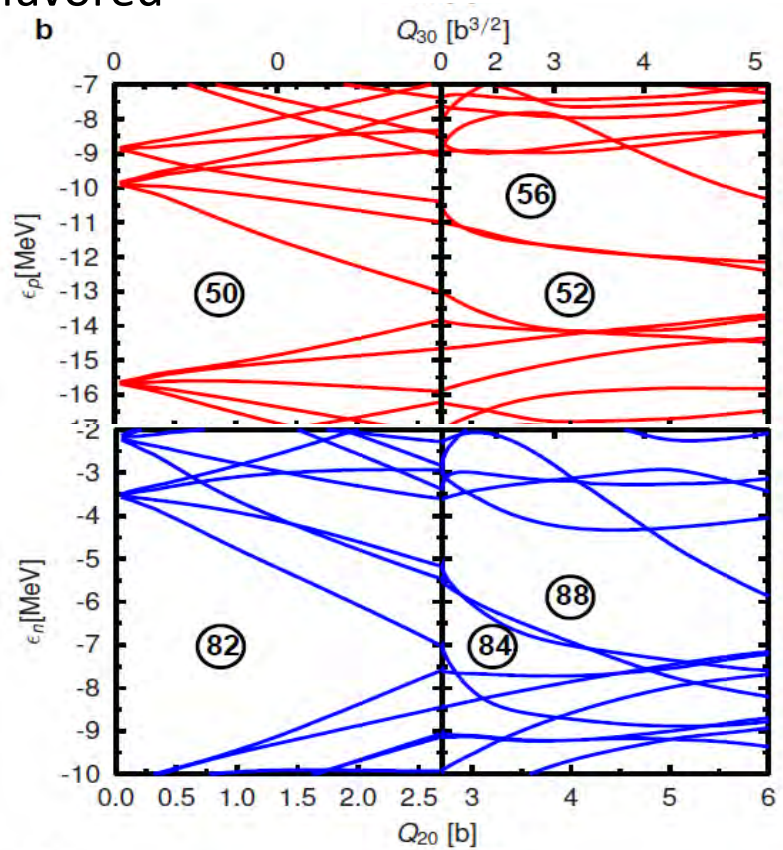


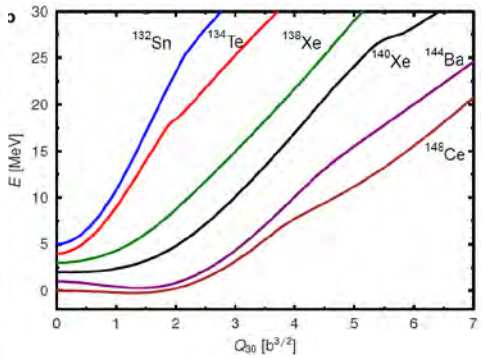
Fragments stabilization : octupolar deformation?

- Stability of the heavy peak
  - constant A ; “mode” analysis reveals Z consistancy
- Liquid drop deformation + attraction in neck -> octupolar deformation
  - ^{132}Sn expensive to deform : unfavored fission path
  - Octupole-deformed nuclei such as ^{144}Ba are favored



Andreyev Rep. Prog. Phys. 81 (2017)

