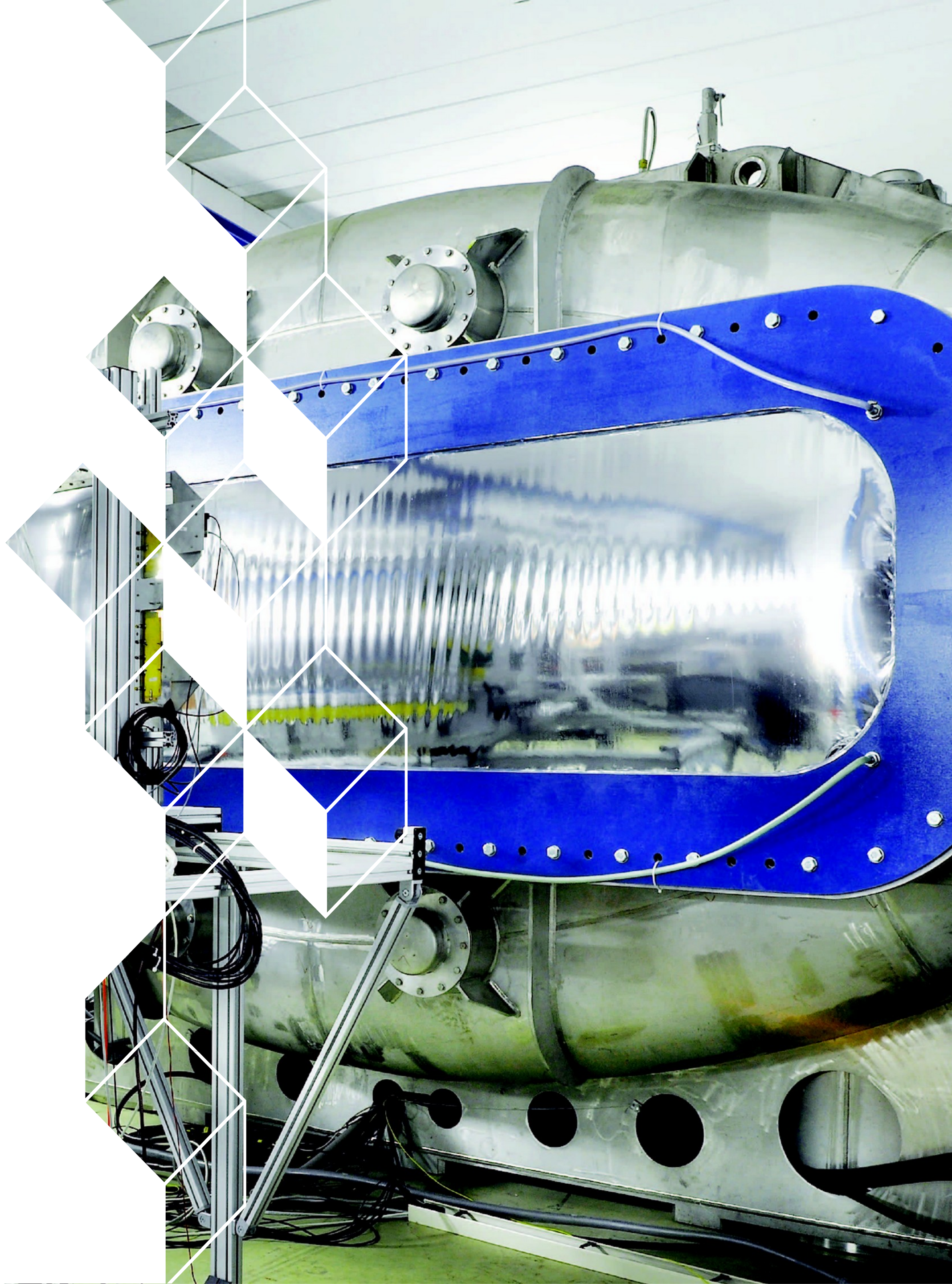


Mapping the new asymmetric fission island

EuNPC, Caen, September 2025

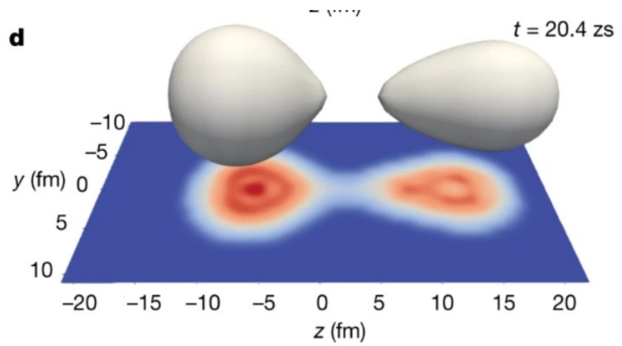
Pierre Morfouace[1,2], Julien Taieb[1,2], Audrey Chatillon[1,2] for the R^{3}B collaboration

[1] CEA, DAM, DIF, 91297 Arpajon, France
[2] Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France

1. Motivations

Why measuring fission fragments?

- **Important fondamental questions/open questions**
  - Signatures of the underlying nuclear structure effects in the fission process.
  - These yields provide important information about reaction mechanisms, energy dissipation, excitation energy sharing and deformation at scission.



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- **Important fondamental questions/open questions**
  - Signatures of the underlying nuclear structure effects in the fission process.
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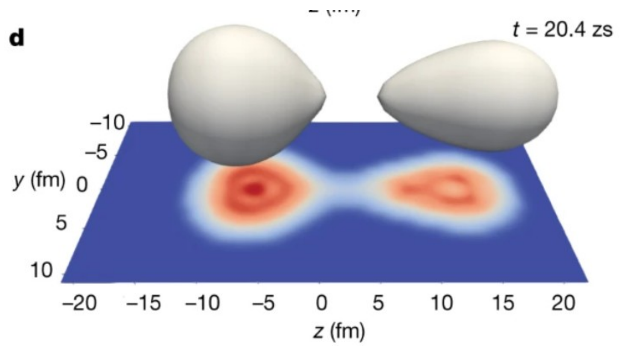
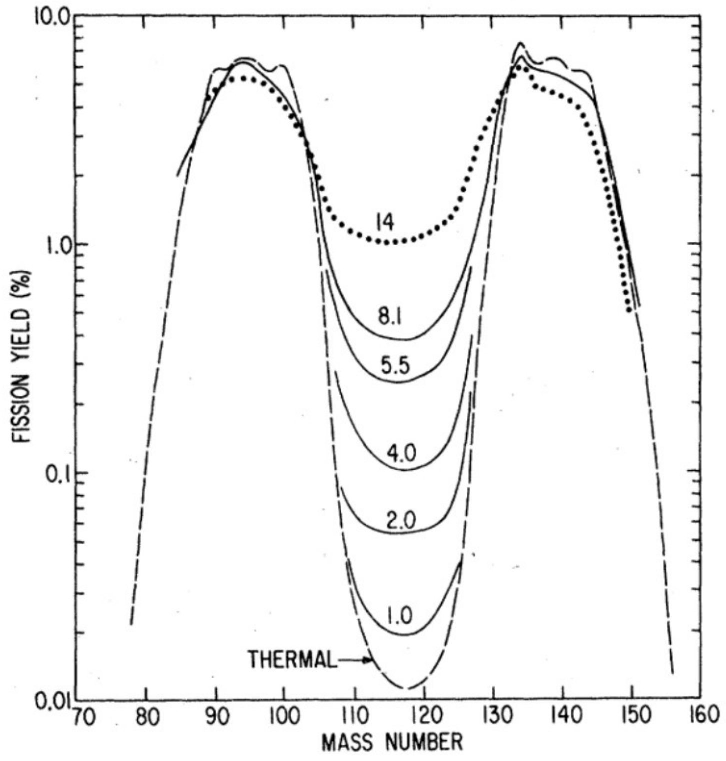
  - Shell effect damping with excitation energy.
    - See talk of Theodore Efremov
    - See talk of Alex Cobo





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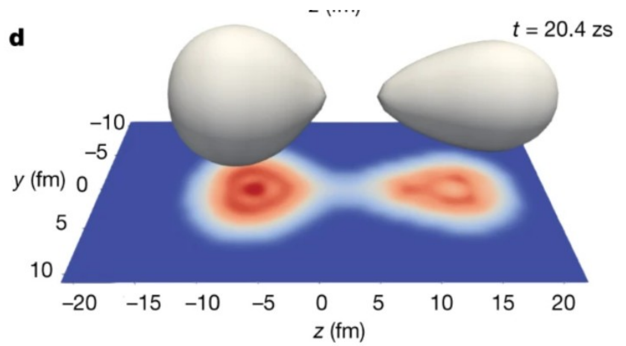
  - Fission recycling in r-process.



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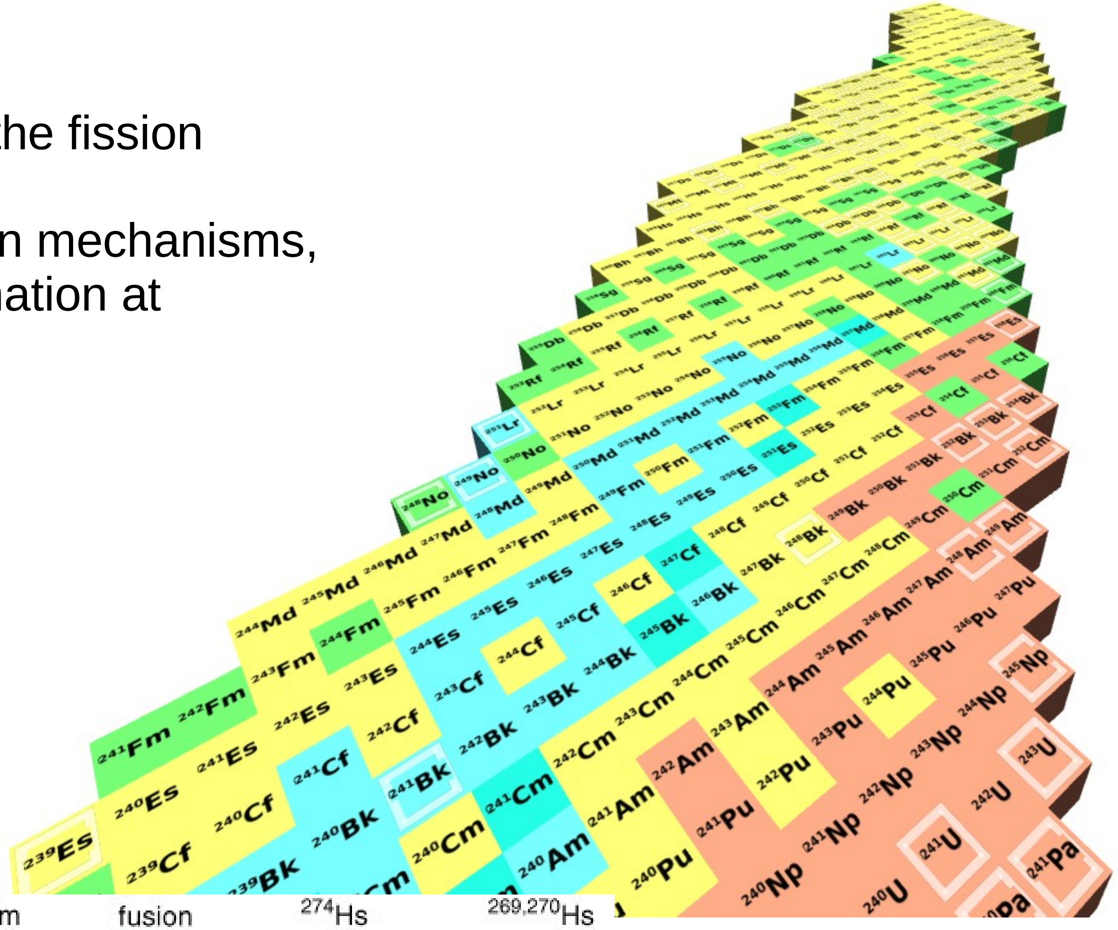
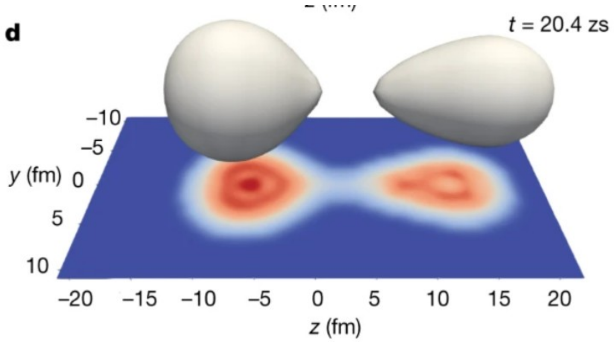
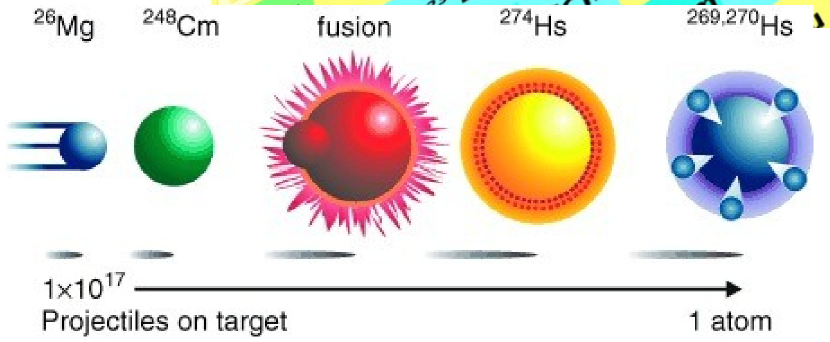
  - Fission recycling in r-process.
  - The quest for super-heavy elements.







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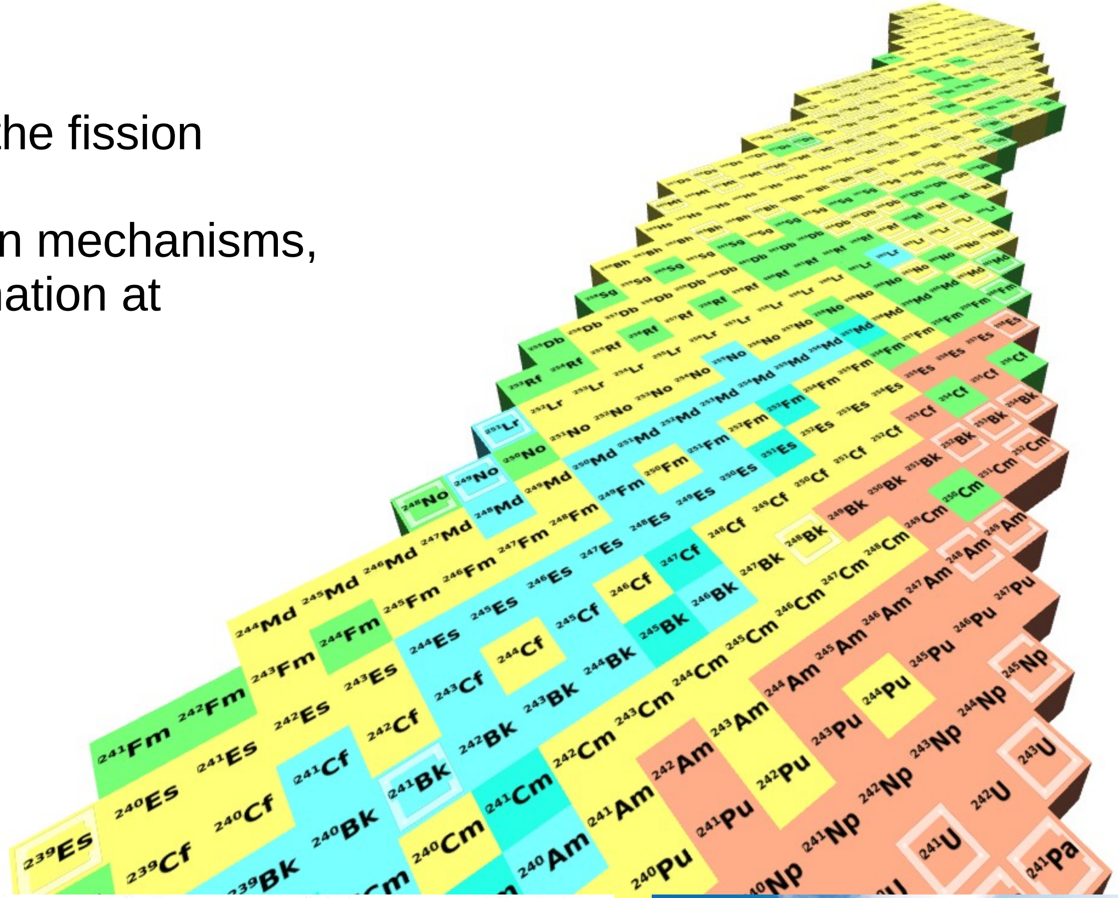

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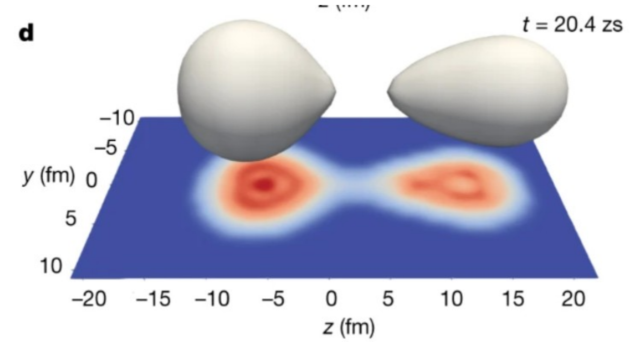
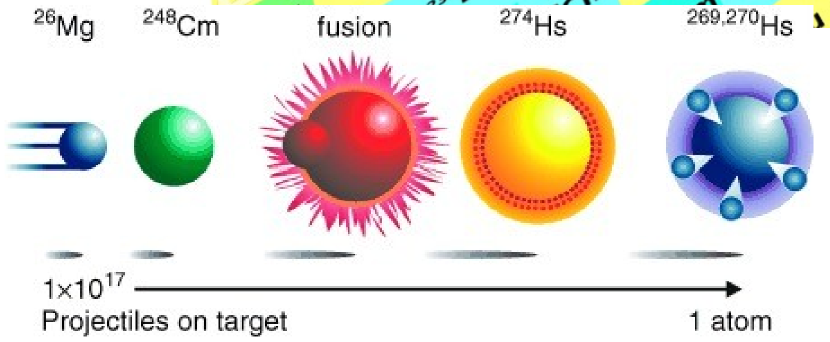
  - The quest for super-heavy elements.

