Les fragments de fissions : une observable clé pour la compréhension de la fission nucléaire

Congrès général des 150 ans de la Société Française de Physique

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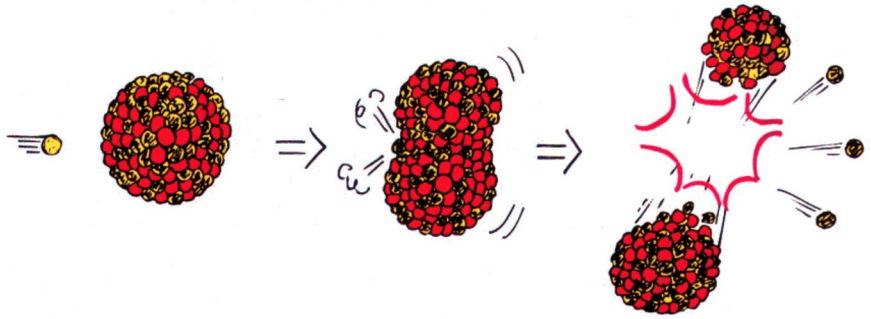
Contents

1. Motivation and experimental techniques
   - Activation method
   - Direct kinematics
   - Inverse kinematics
2. SOFIA/R^{3}B setup at GSI
3. Recent results
4. Outlook

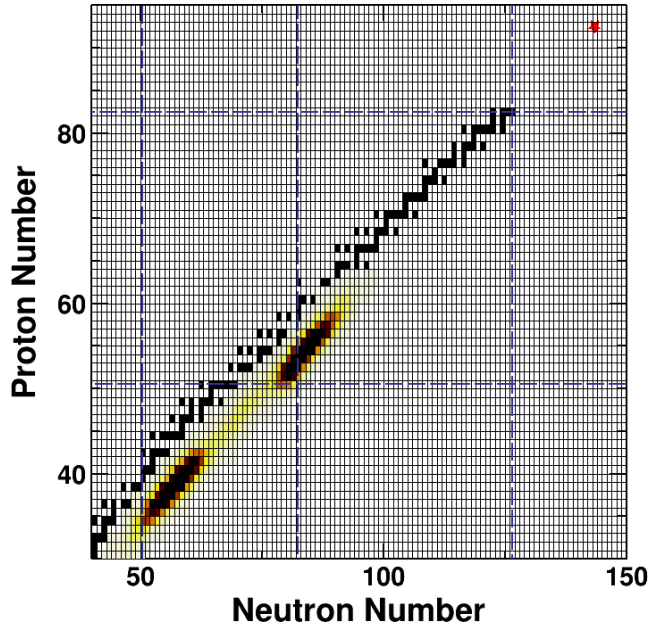
1. Motivations

Fission fragment yields : What is it ?

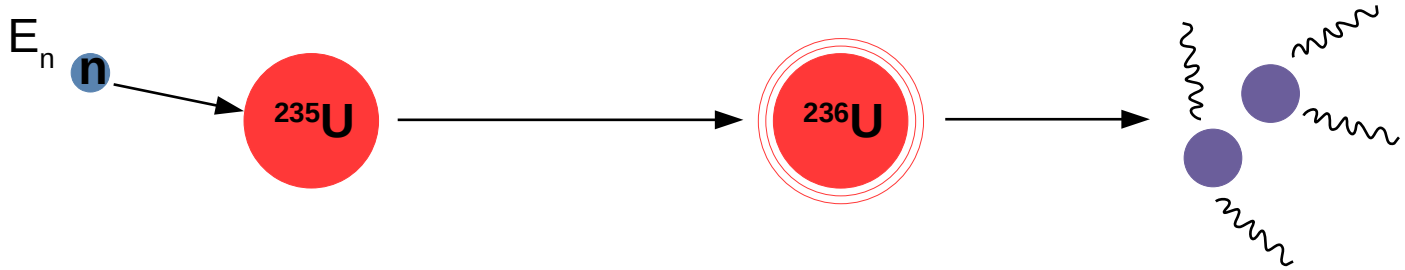


Three different categories

- Primary fragments: before prompt neutron emission
- **Secondary fragments (what we are after)**: after neutron evaporation => *independent yields*
- Secondary fission products: afetr all decays (β decay, delayed neutrons...) => cumulatve yields

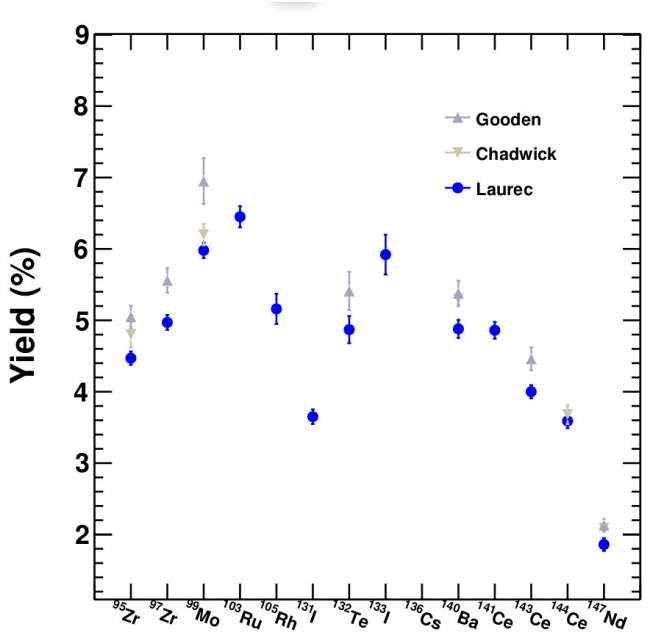


Experimental approach (1) : activation

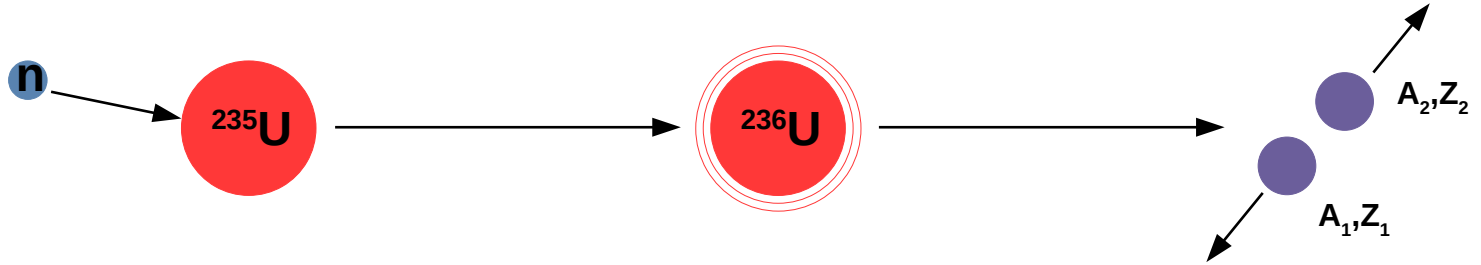


Activation technique

- Irradiation of an actinide sample from neutron flux of known energy
- Radiochemistry and/or gamma spectropscopy
- Access to cumulative yield.

