



Fission studies in inverse kinematics using the SOFIA/R³B experimental setup at the GSI/FAIR facility

José Luis Rodríguez-Sánchez

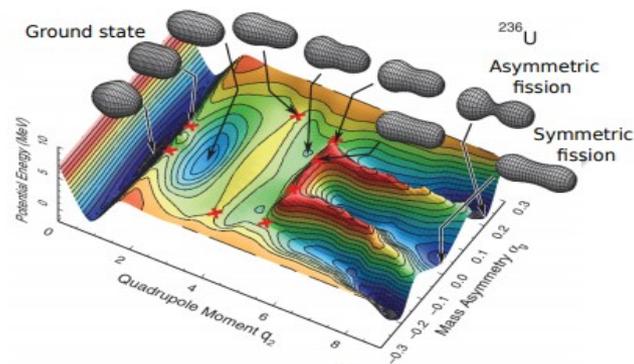
University of Coruña

10th March 2026



Nuclear dynamics

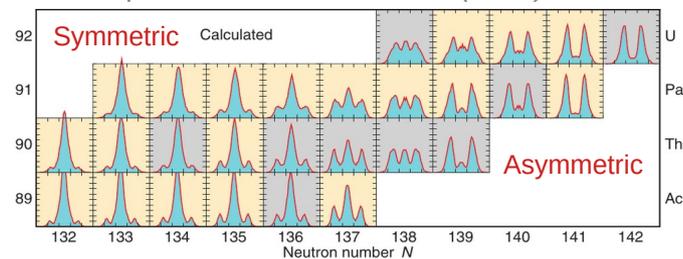
- Dissipation



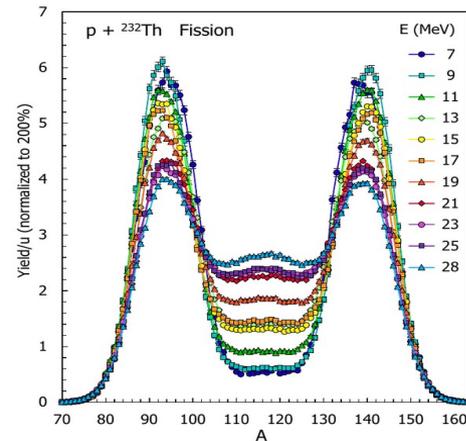
Nuclear structure at large deformations

- Fission modes
- Damping of shell effects

Randrup et al., *PRC* **88**, 064606 (2013)

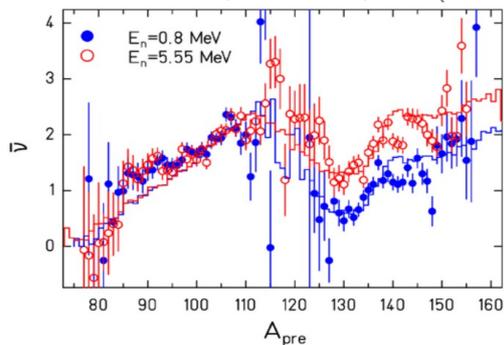


Berriman et al., *PRC* **105**, 064614 (2022)