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



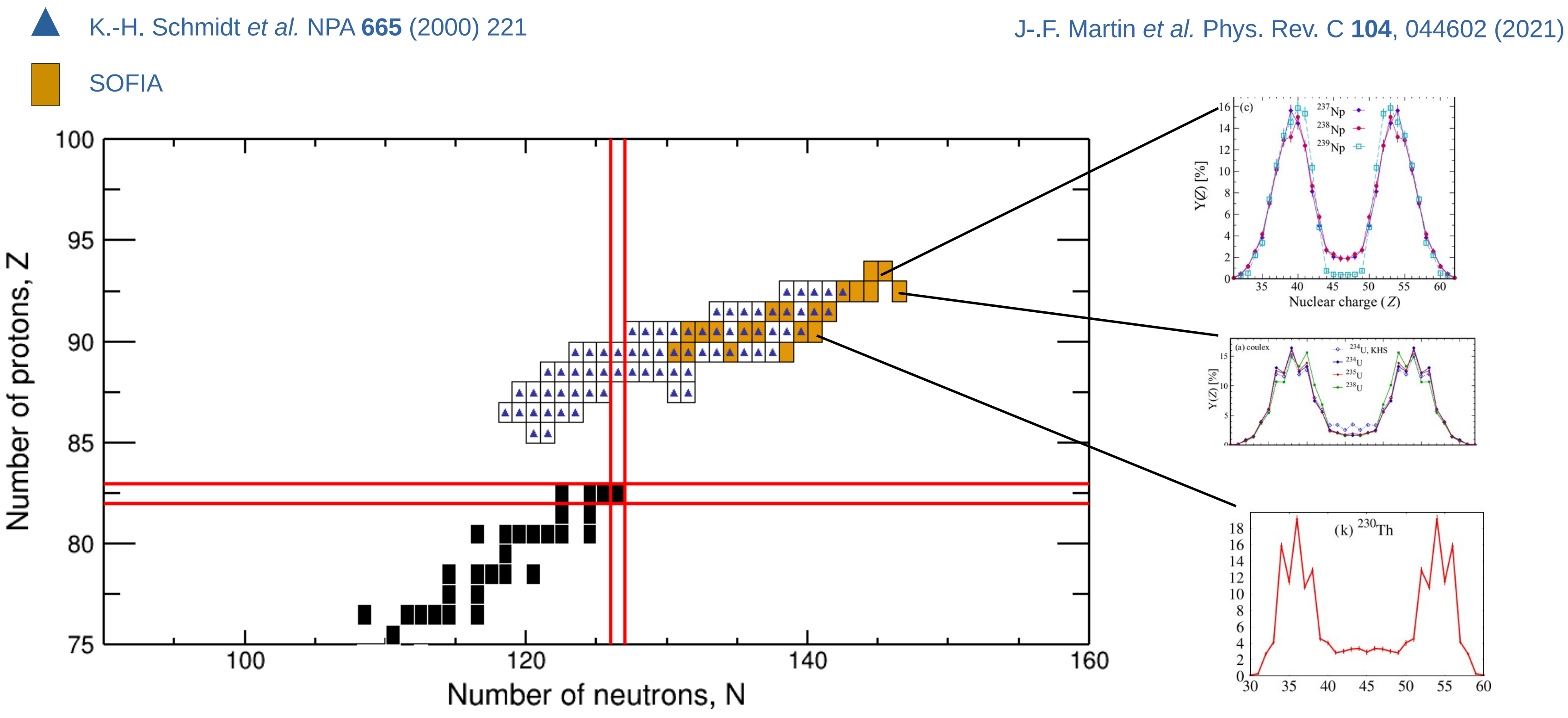


R^{3}B/SOFIA fission experiment goals

- Identification in charge and mass of the fissioning system (A_{CN}, Z_{CN}).
- Identification in charge and mass of the two fission fragments in coincidence.
- The measurement of fission fragment yields enable us to highlight the different fission modes
  - ✓ symmetric/asymmetric fission
  - ✓ Compacity at scission (neutron multiplicity)
  - ✓ What shell effects at stake thanks to the charge measurement.

- Important to test theoretical interactions
  - ✓ Precise data in the actinide region
  - ✓ Need new data in exotic regions (such as neutron-deficient region) to probe the isospin dependence of the fission models.

Fission yields to probe fission modes



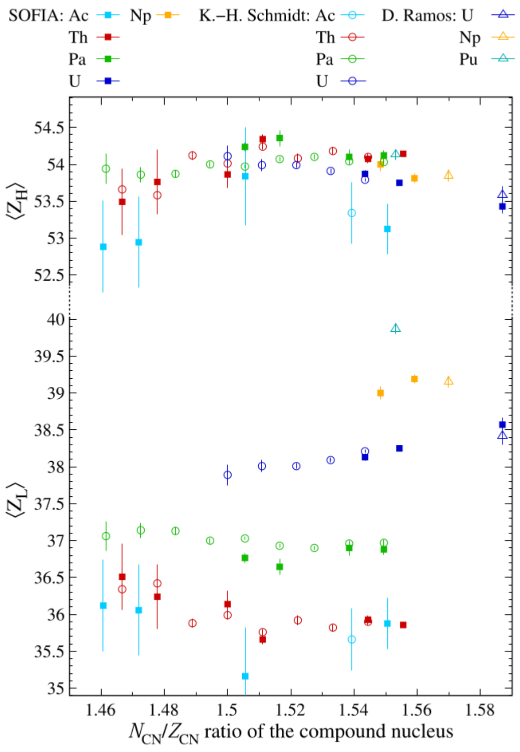
Fission yields to probe fission modes

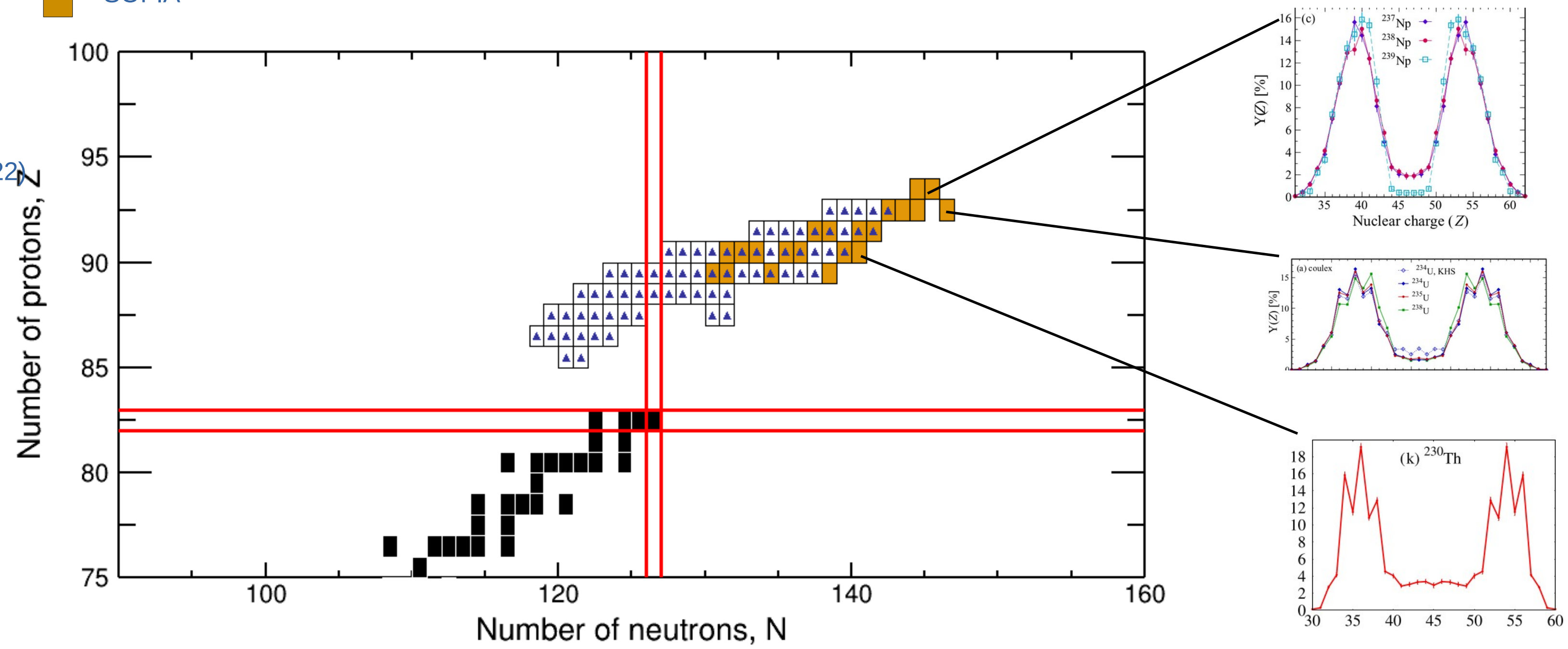
K.-H. Schmidt *et al.* NPA **665** (2000) 221

SOFIA

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

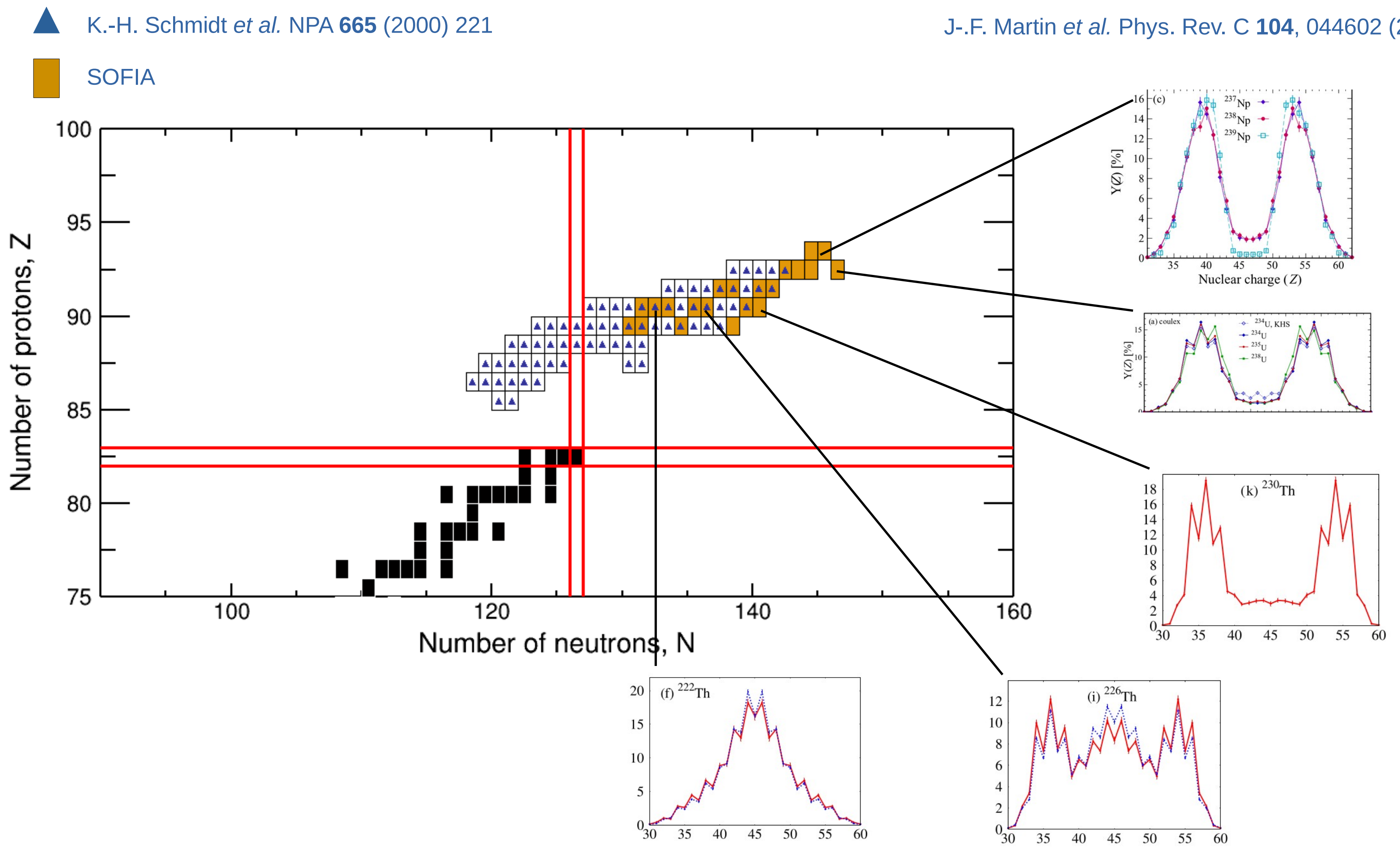
A. Chatillon *et al.* Phys. Rev. C **106**, 024618 (2022)





In this region : Z≈54 (Xe) stabilisation

Fission yields to probe fission modes



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

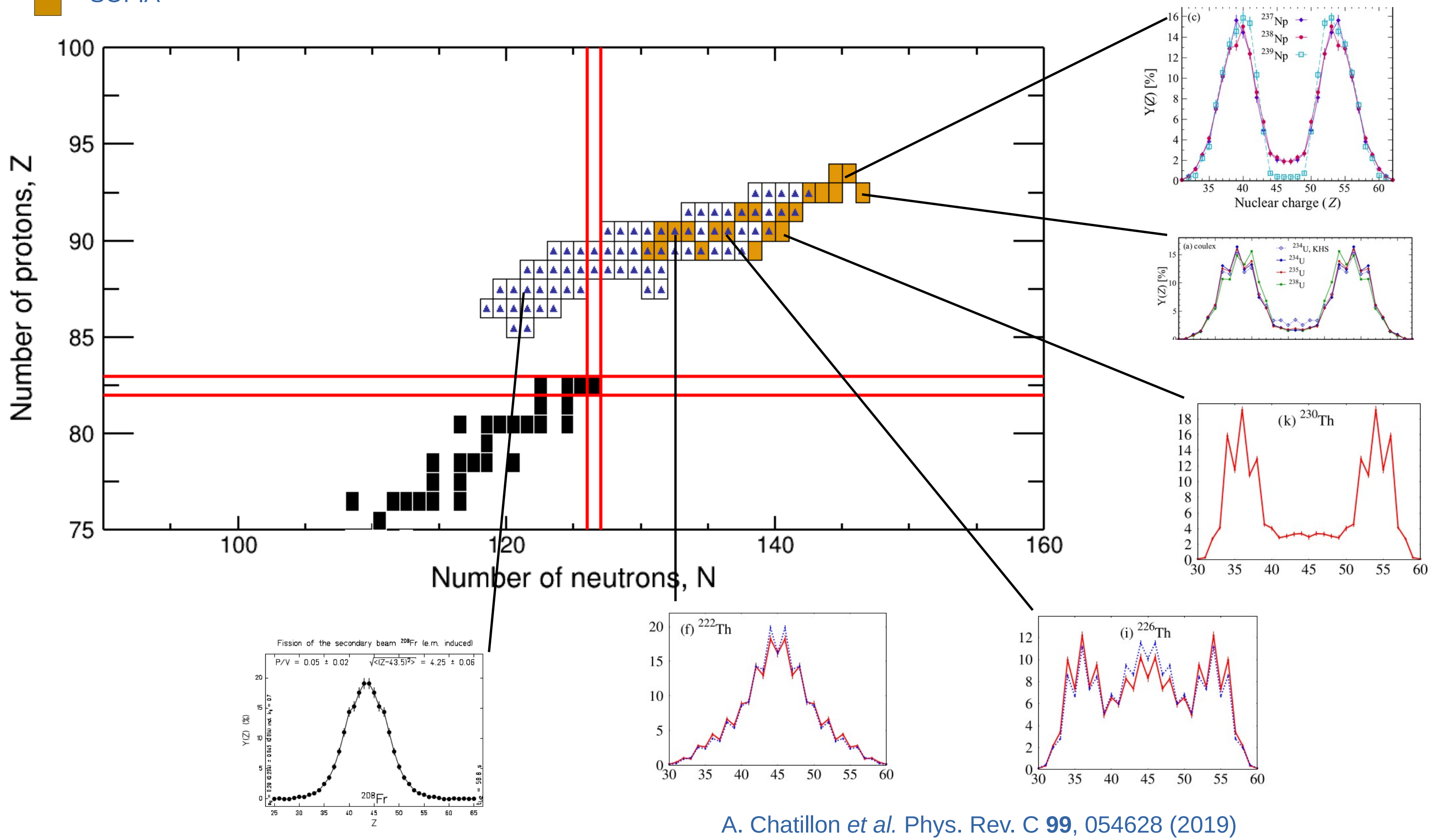
New symmetric compact fission mode.