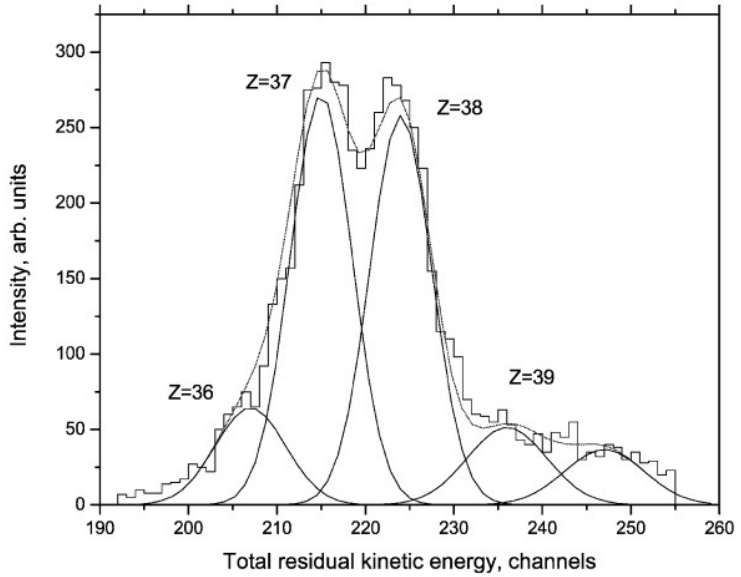


Experimental approach (2) : « In flight »



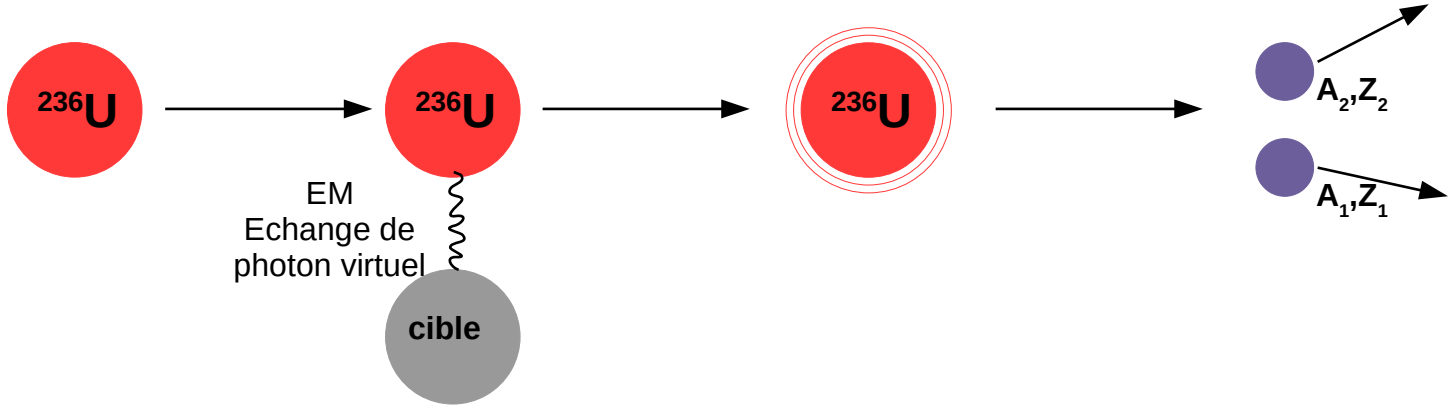
In flight method : neutron capture on actinide target

- Neutron induced fission (often thermal).
- Example : Lohengrin spectrometer at ILL → Mass distribution and charge up to Z ≈ 40.
- Measure of the charge above 40 impossible.
- Needs target → access to quasi-stable elements
- Partial isotopic yields
- Hard to measure with non-thermal neutrons



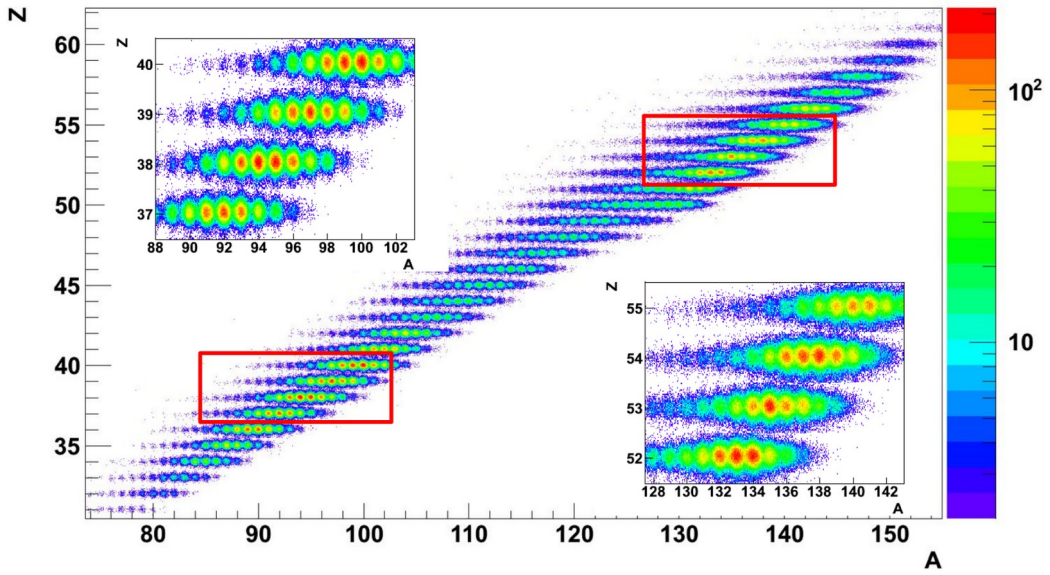
D. Rochman *et al.* Nucl. Phys. A **710** 3-28 (2002)

Experimental approach (3) : Inverse kinematics at SOFIA



Alternative methode : inverse kinematics

- The fissioning system is the beam.
- The fission is induced by Coulomb excitation.
- Total mass and charge distribution measured.
- Full isotopic yields.
- One step further from the pioneer work of K.-H. Schmidt K.-H. Schmidt *et al*. NPA **665** (2000) 221



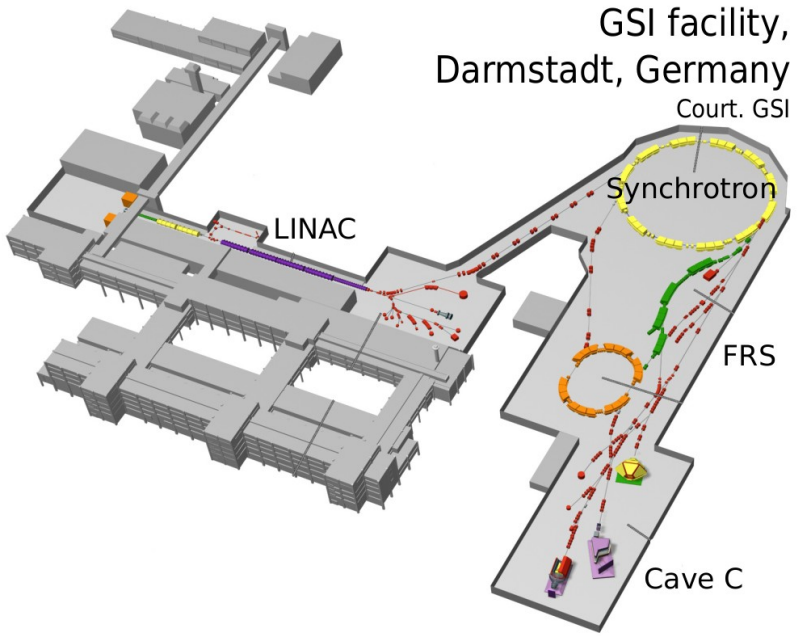
Goals of the SOFIA experiments

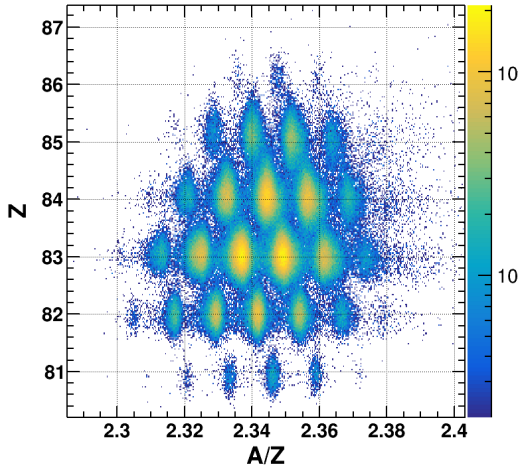
- **Identification in charge Z, and mass A, of the compound nucleus and both fission fragments**
  - Provide fission yields for a wide range of fissioning system
  - Asymmetric/symmetric fission → shell effects
- **Measurement after prompt-neutron emission but before any β-decay**
  - Accurate measurement of the total prompt-neutron multiplicity
  - Give insights of compacity/deformation at scission
- **Three experiments performed at GSI/R^{3}B**
  - 2012 : stydy of ^{234,235,238}U, ^{237,238}Np and $^{222\text{-}230}$Th
  - 2014 : focus on ^{236}U
  - 2021 : study of 100 neutron-deficient fissioning systems from Pt to Th

2. SOFIA/R^{3}B setup at GSI

Inverse kinematics at relativistic energy at GSI

- **Actinide or pre-actinide accelerated at relativistic energy (around 700 MeV/u)**
  - ✔ Fragmentation of a ^{238}U beam a 1 A.GeV on a Be target
  - ✔ GSI/FRS : selection of a cocktail beam





