Fission fragment yields:
Overview of recent measurements

ENST Workshop: Dynamics of Nuclear Fission

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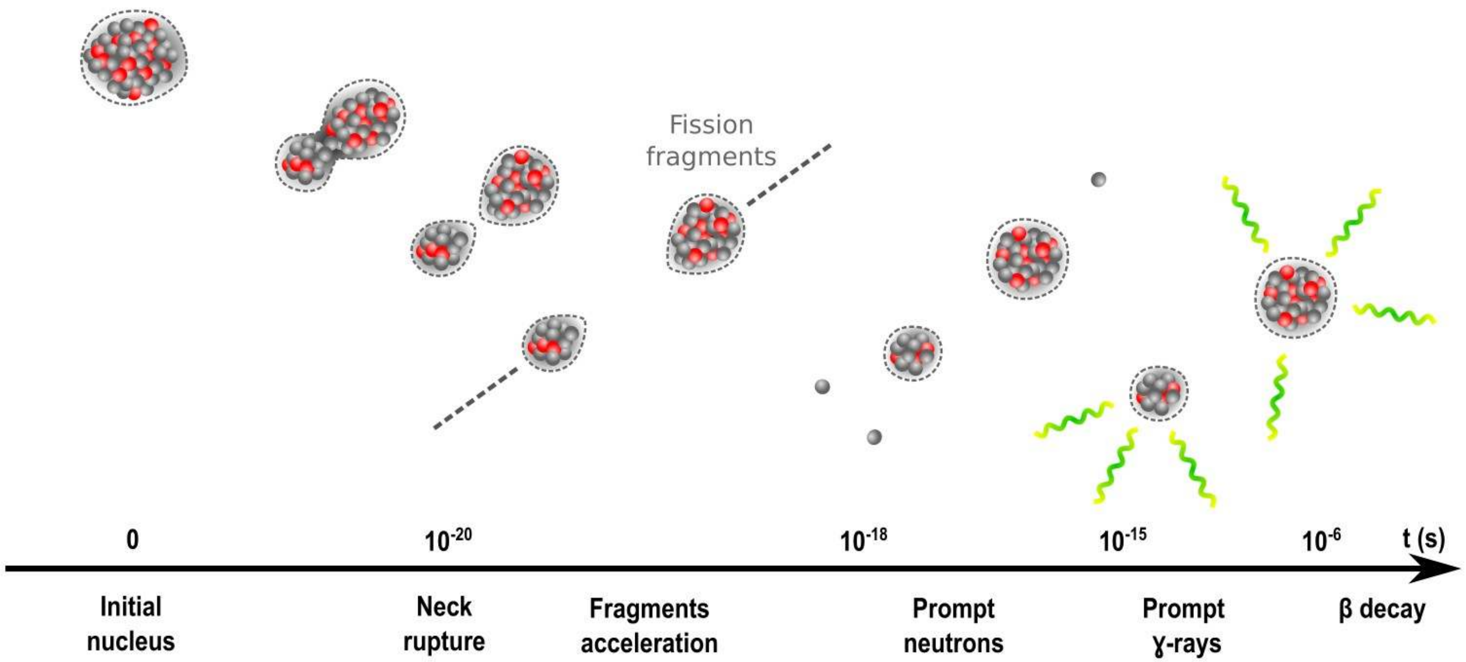
Outlook

1. Motivations
   - Why do we measure fission fragment yields?
2. Direct kinematics
   - Activation technique
   - “In-flight” methods
3. Inverse kinematics
   - GSI/SOFIA
   - fusion/fission
   - VAMOS
4. Conclusion

1. Motivations

Fission fragments: definition



- Primary fission fragments : before prompt neutron emission
- **Secondary fission fragments**: after neutron evaporation → *independent yields*
- **Fission products :** after β-decay→ *cumulative yields*

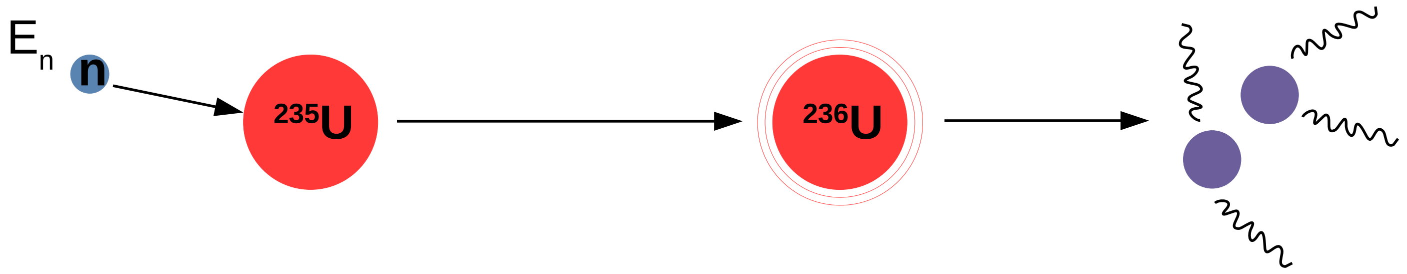
Why measuring fission fragments?

- **Important fondamental questions/open questions**
  - The fission yields are the signatures of the underlying nuclear structure effects in the fission process.
  - These yields provide crucial information about reaction mechanisms, energy dissipation, and the underlying dynamics of the process.
  - What shell effetcts at stake ?
  - Shell effect damping with excitation energy.
  - Excitation energy sharing, deformation at scission.
  - Fission recycling in r-process.

- **Important for nuclear applications**
  - Defense
  - Burnup, reactor simulation
  - Gen-IV using fast neutrons

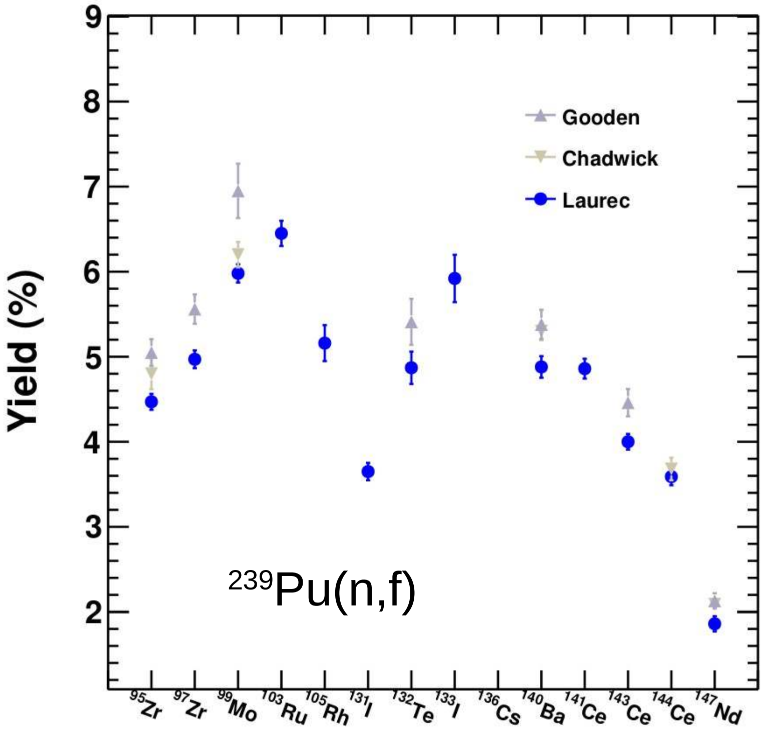
2. Direct kinematics

Direct kinematics: Activation



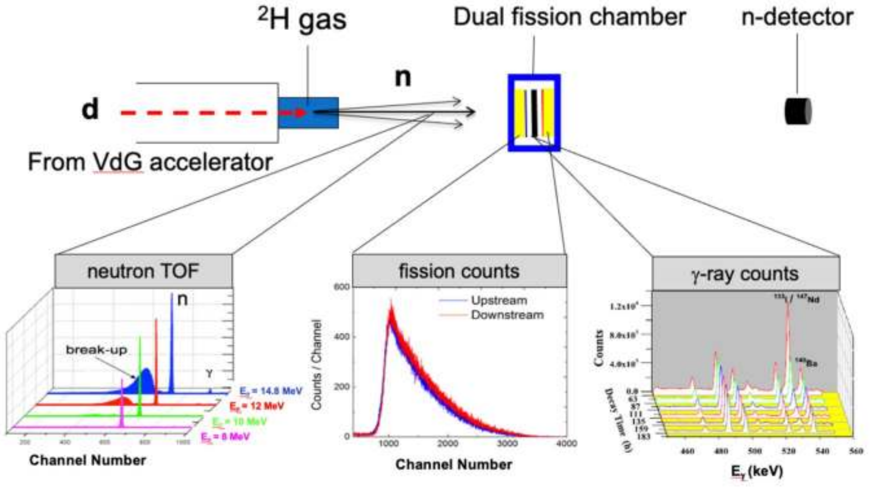
Activation technique

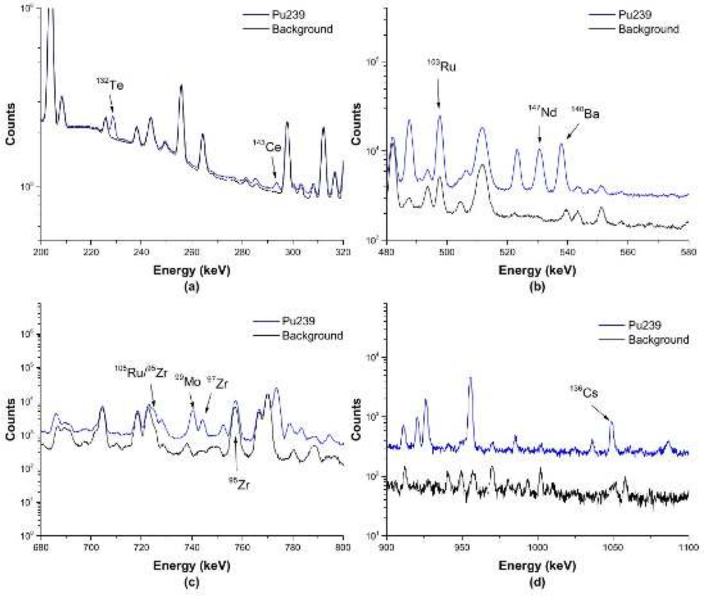
- Neutron energy well defined → Excitation energy well defined.
- Irradiation of an actinide sample from neutron flux of known energy.
- Radiochemistry and/or gamma spectropscopy.
- Access to cumulative yield.
- Try shorter run cycle to measure short-lived fragments



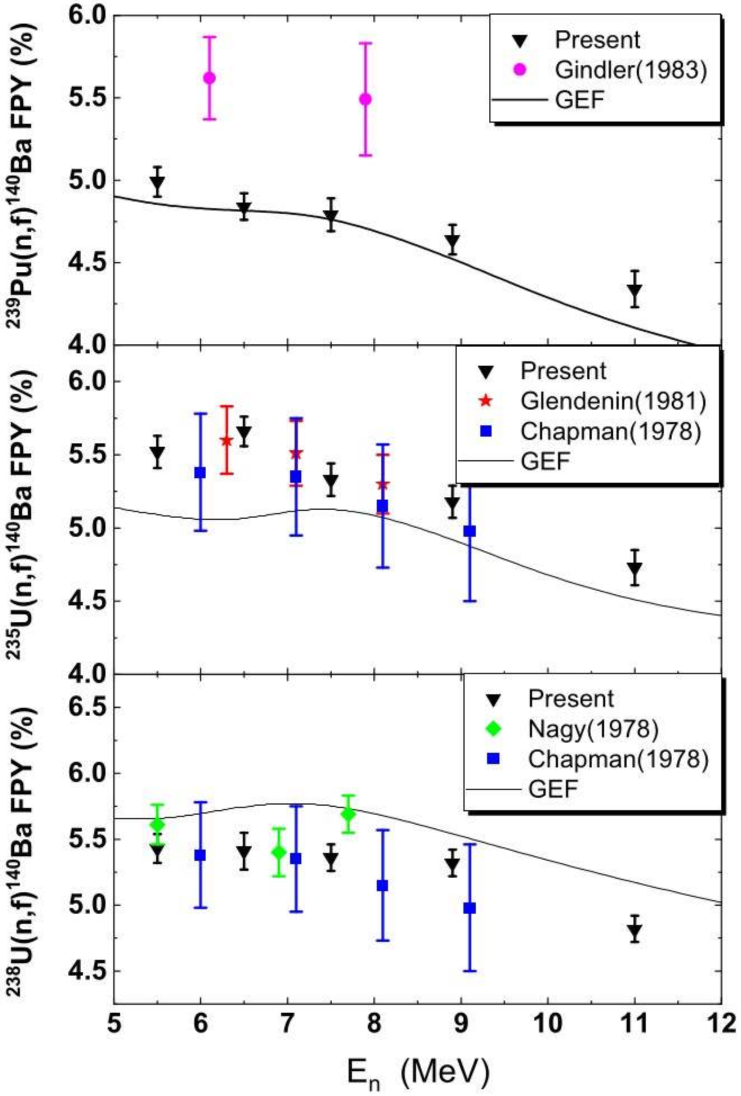
M. B. Chadwick *et al.* Nuclear Data Sheets **111** (2010) 2923-2964
J. Laurec *et al.* Nuclear Data Sheets **111** (2010) 2965-2980
M. E. Gooden *et al.* Nuclear Data Sheets **131** (2016) 319-356
M. E. Gooden *et al.* Phys. Rev. C **109** 04460 (2024)

Direct kinematics: Activation, recent measurements at TUNL





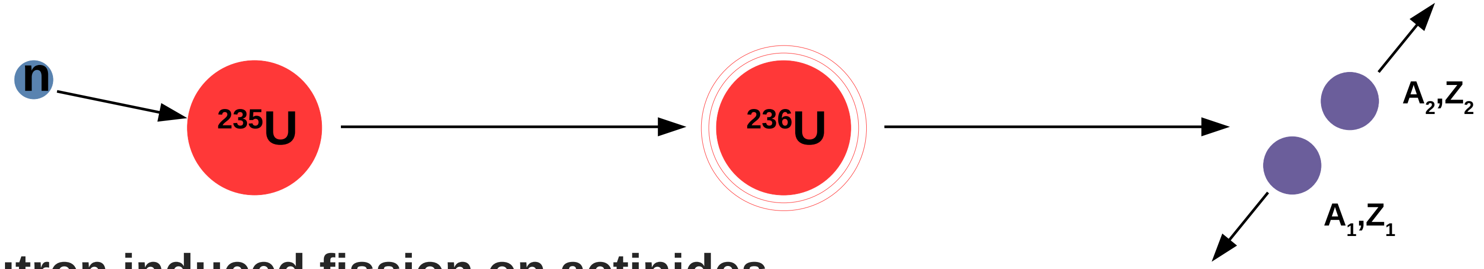
M. E. Gooden *et al.* Phys. Rev. C **109** 04460 (2024)



In flight method : neutron capture on actinide target

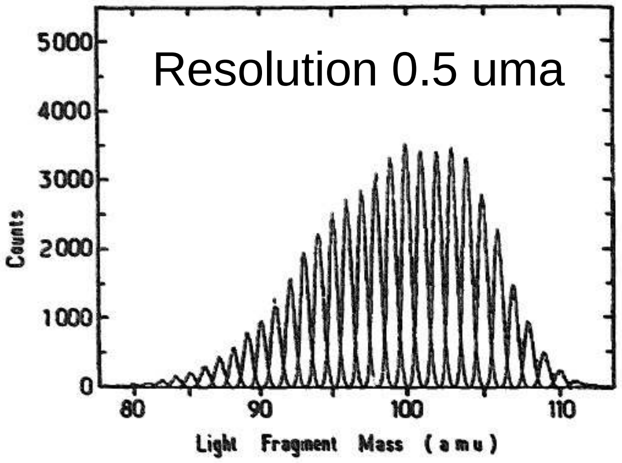
- Gamma spectroscpy after few days of irradiation
- Rather thick target
- Obsolute cumulative fission product yields.
- Different neutron energies → Evolution of fragment yields

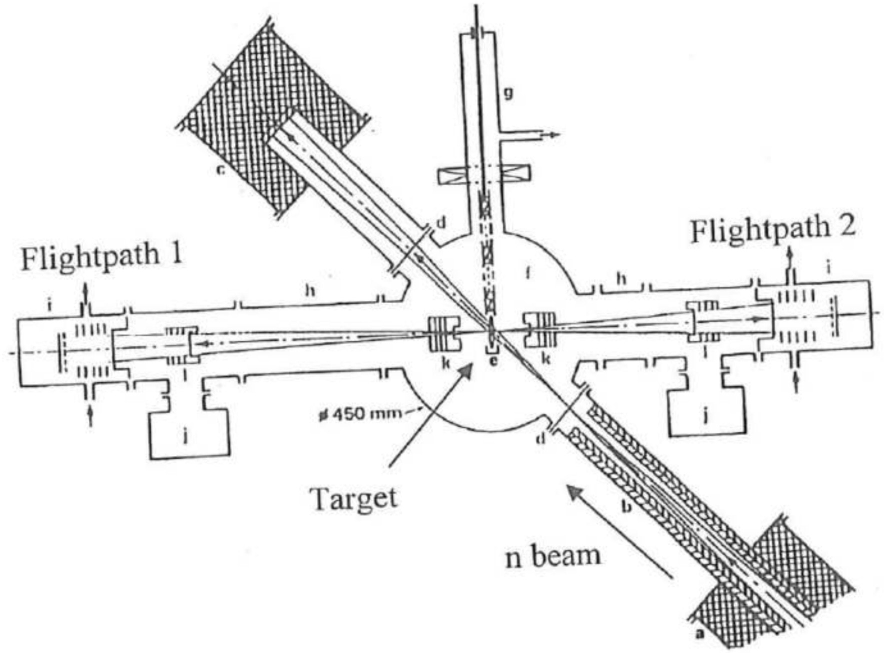
“In-flight” methods : 2E-2v methods



In flight method : neutron induced fission on actinides.

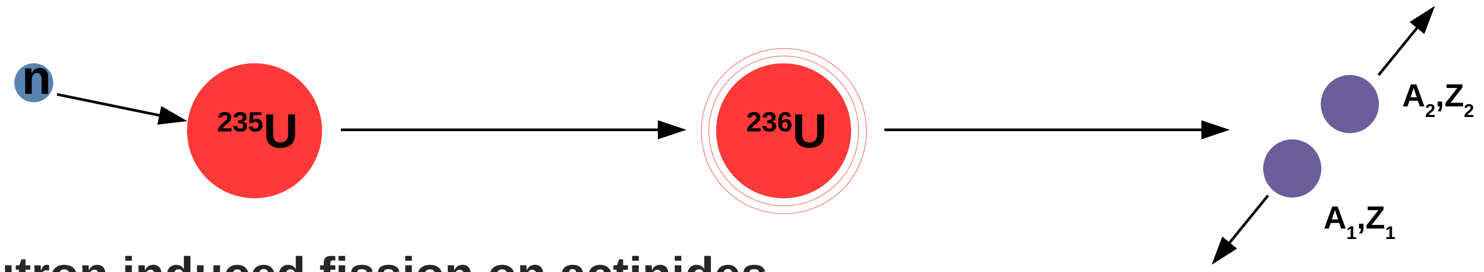
- Detect both fragments in coincidence.
- Measure their energy typically in ionization chamber.
- Measure time-of-flight.
- Historically the Cosi Fan Tutte provided a lot of excellent data.





A. Oed *et al.* Nucl. Instr. and Meth. In Physics Research **219** (1984)
N. Boucheneb *et al.* Nuclear Physics A **535** (1991)

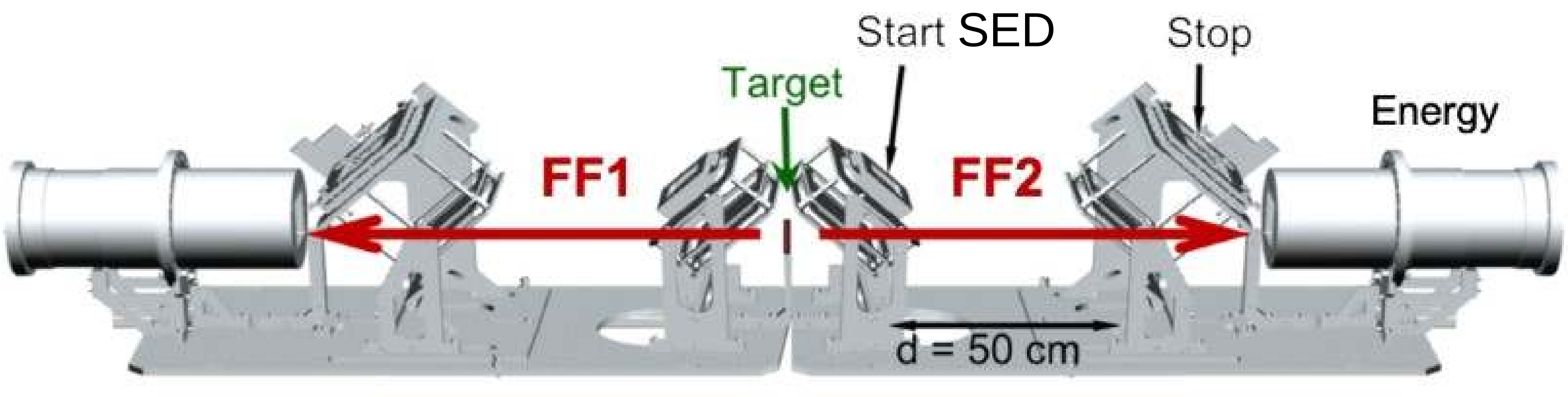
“In-flight” methods : 2E-2v methods



In flight method : neutron induced fission on actinides.