Fission yields to probe fission modes

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

A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)
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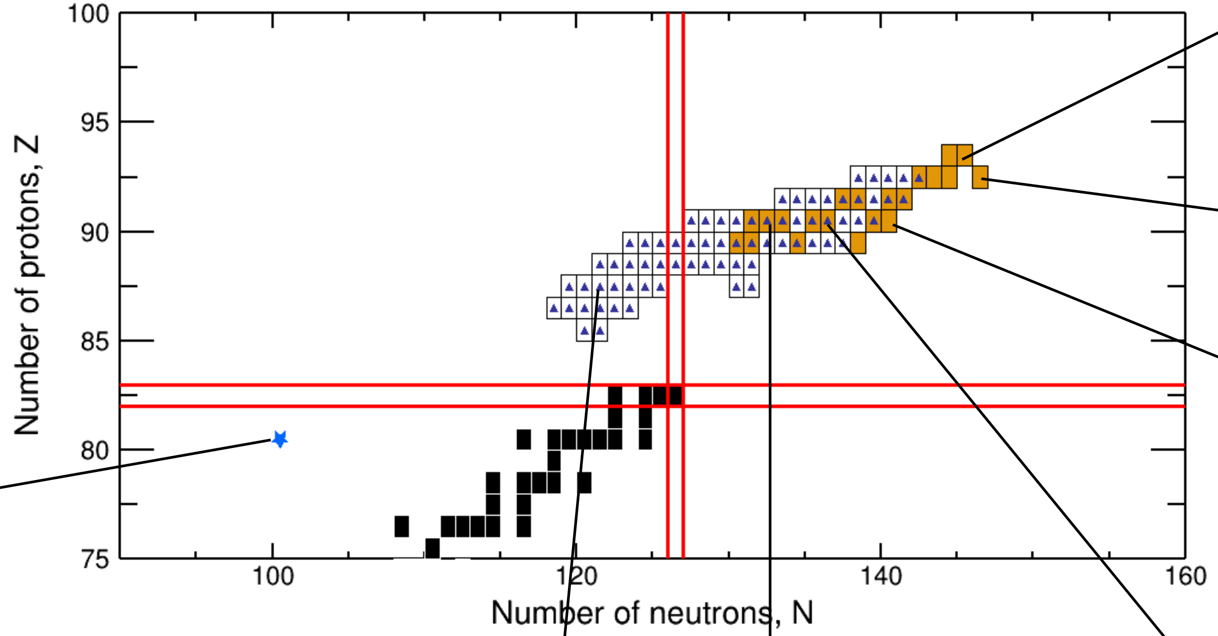
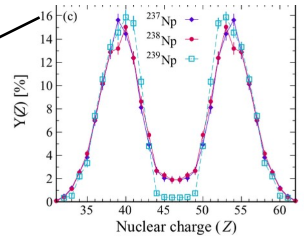
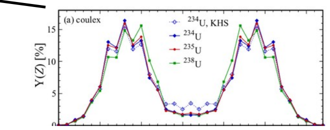
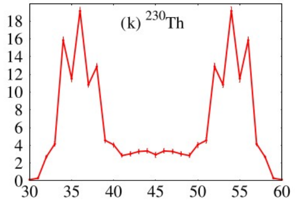
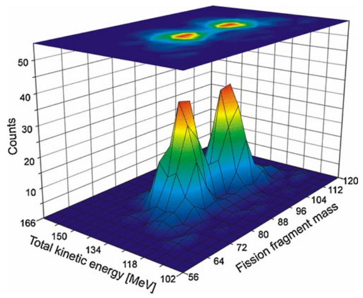


J.-F. Martin *et al.* Phys. Rev. C **104**, 044602 (2021)

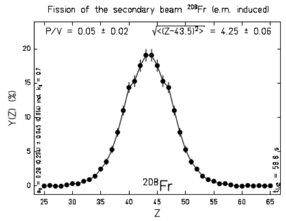




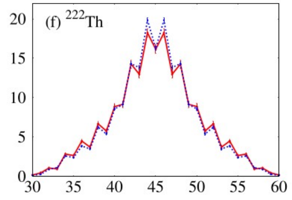


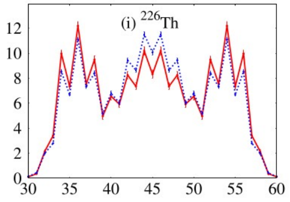


A. N. Andreyev *et al*. Phys. Rev. Lett. **105**, 252502 (2010)



S. Steinhauser *et al.* Thesis work

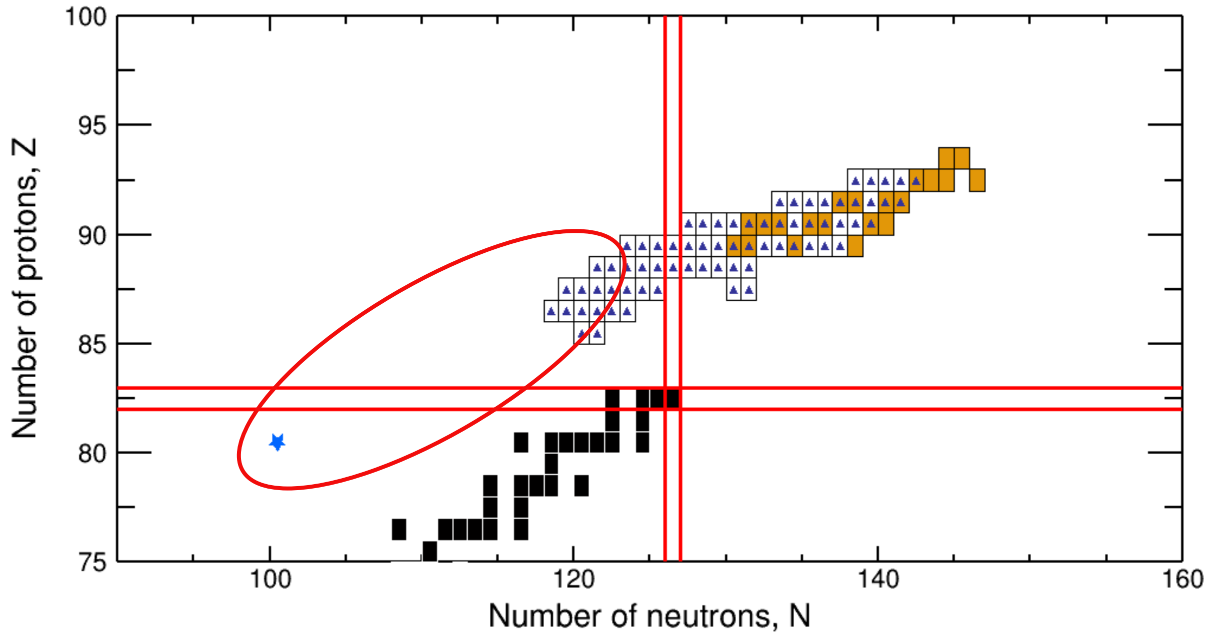




A. Chatillon *et al.* Phys. Rev. C **99**, 054628 (2019)
A. Chatillon *et al.* Phys. Rev. Lett. **124**, 202502 (2020)

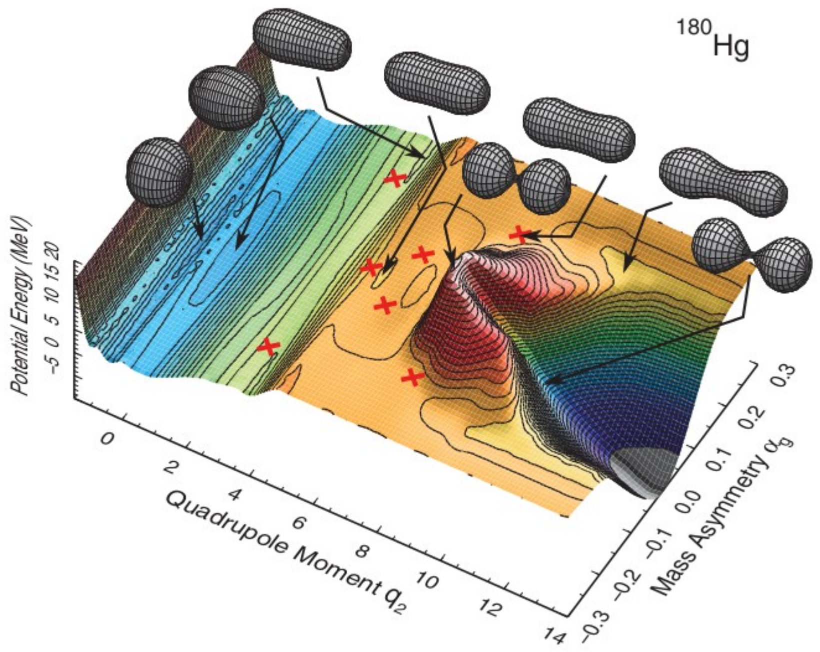
Fission yields to probe fission modes

A new island of asymmetric fission ?



- **What mechanism responsible of this new asymmetric split ?**
- **What shell effect ?**
- **What are the boundaries?**
- **...**

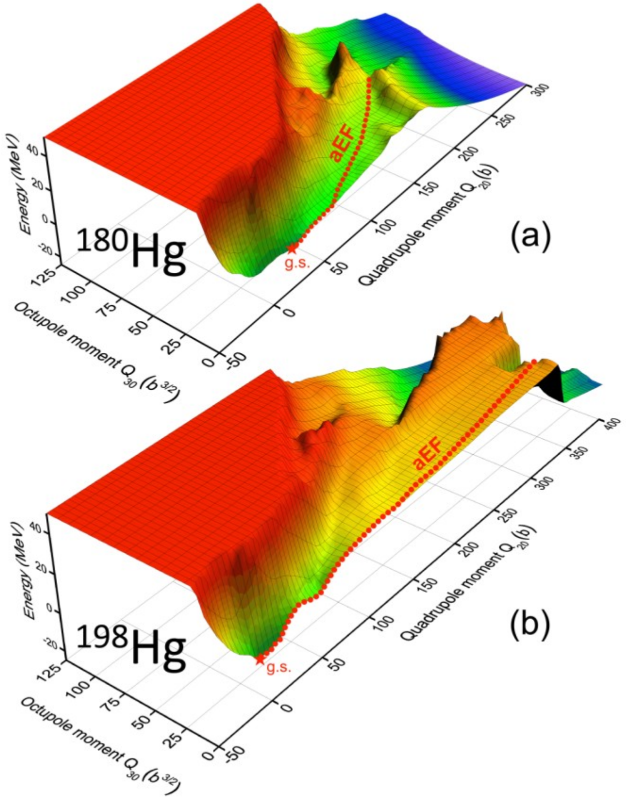
Trigged a lot of theoretical activities...



T. Ichikawa *et al.* Phys. Rev. C **86**, 024610 (2012)

Macro-micro calculations in a 5D space

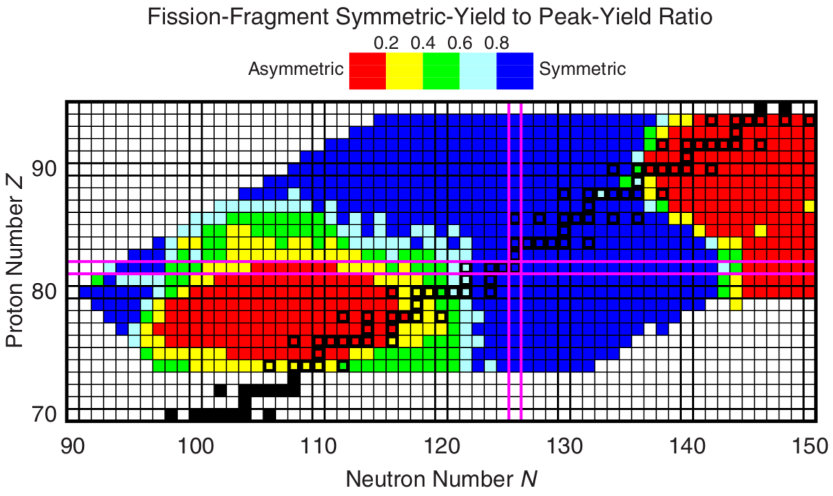
- Barrier blocked in the symmetric valley.
- Fission independent of structure effetc in the fragments?



M. Warda *et al.* Phys. Rev. C **86**, 024601 (2012)
J. D. McDonnell *et al.* Phys. Rev. C **90**, 021302(R) (2014)

- Mean field calculations using Skyrme SkM* or Gogny D1S interaction

Trigged a lot of theoretical activities…



PHYSICAL REVIEW C **85**, 024306 (2012)

Calculated fission yields of neutron-deficient mercury isotopes

Peter Möller,[1,*] Jørgen Randrup,[2] and Arnold J. Sierk[1]
[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 9 November 2011; revised manuscript received 12 January 2012; published 10 February 2012)

The recent unexpected discovery of asymmetric fission of ^{180}Hg following the electron-capture decay of ^{180}Tl has led to intense interest in experimentally mapping the fission-yield properties over more extended regions of the nuclear chart and compound-system energies. We present here a first calculation of fission-fragment yields for neutron-deficient Hg isotopes, using the recently developed Brownian Metropolis shape-motion treatment. The results for ^{180}Hg are in approximate agreement with the experimental data. For ^{174}Hg the symmetric yield increases strongly with decreasing energy, an unusual feature, which would be interesting to verify experimentally.

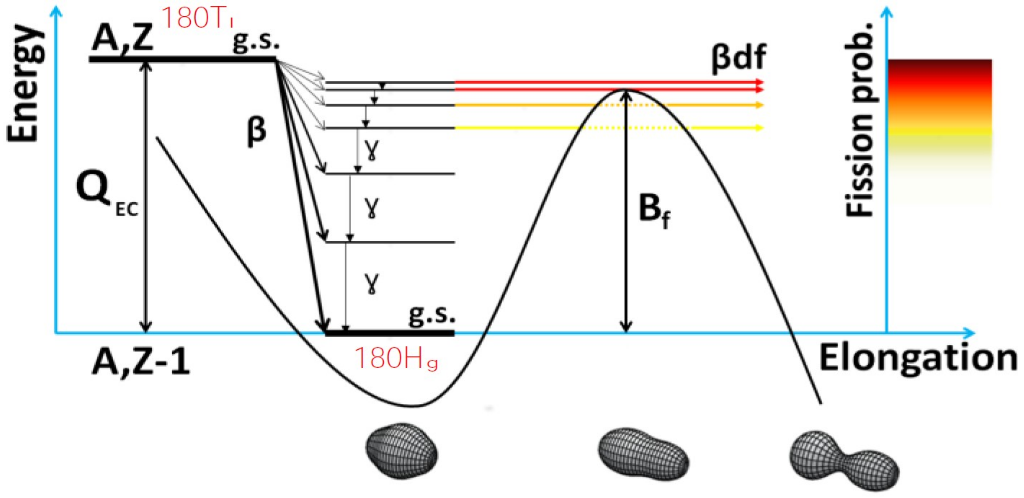
P. Moller *et al.* Phys. Rev. C **91**, 044316 (2015)
stochastic calculations giving a theoretical map of the evolution of the fission.

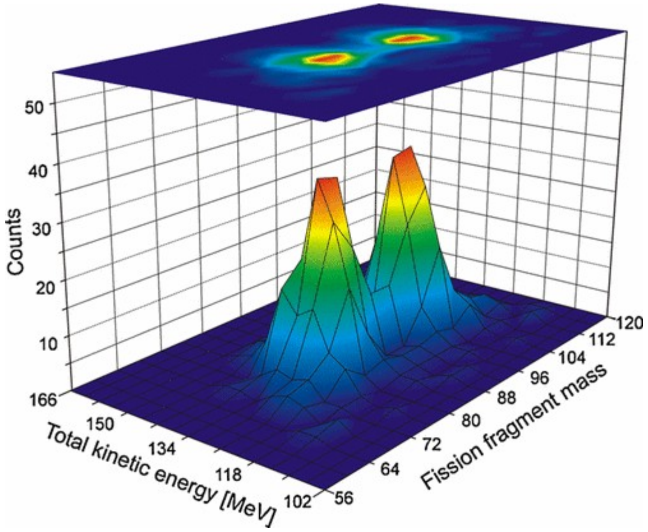
The models do not agree with each other
- **Independent of fragment structure effect?**
- **What are the limits?**

=> Need new data.

Trigged a lot of experimental activities

- **β-decay delayed fission**
  - Only a few nuclei accessible with this technique
  - We need $Q_{\beta} > B_f$
  - Probe low energy fission
  - Measure mass ratio M1/M2 only.