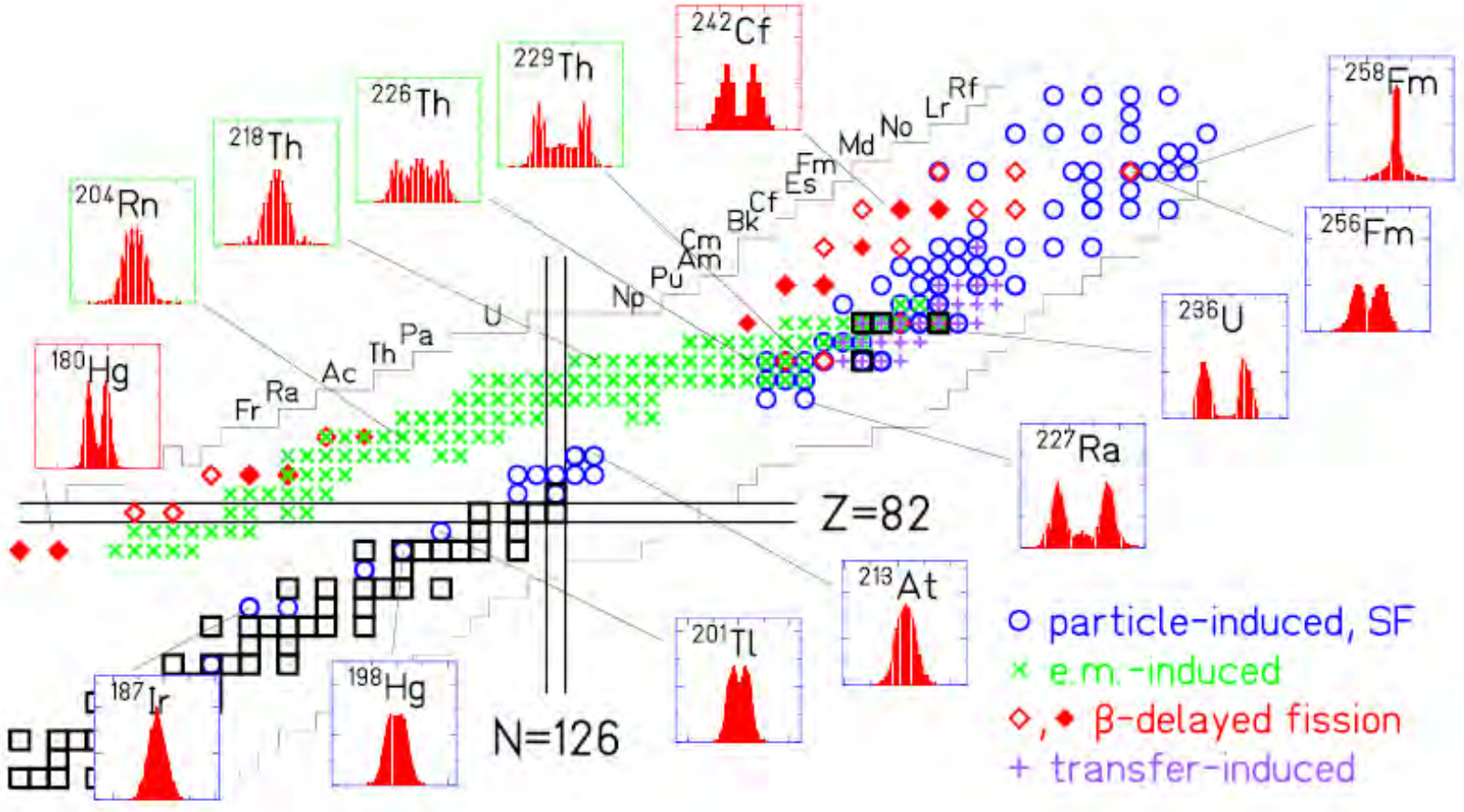




Scamps and Simenel arXiv:1804.03337 (2018)

Fission along the nuclear chart

- Asymmetric fission is related to 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 (^{180}Hg)
  - No effect of ^{50}Zr ?

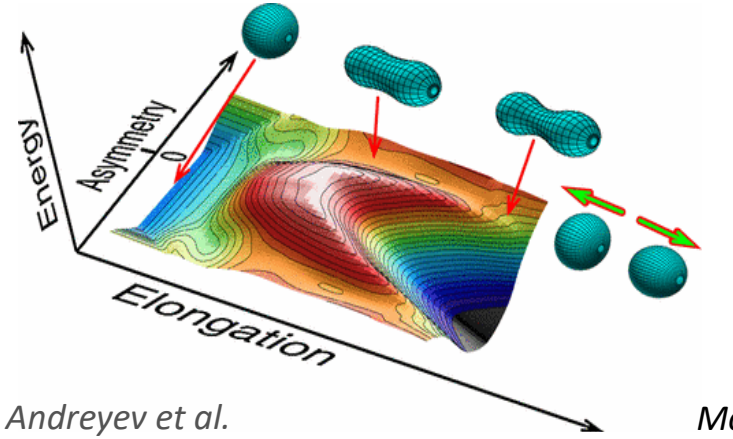


Andreyev, Rep. Prog. Phys. 81 (2017)

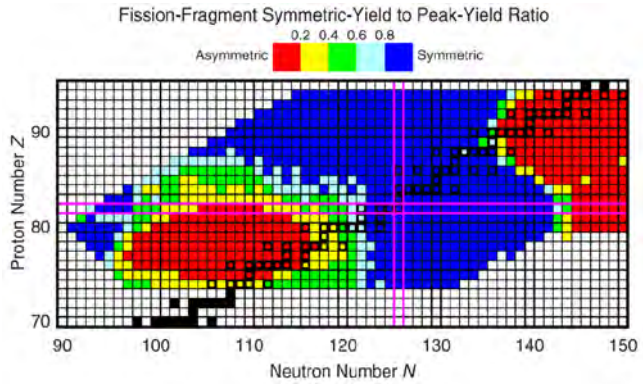
Fission modes in neutron-deficient pre-actinides