Inverse kinematics at relativistic energy

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  - ✔ Fragmentation of a ^{238}U beam a 1 A.GeV on a Be target
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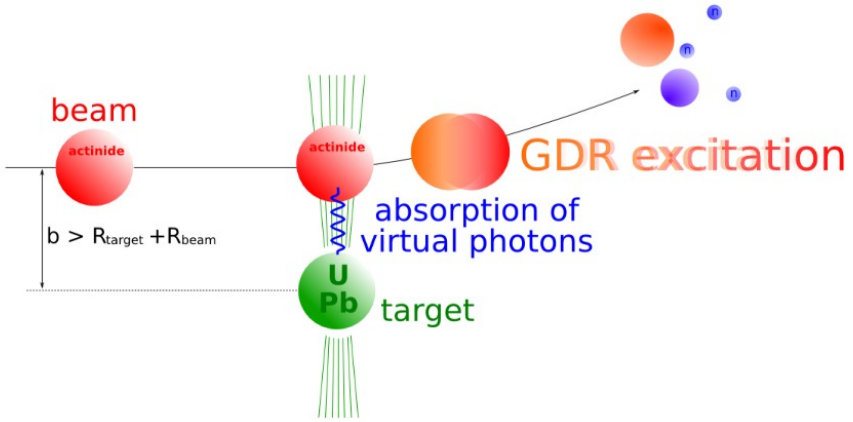
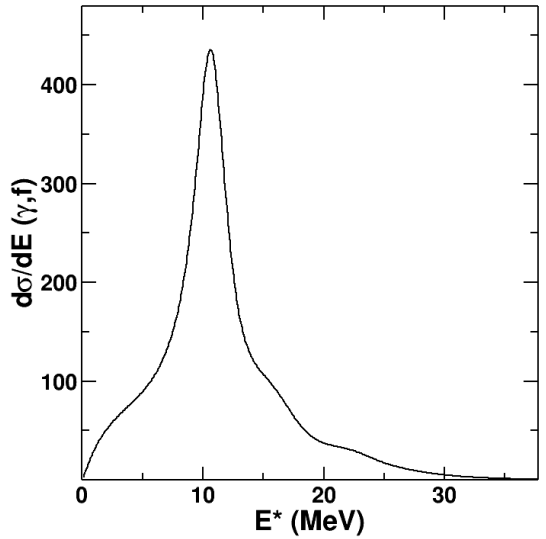
- **Coulomb induced fission of the relativistic beam**
  - ✔ Large cross section (around 3 barns)
  - ✔ <E*> around 14 MeV





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- **Coulomb induced fission of the relativistic beam**
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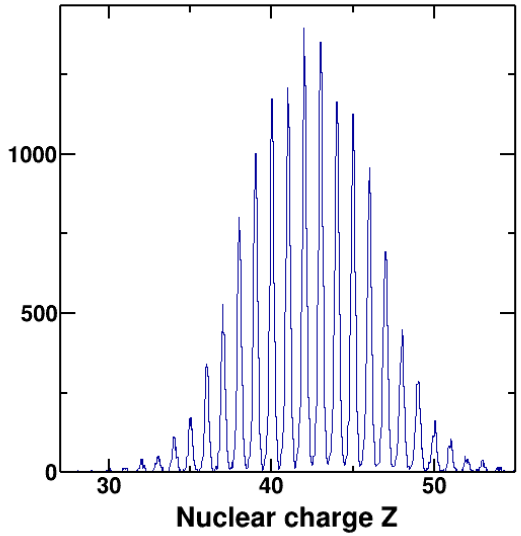
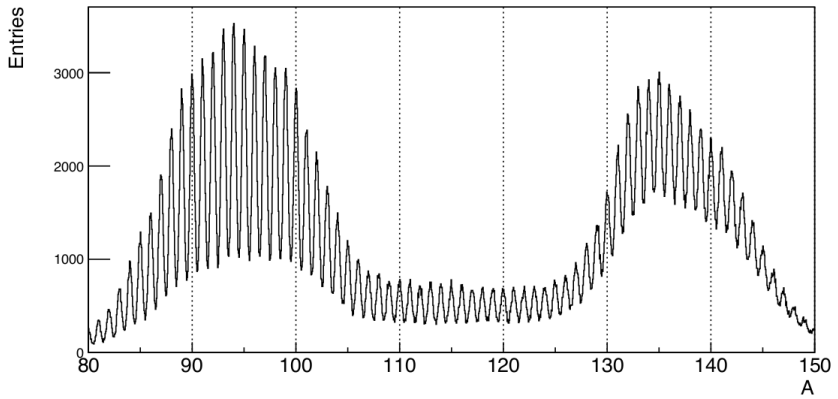
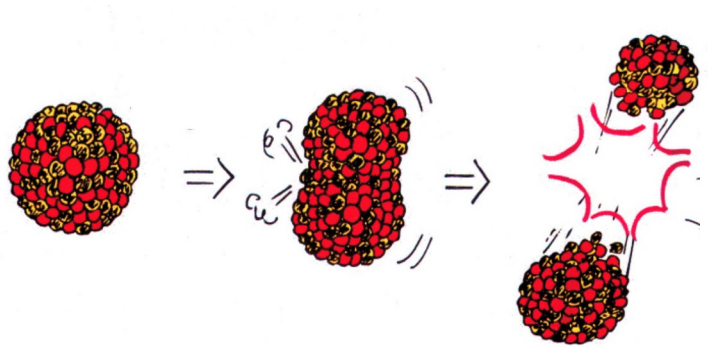
- **Both fission fragments are identified in coincidence in a dedicated experimental setup**



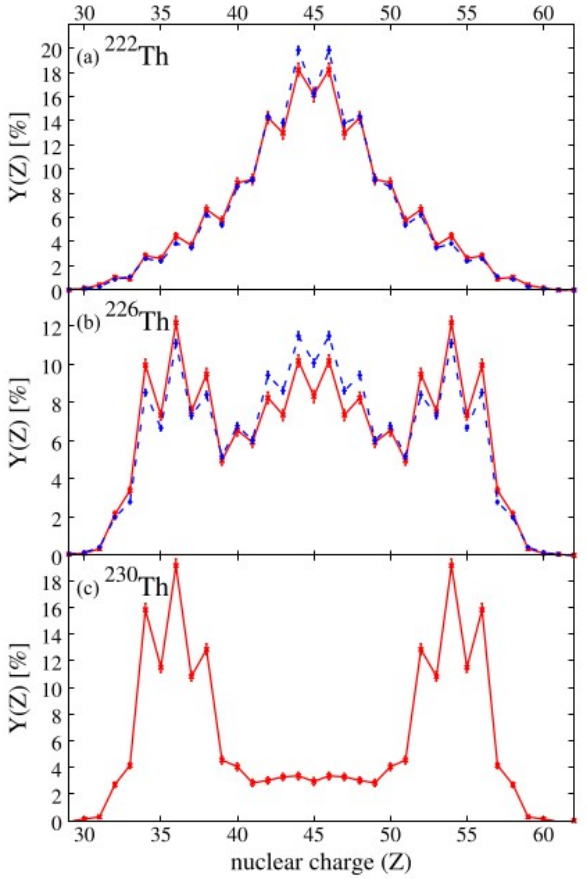




3. Recent results

New fission modes in neutron-defficient Th

- From ^{230}Th down to ^{222}Th
  - ✓ Measurement of the charge distribution
    - ➔ Clear transition from asymmetric to symmetric fission