- Detect both fragments in coincidence.
- Measure their energy typically in ionization chamber.
- Measure time-of-flight.
- Historically the Cosi Fan Tutte provided a lot of excellent data.
- Other 2E-2v spectrometers
  - Spider C. Arnold *et al.* NIM A **764** (2014)
  - Verdi S. Oberstedt *et al.* EPJ Web of Conferences Vol. 8 (EDP Sciences) p. 03005
  - FALSTAFF D. Doré *at al.* Nuclear Data Sheets **119** (2014) 346-348

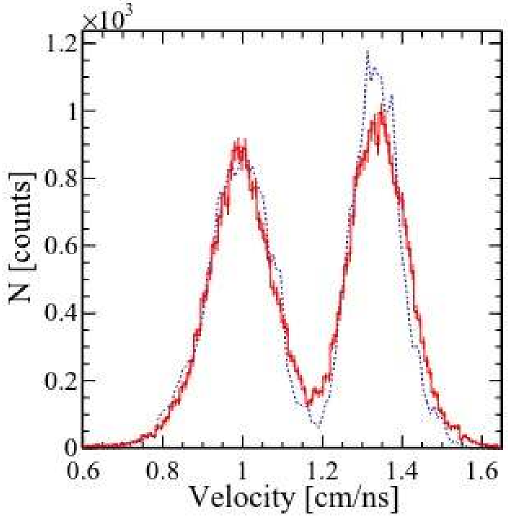
“In-flight” methods: FALSTAFF 2E-2v

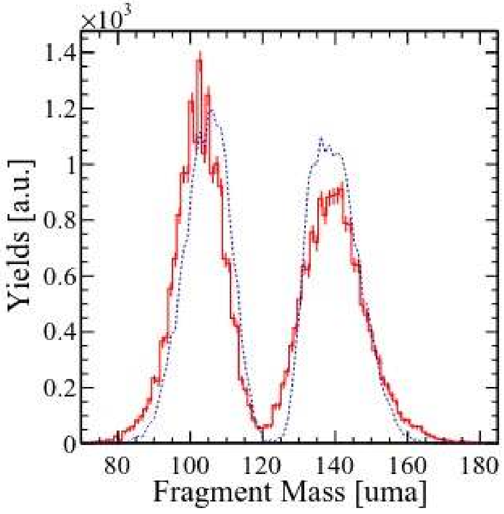


FALSTAFF goals :

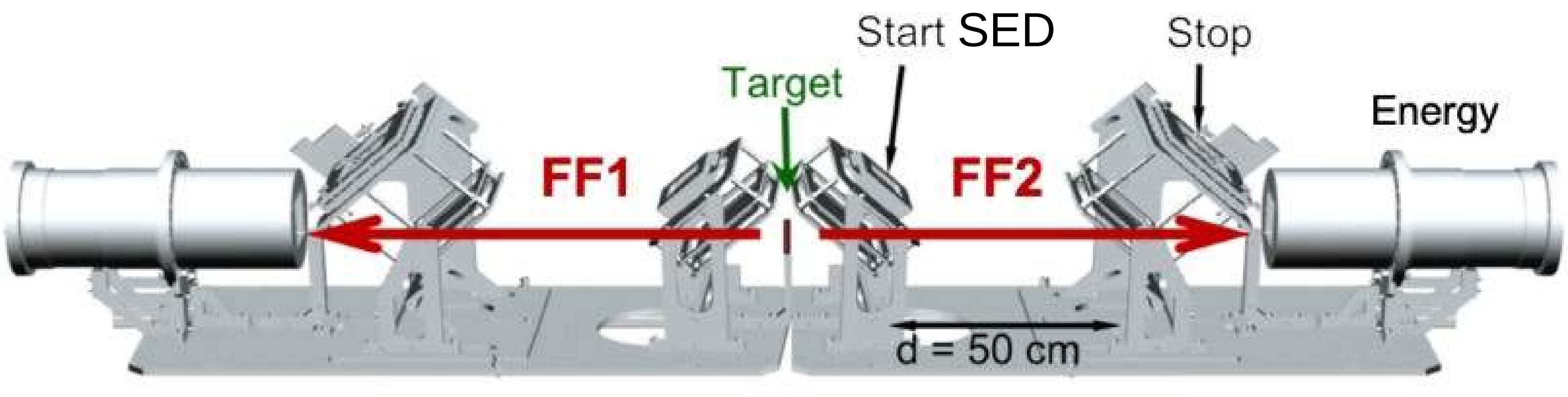
- Detect both fragments in coincidence.
- Measure their kinetic energy.
- Identify their mass. Mass before neutron evaporation obained via the 2V method.
- Spatial resolution around 2 mm.
- Timing resolution around 120 ps.

D. Doré *at al.* Nuclear Data Sheets **119** (2014) 346-348
Q. Deshayes *et al.* EPJ Web of Conferences **239** 05012 (2020)





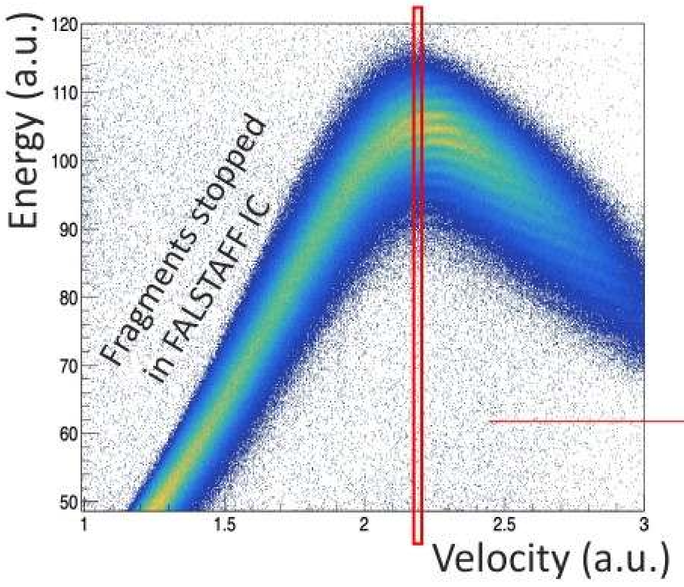
“In-flight” methods: FALSTAFF 2E-2v

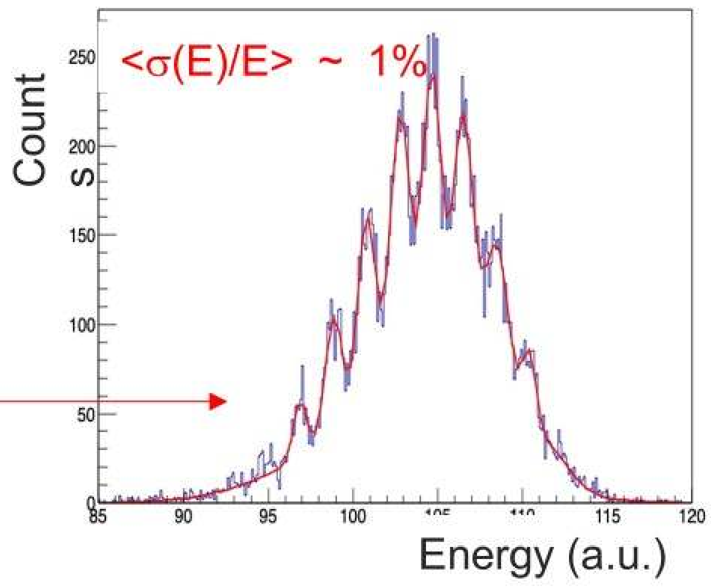


FALSTAFF goals :

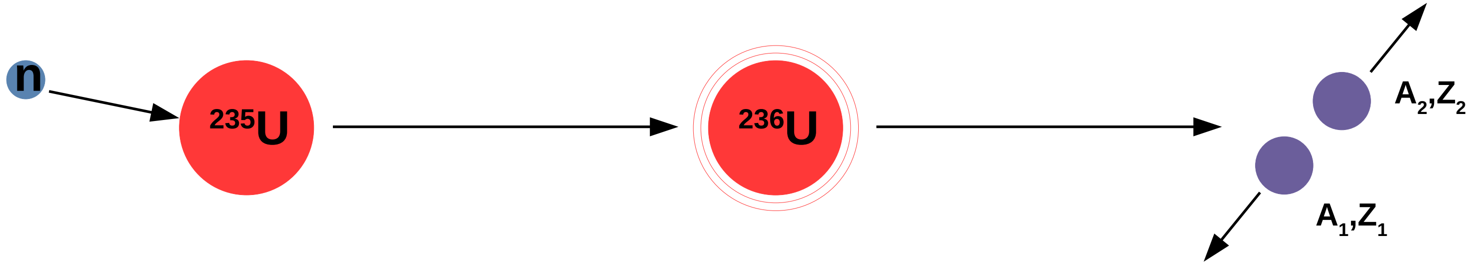
- Detect both fragments in coincidence.
- Measure their kinetic energy.
- Identify their mass. Mass before neutron evaporation obained via the 2V method.
- Spatial resolution around 2 mm.
- Timing resolution around 120 ps.
- Provide information on their nuclear charges.
- Future experiments at NFS to measure the evolution of yields as a function of the neutron energy.

D. Doré *at al.* Nuclear Data Sheets **119** (2014) 346-348
Q. Deshayes *et al.* EPJ Web of Conferences **239** 05012 (2020)



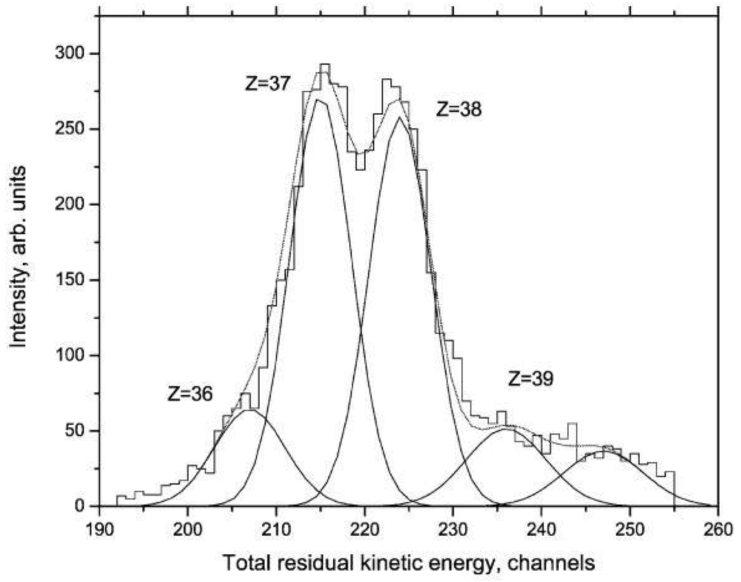


“In-flight” methods: Z measurement



In flight method : neutron capture on actinide target

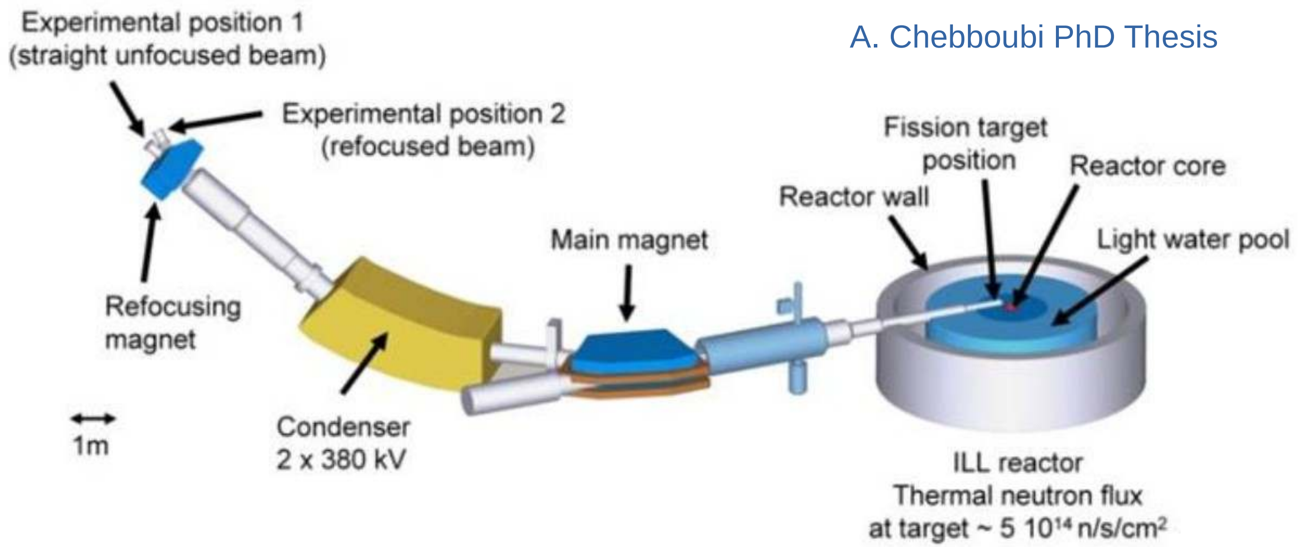
- ✔ Neutron induced fission (often thermal).
- ✔ Knowledge of the excitation energy degree of freedom.
- ✗ Measure of the charge above 40 impossible.
  - ➔ Example : Lohengrin spectrometer at ILL
    → charge up to Z ≈ 40.
- ✔ Needs target → access to quasi-stable elements
- ✔ Partial isotopic yields.



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

“In-flight” methods: The Lohengrin spectrometer

A. Chebboubi PhD Thesis



Lohengrin spectrometer

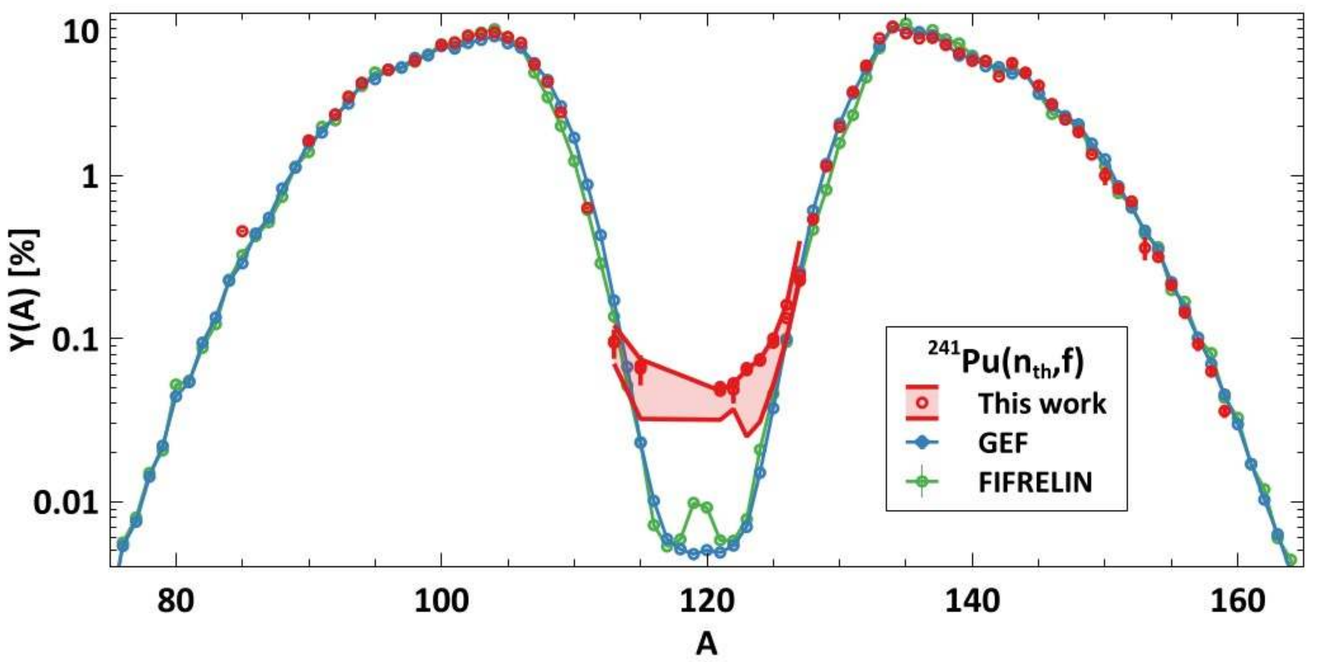
- ✓ Thermal neutron induced fission
- ✓ Precise measurement of fission product mass yields Y(A)
  - ➔ Selection with mass over ionic charge A/q
  - ➔ Selection with kinetic energy over ionic charge E/q
- ✓ Measurement of fission product isotopic yields P(Z)
  - ➔ Using High purity Germanium detectors .
  - ✗ Results are dependent on the knowledge of nuclear strucutre (decay scheme...)

“In-flight” methods: The Lohengrin spectrometer

Lohengrin spectrometer recent results

- On ^{241}Pu(n_{th},f)
- Few data exist for ^{241}Pu because complicated to make a target.
- But important for burn up.
- GEF underestimate the symmetry region

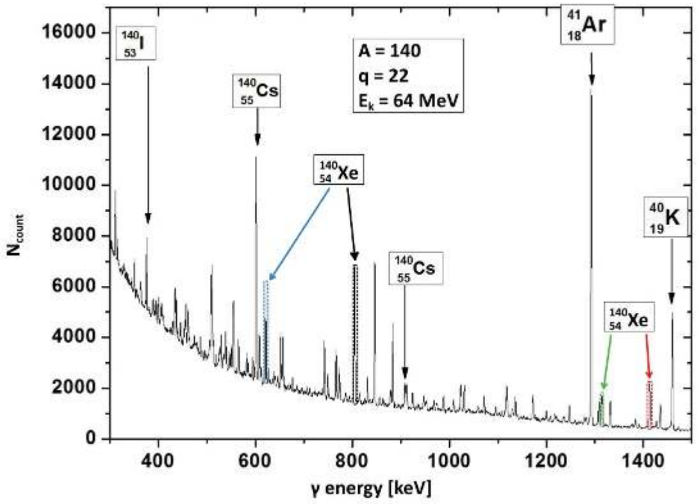
S. Julien-Laferrière PhD Thesis



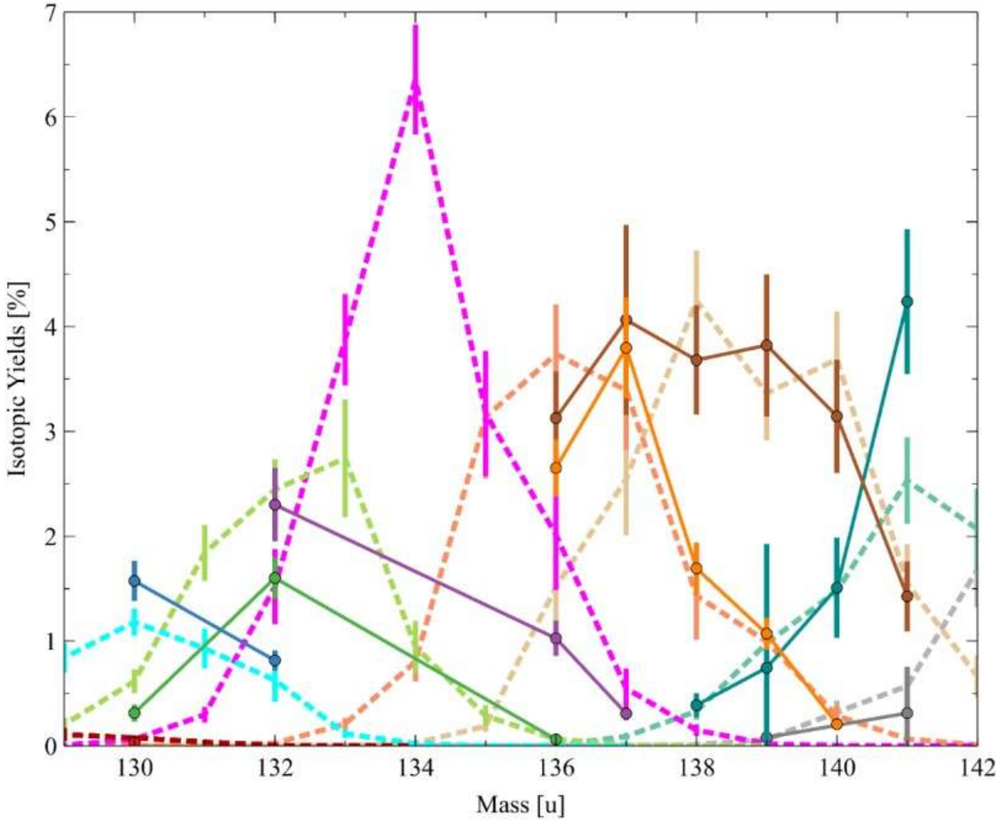
“In-flight” methods: The Lohengrin spectrometer

Lohengrin spectrometer recent results

- On $^{241}Pu(n_{th},f)$
- GEF underestimate the symmetry region
- Extraction of isotopic yields for some masses usin HPGe → Rely on known nuclear structure decay schemes.