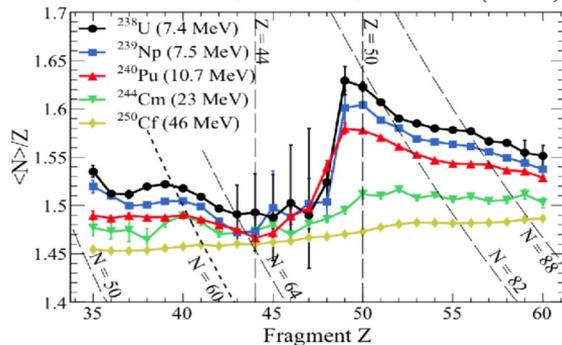


Energy sorting between fission fragments

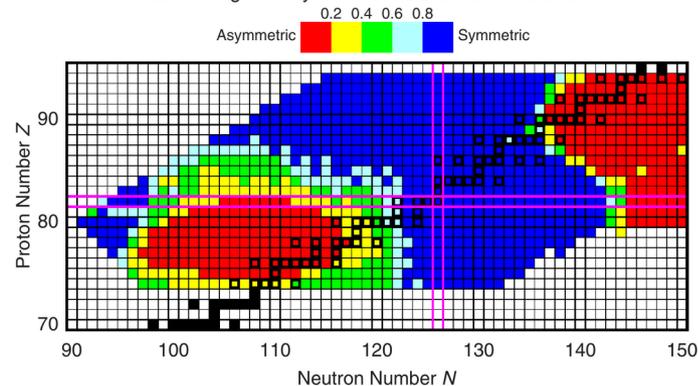
Schmidt et al., *NDS* **131**, 107 (2016)



Ramos et al., *PRC* **97**, 054612 (2018)



Fission-Fragment Symmetric-Yield to Peak-Yield Ratio



Coulomb-induced fission reactions

- Active target with Pb and U foils
- **Large** fission cross sections (> 1 b)
- **Low** excitation energies < 30 MeV
- Fission modes, pairing, energy sharing, ... and evolution with isospin

Spallation-induced fission reactions

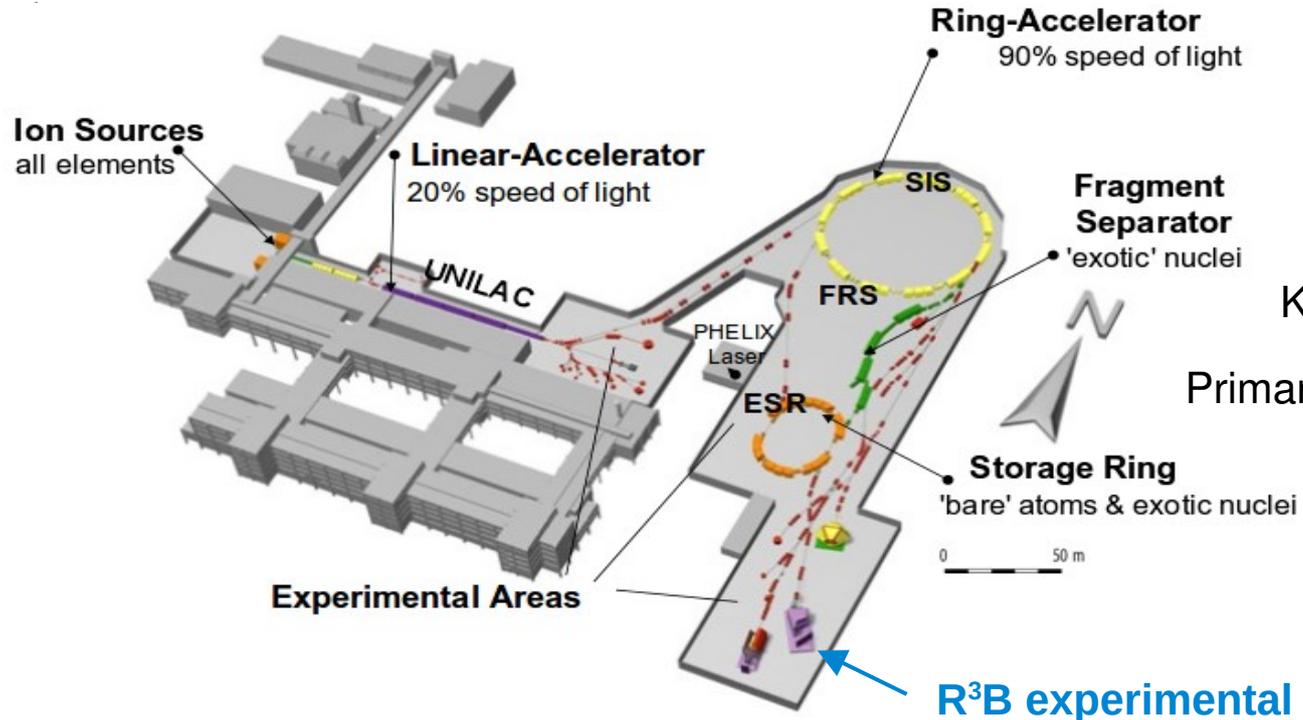
- Liquid hydrogen targets
- **Moderate-to-large** fission cross sections (> 100 mb)
- **High** excitation energies $\gg 60$ MeV
- Fission dynamics