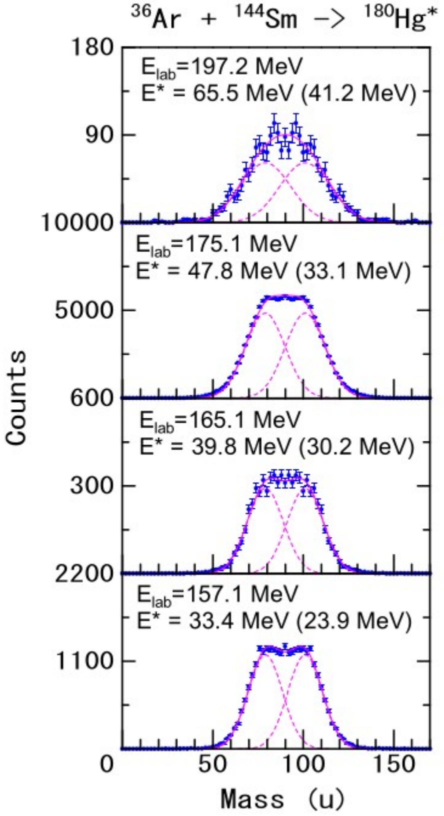


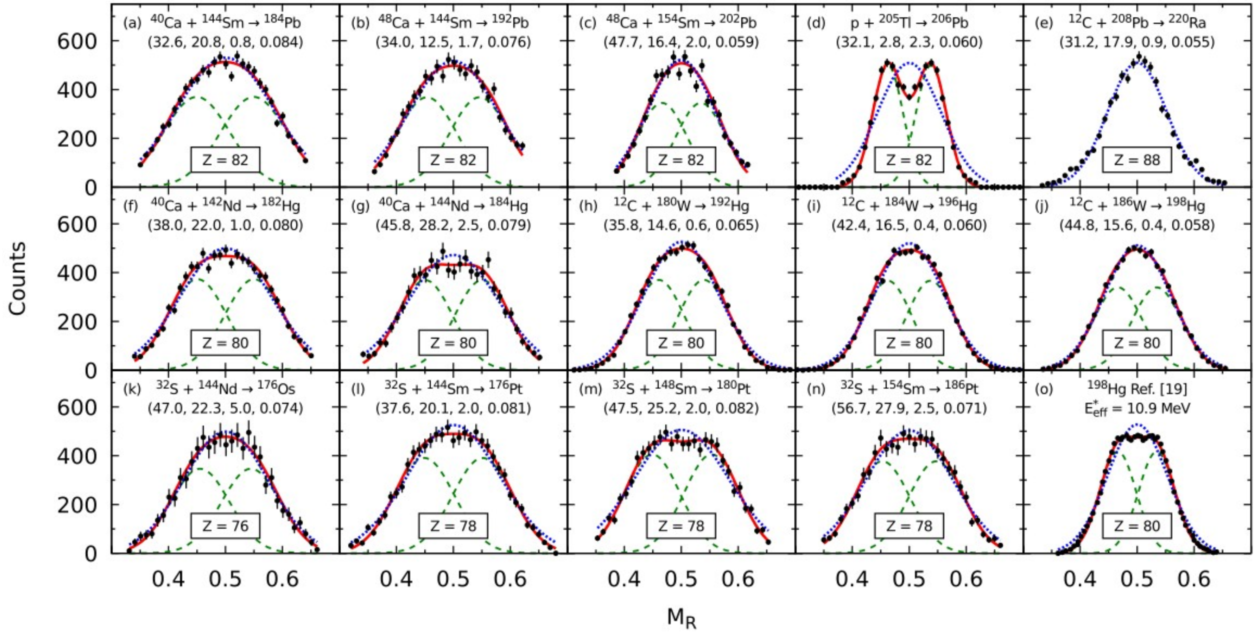
A. N. Andreyev *et al*. Phys. Rev. Lett. **105**, 252502 (2010)

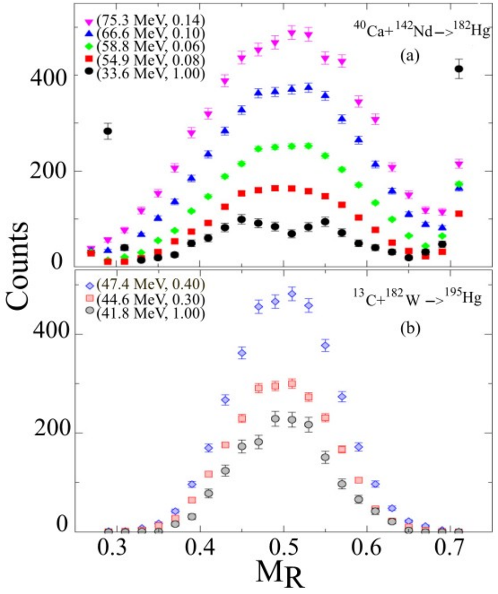
Trigged a lot of experimental activities

- **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)







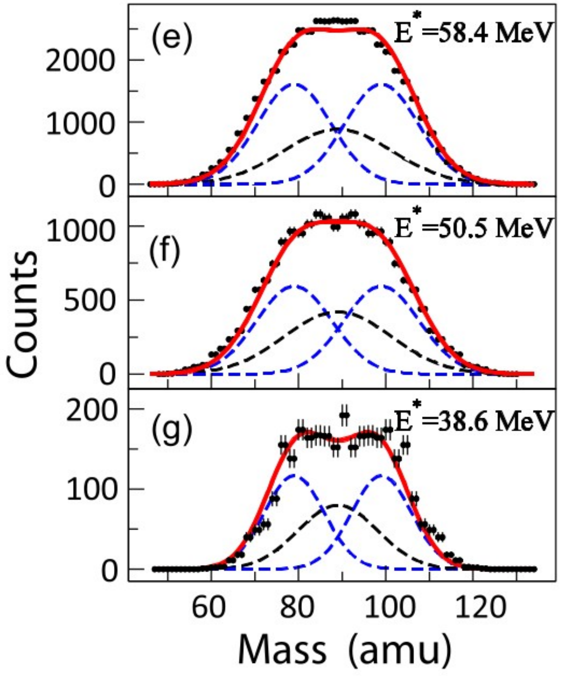
E. Prasad *et al.* Phys. Lett. B **811**, 135941 (2020)

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

Focus on fusion-fission experiments

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)

Focus on fusion-fission experiments

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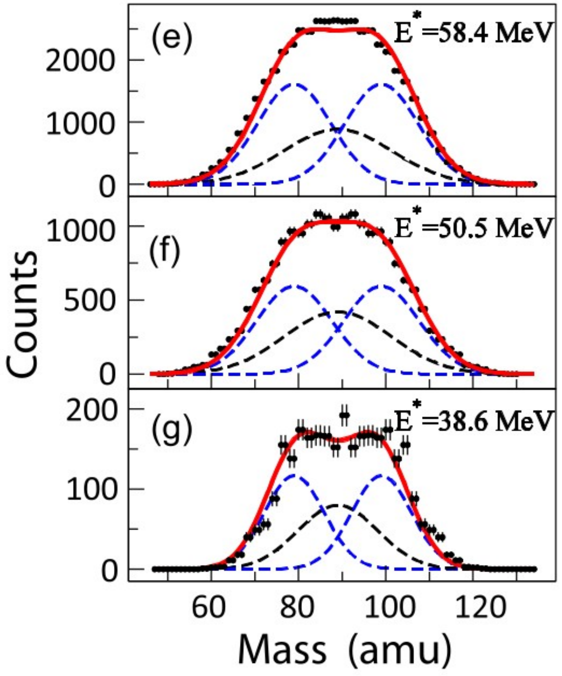
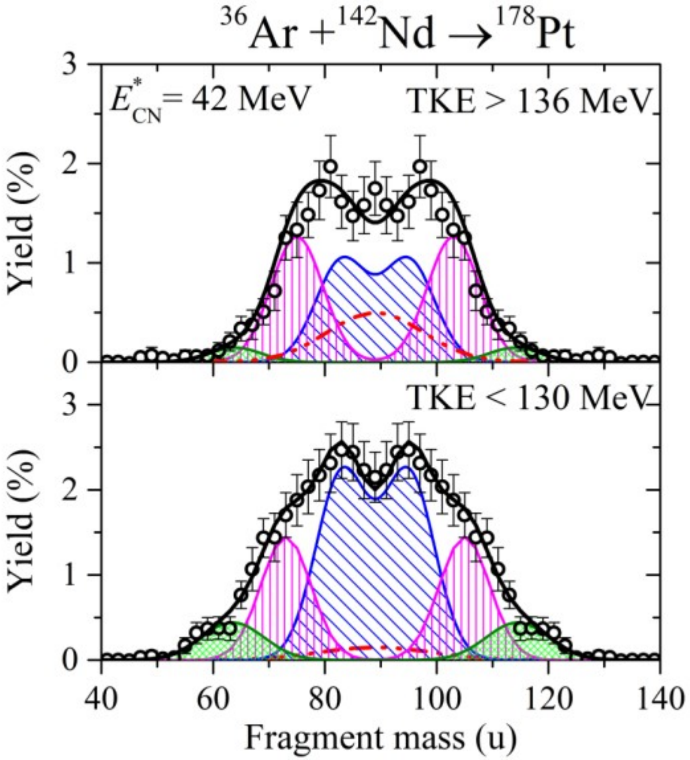


I. Tsekhanovich *et al.* Phys. Lett. B **790**, 583-588 (2019)

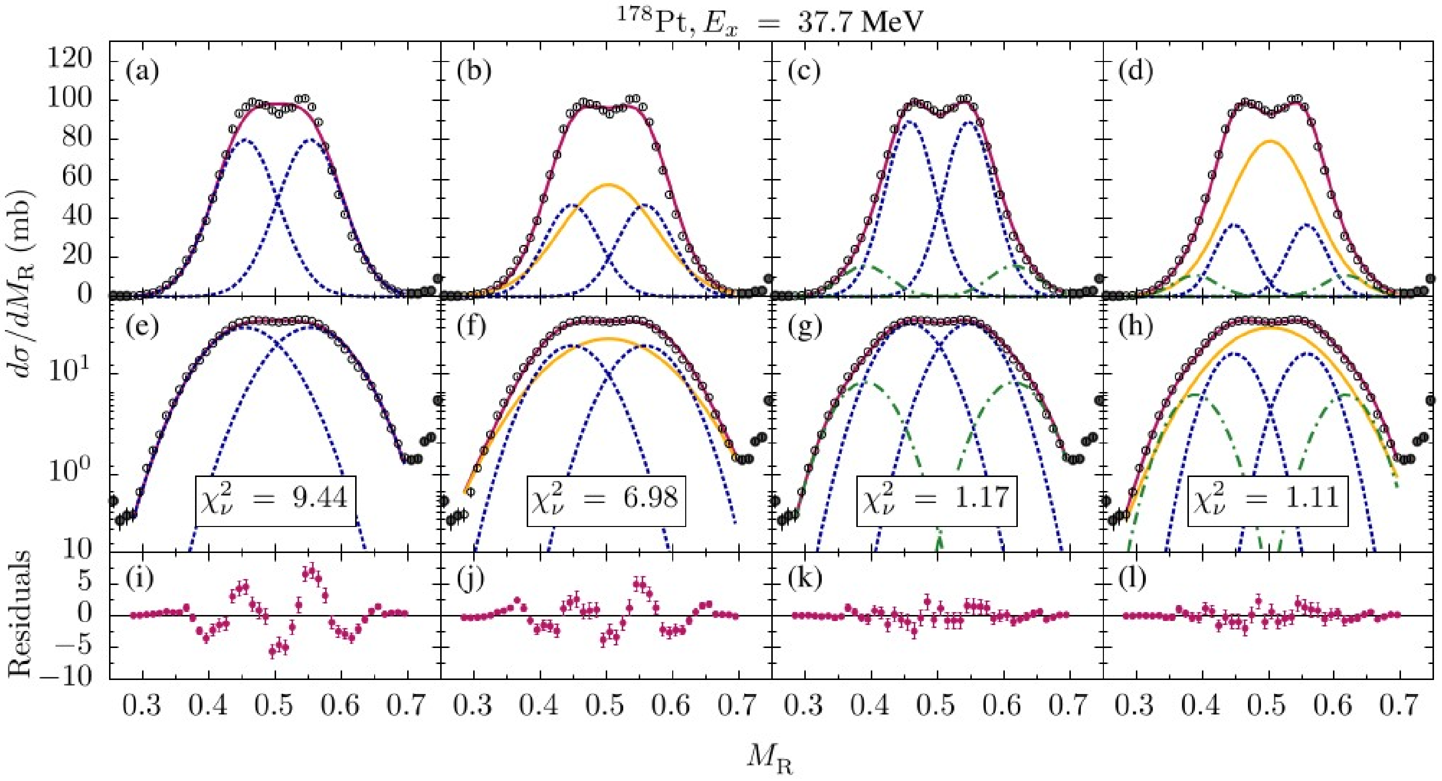
- Kozulin et al
  - ^{142}Nd target and ^{36}Ar beam at 172, 192 and 212 MeV at Dubna.
  - FFMD measured with CORSET spectromter → **Fitted with 4 modes.**



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

Focus on fusion-fission experiments

- Swinton-Bland 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. Swinton-Bland *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

Focus on fusion-fission experiments

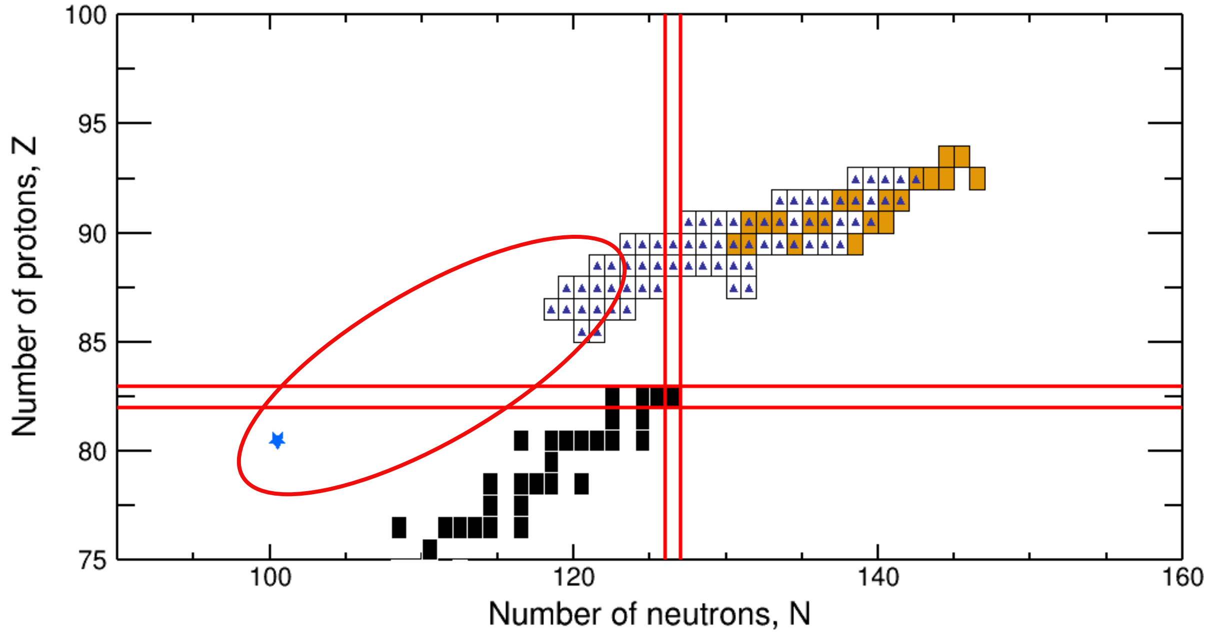
- Fusion-fission is an interesting tool to probe fission modes in neutron-deficent region.
- But only FFMD is measured with resolution of 3 to 5 uma.
- Large excitation energy => vanishing of structure effect.
- Gaussian fit to extract different fission modes (not easy).

✗ **Z information is missing, never measured.**

➔ **Charge distribution is important to understand the origin of this new asymmetric fission.**