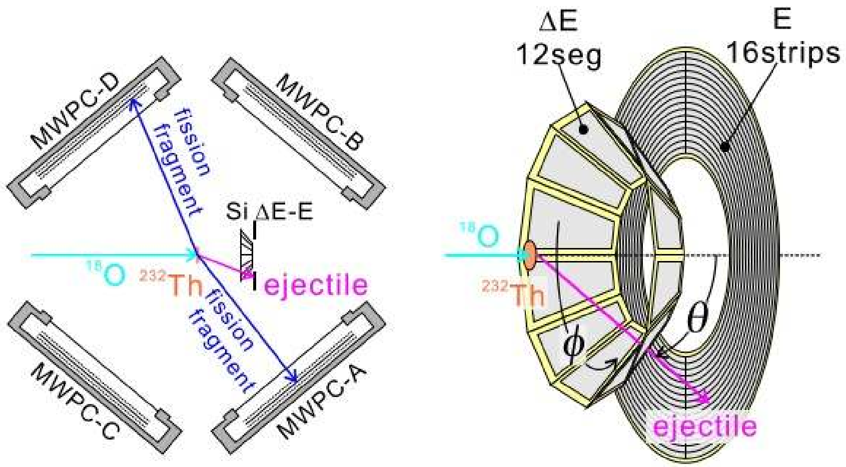
S. Julien-Laferrière PhD Thesis

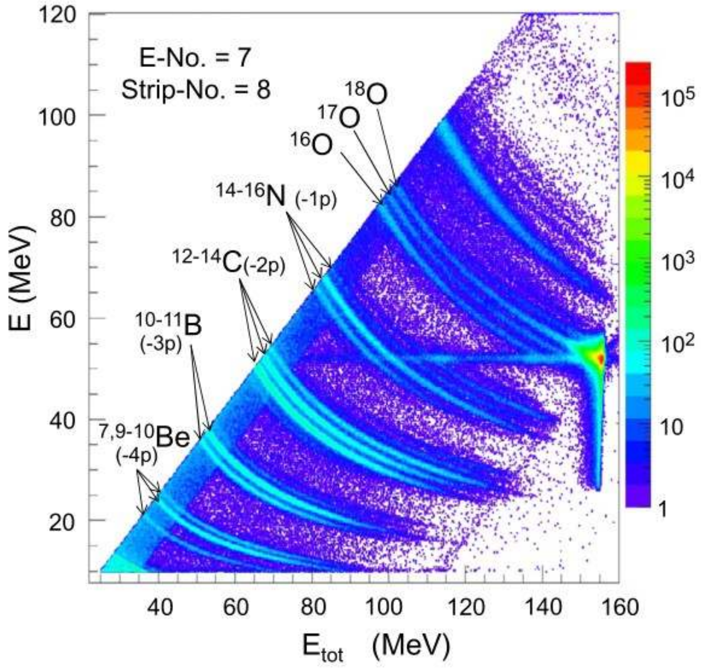


Multi-nucleon reaction in direct kinematics

Nishio experiments

- ^{18}O beam of 157 MeV on ^{232}Th target.
- Depending on the transfer channel different fissioning system accessible !
  - Detection of the ejectile in the silicon detector.
  - Characterization of the fissioning system
  - Excitation energy with the missing mass technique
- Identification of the fragment mass with the MWPC
  - Resolution **σ** = 6.5 uma



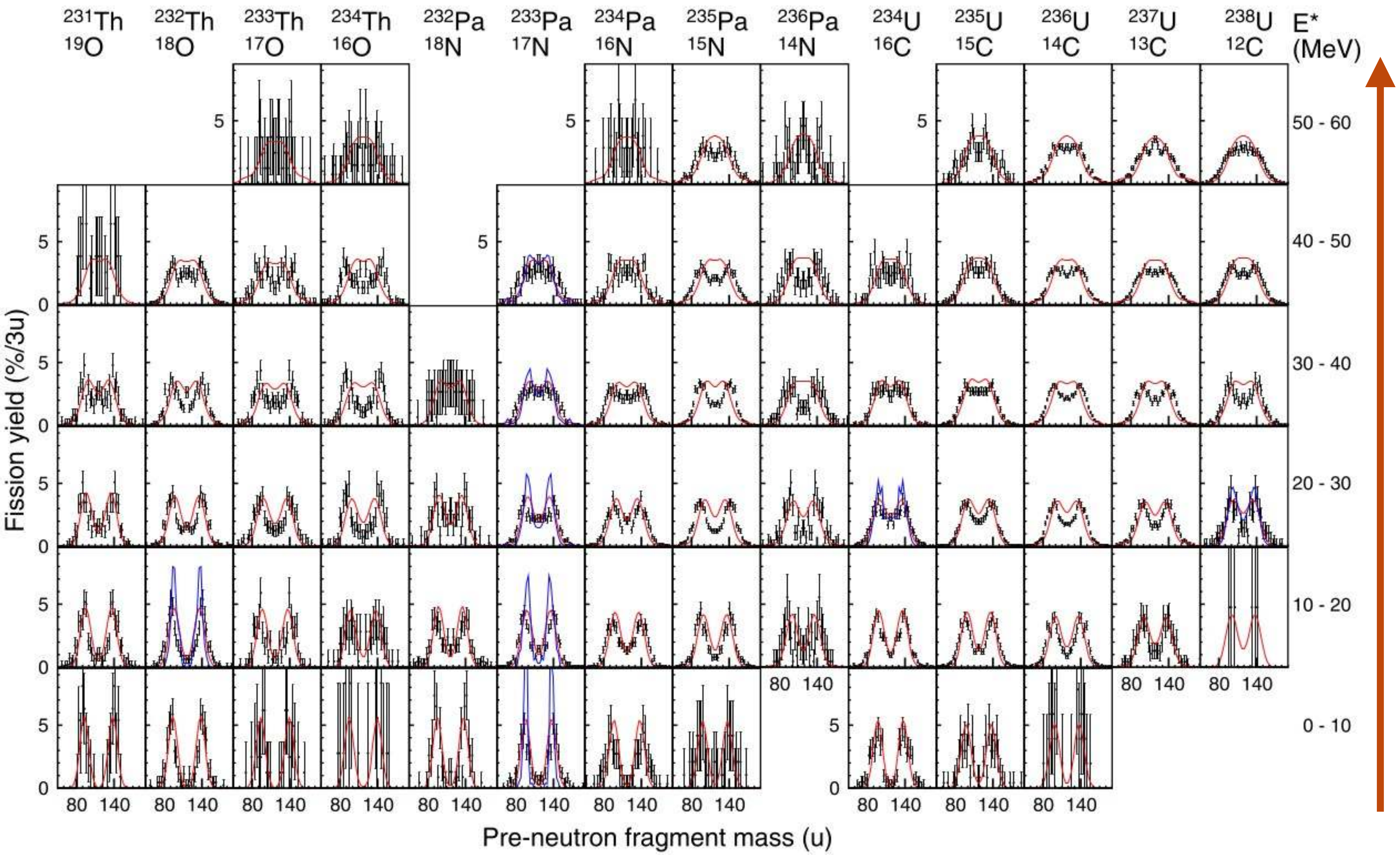


R. Leguillon *et al.* Phys. Lett. B **761** 125-130 (2016)

Multi-nucleon reaction in direct kinematics

Nishio experiments

- Numerous fissioning systems accessible.
- Evolution with E* (10 MeV bins)
  - Probing the shell effect damping.
  - Mass distribution only.
  - No Z information.



Direct kinamtics: conclusion

A lot of different experimental approches

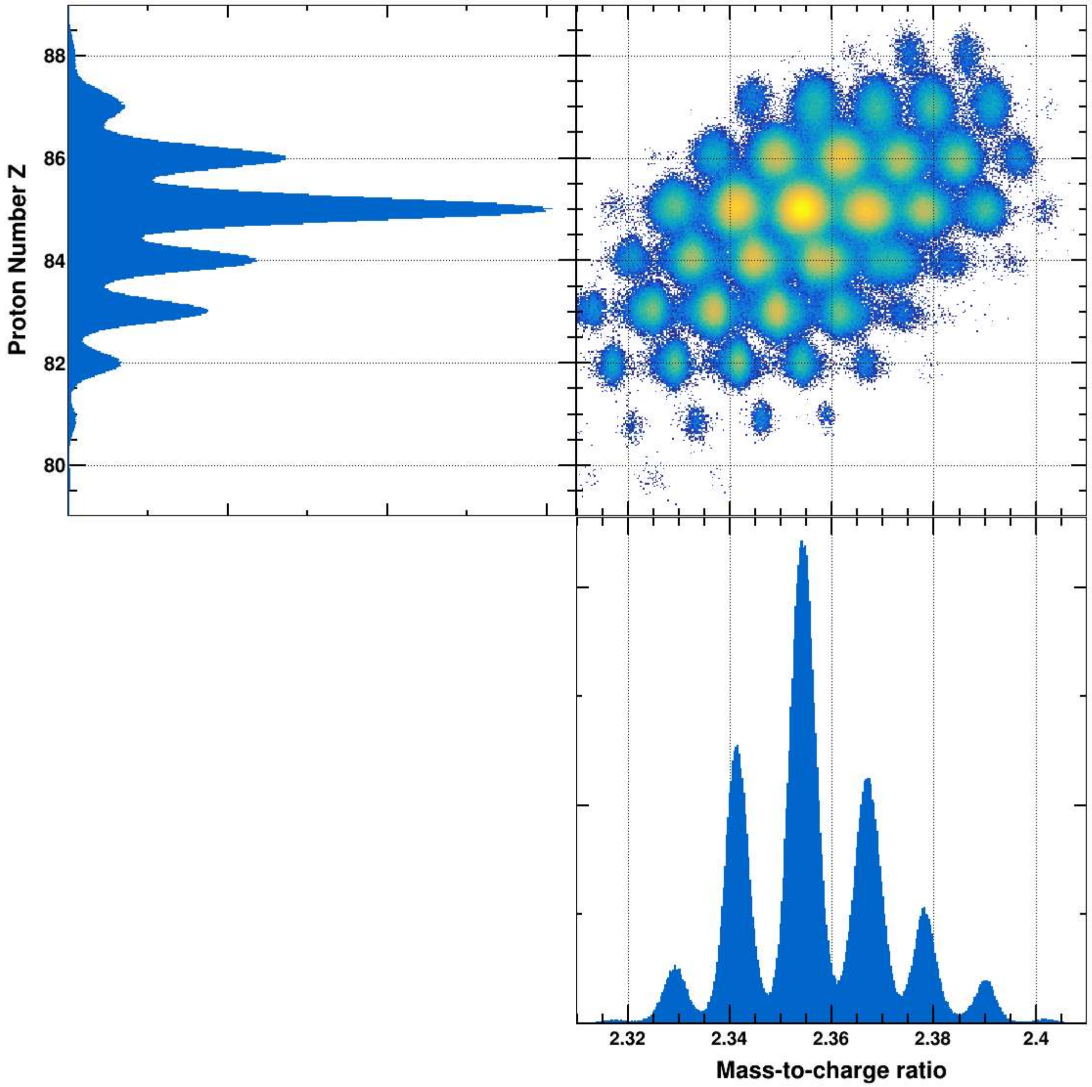
- With neutron beam
  - ✓ Lot of data.
  - ✓ Knowledge of the excitation energy degree of freedom.
  - ✓ Activation technique → cumulative yields.
  - ✓ 2E-2v spectrometers.
  - ✓ Logengrin spectrometer.
  - ✗ Limited Z information.

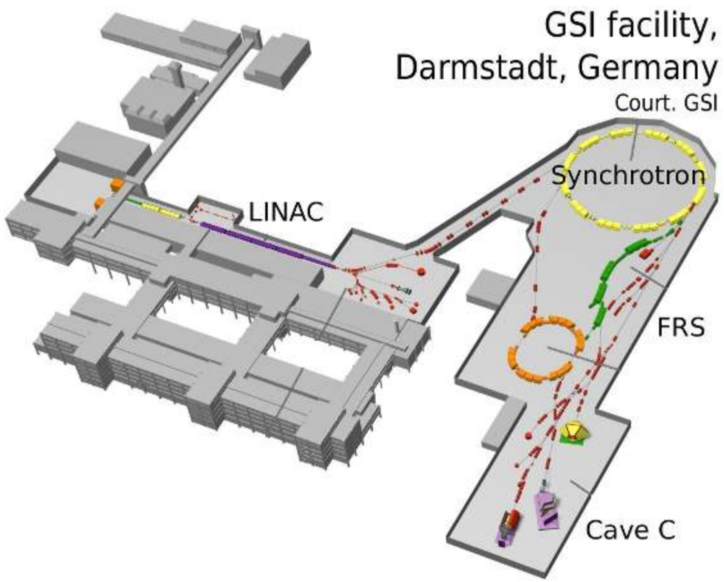
- Multi-nucleon transfer
  - ✓ Multiple fissioning systems accessible.
  - ✓ Probing the shell damping with E*.
  - ✓ Only mass distribtuion with limited resolution.
  - ✗ No Z information.

3. Inverse kinematics

The inverse kinematics at relativistic energies

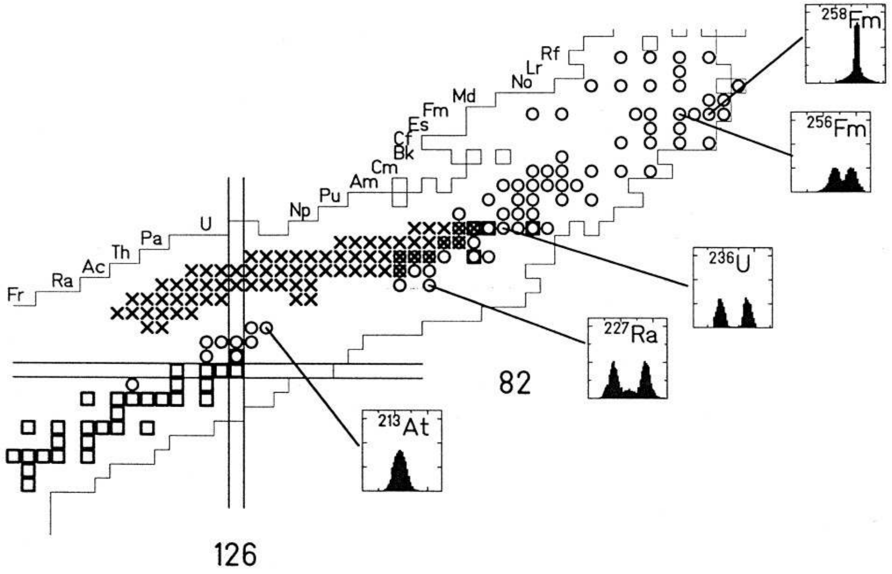
- Primary beam of ^{238}U at 1 GeV/u.
- Fragmentation of ^{238}U on a Be target and production of cocktail beams with a selection in (Brho, ΔE).
- Transportation through the FRS of the cocktail beams to the experimental cave.

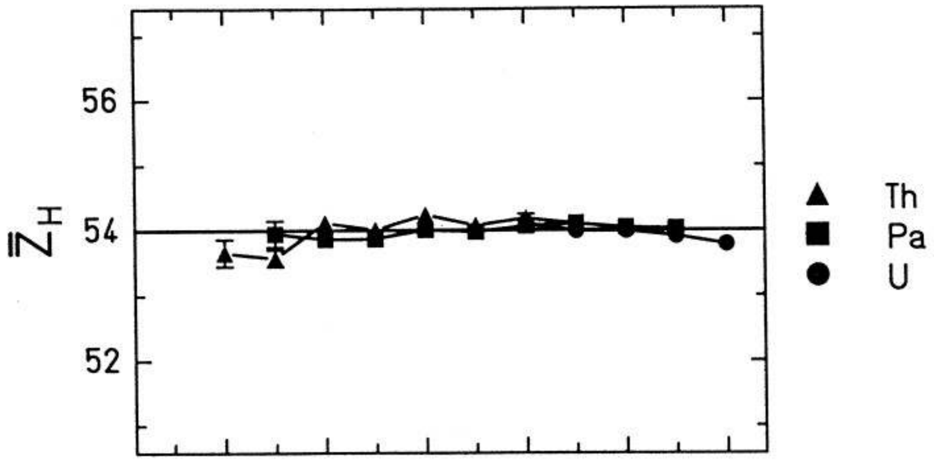




The inverse kinematics at relativistic energies

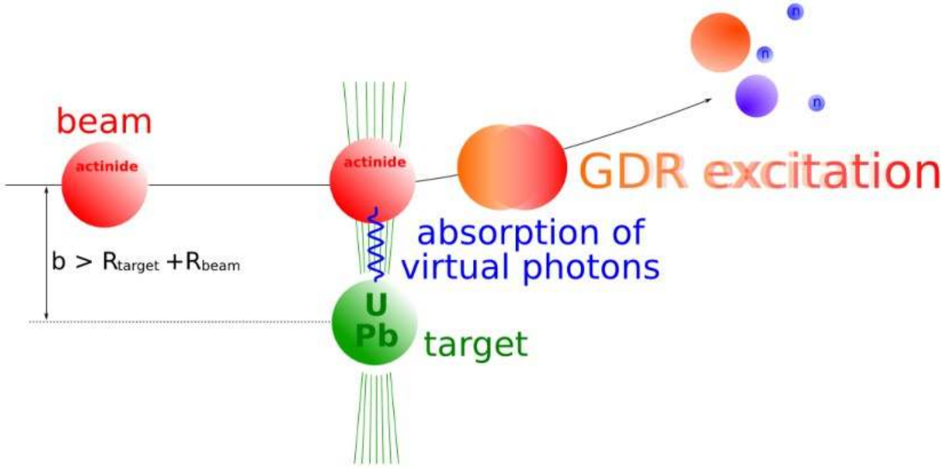
- Pioneer experiment 25 years ago by K.-H. Schmidt
  K.-H. Schmidt et al. Nucl. Phys. A 665 (2000) 221
- Fragment charge distribution measured of numerous fissioning systems
- Important results: stabilization of Z_H=54

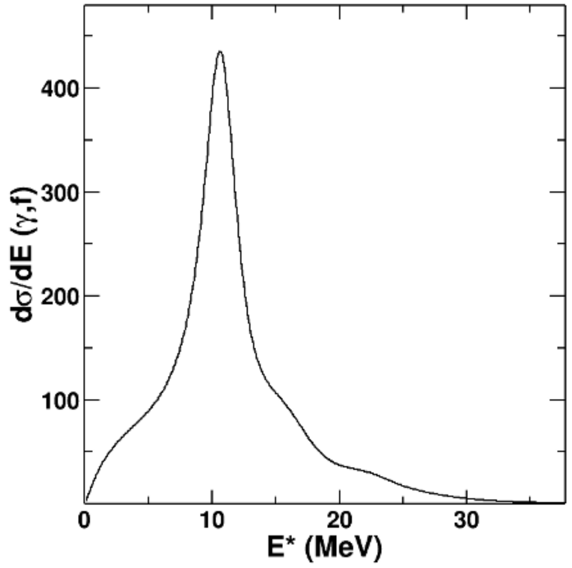




The inverse kinematics at relativistic energies

- Coulomb induced fission of the relativistic beams (around 750 MeV/u)
  - ✔ Large cross section (around 2-3 barns).
  - ✗ <E*> around 14 MeV.