Quasi-free (p,2p)-induced fission reactions

- Liquid hydrogen targets
- **Small** fission cross sections (< 10 mb) but with access to the excitation energy
- **Low** excitation energies < 35 MeV
- Fission modes, pairing, energy sharing, ... and evolution with isospin
- Fission barriers

The GSI facility

Heavy projectiles accelerated at relativistic energies



Species: ^{238}U , ^{209}Bi , ^{208}Pb , ...

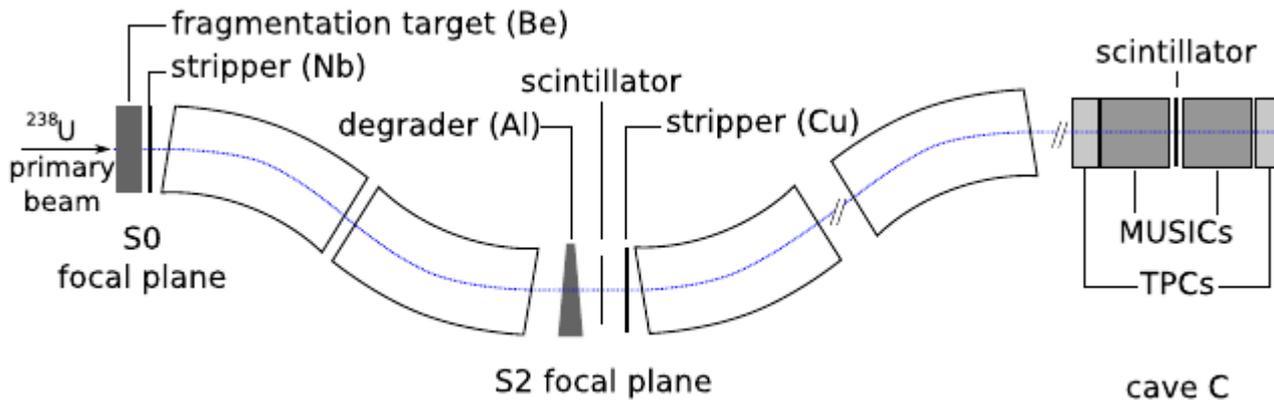
Kinetic energy: 500-1050 MeV/u

Primary beam intensities $\sim 3 \times 10^9$ ions/spill