A. Chatillon *et al*. Phys. Rev. C **99**, 054628 (2019)
A. Chatillon *et al*. Phys. Rev. Lett. **124**, 202502 (2020)

New fission modes in neutron-defficient Th

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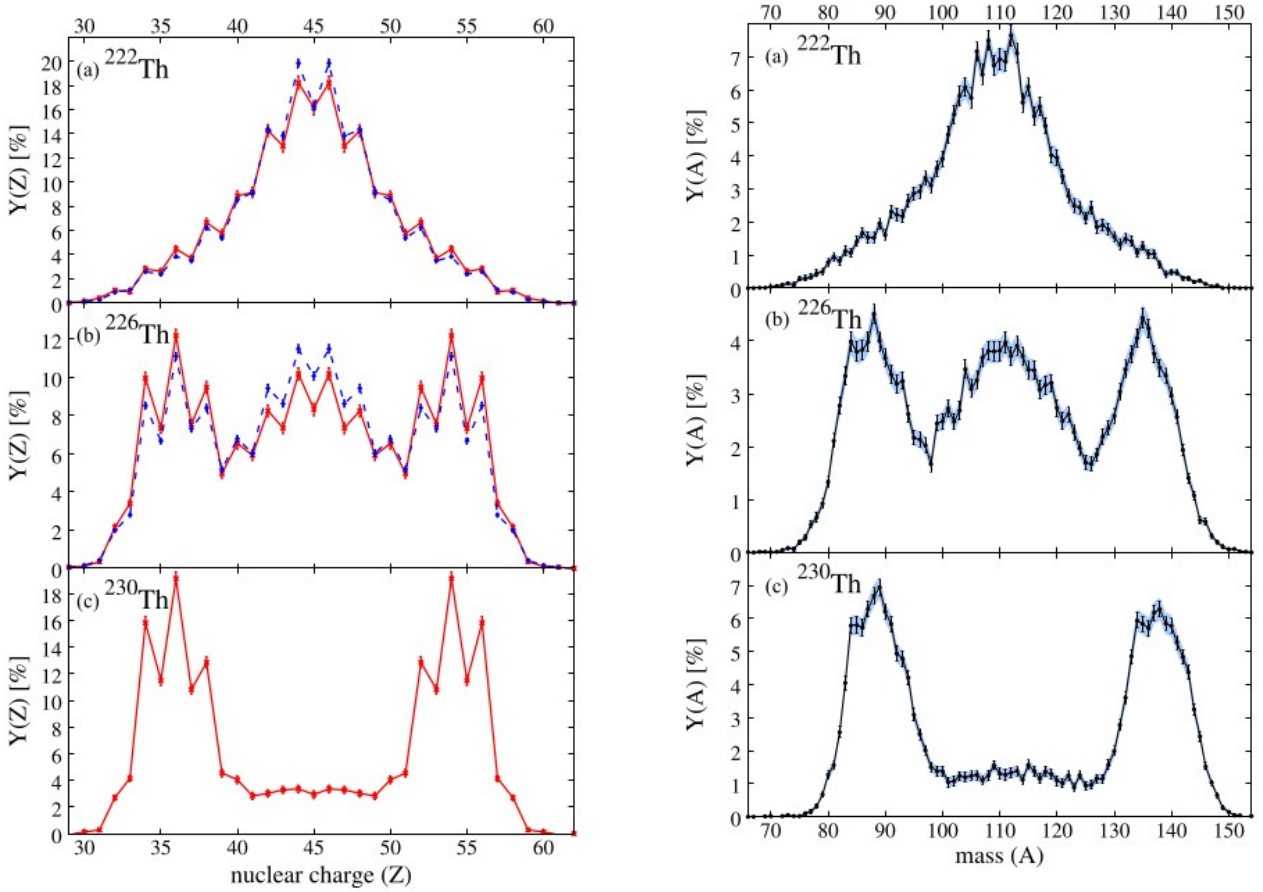
  - ✔ Measurement of the mass distribution (new!)



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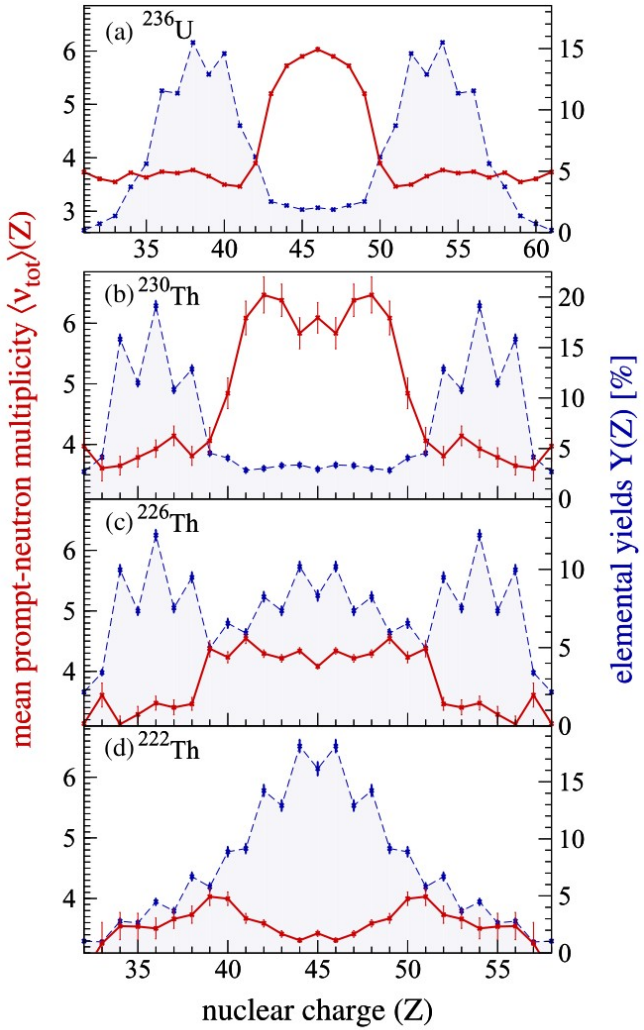
  - ✔ Measurement of the charge distribution
    - ➔ Clear transition from asymmetric to symmetric fission
  - ✔ Measurement of the mass distribution (new!)
    - ➔ Access to the total neutron multiplicity
    - ➔ The symmetric fission mode in ^{222}Th is a compact mode with a low neutron multiplicity.
    - ➔ Role of the tensor force

R. N. Bernard *et al*. Phys. Rev. C **101**, 044615 (2020)



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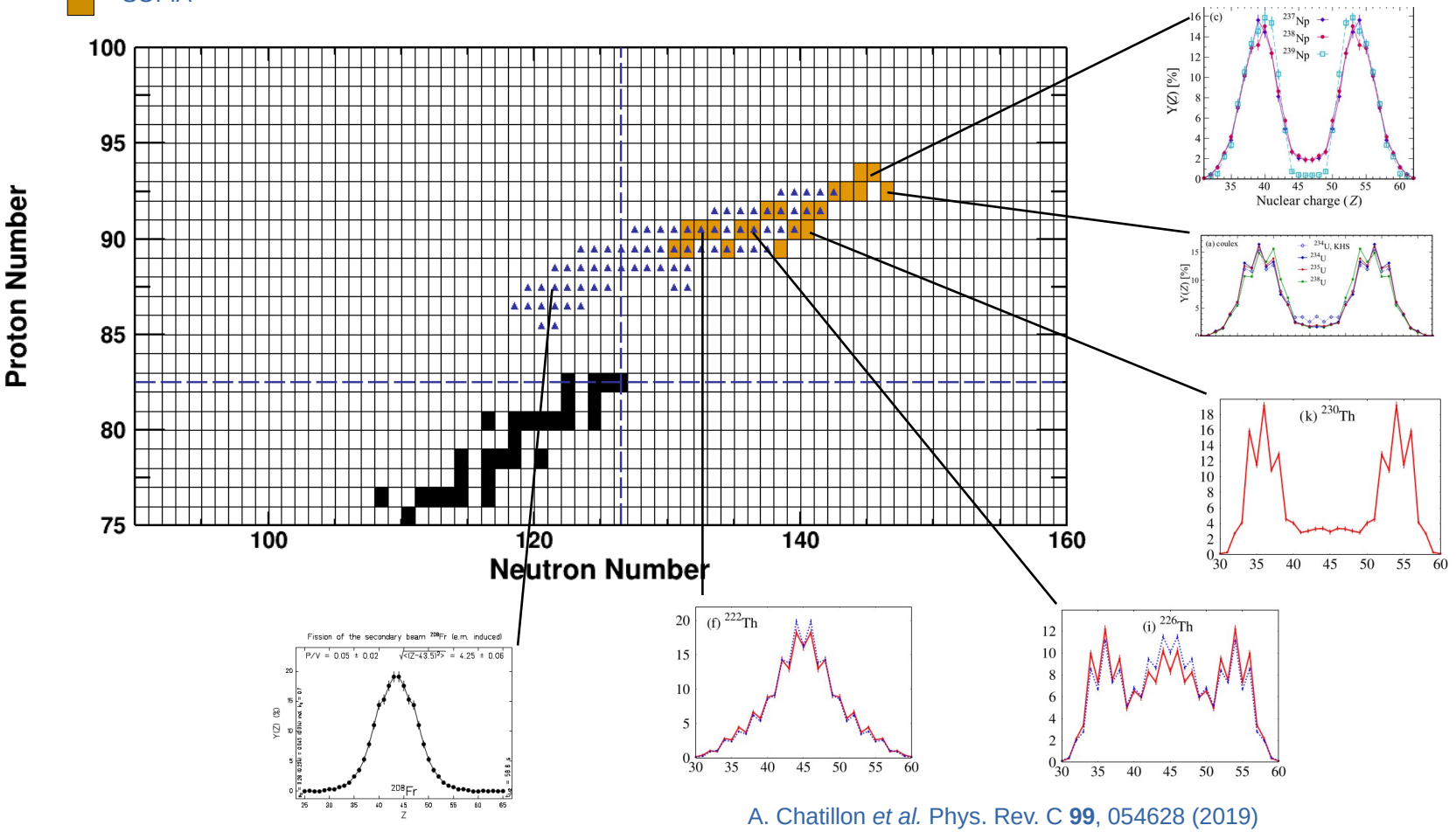
Mapping the fission modes with the yields