The inverse kinematics at relativistic energies

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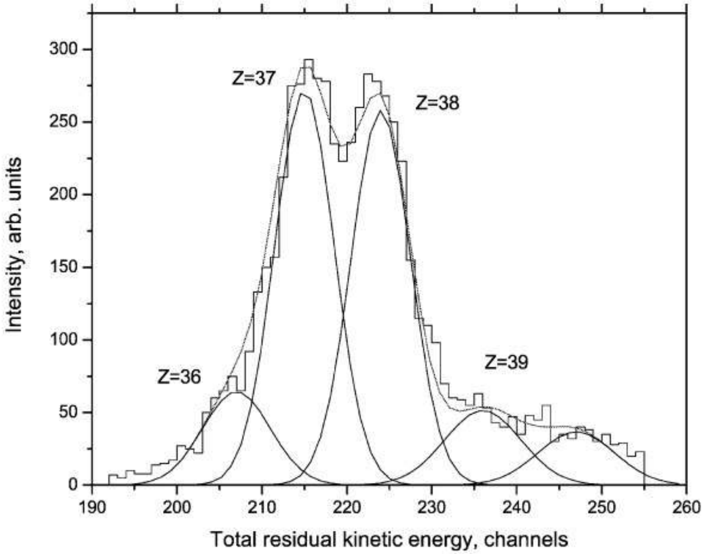
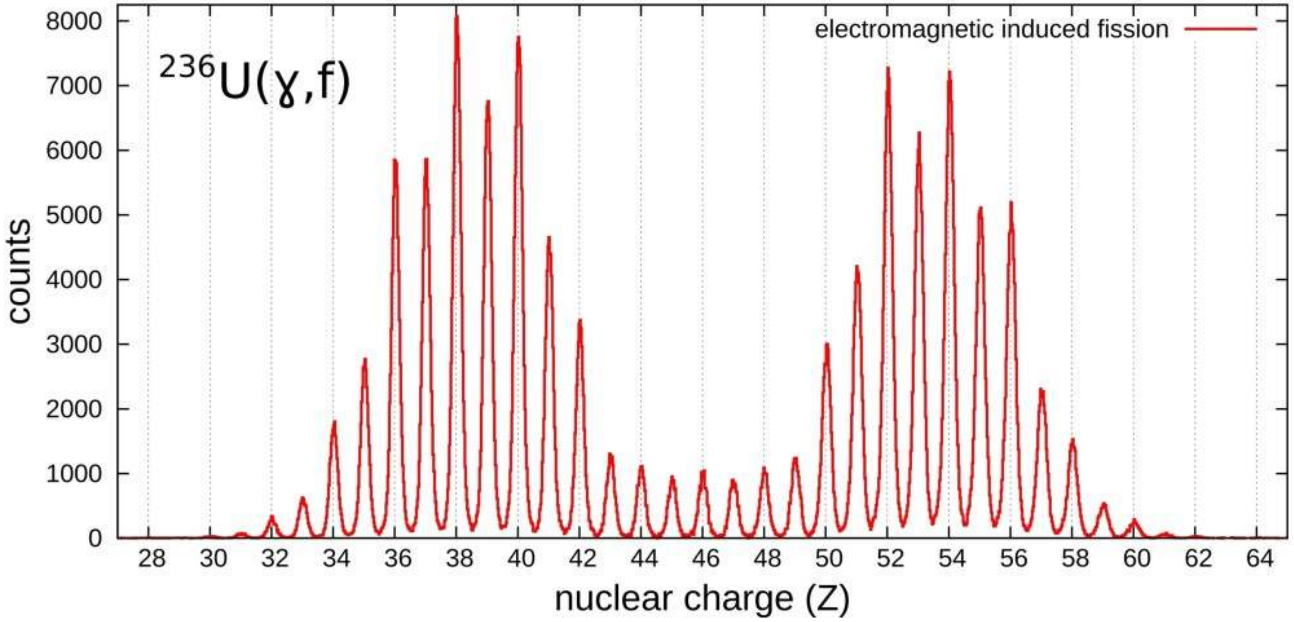
- Both fission fragments are identified in coincidence in the SOFIA spectrometer (both charge and masse)





The inverse kinematics at relativistic energies

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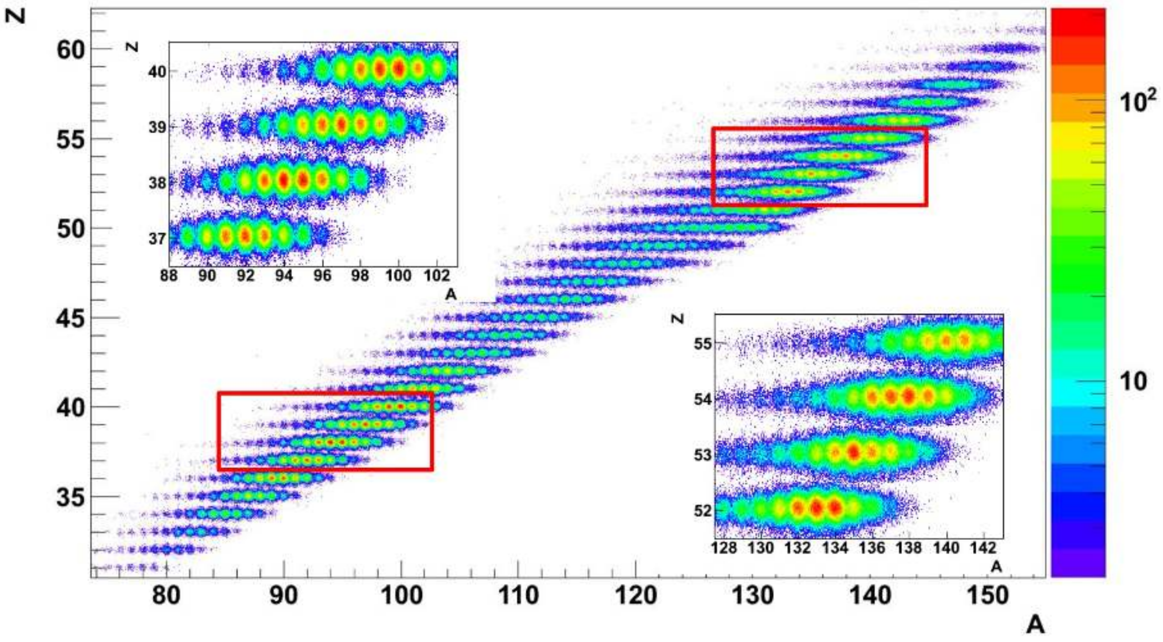
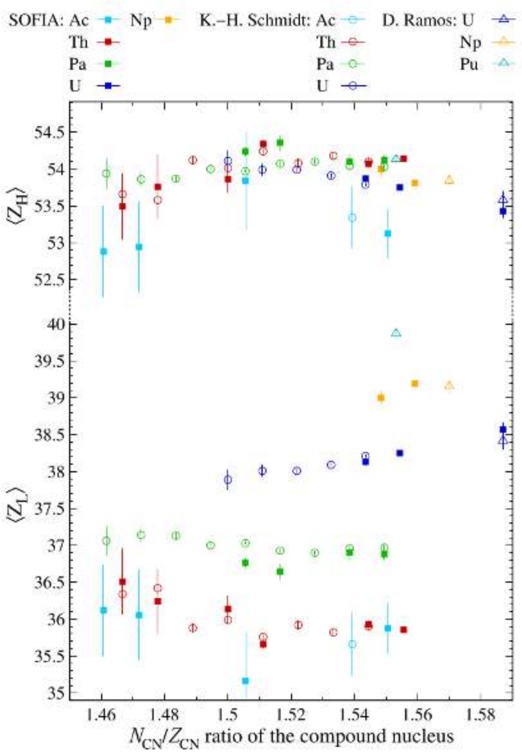
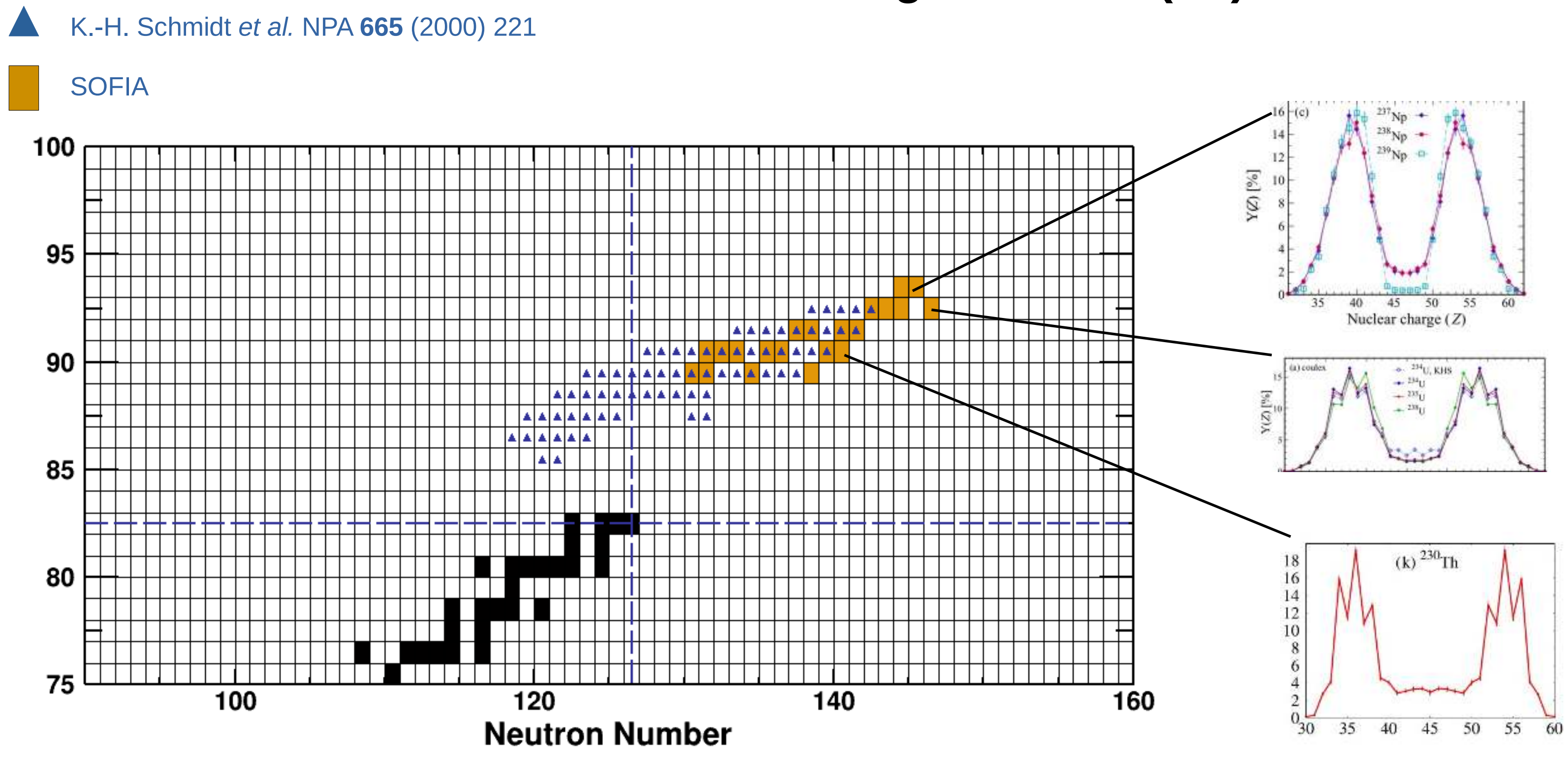
  - ✓ Large cross section (around 2-3 barns).
  - ✗ <E*> around 14 MeV.
- Both fission fragments are identified in coincidence in the SOFIA spectrometer (both charge and masse)
  - ✓ ΔZ = 0.31 charge unit
  - ✓ ΔA = 0.55 to 0.80 mass unit



The SOFIA experiments



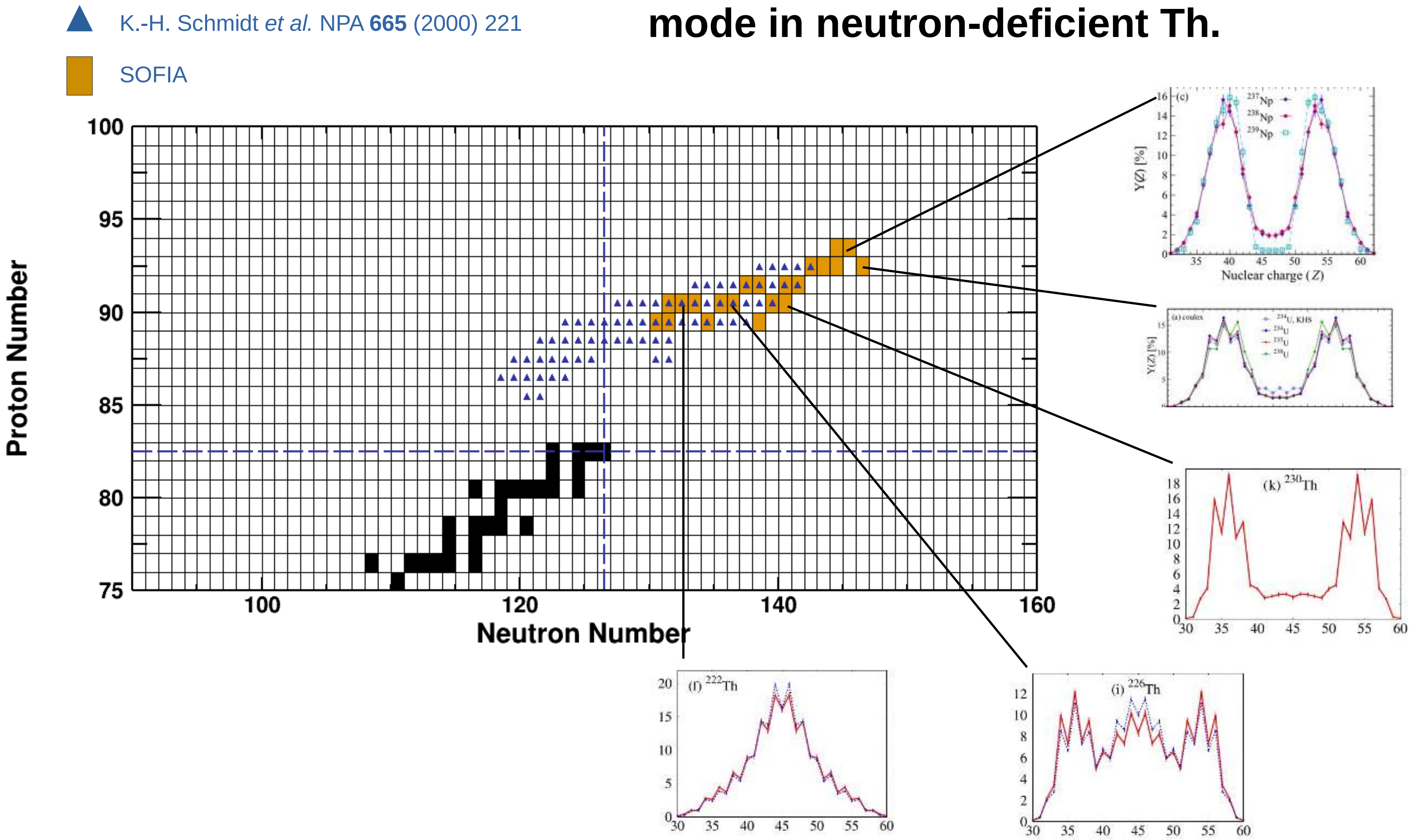
In this region : Z≈54 (Xe) stabilisation



E. Pellereau *et al.* Phys. Rev. C **95**, 054603 (2017)
J-.F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)
A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)
A. Chatillon *et al.* Phys. Rev. C **106**, 024618 (2022)

The SOFIA experiments

A new compact symmetric fission mode in neutron-deficient Th.



E. Pellereau *et al.* Phys. Rev. C **95**, 054603 (2017)
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A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)
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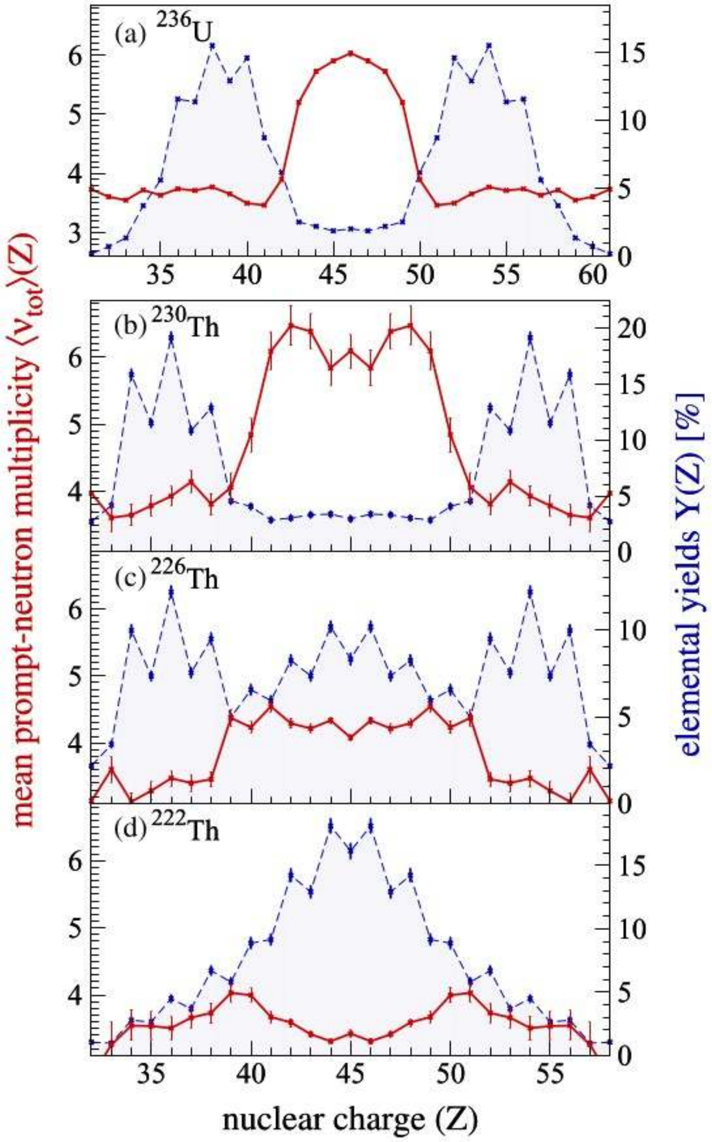
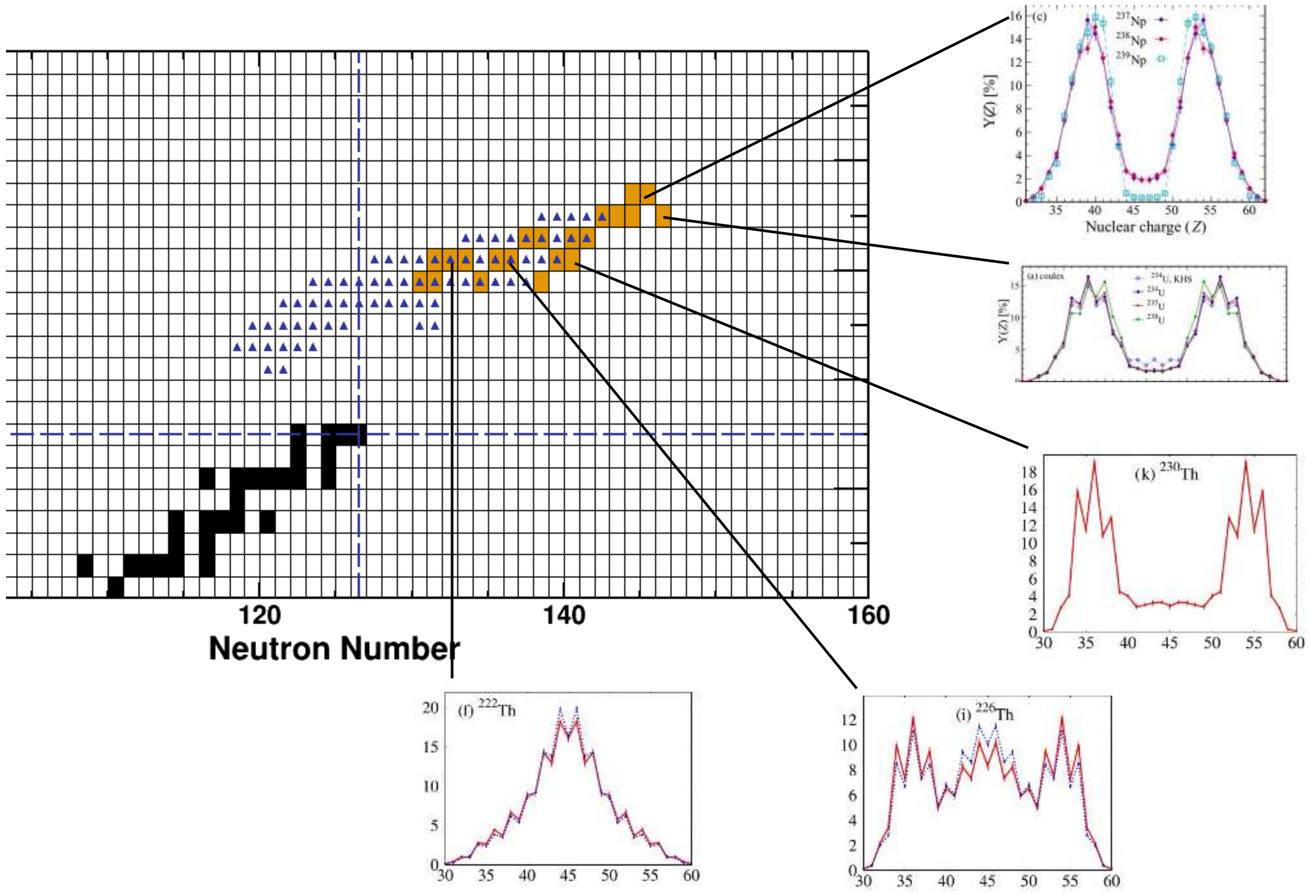
The SOFIA experiments



A new compact symmetric fission mode in neutron-deficient Th.