- β-delayed fission at ISOLDE
- Asymmetry in masses 180-190

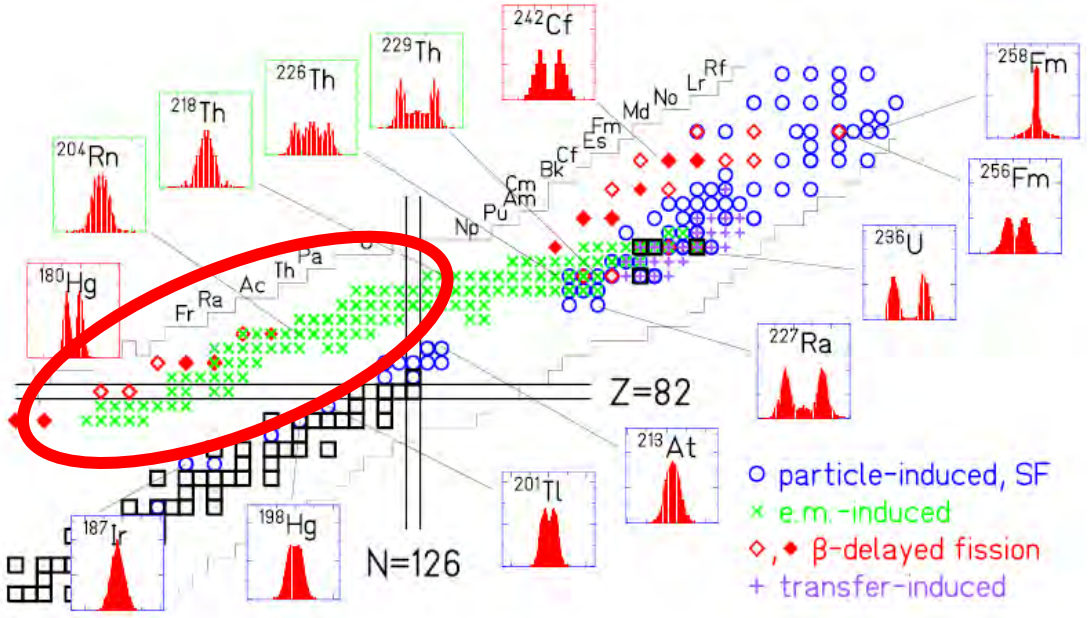
- Objective of the next SOFIA measurement (spring 2020)

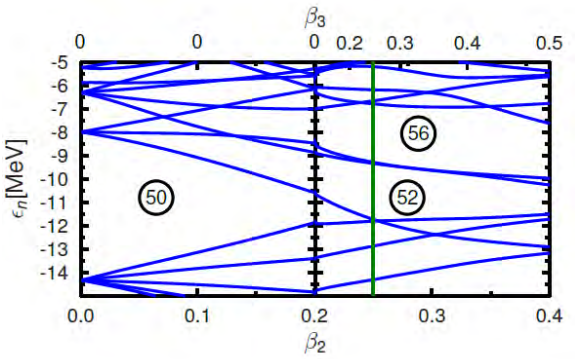


Andreyev et al.
Phys. Rev. Lett. ***105****, 252502*

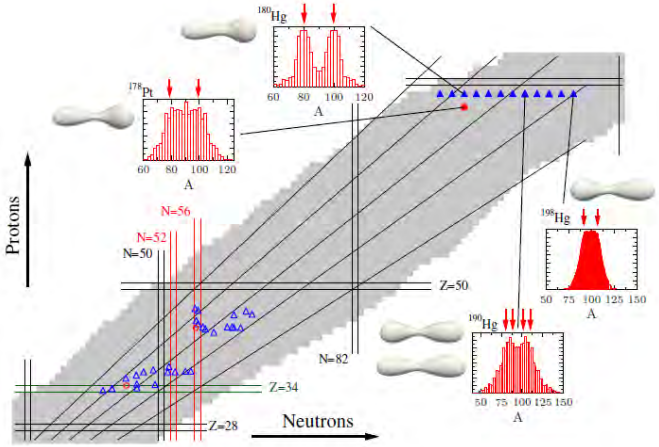


Moller and Randrup, Phys. Rev. C 91 044316 (2015)





Scamps and Simenel,
arXiv:1904.01275 (2019)



Summary and outlook

- First measurement of mass and neutron numbers in the light thorium chain
- Sharp transition to symmetric fission
- Upcoming results about neutron evaporation (hence, fragments deformation)

- Upcoming measurement in the light Pb region : detailed study of “new” asymmetric fission

- Energy-dependency of yields : (p,2pf)
- 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

- Increased number of combined observables
  - SOFIA coupling with NeuLAND : neutron tagging
  - SOFIA coupling with CALIFA : gamma multiplicity