K.-H. Schmidt *et al.* NPA **665** (2000) 221

SOFIA

J-.F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)



S. Steinhauser *et al.* Thesis work

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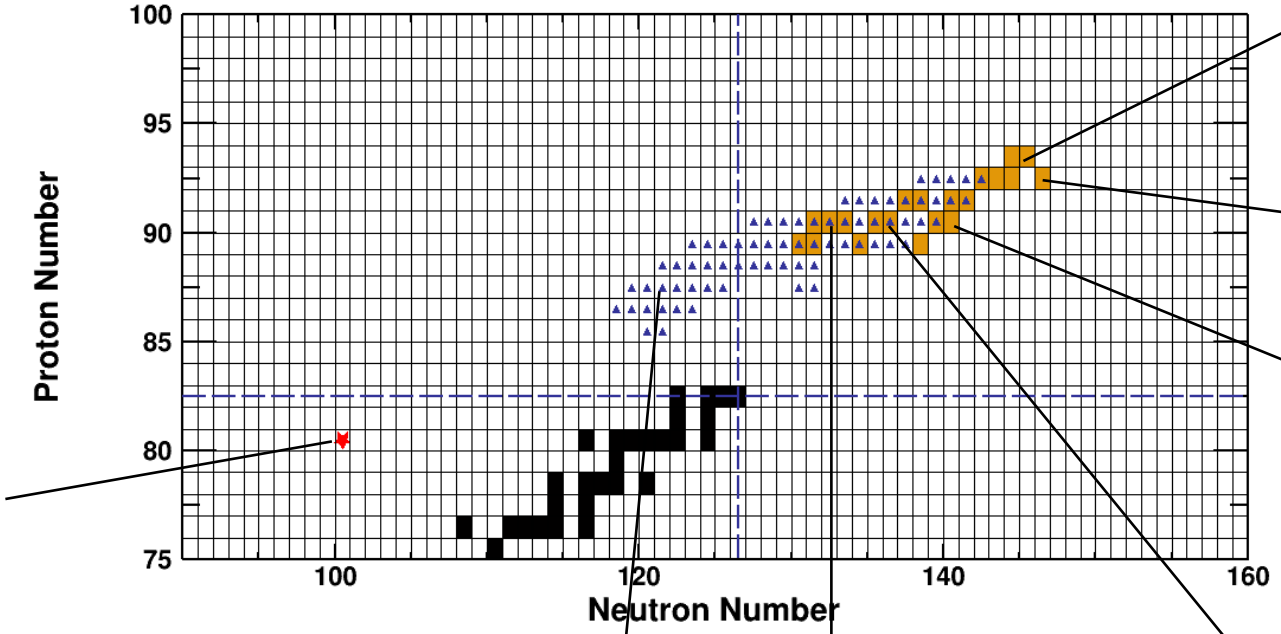
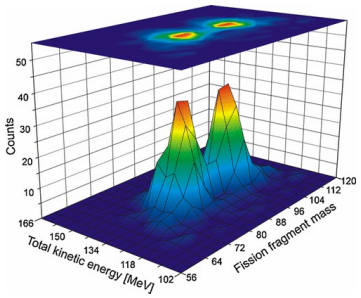
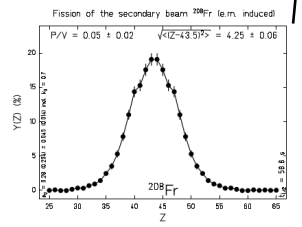




A. N. Andreyev *et al.* Phys. Rev. Lett. **105**, 252502 (2010)



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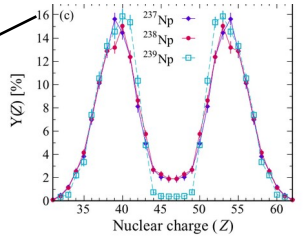

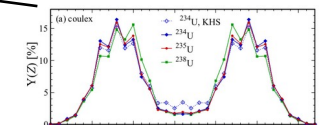

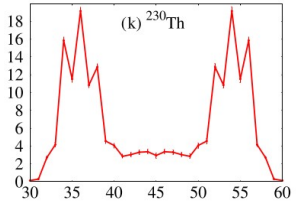

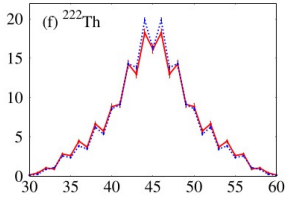

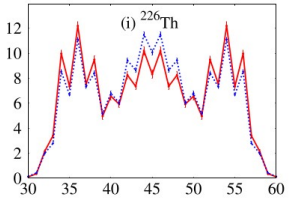

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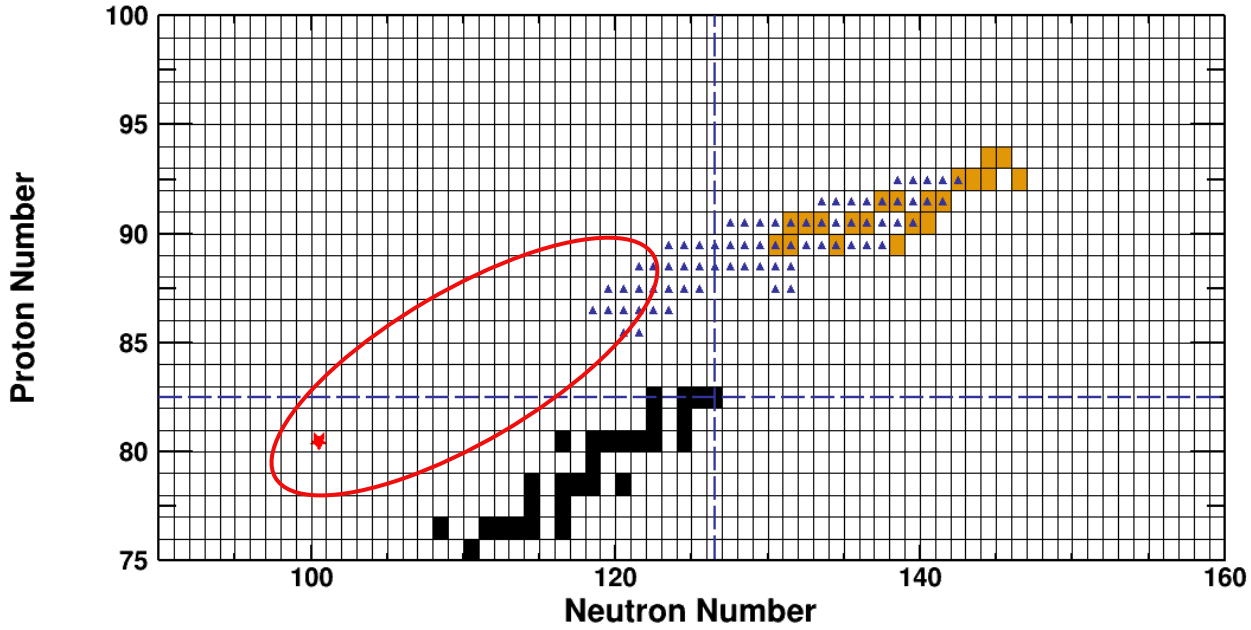
Mapping the fission modes with the yields