Reactions with **Relativistic Radioactive Beams**

Secondary beam identification

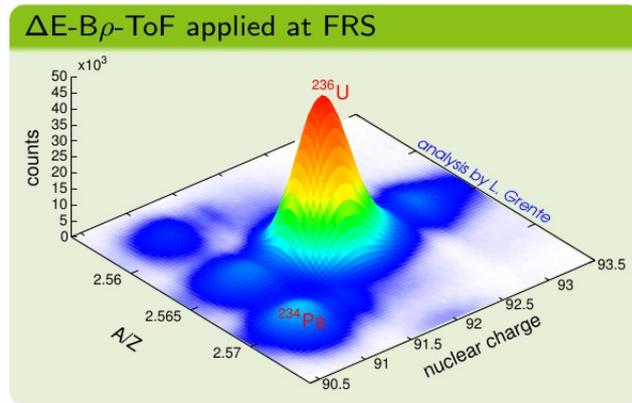
Fragment separator FRS



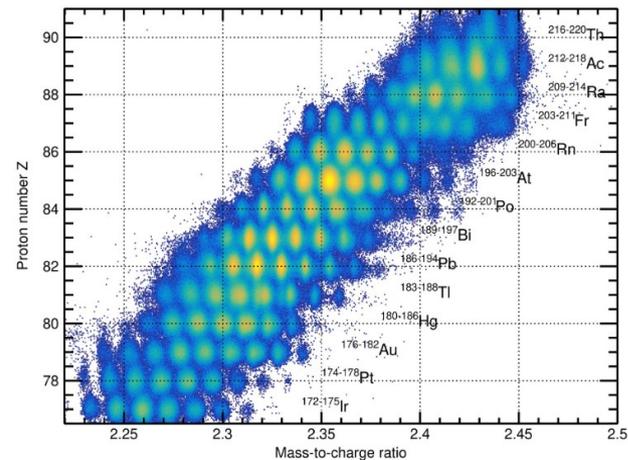
H. Geissel et al., NIM B 70, 286 (1992)

flight path $\sim 138\text{m}$

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



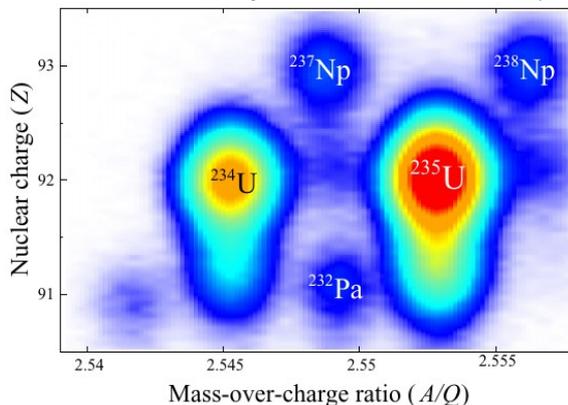
P. Morfouace et al., Nature 641, 339 (2025)



Identification

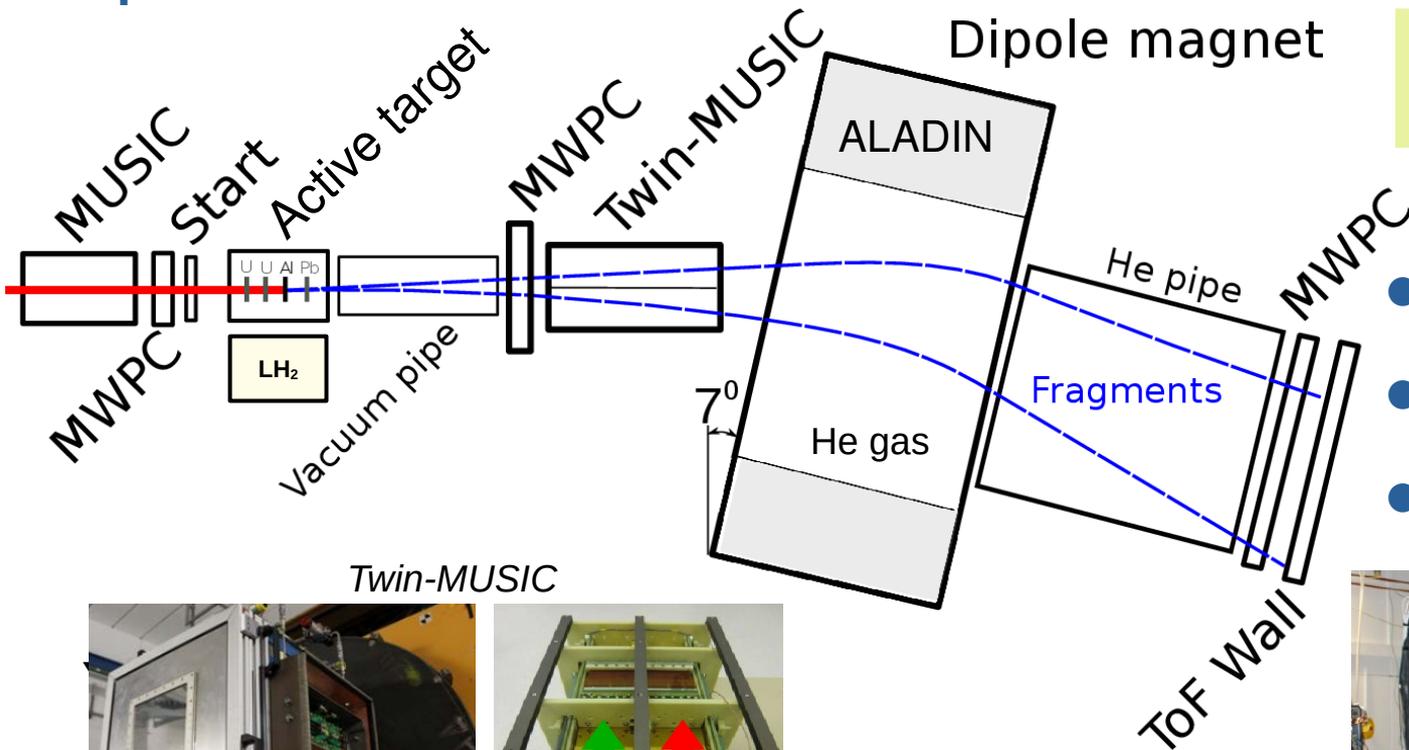
- Charge “Q” measured with MUSICs
- X_{S2} position from mid-focal plane
- β from ToF measurements