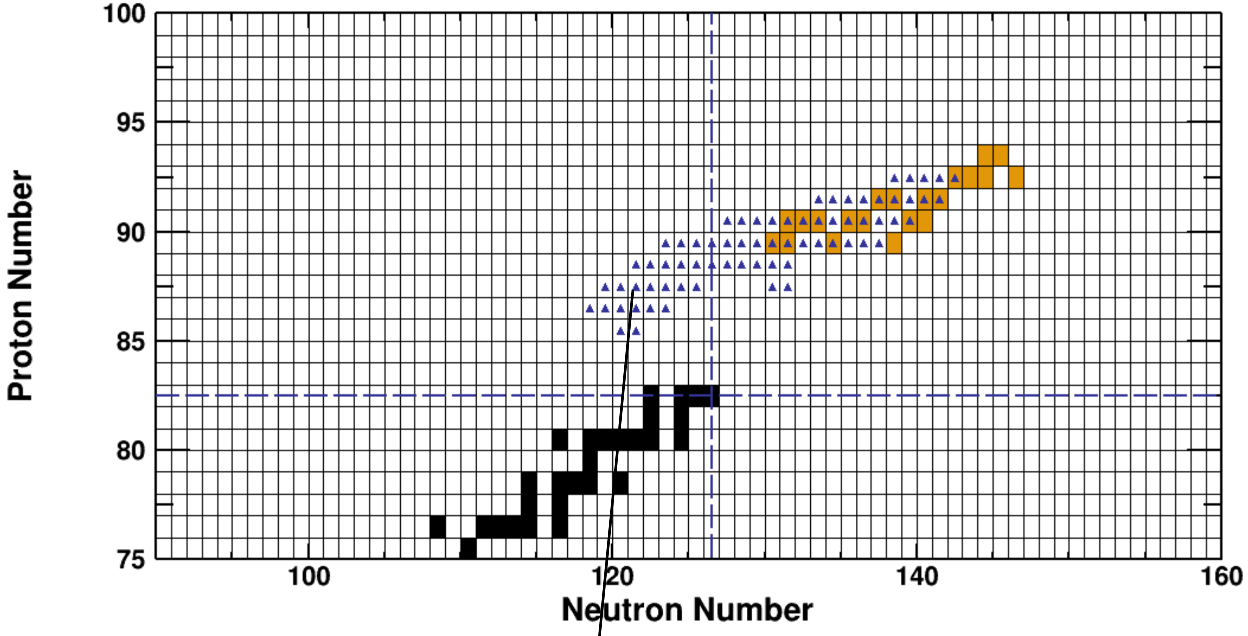


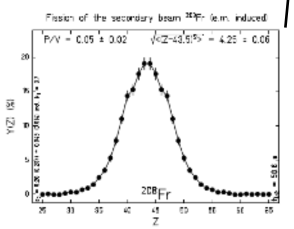
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

Fission yields to probe fission modes

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

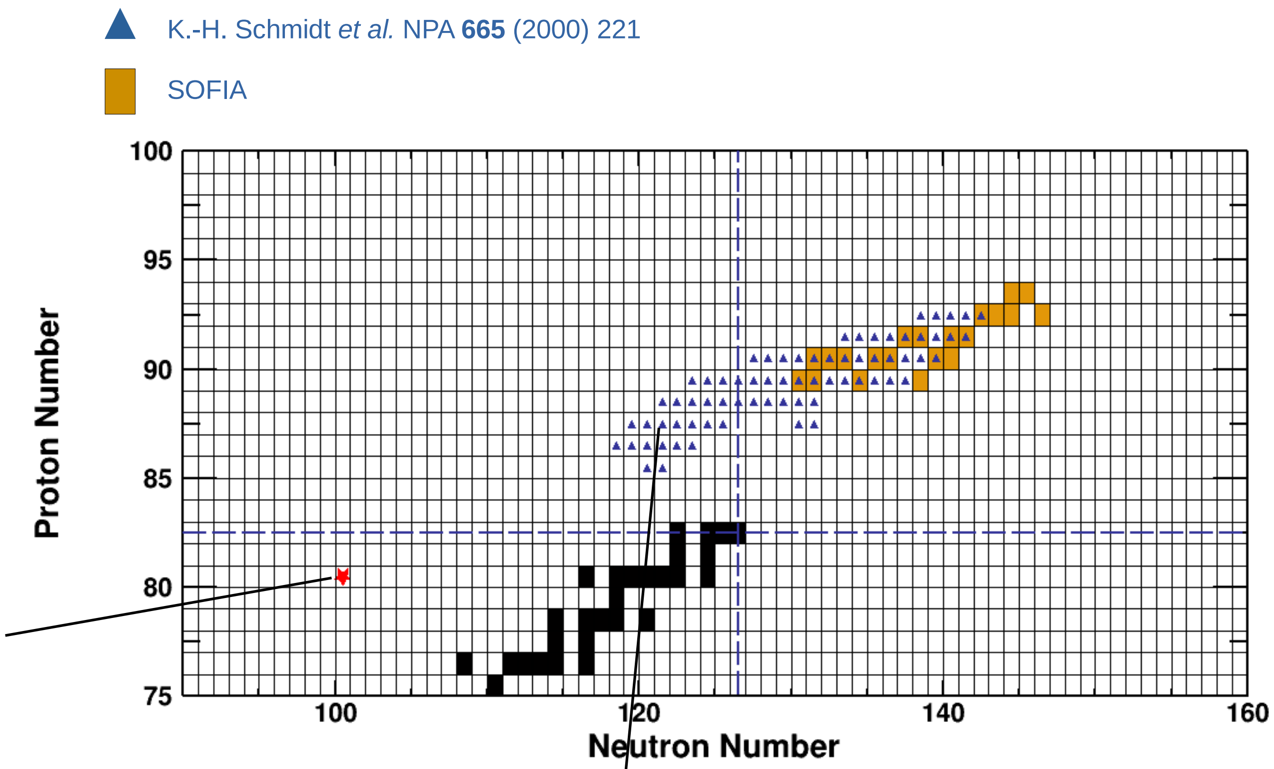
■ SOFIA

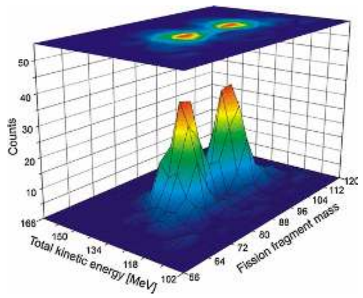




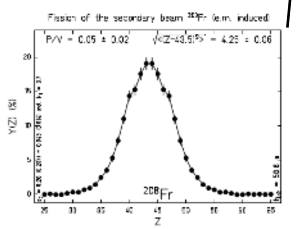
S. Steinhauser *et al.* Thesis work

Fission yields to probe fission modes





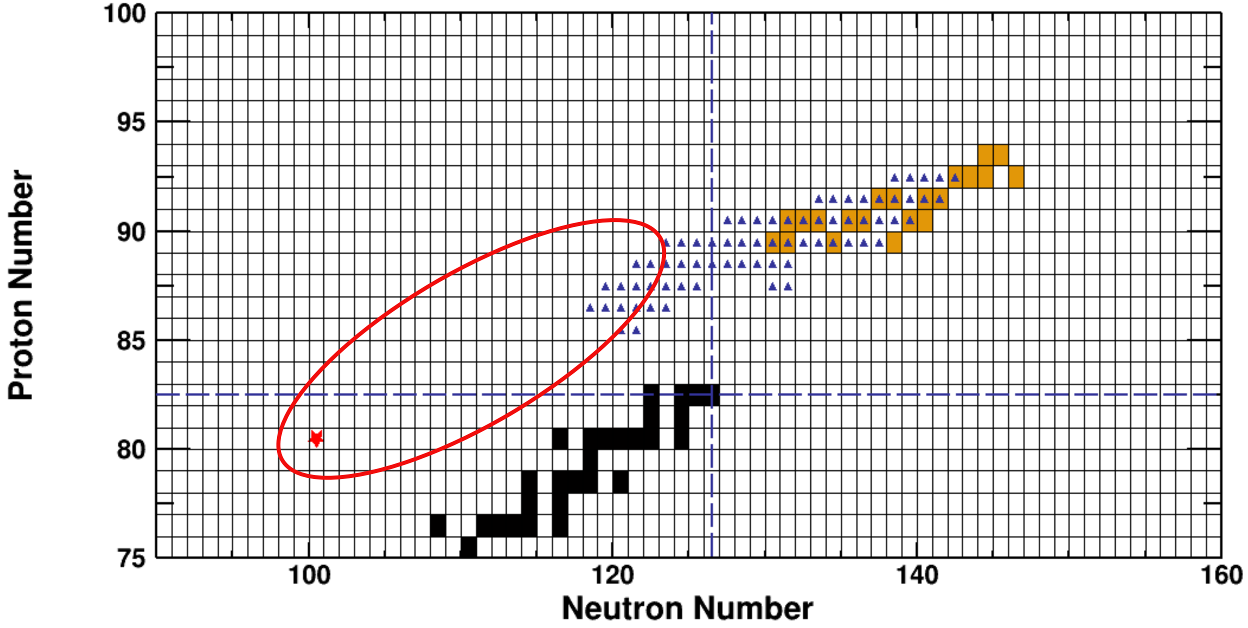
A. N. Andreyev *et al*. Phys. Rev. Lett. **105**, 252502 (2010)



S. Steinhauser *et al.* Thesis work

Fission yields to probe fission modes

A new island of asymmetric fission ?



➔ **What mechanism responsible of this new asymmetric split ?**

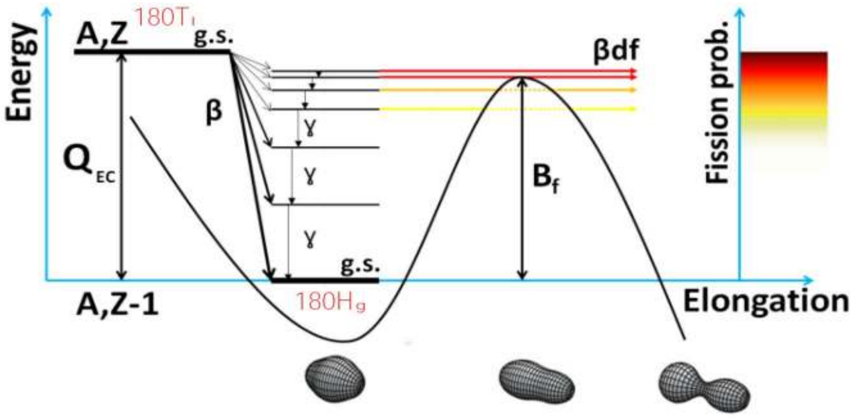
➔ **What shell effect ?**

➔ **What are the boundaries?**

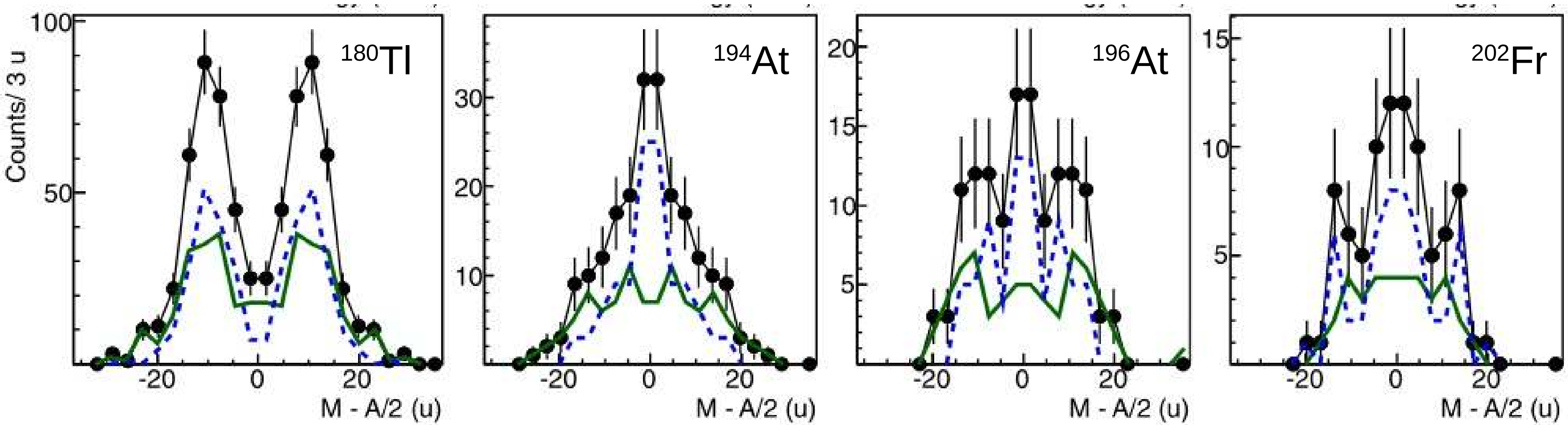
➔ **...**

Trigged a lot of experimental activities

- **β-decay delayed fission**
  - Only a few nuclei accessible with this technique
  - We need Q_β of the order B_f
  - Probe low energy fission
  - Measure mass ratio M1/M2.



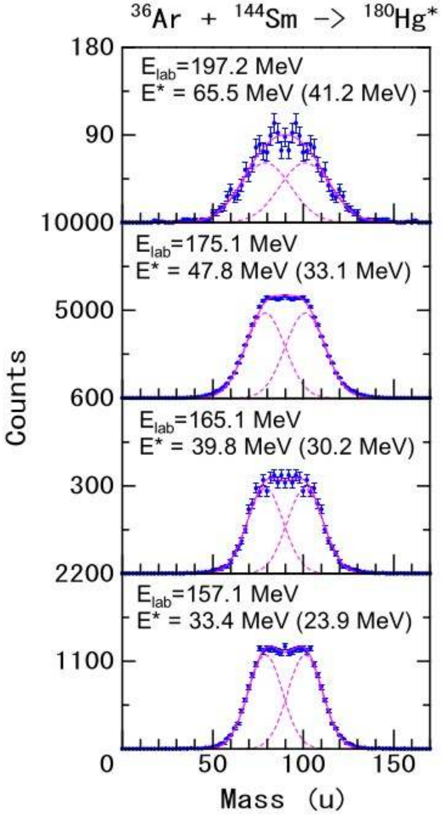
A. N. Andreyev *et al*. Phys. Rev. Lett. **105**, 252502 (2010)
L. Ghys **et al.** Phys. Rev. C **90** 041301R (2014)

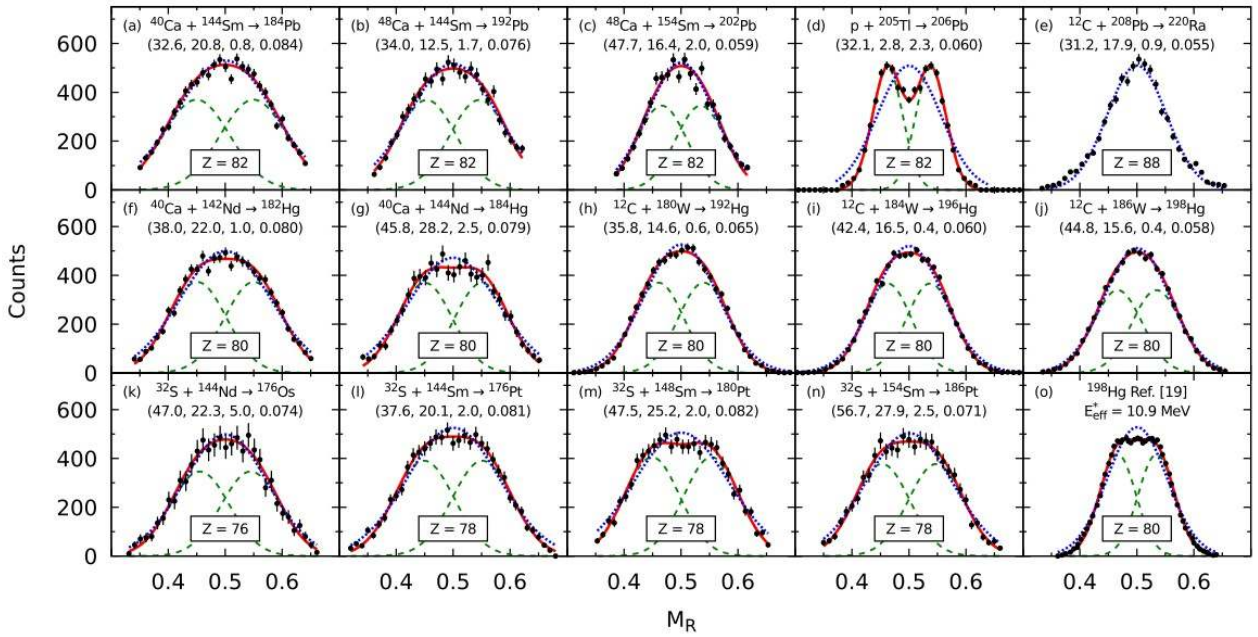


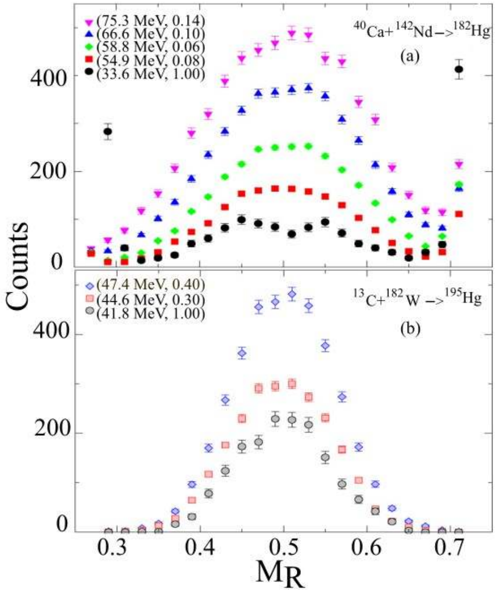
Trigged a lot of experimental activities

- **Fusion-fission**
  - A selection of beam and target to access neutron-deficient systems.
  - Large excitation energy => vanishing of structure effects
  - Only mass distribution with a resoltuion of σ ≈ 3-5 u.