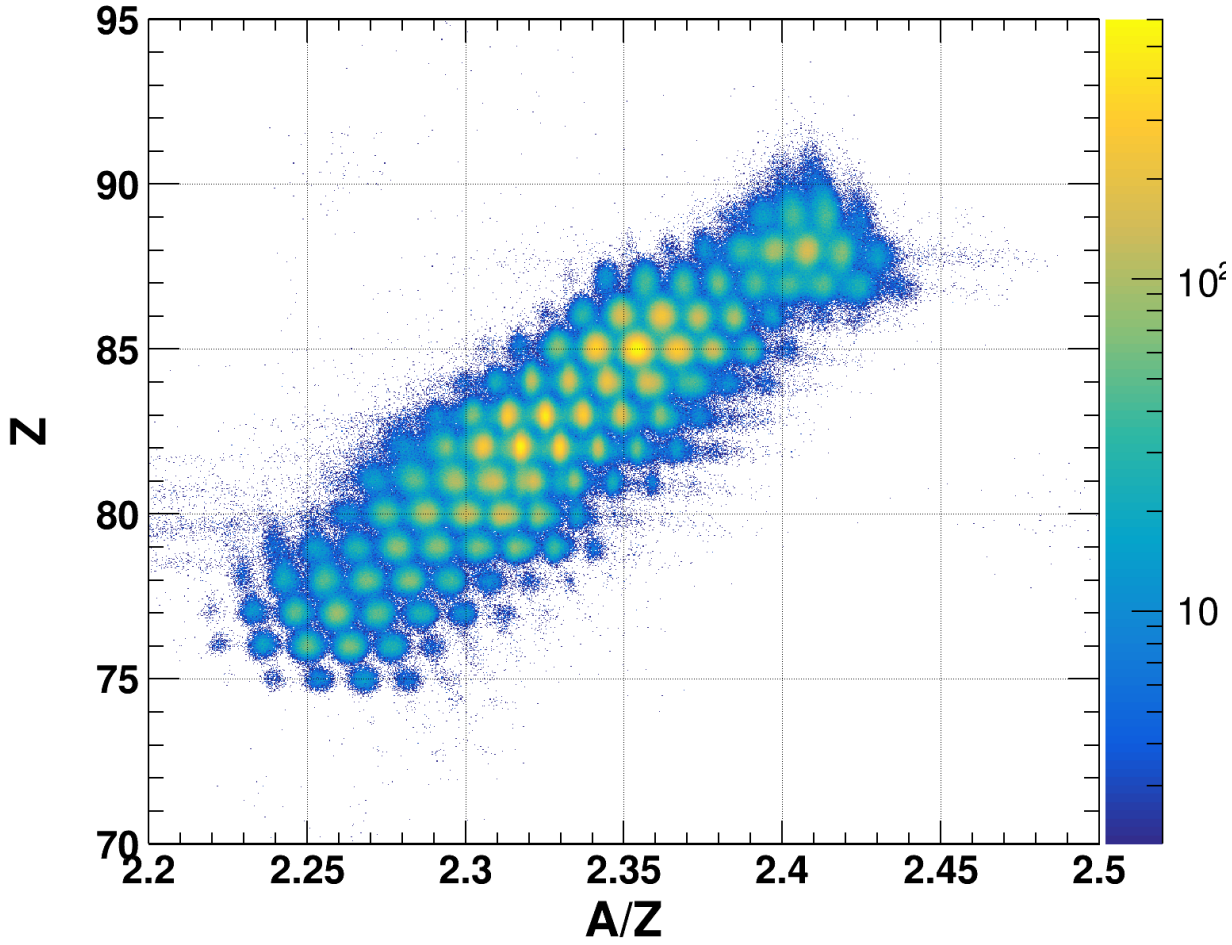
New island of asymmetric fission ?



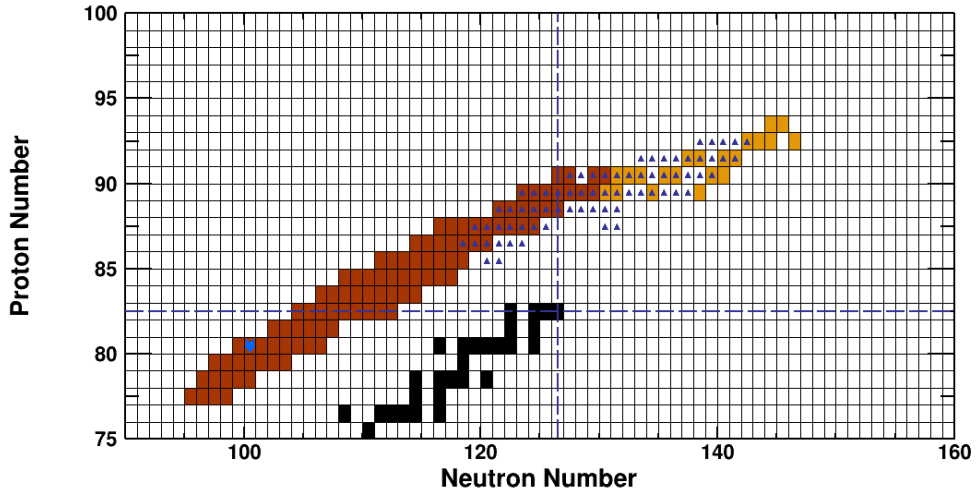
- **What mechanism is responsible for this new asymmetric split ?**
- **What shell effects ?**
- **Whar are the limits ?**
- **...**

New SOFIA experiment in 2021

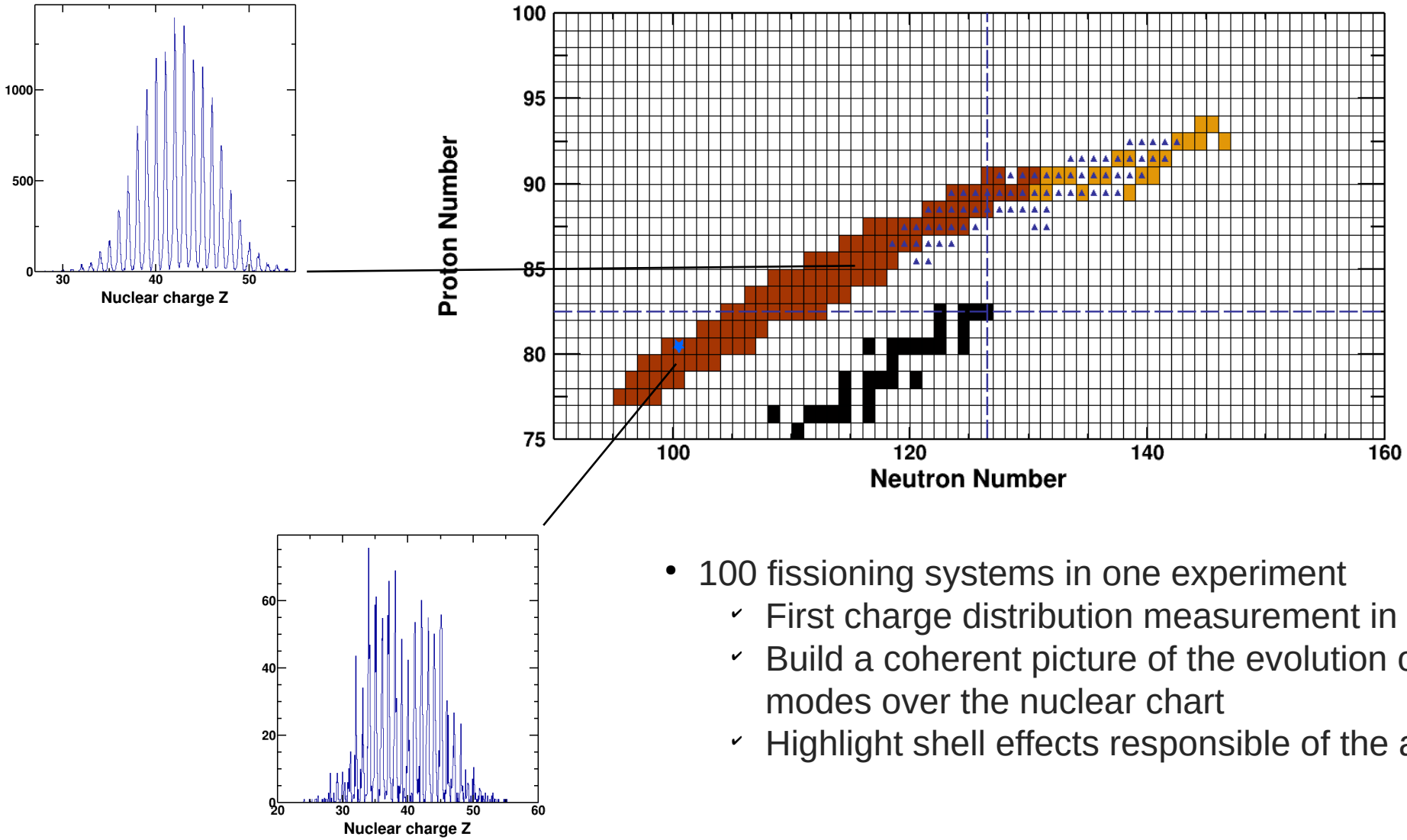
Mapping this new island of asymmetric fission by measuring the fragment yields