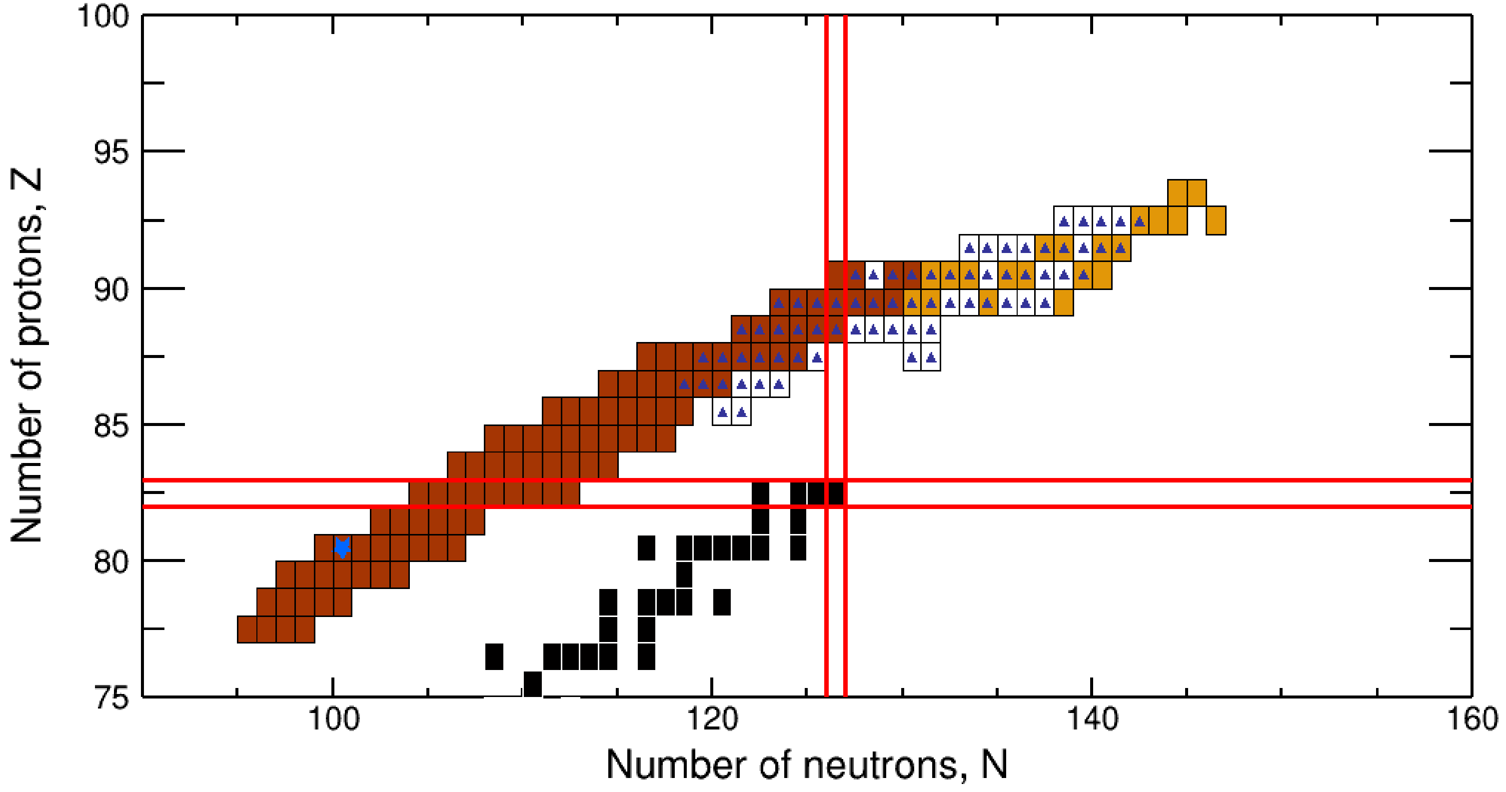
New R^3B/SOFIA experiment in 2021

Mapping this new asymmetric fission island



New R^3B/SOFIA experiment in 2021

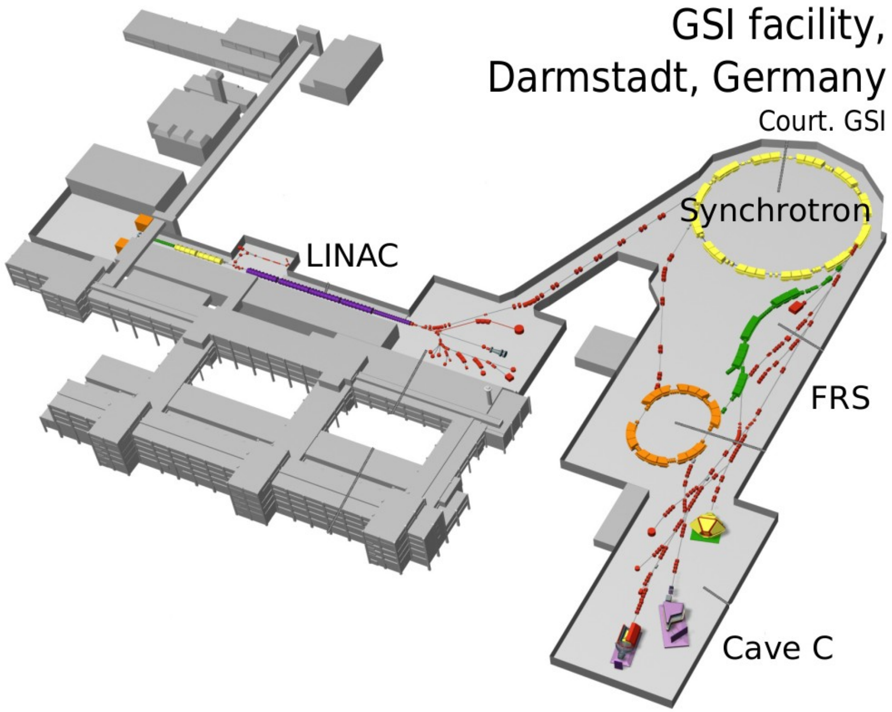
- **100 fissioning systems in one experiment !**
- **Establishing a connection between the neutron-deficient subleab region and the actinide region.**



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

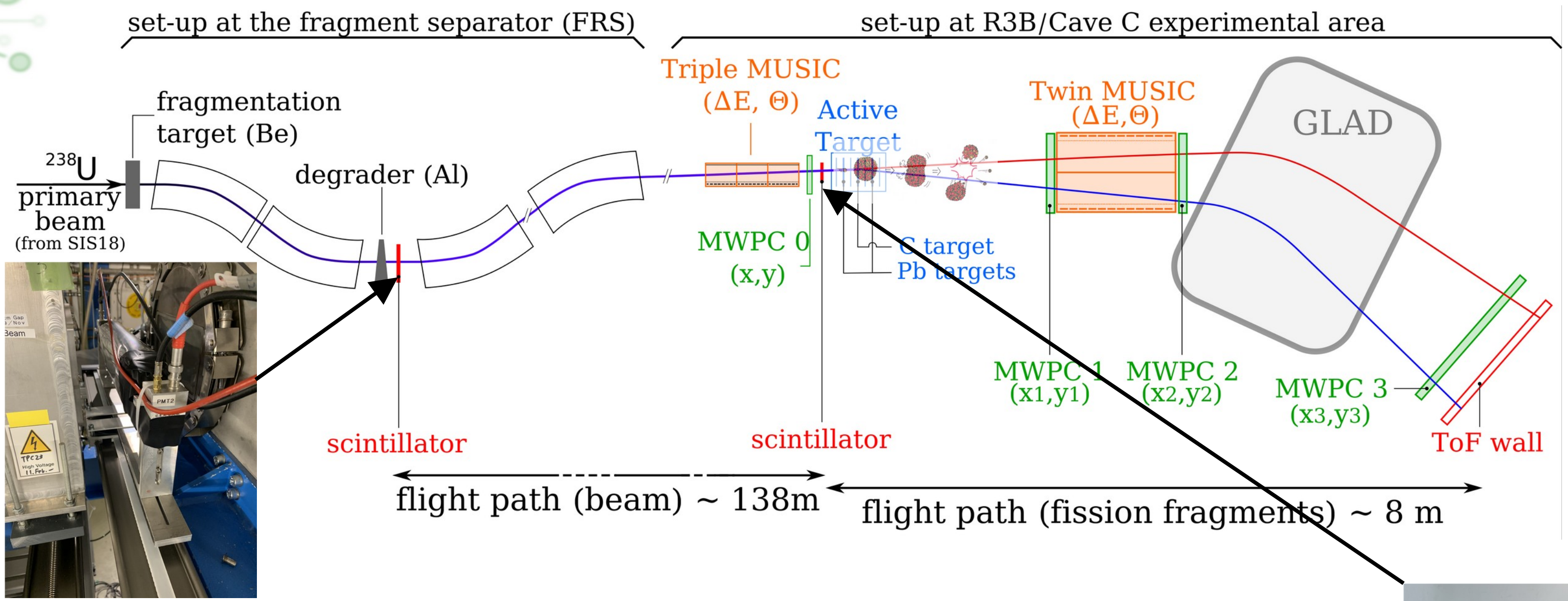
Inverse kinematics at GSI

New SOFIA campaign in 2021 to map the fission modes in the neutron-deficient region around lead.



- Primary beam of ^{238}U at 1 GeV/u.
- Production and identification of the secondary beam through the FRS.
- Fission in cave C and identification of both fission fragments
- 12 FRS settings from ^{175}Pt up to ^{221}Pa

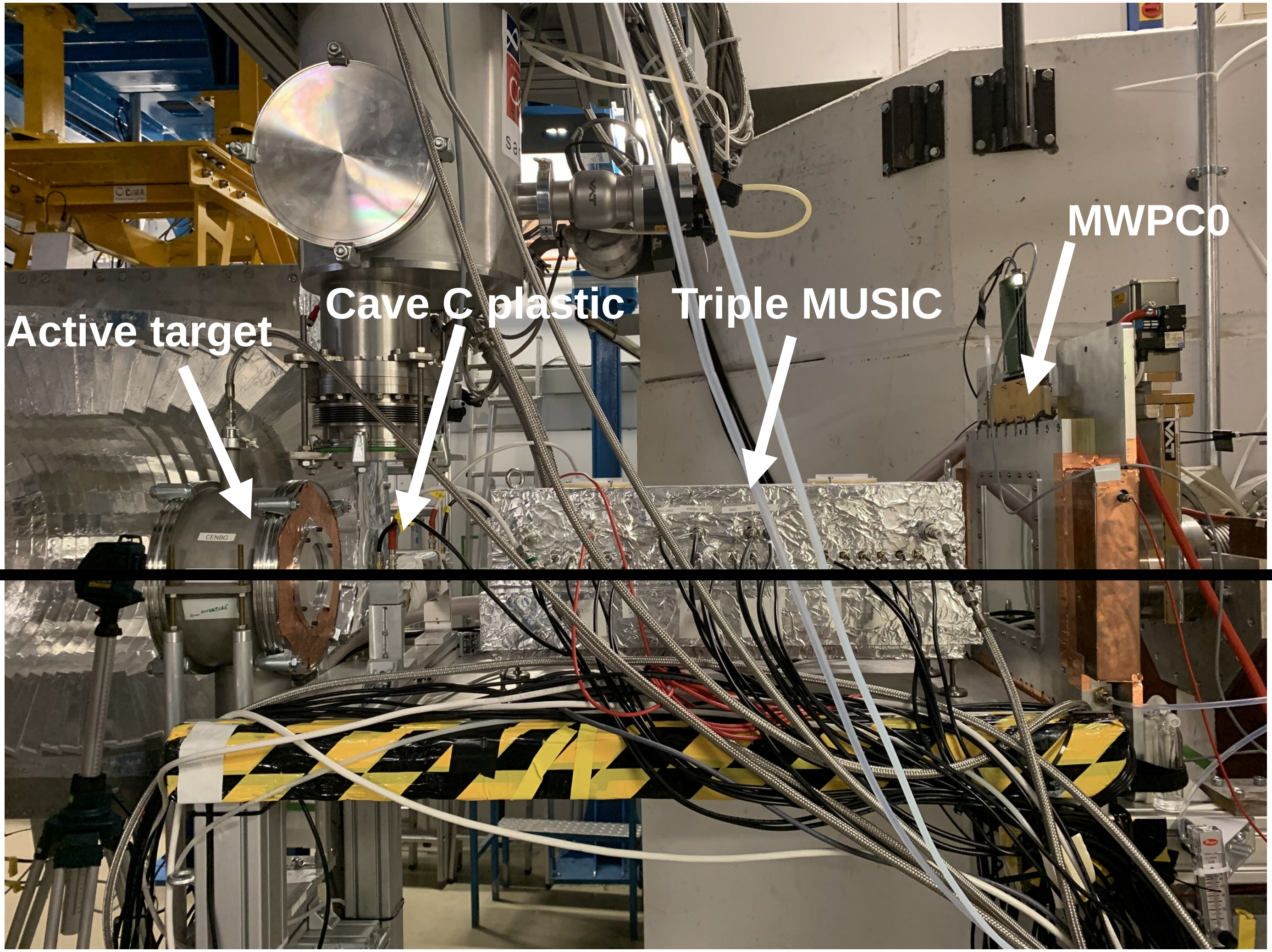
Experimental setup



- Plastic at S2 for time and position measurement.
- Plastic at Cave C for start and ToF.
- Triple-MUSIC for charge identification of the secondary beam.
- Active target with three cathodes (2 lead + 1 carbon) to induced fission.
- MWPC for (x,y) measurements of the beam and the fission fragments.
- Twim-MUSIC for charge identification of the fission fragments.
- Tof Wall frotime of flight of the fission fragments.

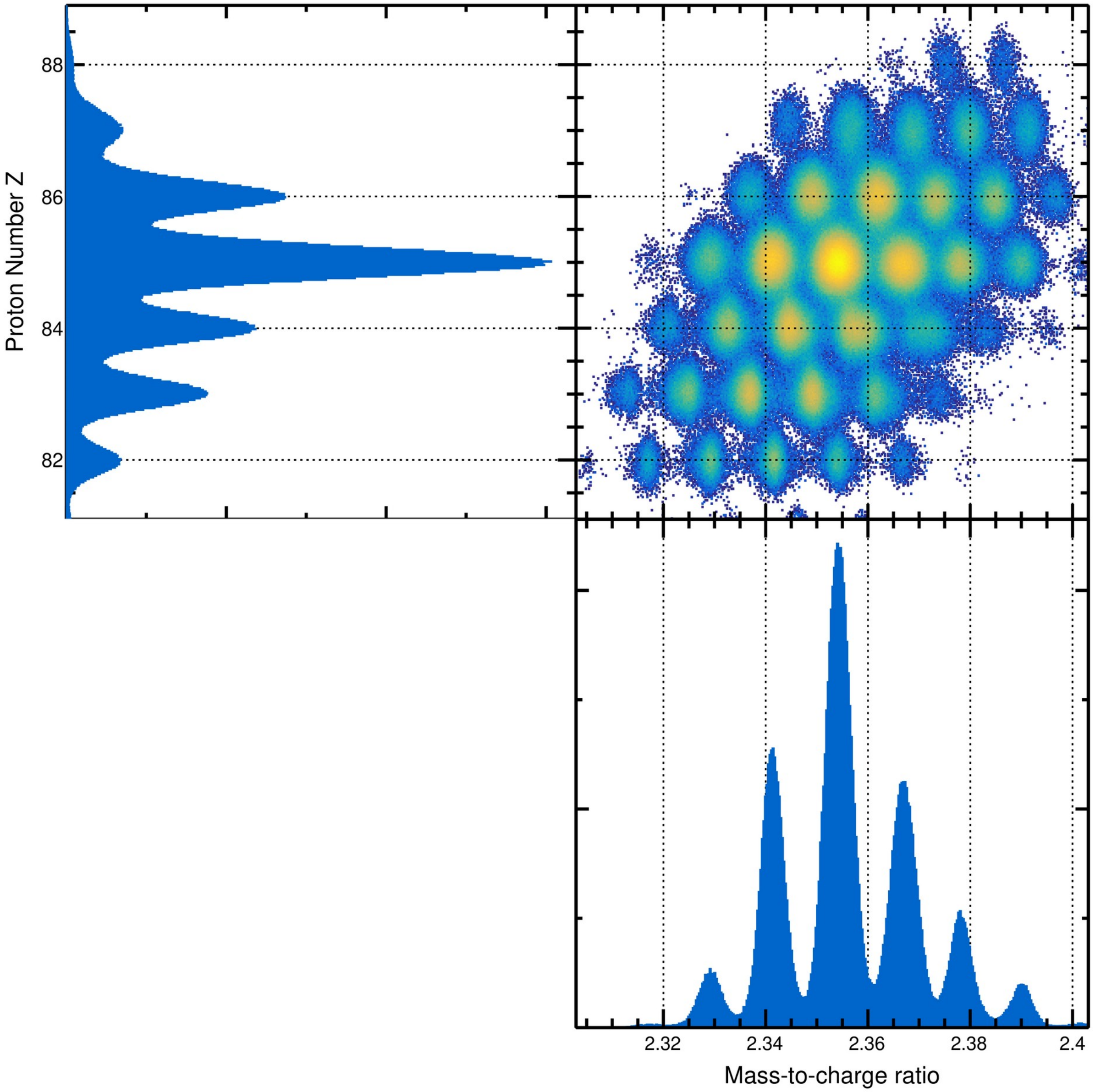
$$B\rho = B\rho_0(1 - X_{S2}/D_{S2})$$
$$A/Q = B\rho/(3.10716*\gamma*\beta)$$