$$\frac{A}{Q} = \frac{B\rho_0}{\beta\gamma} \left(1 - \frac{x_{S2}}{D}\right)$$



SOFIA experimental setup at R³B (2012-2014)

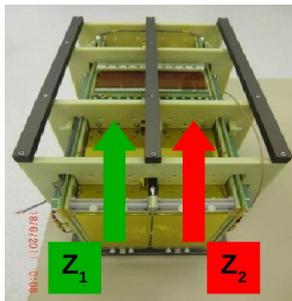
Complete kinematics measurements



Coulex-induced fission
Spallation-induced fission

- Magnetic field ~2 Tm
- Position resolution 250 μm (FWHM)
- ToF resolution 40 ps (FWHM)

Twin-MUSIC

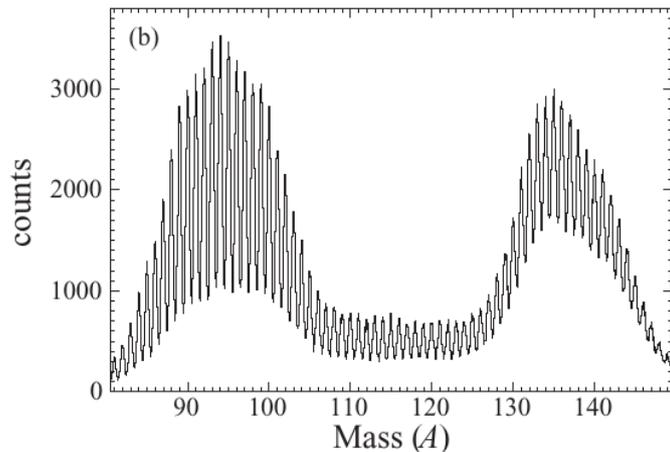
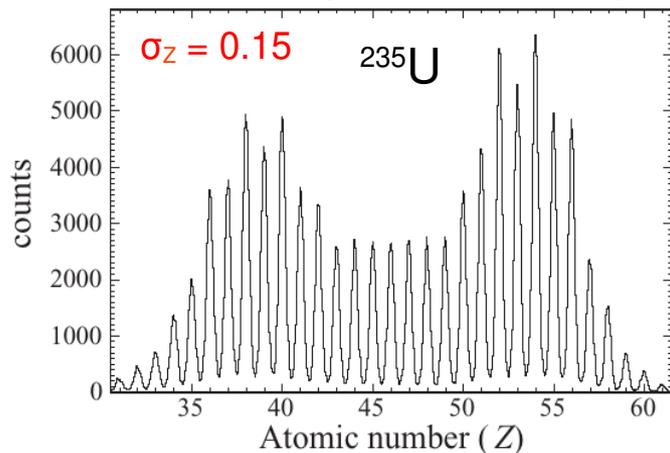