- 100 fissioning systems in one experiment
  - From ^{175}Pt to ^{220}Th
  - Very exotic systems
  - Bridge between neutron-deficient systems up to the well known actinide region.



New SOFIA experiment in 2021



- 100 fissioning systems in one experiment
  - ✔ First charge distribution measurement in this region
  - ✔ Build a coherent picture of the evolution of the fission modes over the nuclear chart
  - ✔ Highlight shell effects responsible of the asymmetric split.

4. Outlook

Outlook

- The inverse kinematics is a very powerful tool to measure key observables and in particular fission fragment yields.
  - The boost of the system helps to measure the fragments charge distribution.
  - Not accessible in other experimental techniques.

- Coulomb-induced fission of relativistic and radioactive beam
  - Accurate measurement of yields and prompt-neutron multiplicty
  - Identification of the full fission-fragment distribution
  - Access to a wide range of fissioning nuclei
  - Provide precise yields needed for nuclear data progam
  - Essential to study microscopic effects, to constrain and discriminate models.

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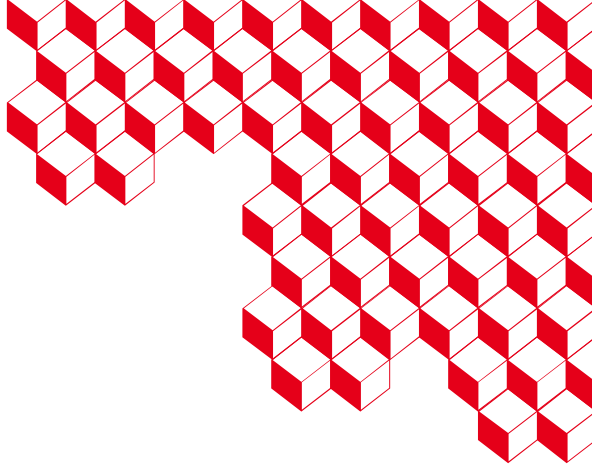
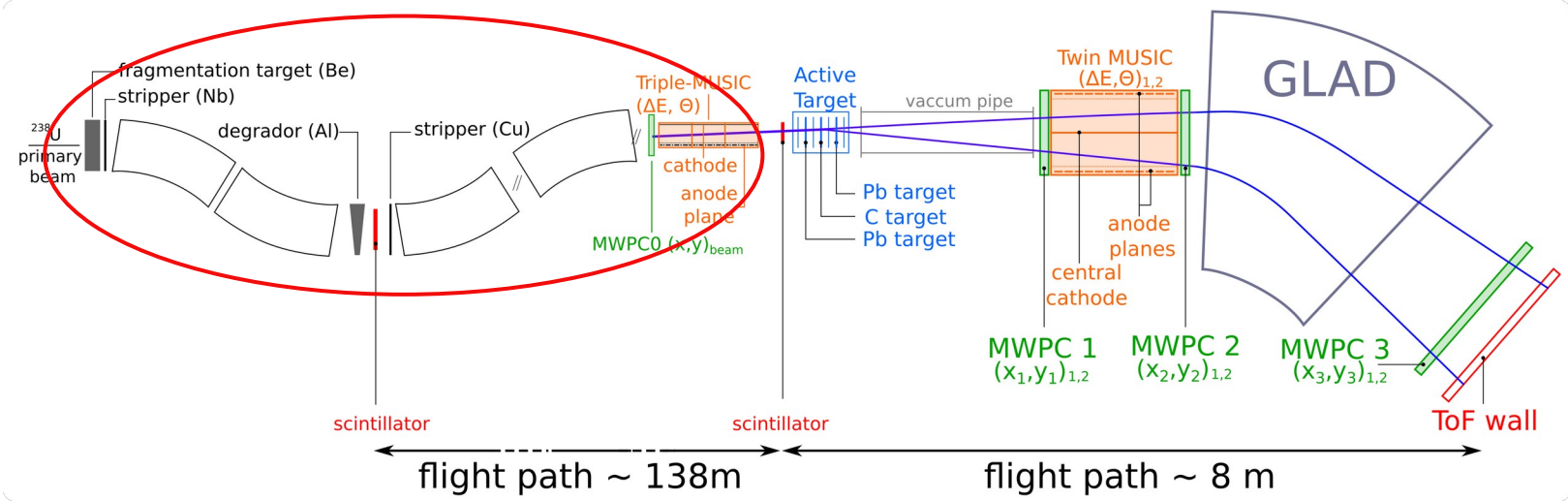
- In SOFIA experiment, knowledge of the excitation energy is missing
  - ✗ Only the excitation energy distribution is known.
  - ✔ Complementary program at VAMOS with PISTA (see Antoine Lemasson) where the excitation energy degree of freedom is measured event by event → Y(A,Z,**E***)

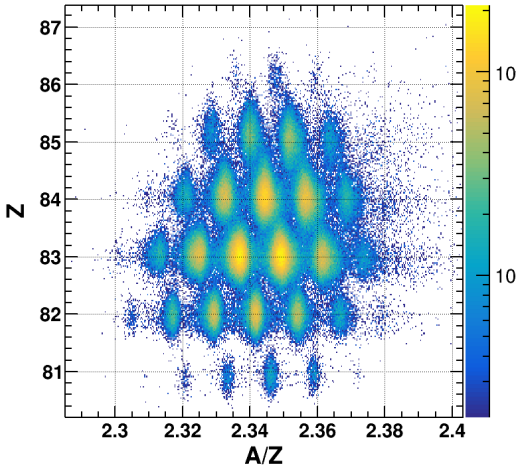


Thank you

Experimental setup



- Incoming beam identification = fissioning system (Time Of Flight - Bρ - ΔE)