Secondary beam identification

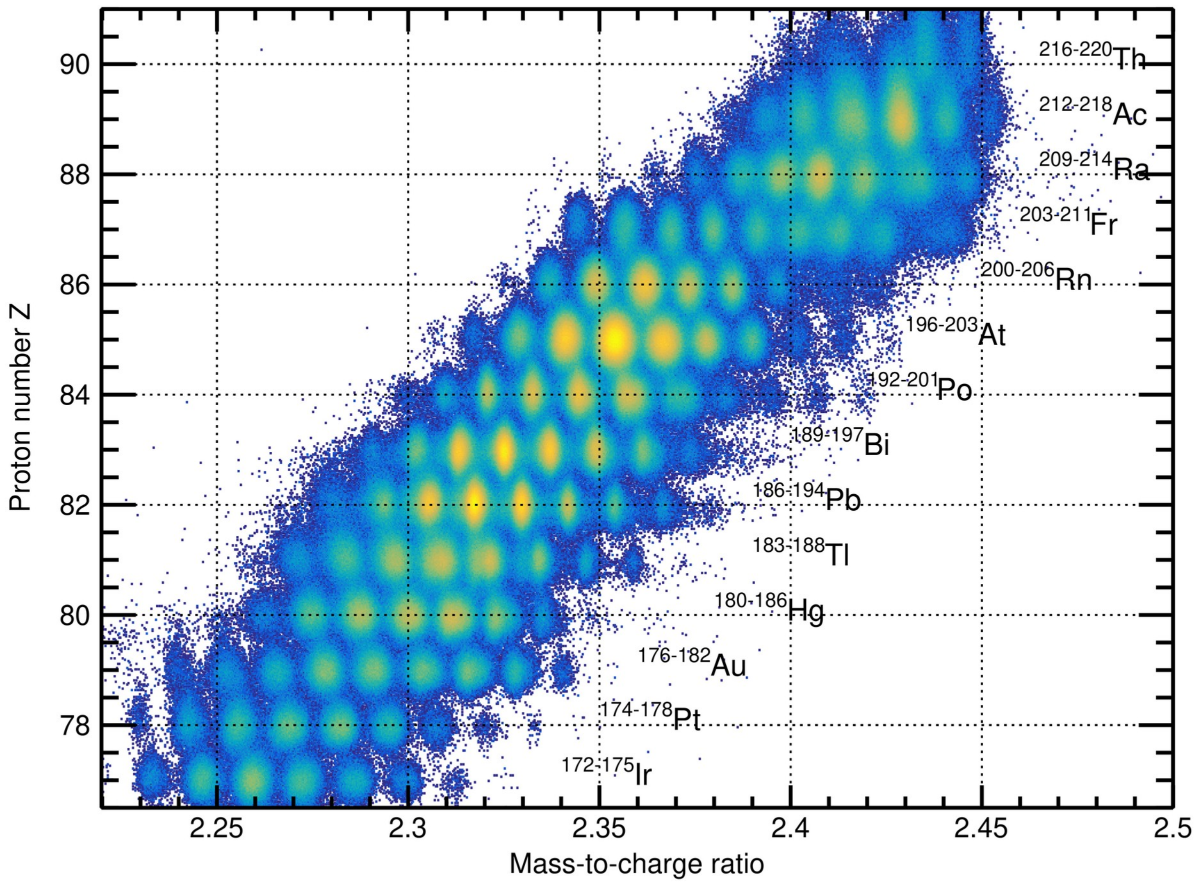


Secondary beam identification

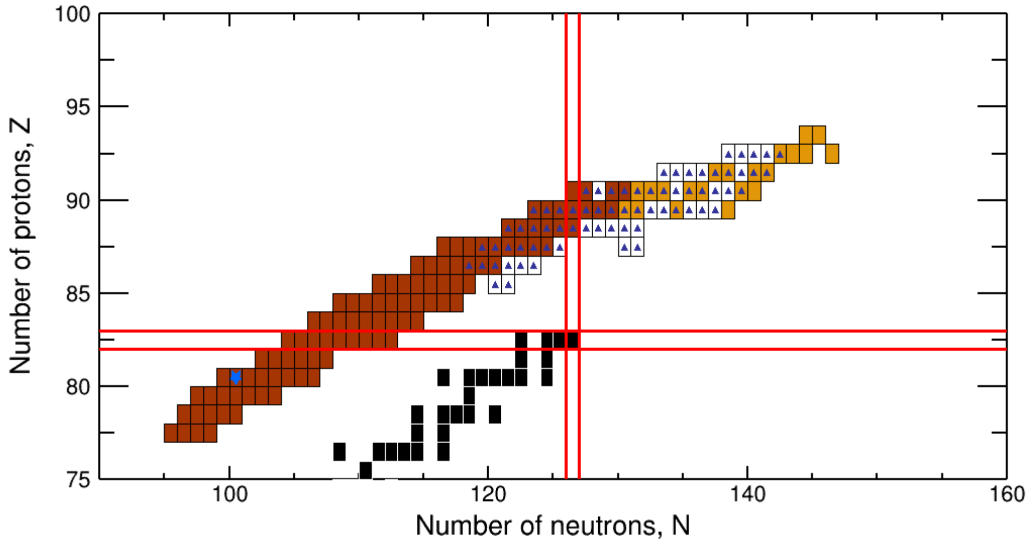
- Secondary beams produced around 700 MeV/u.
- Identified through the Brho – TOF – ΔE technique
- $\Delta A/A = 7.7\text{x}10^{-4} \rightarrow \Delta A = 0.14$ uma
- $\Delta Z/Z = 2.5\text{x}10^{-3} \rightarrow \Delta Z = 0.11$ charge unit



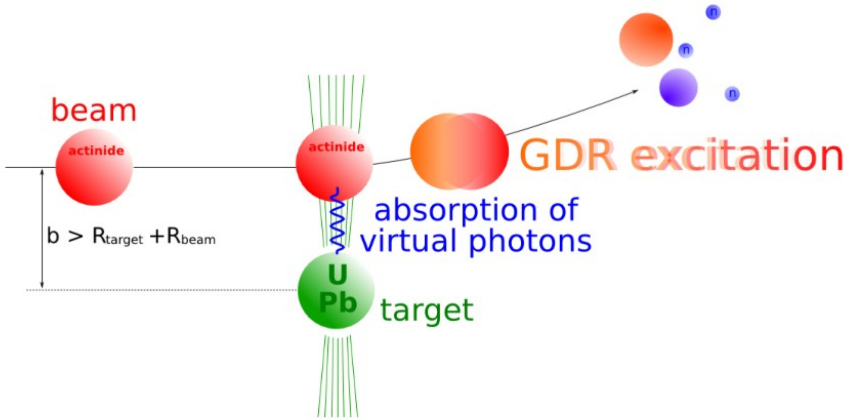
Global view of the studied systems

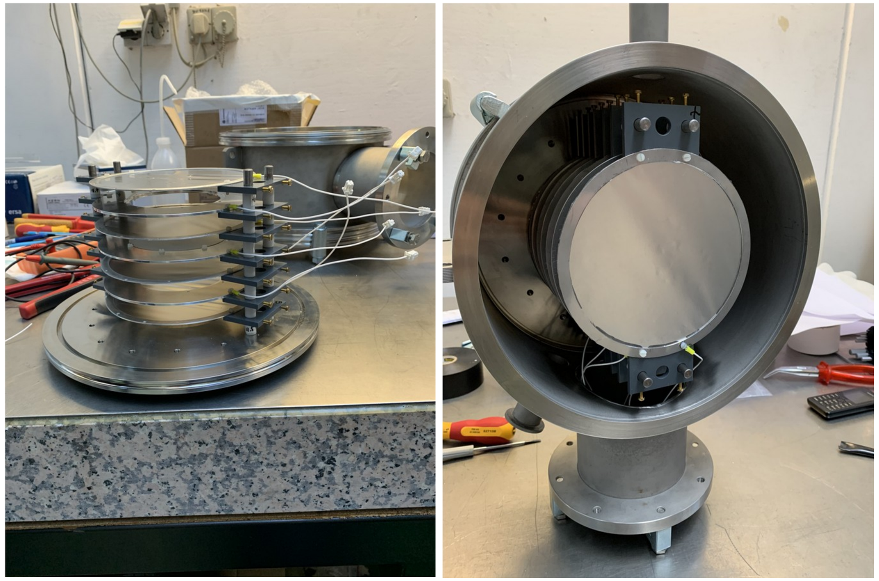


- 100 fissioning systems in one experiment
  - 12 FRS settings
  - From ^{175}Pt up to ^{220}Th
  - Very exotic systems
  - Bridge between the neutron-deficeint sub-lead region and the actinide region.

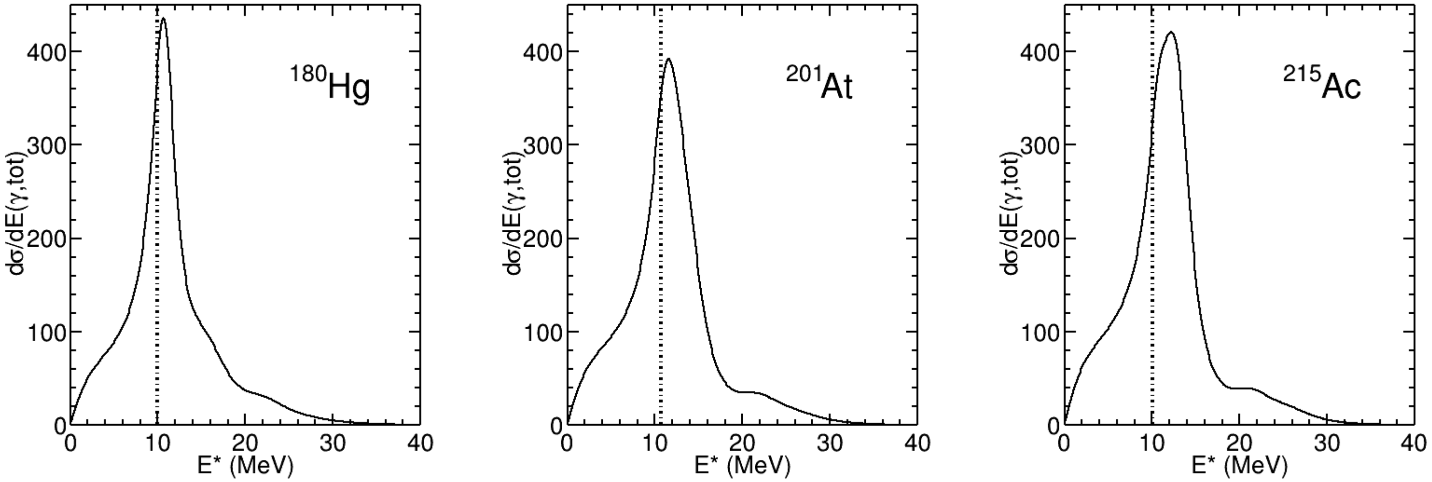


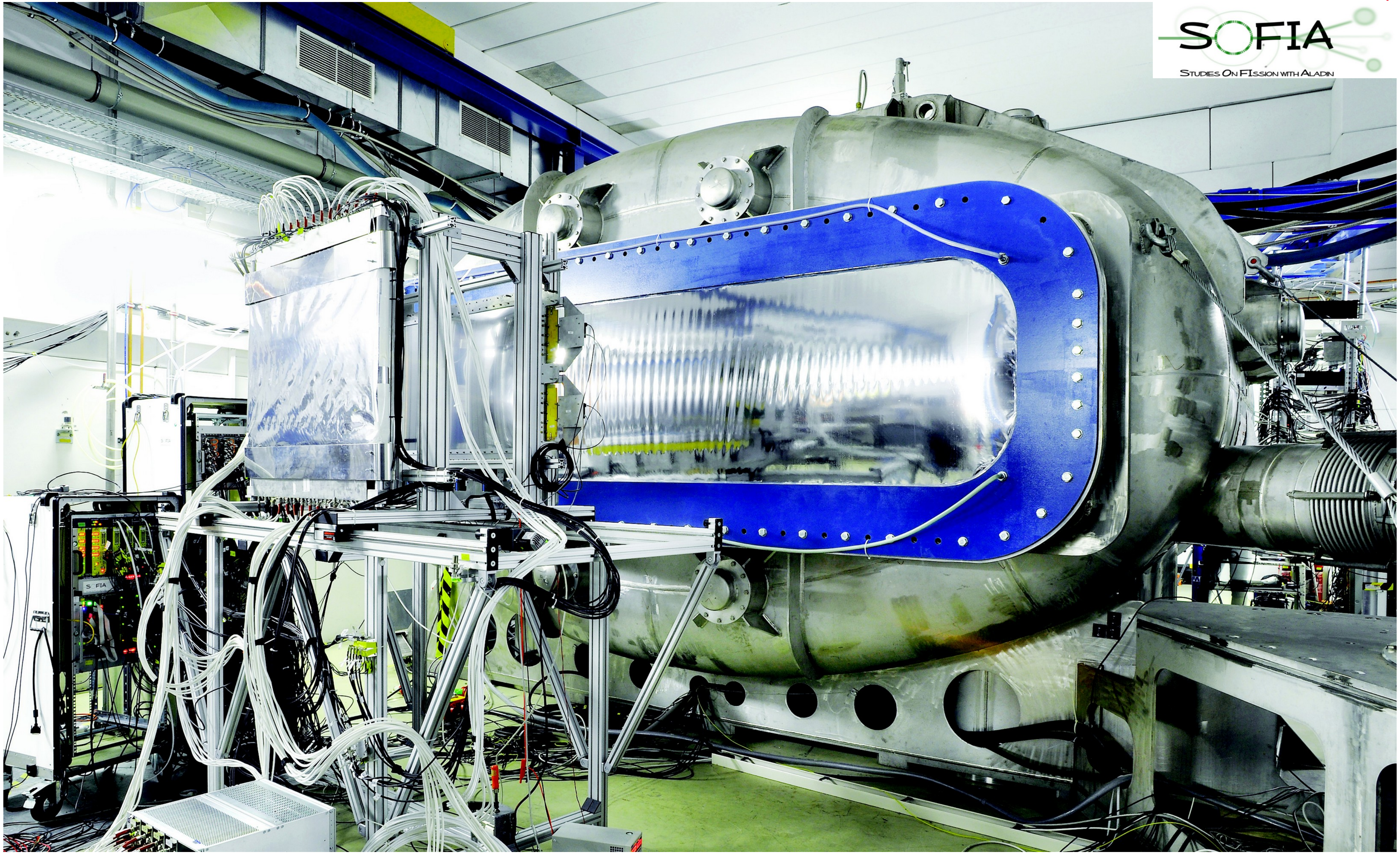
Coulomb induced fission at relativistic energies





- **Coulomb induced fission**
  - Large cross section (around de 3 barns)
  - <E*> around de 14 MeV (excitation mainly through the GDR) → Sensitive to shell effects
- **Active target**
  - 2 lead cathodes (1.5 mm thick)
  - 1 carbon cathode (0.5 mm thick) to subtract the nuclear contribution

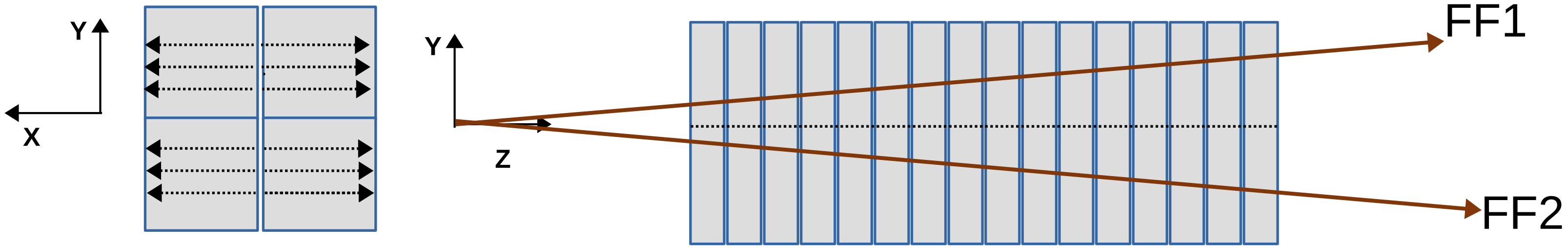


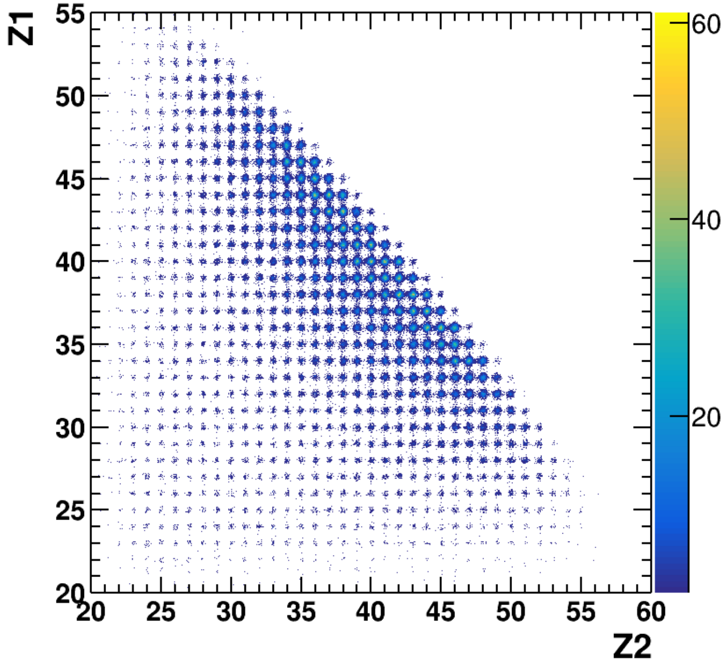

SOFIA
Studies On FIssion with ALADIN

Fission fragment charge identification

Twin MUSIC

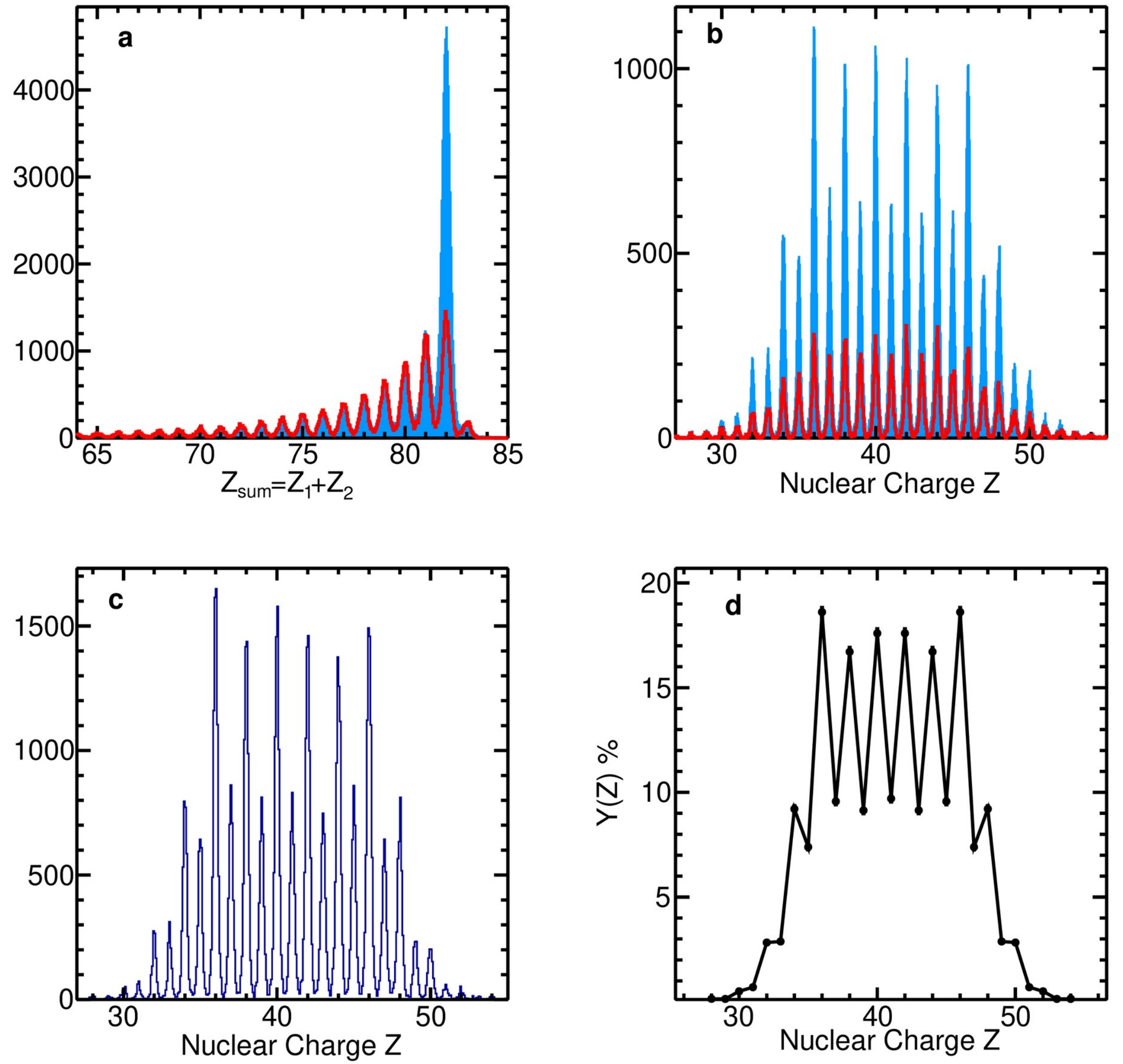
- 4 sections
- 16 anodes per section: $E_{section} = \Sigma^{16} \Delta E_i$
- Horizontal drift time.
  - ➔ X and θ measurement