K. Nishio *et al.* Phys. Lett. B **748**, 89-94 (2015)





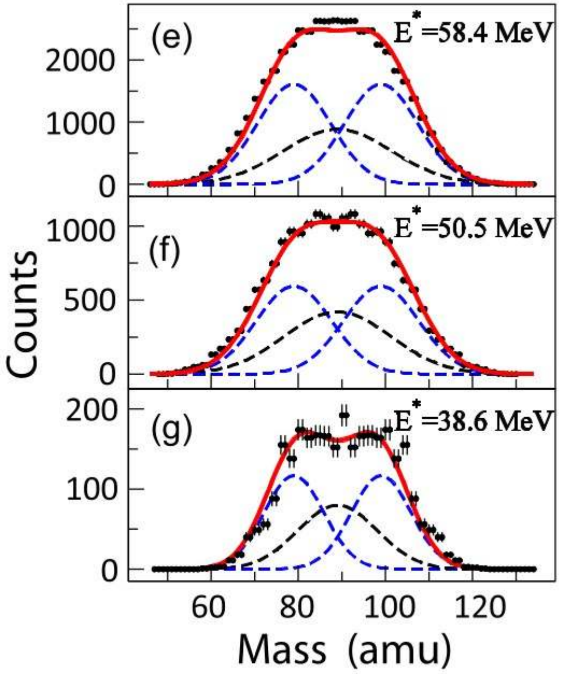


E. Prasad *et al.* Phys. Lett. B **811**, 135941 (2020)

E. Prasad *et al.* Phys. Rev. C **91**, 064605 (2015)

Fusion-fission experiments

- **Fusion-fission**
  - Three different experiments studying ^{178}Pt
    - Tsekhanovich et al
      - ^{142}Nd target and ^{36}Ar beam at 155, 170 and 180 MeV at JAEA.
      - FFMD measured using two-arms (micro-channel plate + MWPC) → **Fitted with 2 modes.**



I. Tsekhanovich *et al.* Phys. Lett. B **790**, 583-588 (2019)

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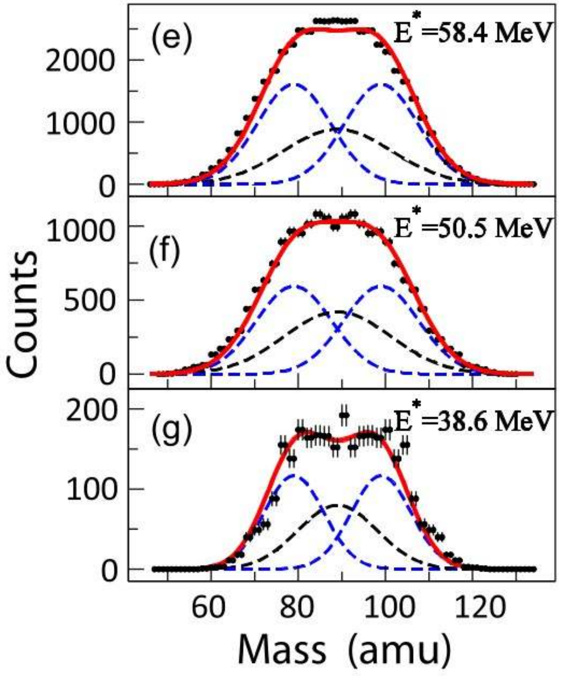
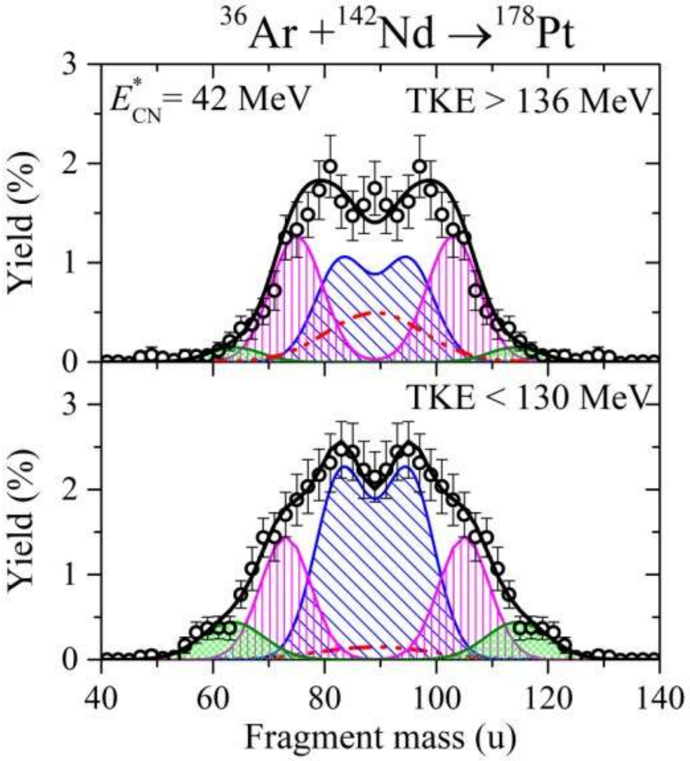


I. Tsekhanovich *et al.* Phys. Lett. B **790**, 583-588 (2019)

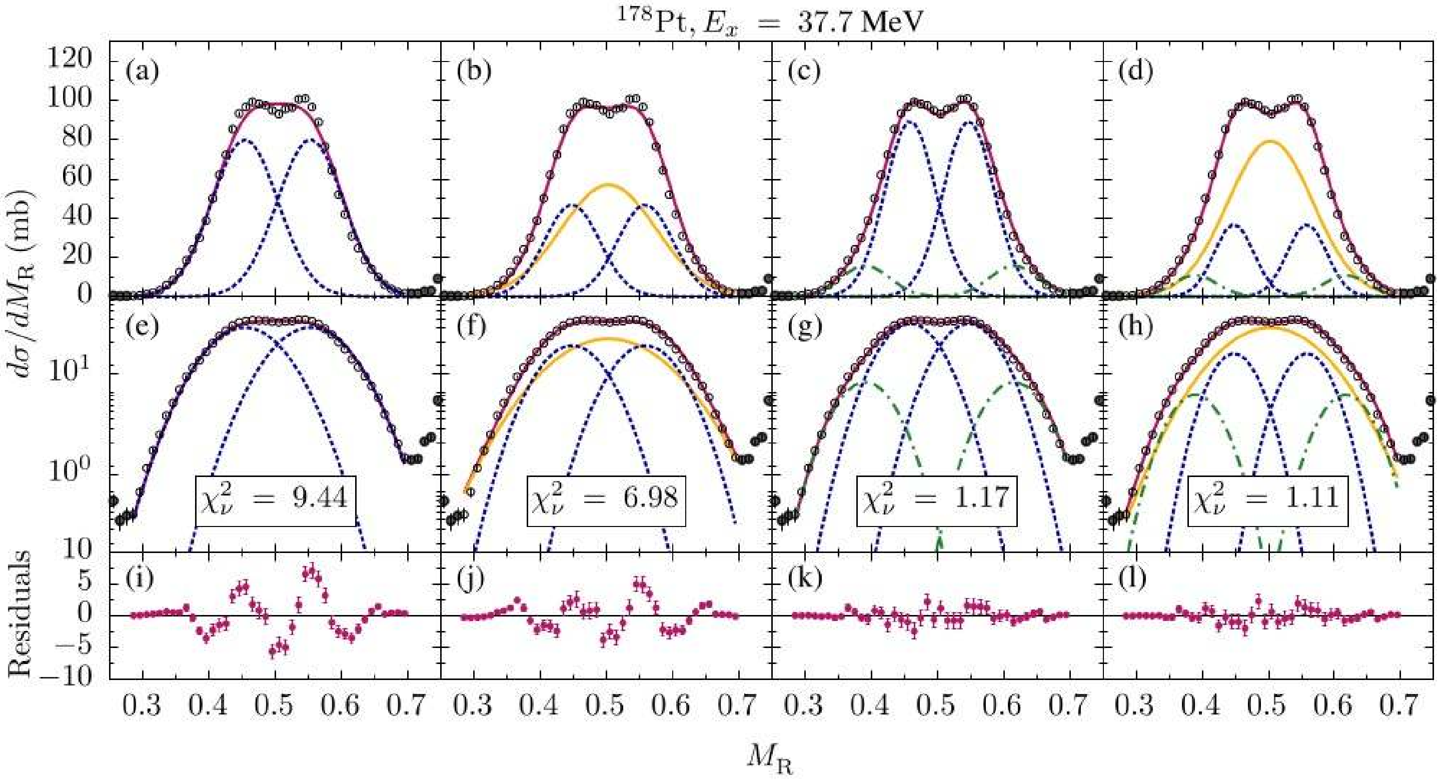
- Kozulin et al
  - ^{142}Nd target and ^{36}Ar beam at 172, 192 and 212 MeV at Dubna.
  - FFMD measured with CORSET spectromter → **Fitted with 4 modes.**



E. M. Kozulin *et al.* Phys. Rev. C **105**, 014607 (2022)

Fusion-fission experiments

- Kozulin et al
  - ^{144}Sm target and ^{34}S beam at 146 MeV at ANU.
  - FFMD measured with CUBE fission spectromter → **Best fitted with 3 modes.**



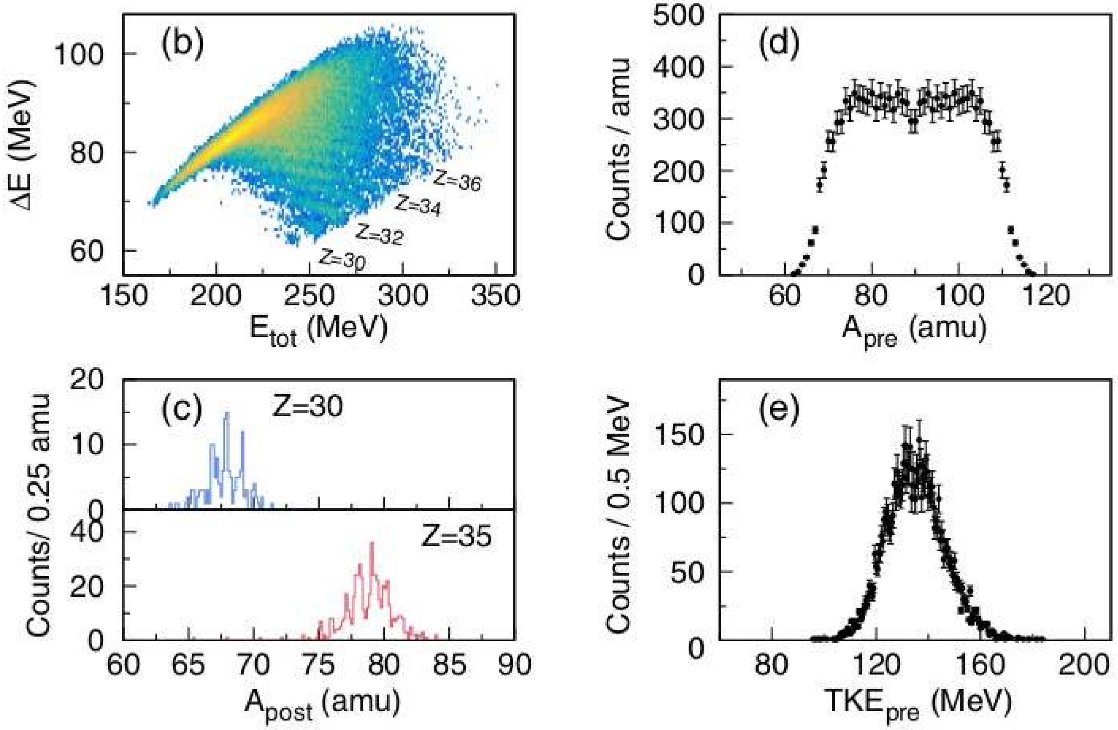
B.M.A. *et al.* Phys. Lett. B **837**, 137655 (2023)

- Fusion-fission is an interesting tool to probe fission modes in neutron-deficent region.
- But only FFMD is measured with resolution of 3 to 5 uma.
- Known excitation energy but high
- Gaussian fit to extract different fission modes
- 3 experiments → 3 different interpretations

Trigged a lot of experimental activities

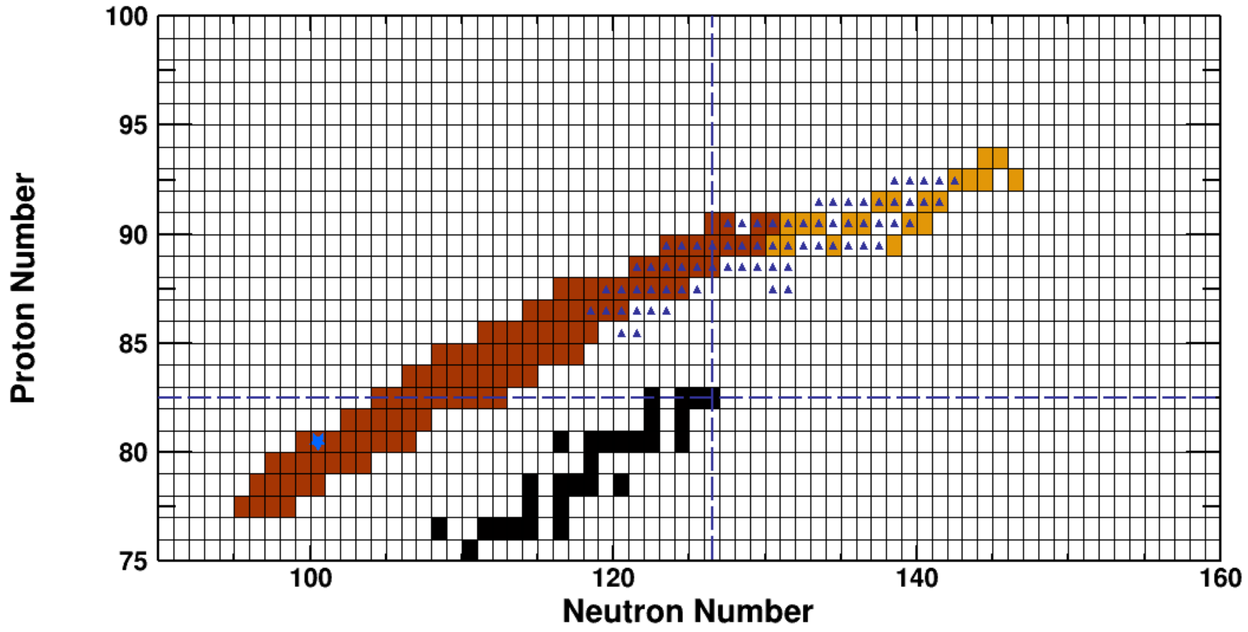
- **Fusion-fission so study ^{178}Hg at GANIL**
  - Mass distribution + charge distribution of the light fragment.
  - Large excitation energy => vanishing of shell effects.
  - Evidence of proton shell effect ?

C. Schmitt *et al.* Phys. Rev. Lett. **126**, 132502 (2021)

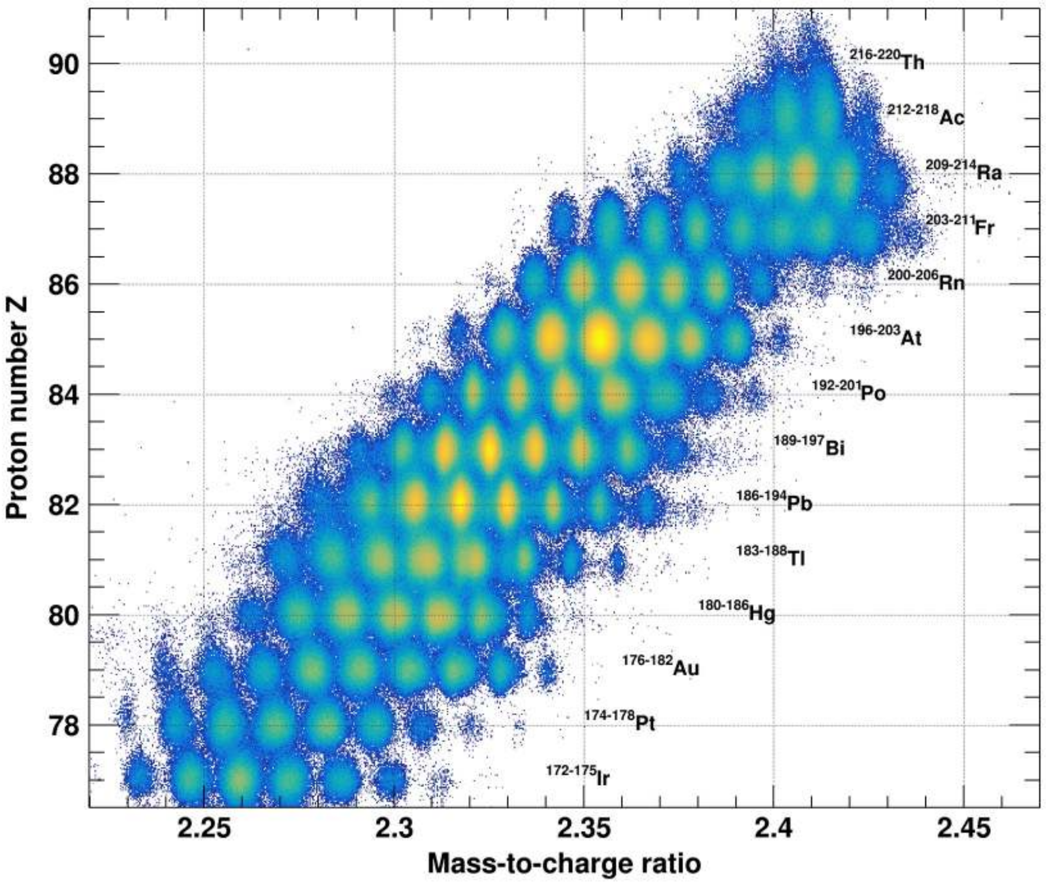


New SOFIA experiment in 2021

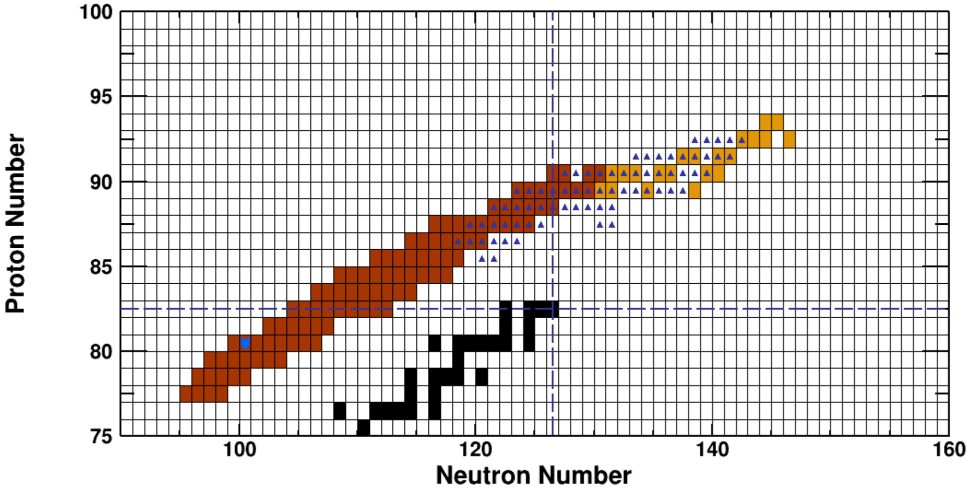
- **100 fissioning systems in one experiment !**
- **Establishing a connection between the neutron-deficient subleab region and the actinide region.**
- ✗ No control of the excitation energy event by event



Global view of the studied systems

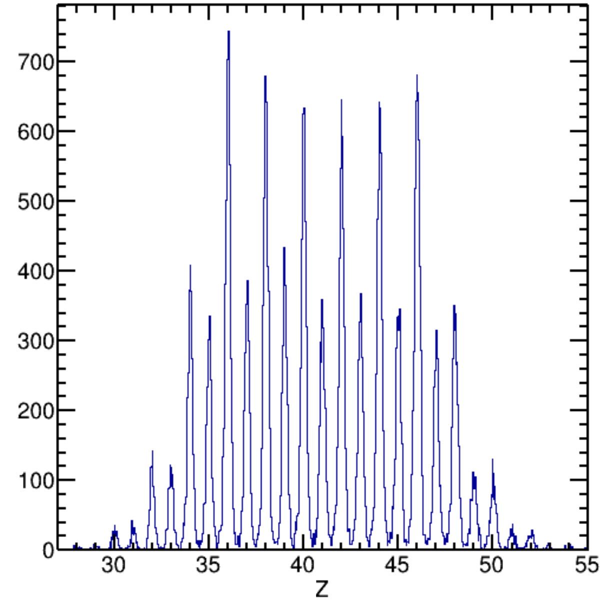


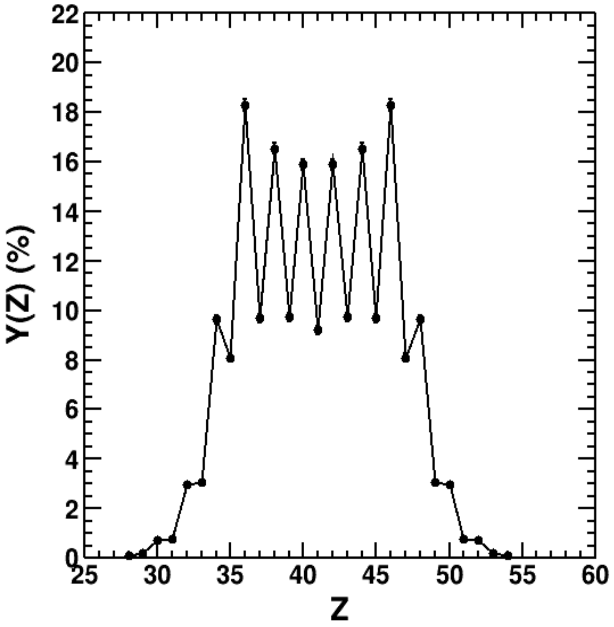
- 100 fissioning systems in one experiment
  - 12 FRS settings
  - From ^{175}Pt up to ^{220}Th
  - Very exotic systems
  - Bridge between the neutron-deficeint sub-lead region and the actinide region.