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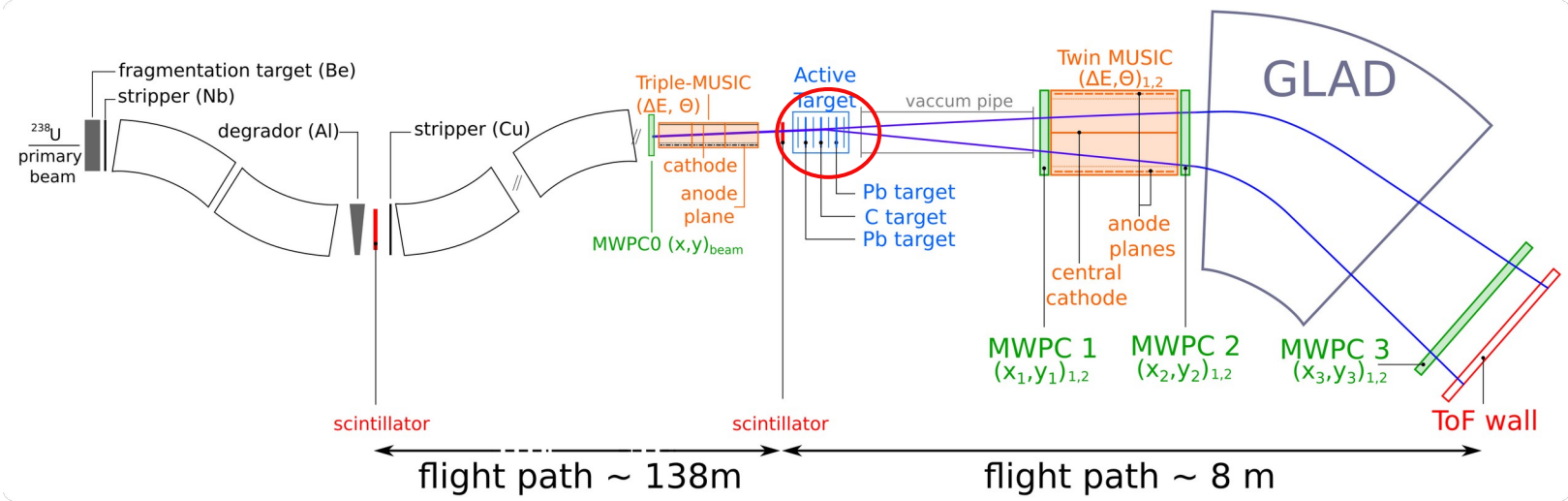
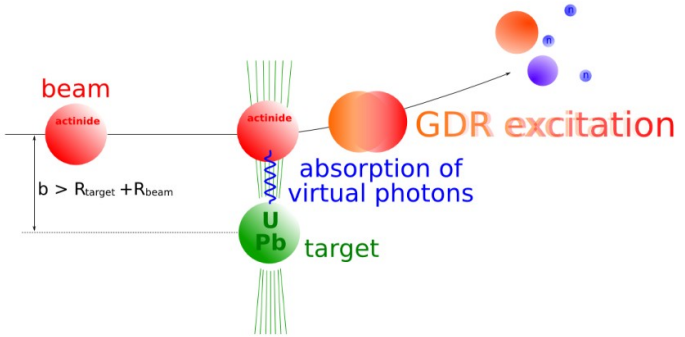


- Incoming beam identification = fissioning system (Time Of Flight - Bρ – ΔE)
- Coulomb induced fission (large cross section)



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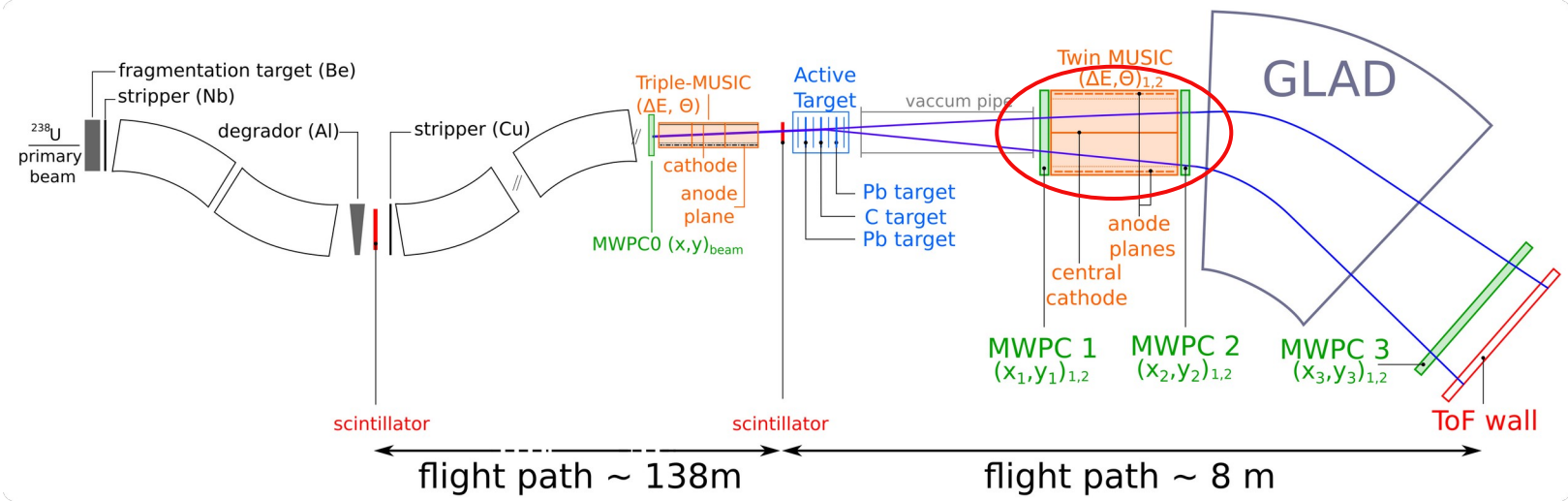
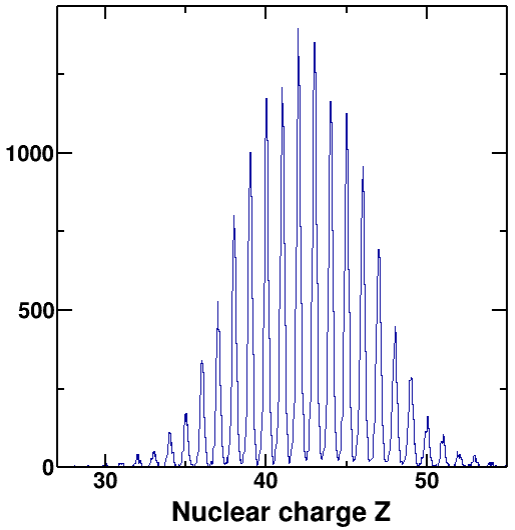


- Incoming beam identification = fissioning system (Time Of Flight - Bρ – ΔE)
- Coulomb induced fission (large cross section)
- Indentification in charge of the fission fragments



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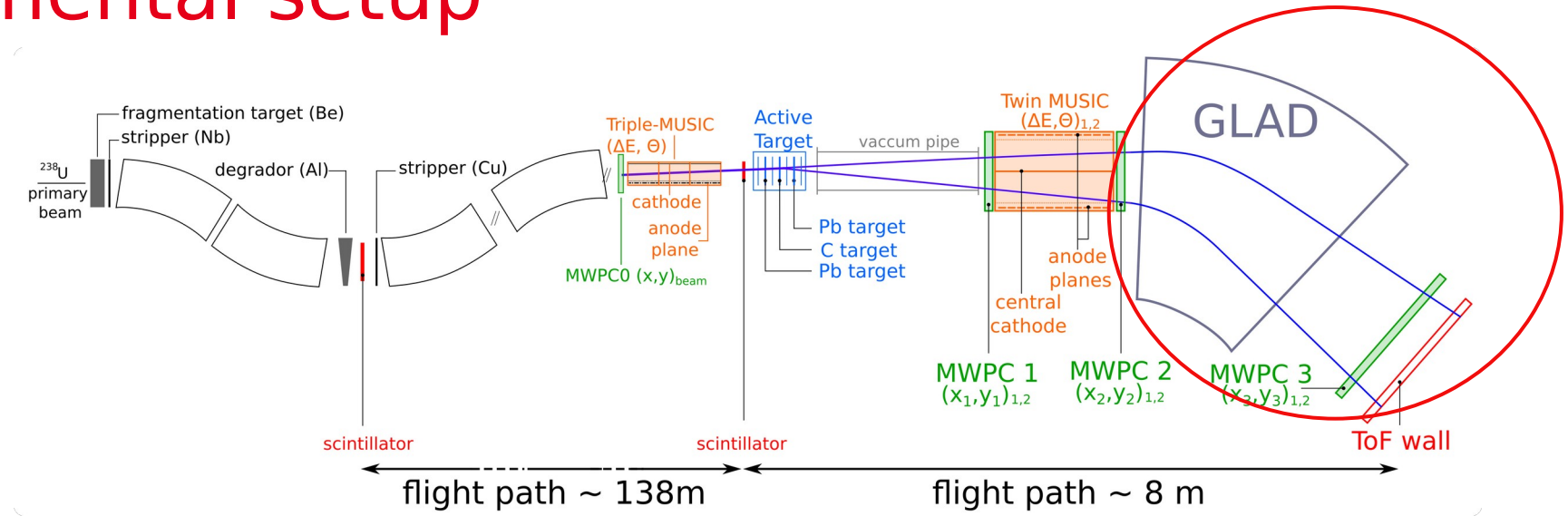

- Incoming beam identification = fissioning system (Time Of Flight - Bρ – ΔE)
- Coulomb induced fission (large cross section)
- Identification in charge of the fission fragments
- Identification in mass of the fission fragments