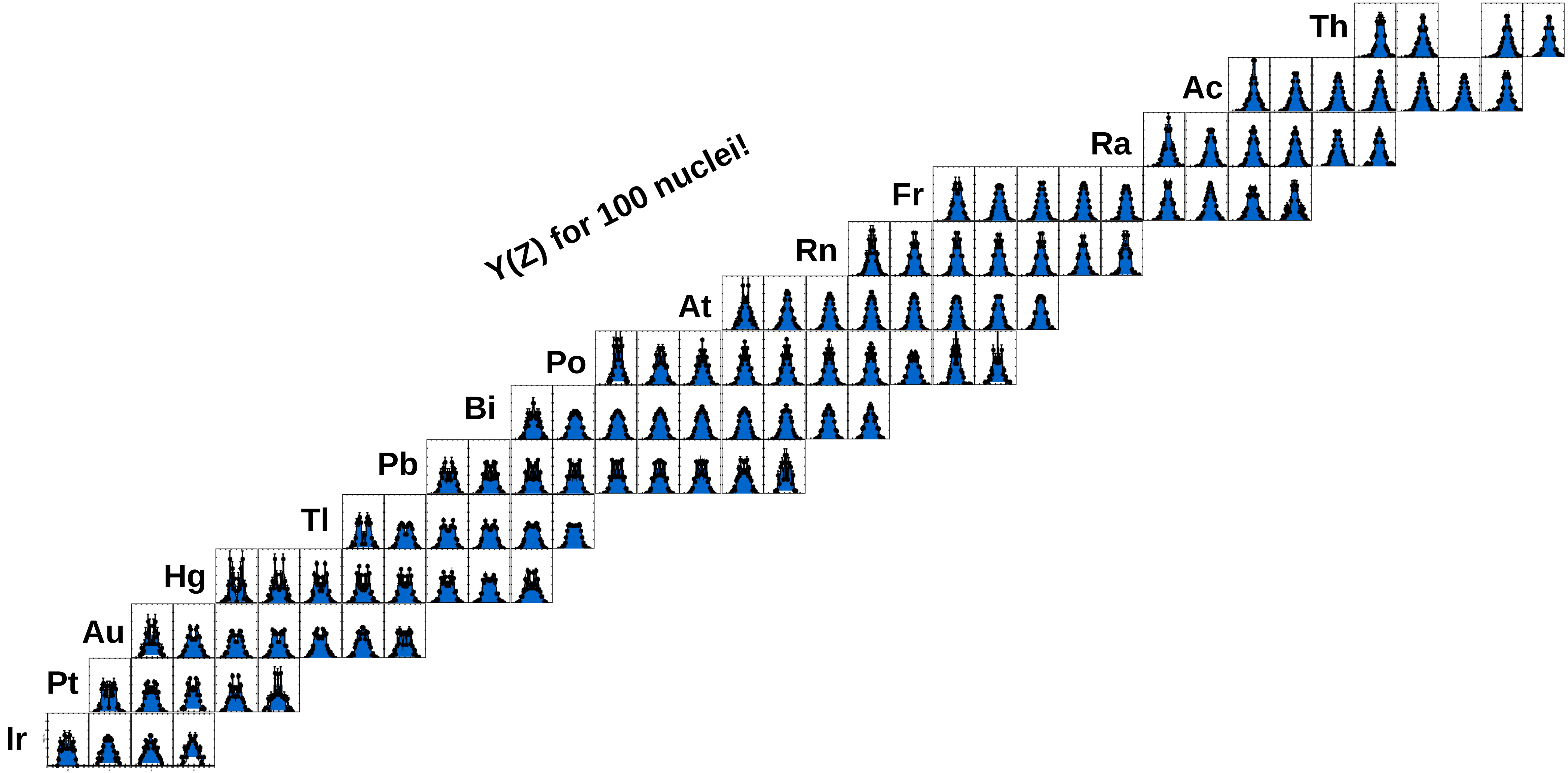
Fission fragment charge identification

- Selection of a fissioning system (here ^{190}Pb)
- Charge identification of both fission fragments in coincidence using the Twin-MUSIC.
- $Z_1 + Z_2 = Z_{beam}$
- When Z_1+Z_2 different from Z_{beam} → Nuclear excitation
- 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.

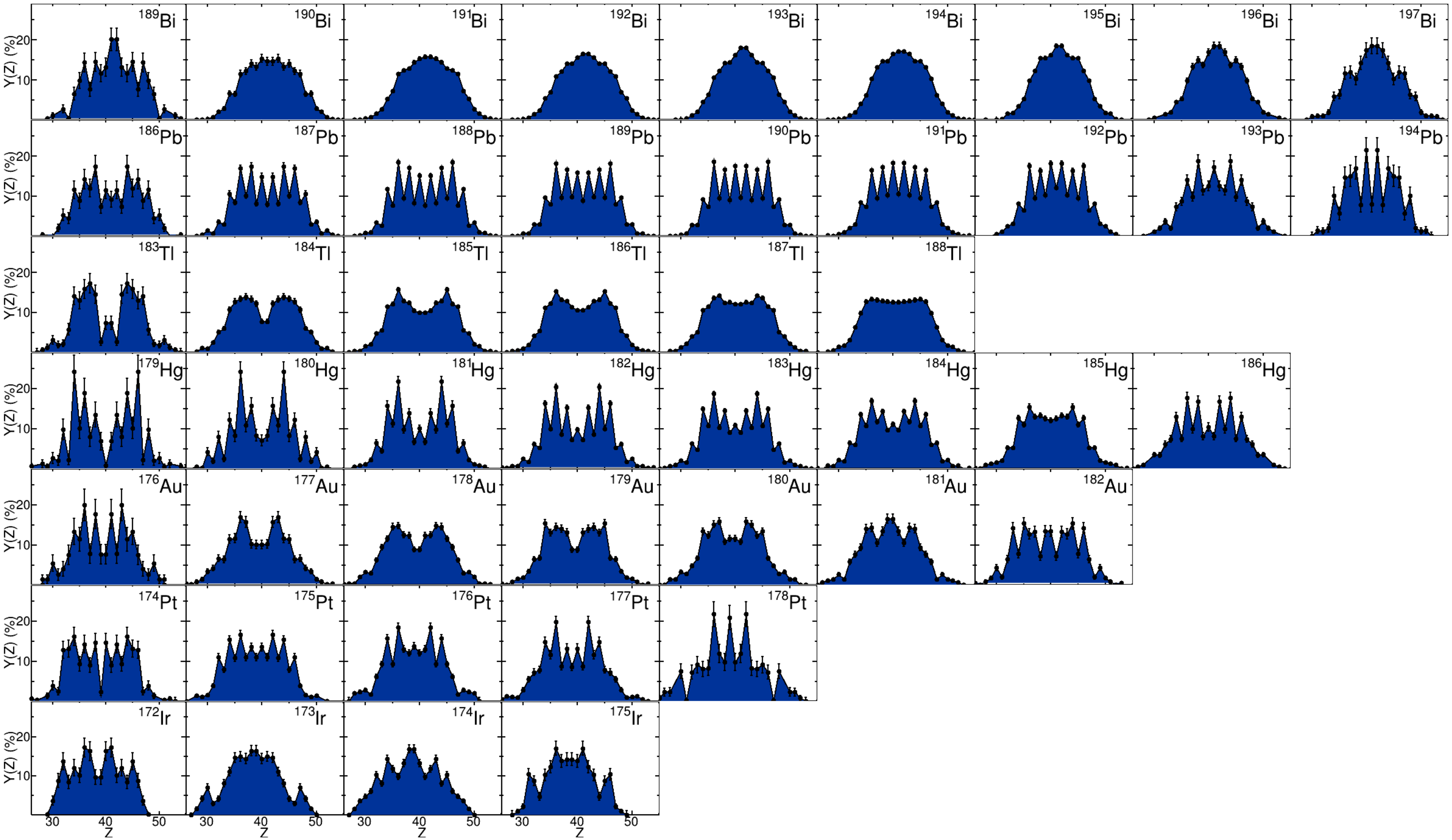


3. Results

Charge yields



Charge yields



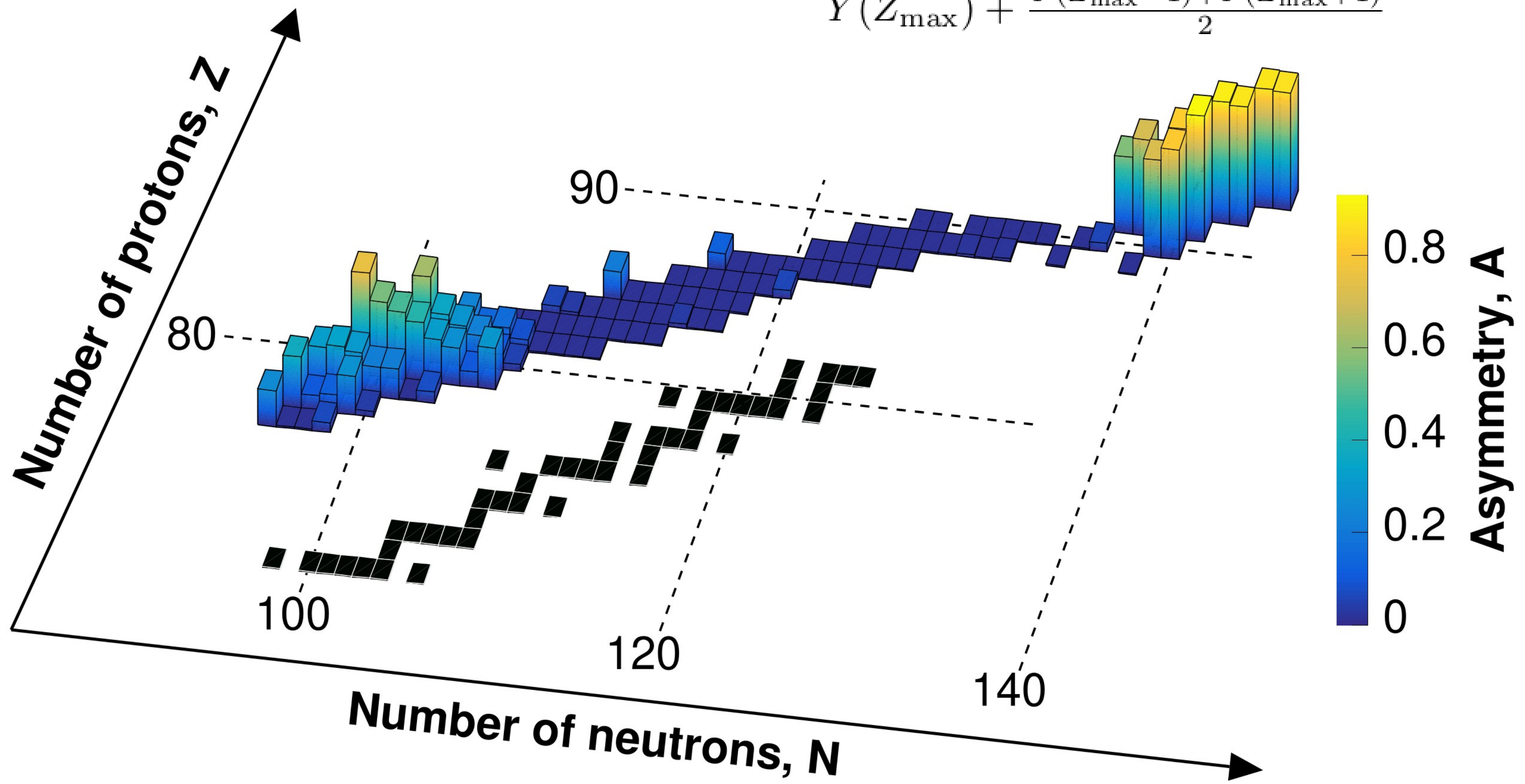
Asymmetry evolution

- Determination of an asymmetry variable to extract a global view of the evolution

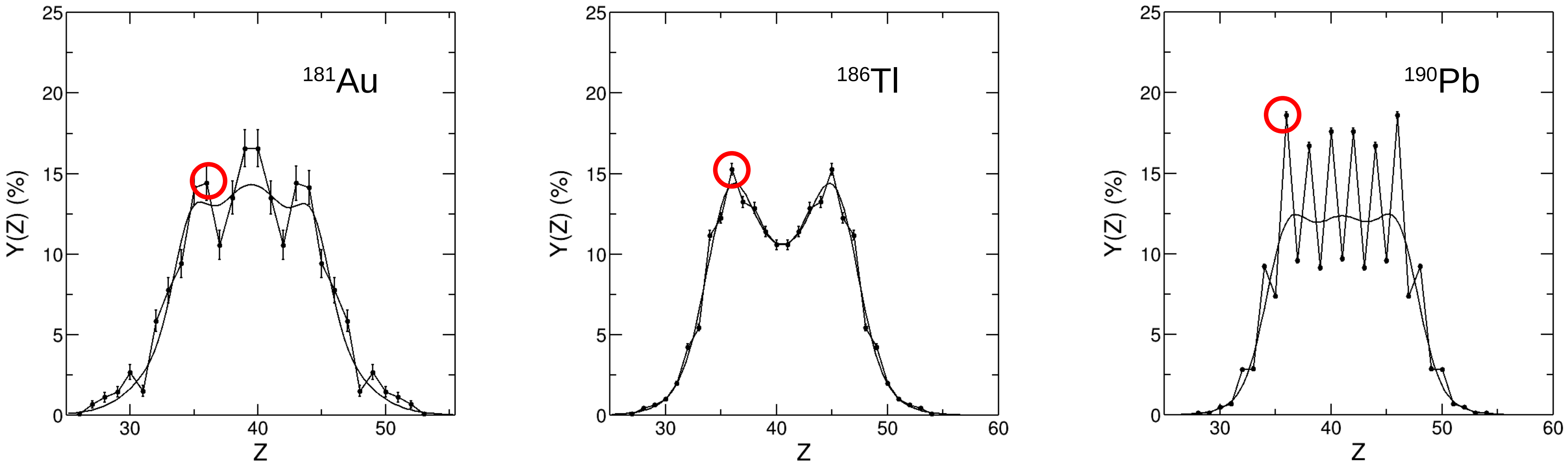
$$\mathcal{A} = 1 - \frac{Y(Z_{\mathrm{sym}}) + \frac{Y(Z_{\mathrm{sym}}-1)+Y(Z_{\mathrm{sym}}+1)}{2}}{Y(Z_{\mathrm{max}}) + \frac{Y(Z_{\mathrm{max}}-1)+Y(Z_{\mathrm{max}}+1)}{2}}$$

Asymmetry map

$$\mathcal{A} = 1 - \frac{Y(Z_{\rm sym}) + \frac{Y(Z_{\rm sym}-1)+Y(Z_{\rm sym}+1)}{2}}{Y(Z_{\rm max}) + \frac{Y(Z_{\rm max}-1)+Y(Z_{\rm max}+1)}{2}}$$