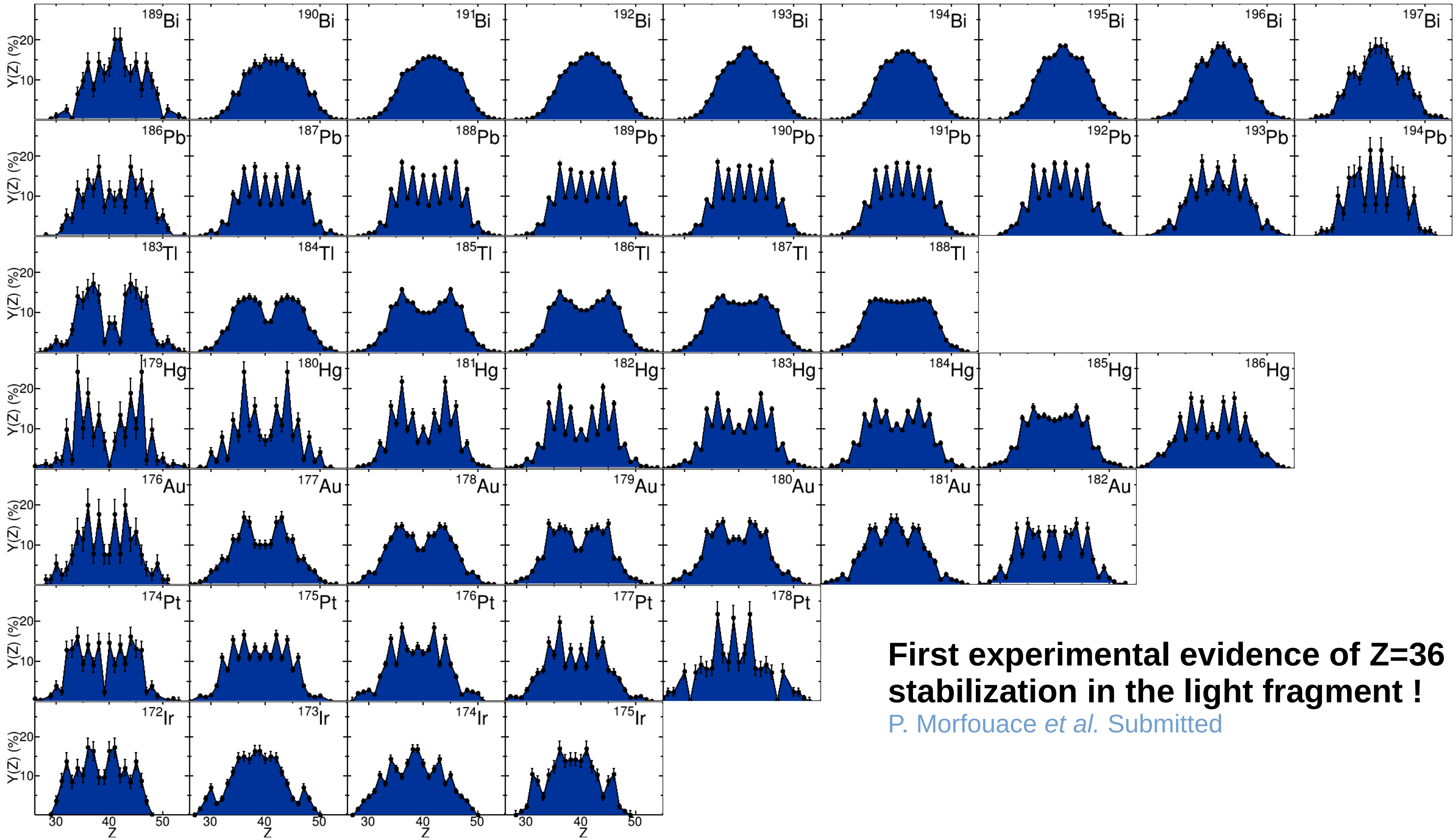
Fission yields

- Selection of a given fission system (here ^{189}Pb)
- Event selection « Coulomb excitation » ($Z_{sum} = Z_{beam}$)
- Nuclear subtracted charge distribution of the Coulomb-induced fission
- Extraction of the fission charge yields for 100 fissioning systems in a systematic and coherent way.





Charge yields



First experimental evidence of Z=36 stabilization in the light fragment !

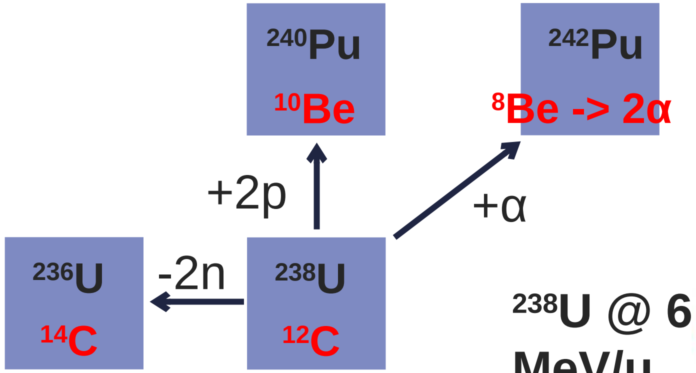
P. Morfouace *et al.* Submitted

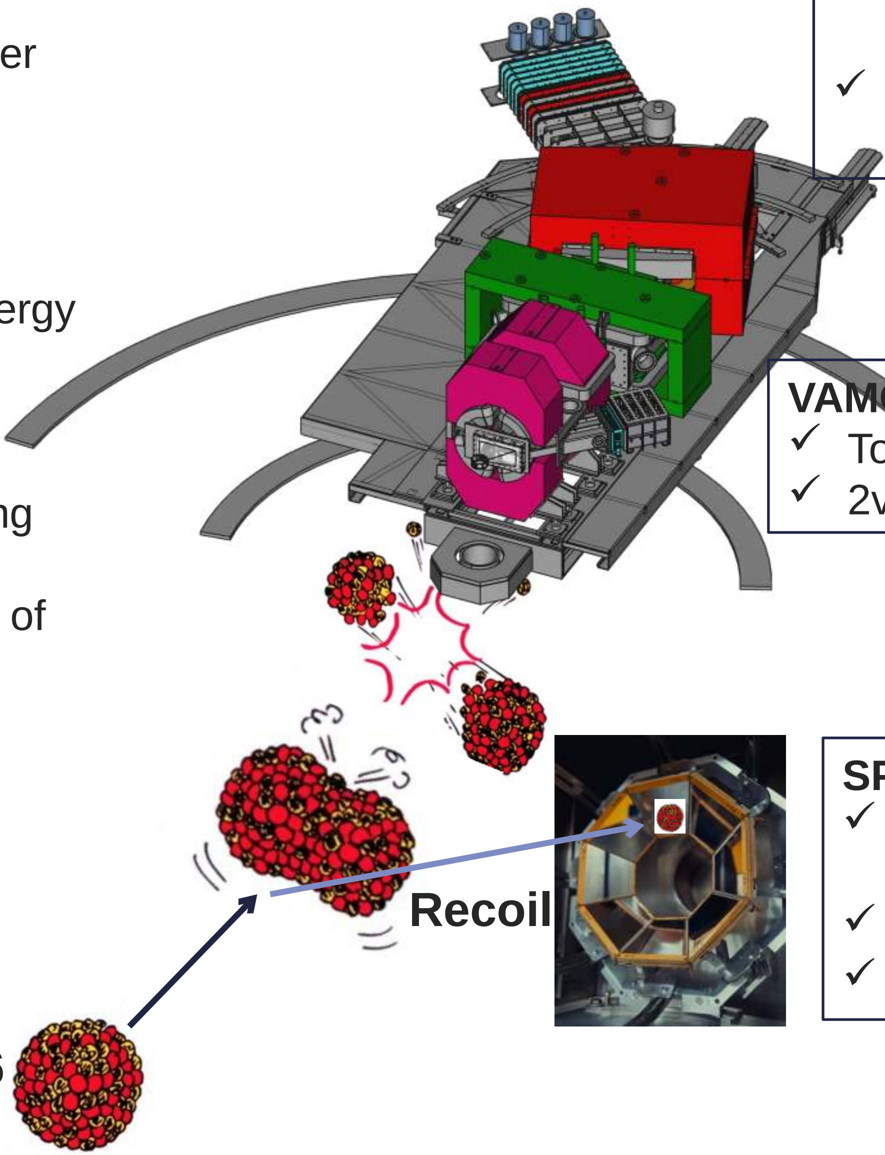
Multi-nucleon transfer experiment with VAMOS

- New opportunites to study fission using heavy ion reactions
  - **Fusion/Fission (VAMOS)**
  - **Transfer induced fission (VAMOS+PISTA)**
- Inverse kinematics
  - Using a ^{238}U beam at 6 MeV/u.
  - The boost provide the capability of fission-fragments nuclear charge identification.
  - Coulomb energies provide low angular straggling and small boost → enable good volicty resolution in the center of mass.
- Use of surrogate reaction
  - Access to « exotic » fissioning system, not possible in n-induced fission
  - Explore the impact of the incoming channel into the final fission fragment distributions.

What can be done at GANIL with VAMOS

- Inverse kinematics using a beam of ^{238}U around Coulomb barrier
  - ✓ Access to fissioning system heavier than ^{238}U
- Transfer-induced fission reaction
  - ✓ Selection of the fissioning system
  - ✓ Measurement of the excitation energy event by event
- Gamma-ray spectrometer
  - ✓ Probe the excitation energy sharing between the fission fragments
  - ✓ Evaluate the excitation probability of the target-like nuclei





VAMOS
- ✓ Direct and complete isotopic fission fragment yields Y(A,Z)
- ✓ Precise center-of-mass fission fragment velocities

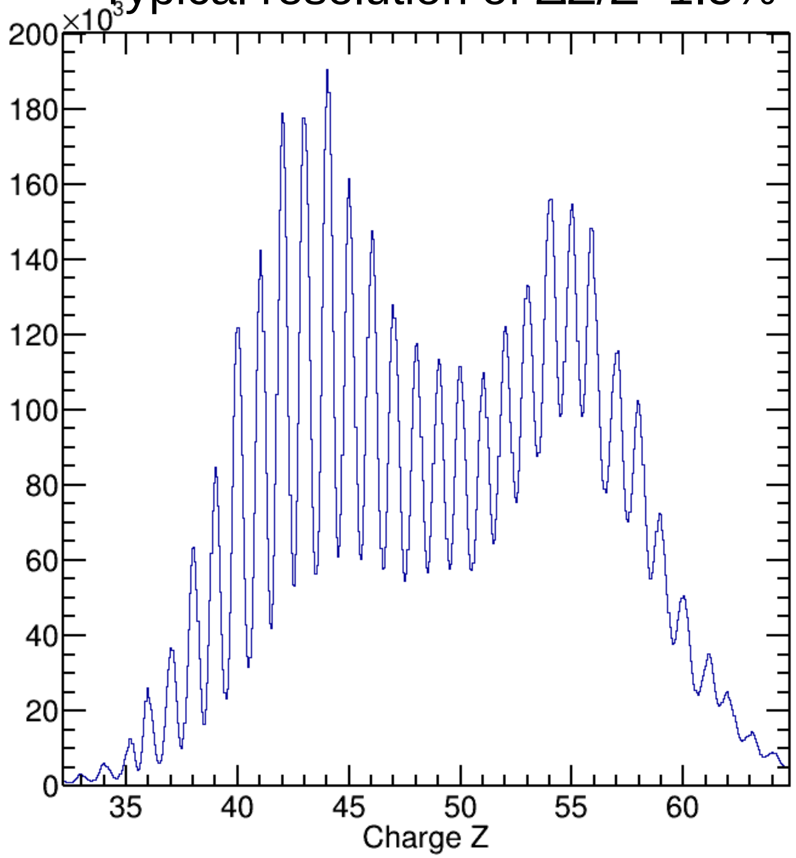
VAMOS second arm
- ✓ Total kinetic energies
- ✓ 2ν measurement

SPIDER → PISTA
- ✓ Characterization of the fissioning system
- ✓ A, Z
- ✓ (E_{lab},$_{lab}$) -> E*

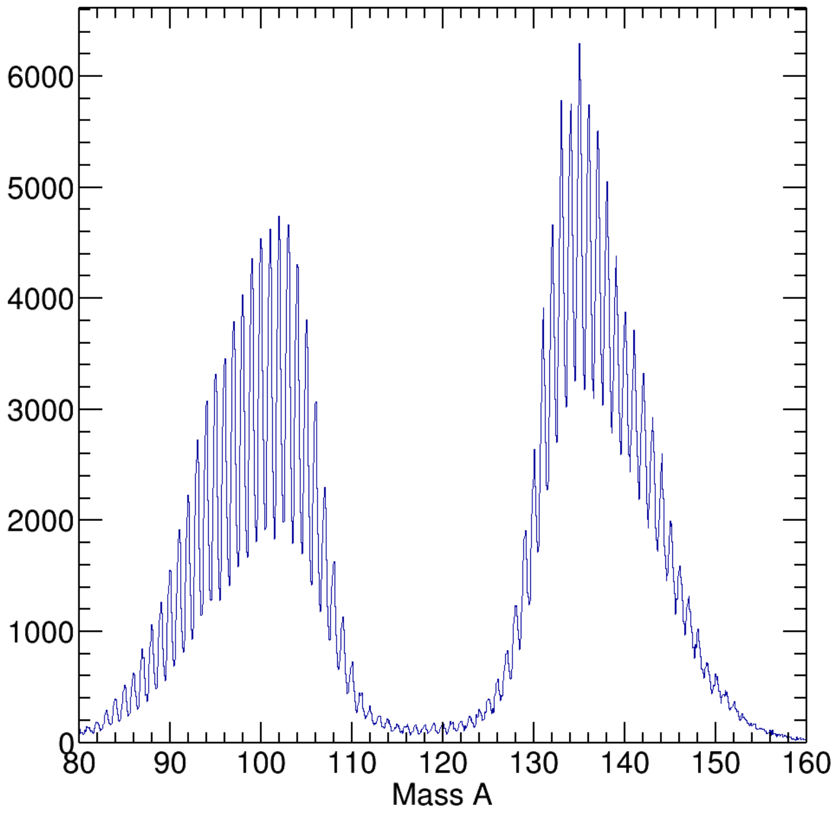
VAMOS : Charge and mass identification

- Detection of the fission fragment few tens of nanoseconds after fission.

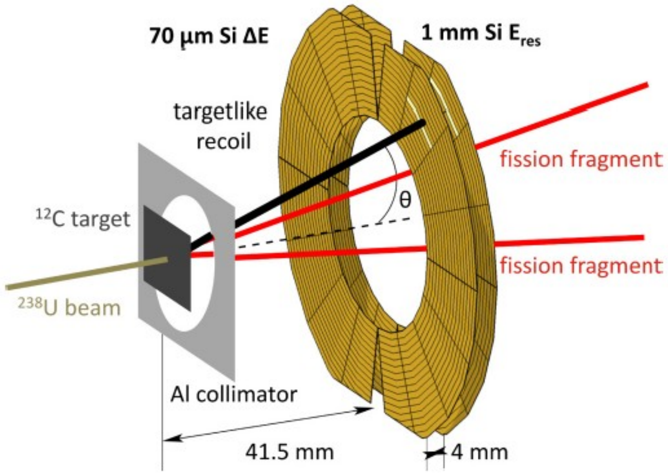
Typical resolution of ΔZ/Z=1.5%



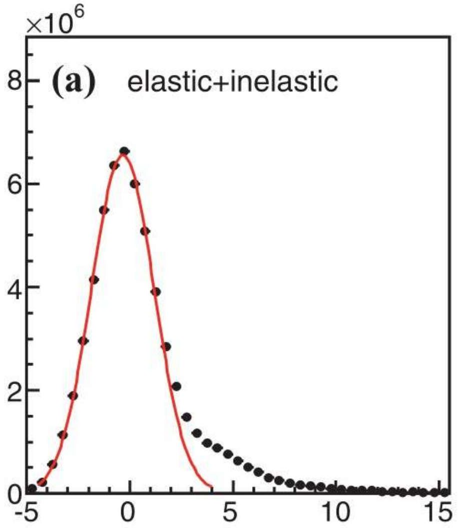
Typical resolution of ΔA/A=0.8%



A rich activity with SPIDER and VAMOS

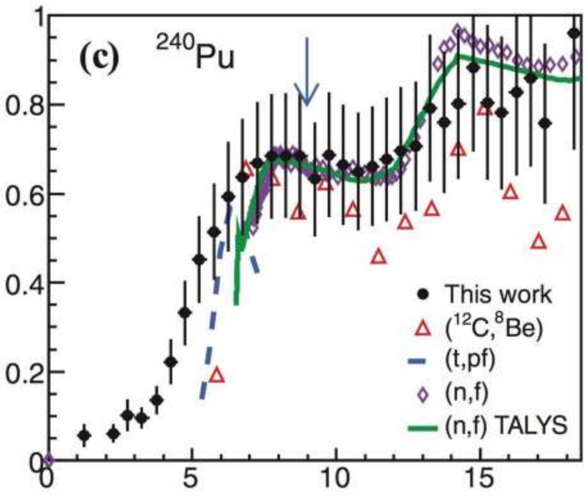


- ΔE = 70 um thickness
- E = 1 mm thickness
- 1,5 mm strips
- 22.5 deg sectors
- Angular coverage : 30 – 47 deg
- Excitation energy resoltuion : FWHM = 2.9 MeV.

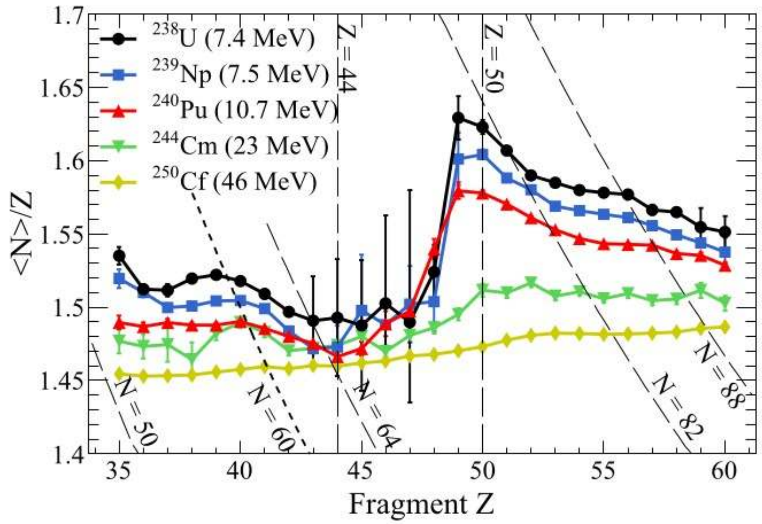


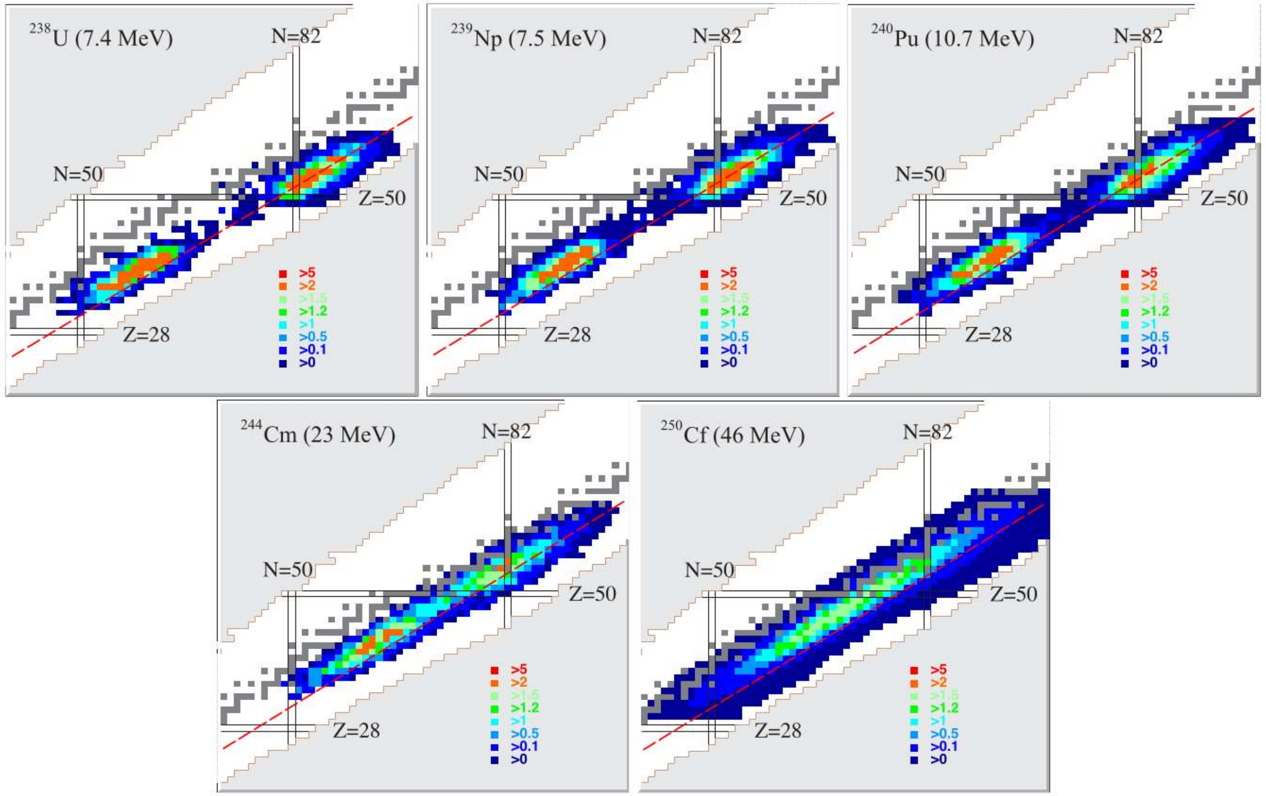
The coupling of SPIDER and VAMOS provided a lot of data, but with a limited resolution in excitation energy.