$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}$$

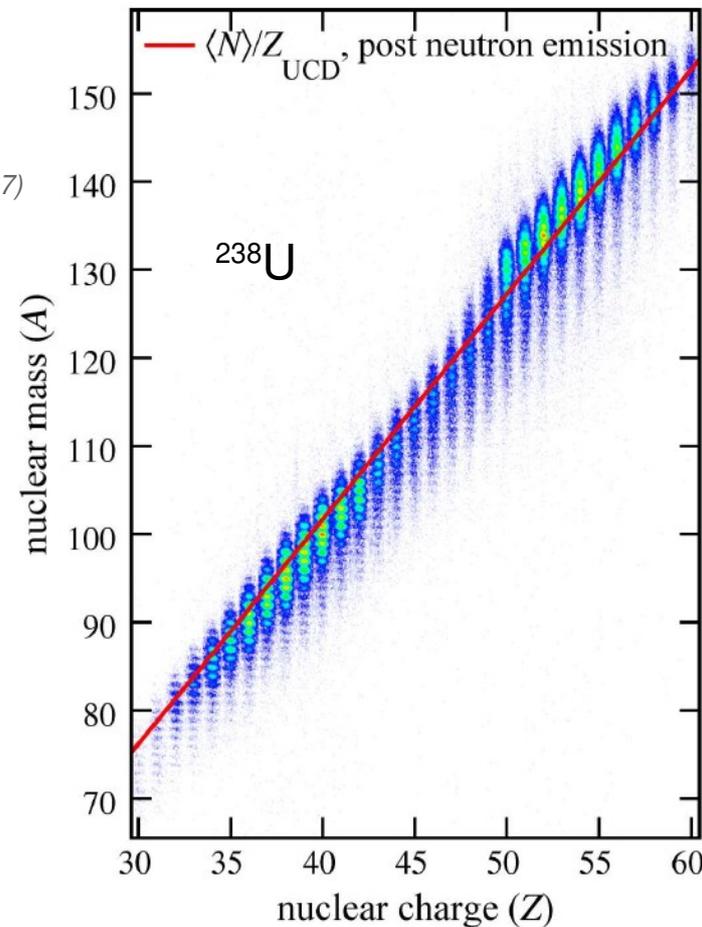
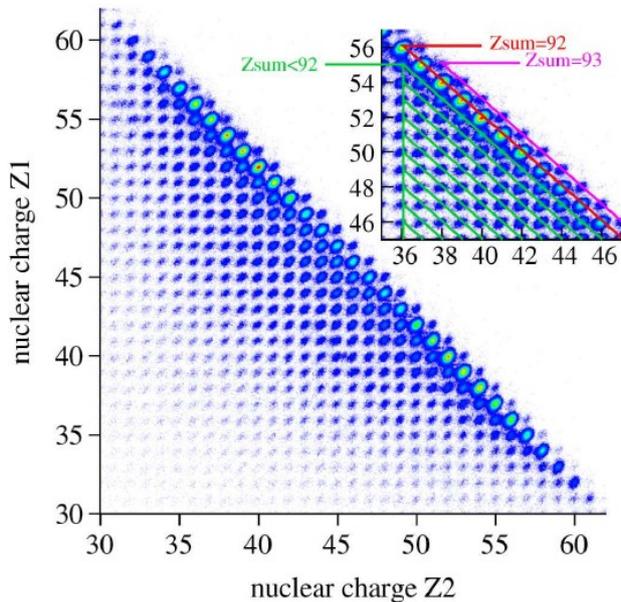