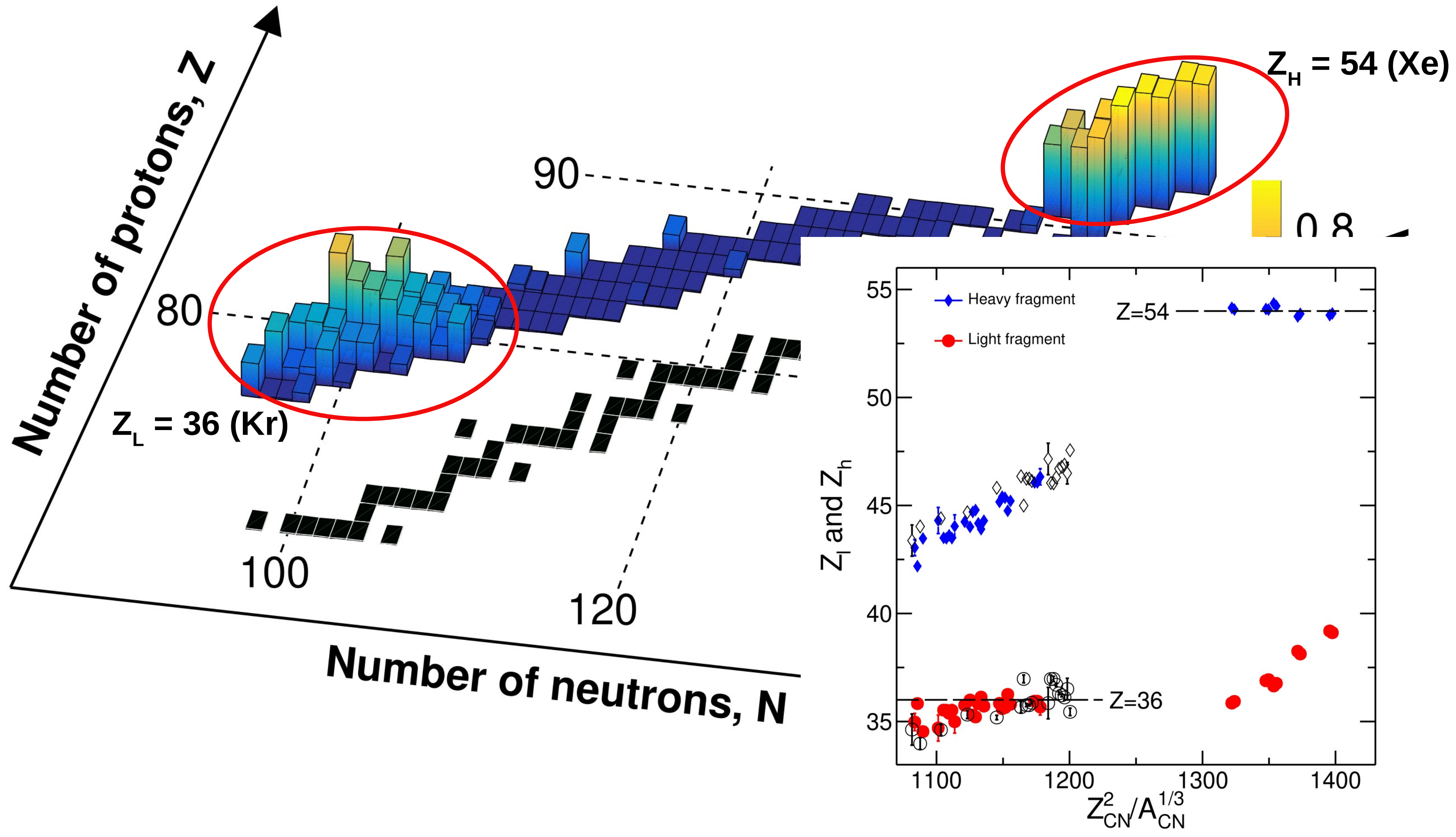


Z=36 stabilization in the light fragment

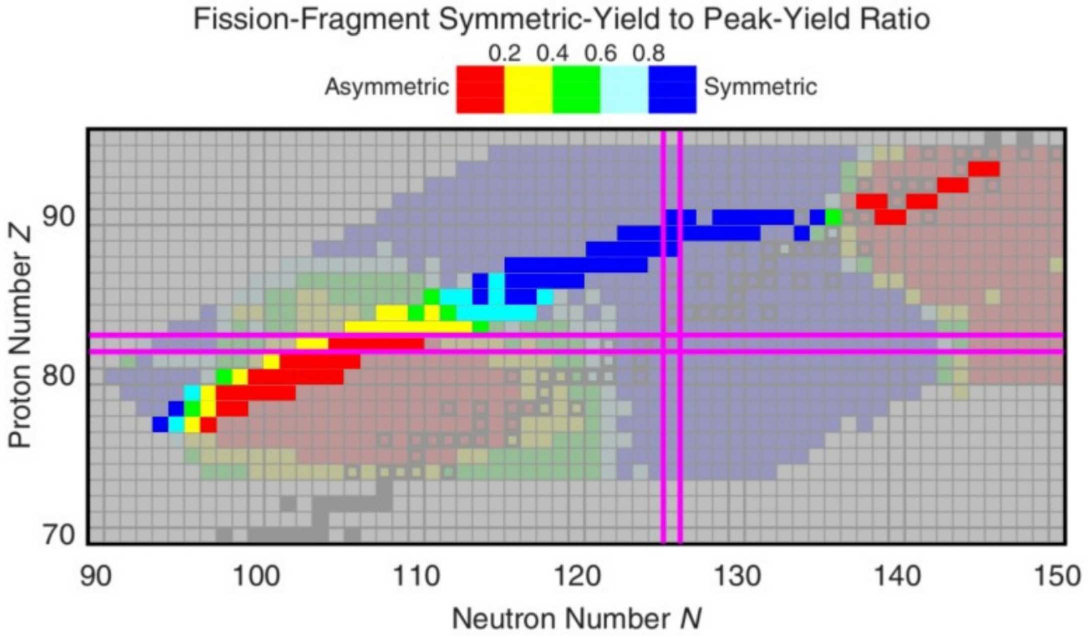


- The data demonstrate a transition to more asymmetric fission as we move toward neutron-deficient systems.
- The population of the light fragment Z=36 is favored in this new asymmetric fission island.
- The associated heavy partners exhibit a range from Z=42 to 46.

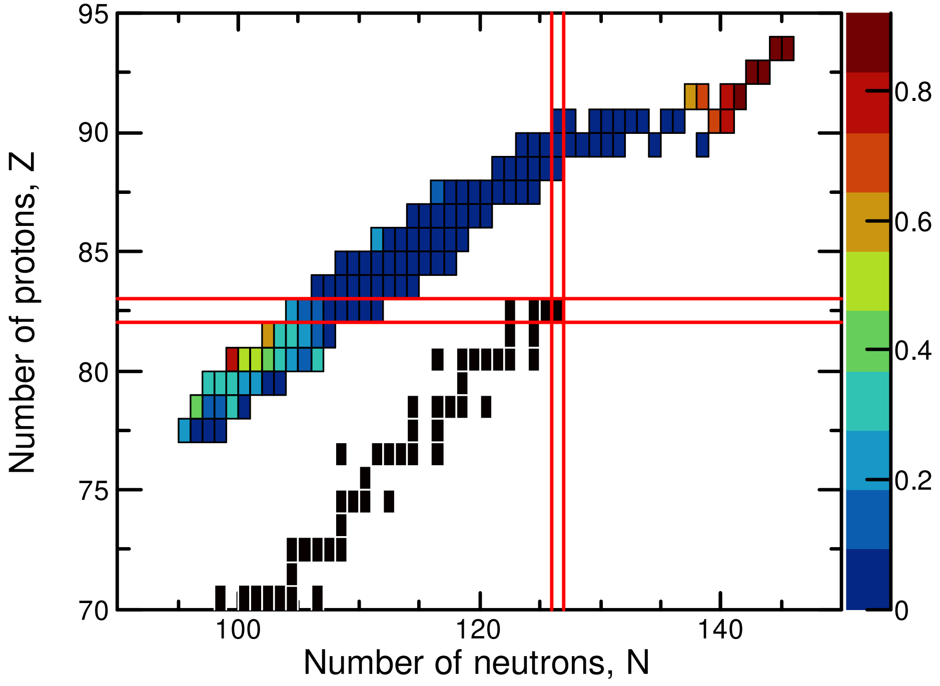
Asymmetry map



Asymmetry map: comparison to calculations



P. Moller *et al.* Phys. Rev. C **91**, 044316 (2015)



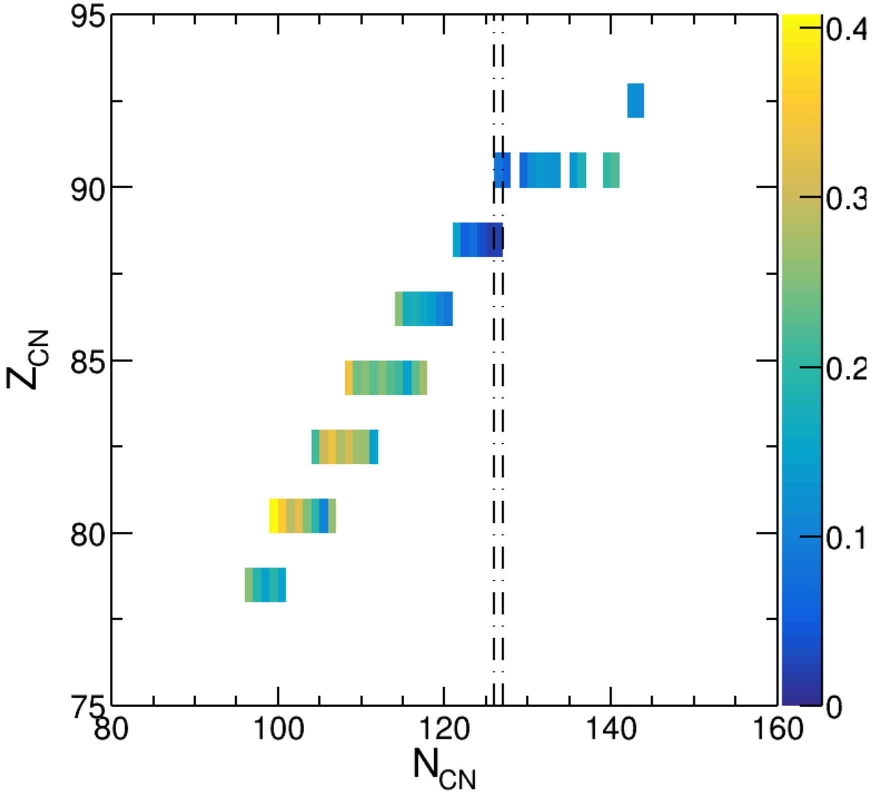
- The position and extent of the new asymmetric fission island are not reproduced by the calculations.
- These new data will strongly constrain the fission models.

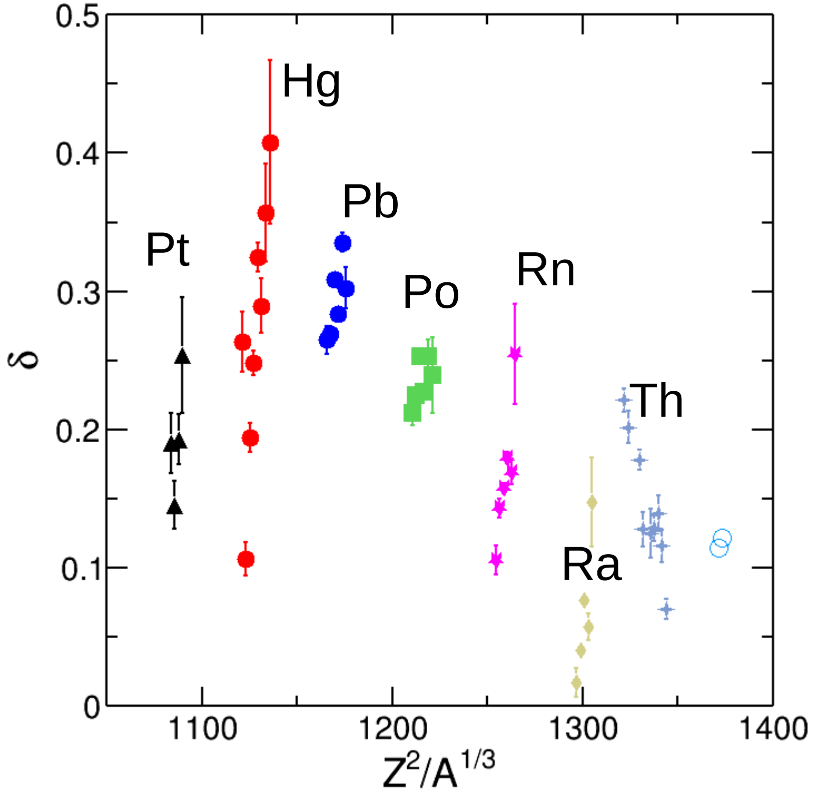
Information from the charge yields

- Global odd-even effect.

$$\delta = \left(\sum_e Y_e - \sum_o Y_o\right) / \sum_{e,o} Y$$

  - ➔ Systematic decrease of δ toward N=126.
  - ➔ A minimum seems to be reached for N=126 (fissioning system).





4. Conclusion

Conclusion

- Measurement of fission charge yields of 100 neutron-deficient nuclei through Coulomb excitation.
  - ✓ We delineate the boundaries of the new island of asymmetric fission.
  - ✓ Direct experimental evidence of proton-shell stabilization at Z=36 in this new asymmetric split.
  - ✓ Asymmetric fission driven by light fragment !
  - ✓ Important data set to test and constrain theoretical models.

- Large scale microscopic calculations (HFB3 with the D1S Gogny interaction) (N. Dubray, N. Pillet, D. Regnier, R. Bernard)
  - ✓ Challenging calculations in this neutron-deficient region.
  - ✓ A lot of discontinuities appear in the PES.
  - ✓ Making the dynamic calculations even more complicated.

- **Overall, we bring compelling evidence of proton-shell stabilization at Z=36 within the light fission fragment in this new asymmetric fission island. In contrast to what happens in the actinide region → Published in Nature.**

Thank you!

R^3B

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Article | Published: 30 April 2025

An asymmetric fission island driven by shell effects in light fragments

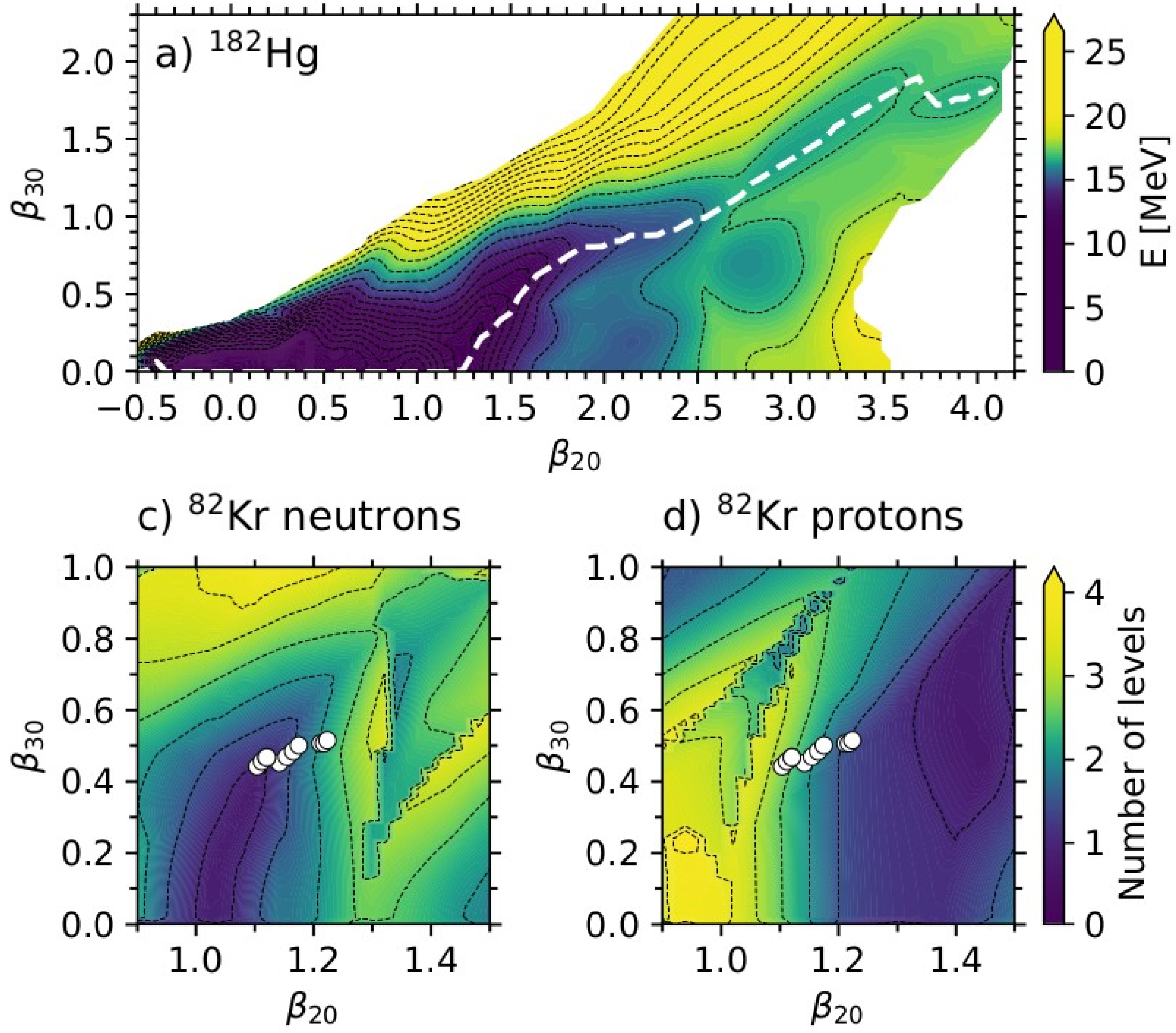
P. Morfouace, J. Taieb, A. Chatillon, L. Audouin, G. Blanchon, R. N. Bernard, N. Dubray, N. Pillet, D. Regnier, H. Alvarez-Pol, F. Amjad, P. André, G. Authelet, L. Atar, T. Aumann, J. Benlliure, K. Boretzky, L. Bott, T. Brecelj, C. Caesar, P. Carpentier, E. Casarejos, J. Cederkäll, A. Corsi, … M. Zhukov

+ Show authors

Nature **641**, 339–344 (2025) | Cite this article

4. Back-up slides

Microscopic calculations using Gogny D1S



- Extended HFB calculations of even-even nuclei in the island of asymmetic fission (Theoretician colleagues CEA-DAM and CEA-DES).
- Potential Energy Surface (PES) generated.
- Favored pre-fragments determined in the path before scission.
- Systematic study of possible shell effects in these light pre-fragments looking at Q_2-Q_3 deformation along the scission path.

  - **Z=36 Kr isotopes favored in the scission path in numerous cases.**
  - **Shell effect in the light fragment.**
  - **No shell effect visible in the associated heavy fragment.**