- M. Caamano et al. PRC 88, 024605 (2013)
- C. Rodriguez-Tajes et al. PRC 89, 024614 (2014)
- Ramos et al. PRC 97, 054612 (2018)
- Ramos et al. PRL 123, 092503 (2019)
- Ramos et al. PRC 99, 024615 (2019)
- ...



A rich activity with SPIDER and VAMOS





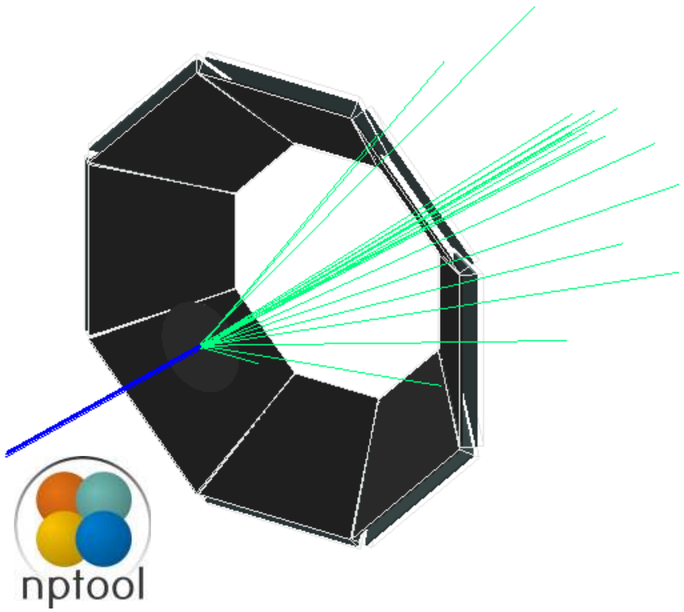
- Direct measurement of isotopic fission yields for different fissioning system, with different excitation energy
- Evidence of shell effect around Z=50 looking at the nuclear charge polarization.
- Structural effects that disappear at higher excitation energy.
- Need a better characterization of the fissioning system in A, Z **and E*.**

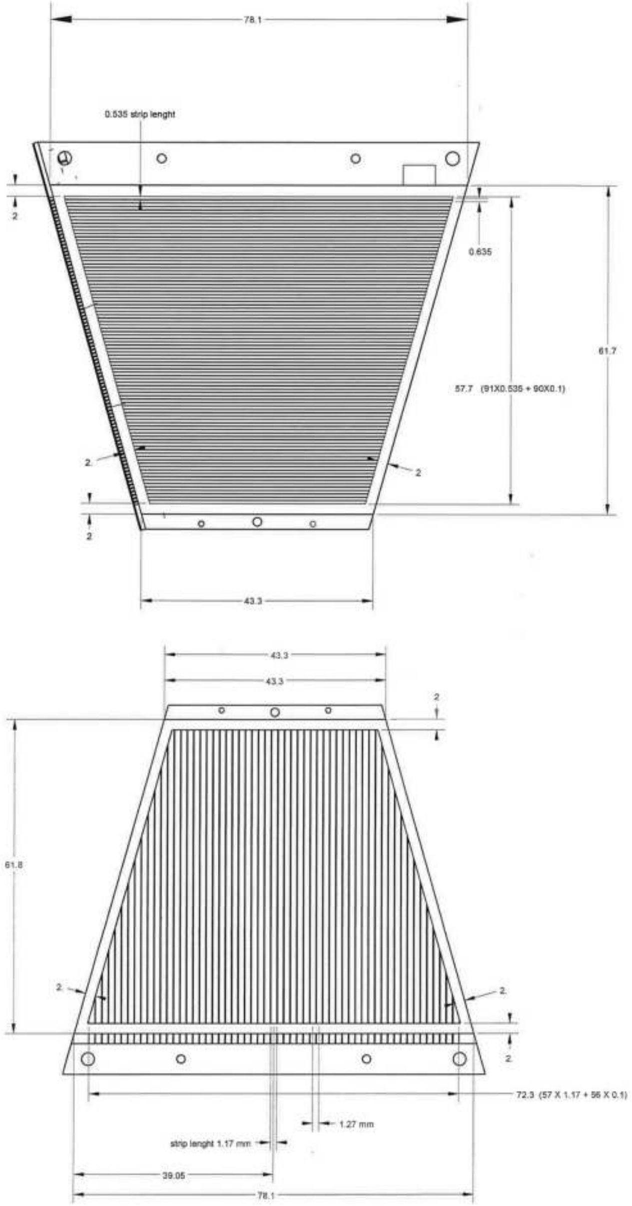
Major upgrade : PISTA, a CEA-DAM/GANIL collaboration

PISTA : 8 telescopes in a petal shape

- **ΔE first stage**
  - 100 um thick
  - 91 horizontal strips
  - Dynamic range : 0-60 MeV

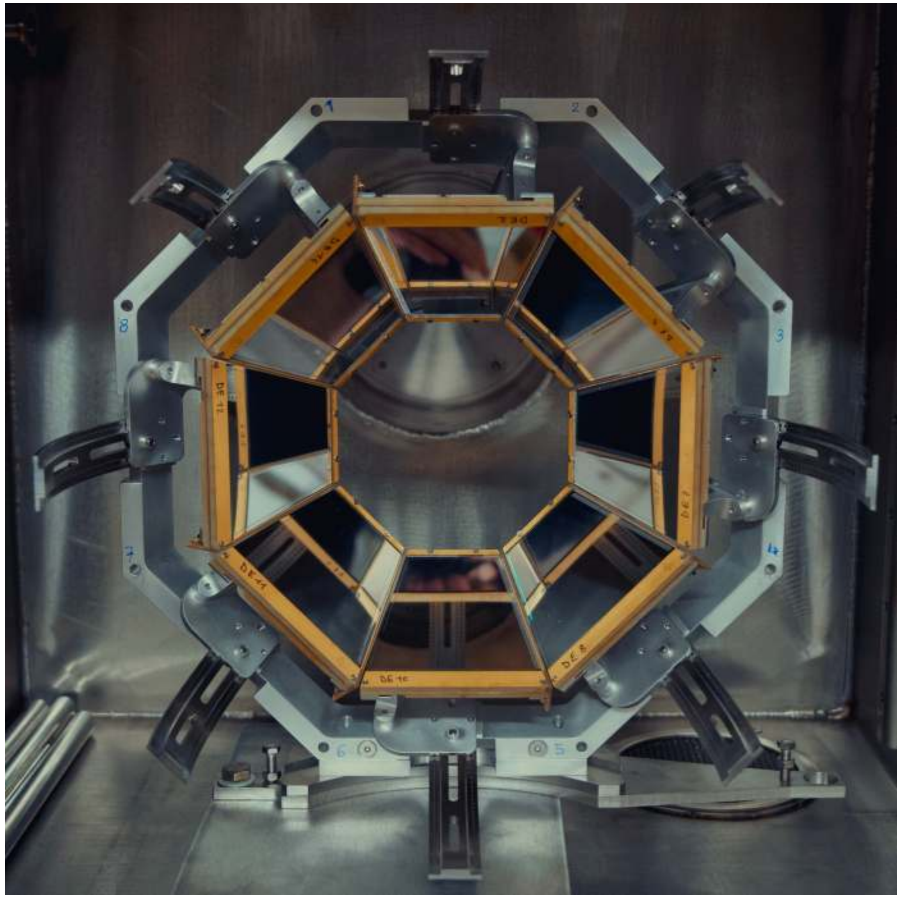
- **E second stage**
  - 1 mm thick
  - 57 vertical strips
  - Dynamic range : 0-200 MeV





Goal : Probe the evolution of fission yields as a function of excitation energy.

Major upgrade : PISTA, a CEA-DAM/GANIL collaboration

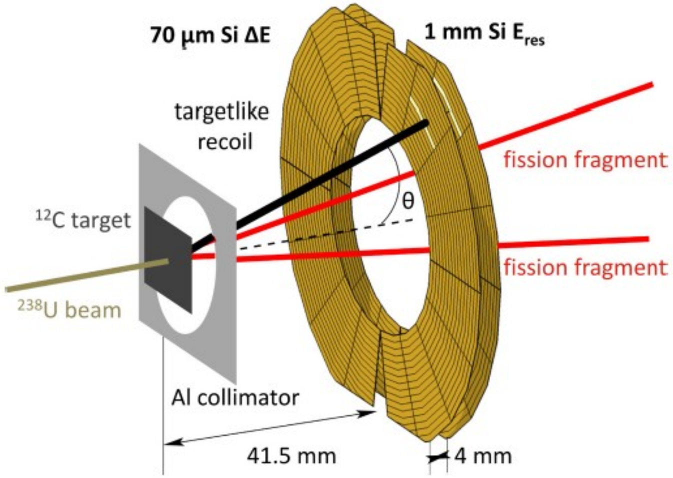


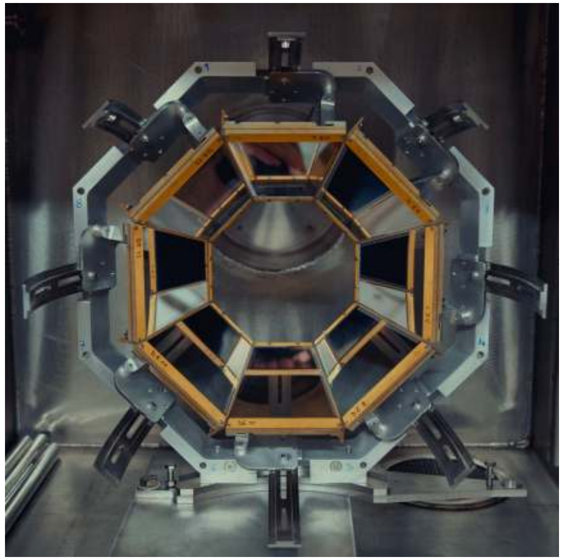
What's new with PISTA (compared to SPIDER)?

- ✓ Angular coverage : 30-60 deg
- ✓ Better identification of the ejectile
- ✓ High granularity means better resolution in E* (FMHW = 700 keV)
- ✓ Dedicated electronics capable of sustaining higher count rate.
- ✓ **Overall, a much better characterization of the fissioning system (A,Z,E*)**

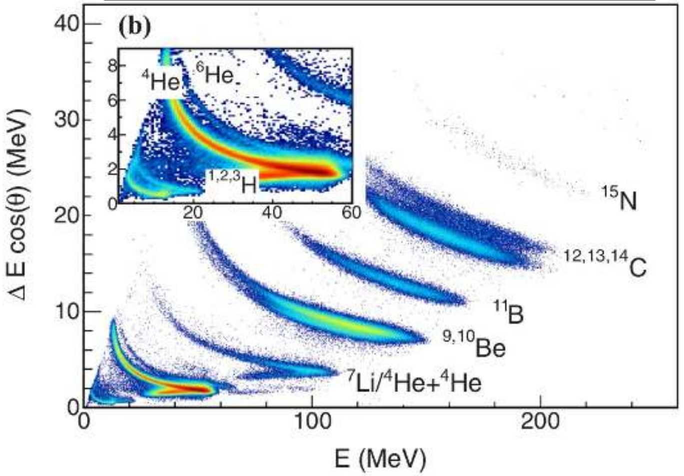
Major upgrade : PISTA

PISTA analysis done by Lucas Bégué-Guillou

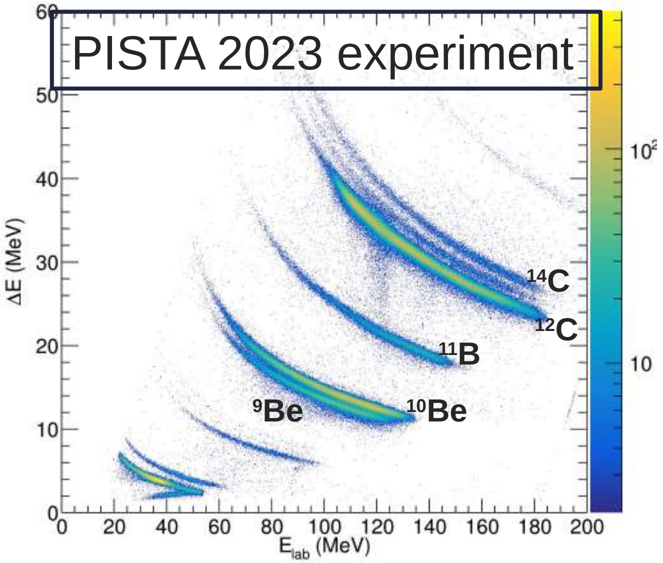




Old generation SPIDER

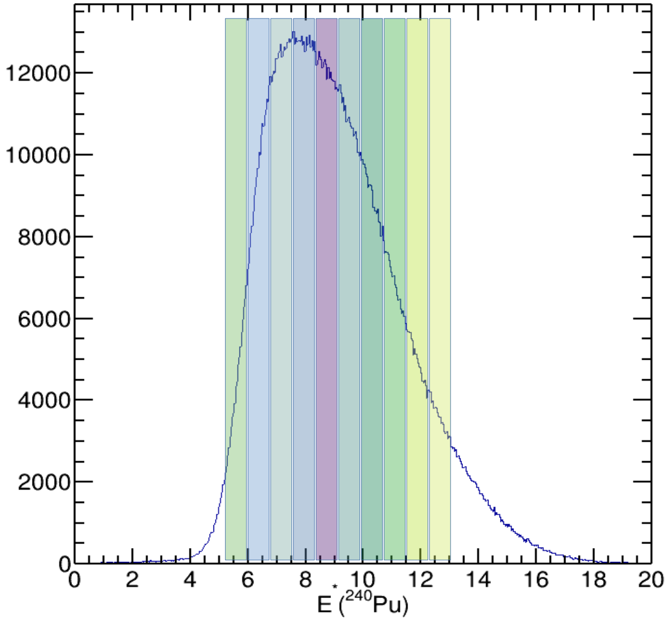


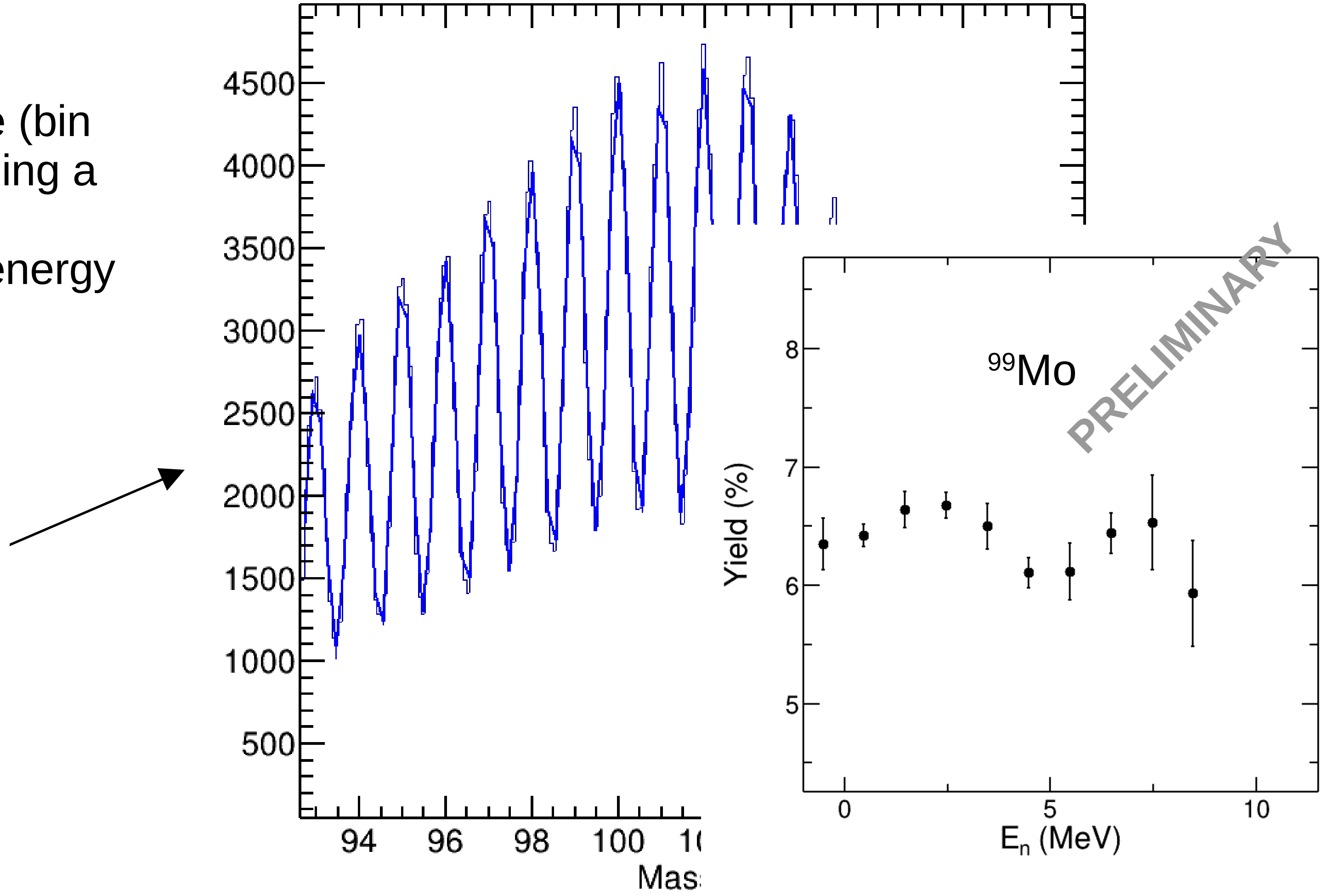
PISTA 2023 experiment



Fission yields with VAMOS

- **Mass distribution**
  - Typical resolution of ΔA/A=0.8%
  - For a given excitation energy range (bin of 1 MeV) we get the mass yield using a multi-gaussian fit.
  - Same work for different excitation energy → Yield evolution





4. Conclusion

Conclusion

- Measurement of fission yields is challenging
  - Different experimental approaches exist and are complementary.

- Direct kinematics techniques provide a data especially for mass distribution and neutron multiplicities.
  - charge distribution limited to Z<38 with.
  - Gamma spectroscopy can be also used to for isotope identification. But relies on known nuclear structure properties.

- Inverse kinematics techniques allow the measurements of both charge and mass.
  - The kinematic boost enables the measurement of the fission fragment charge.
  - Access exotic systems.

- **Overall, the ensemble of measured data are very useful for theoreticians to constrain the development of nuclear fission models.**

Thank you!