Identification of fission fragments

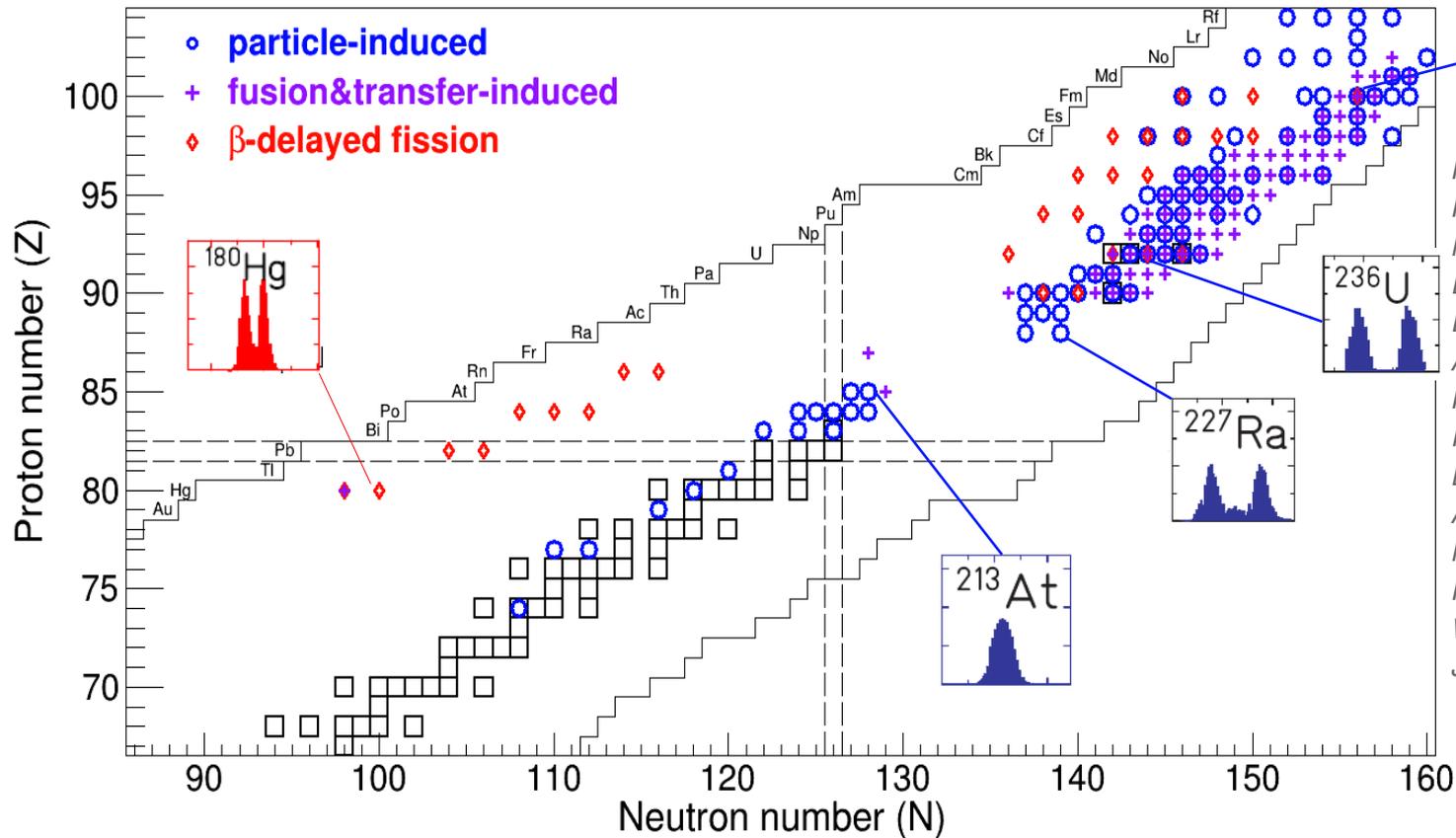
J.F. Martin et al., Phys. Rev. C **104**, 044602 (2021)



E. Pellereau et al., Phys. Rev. C **95**, 054603 (2017)

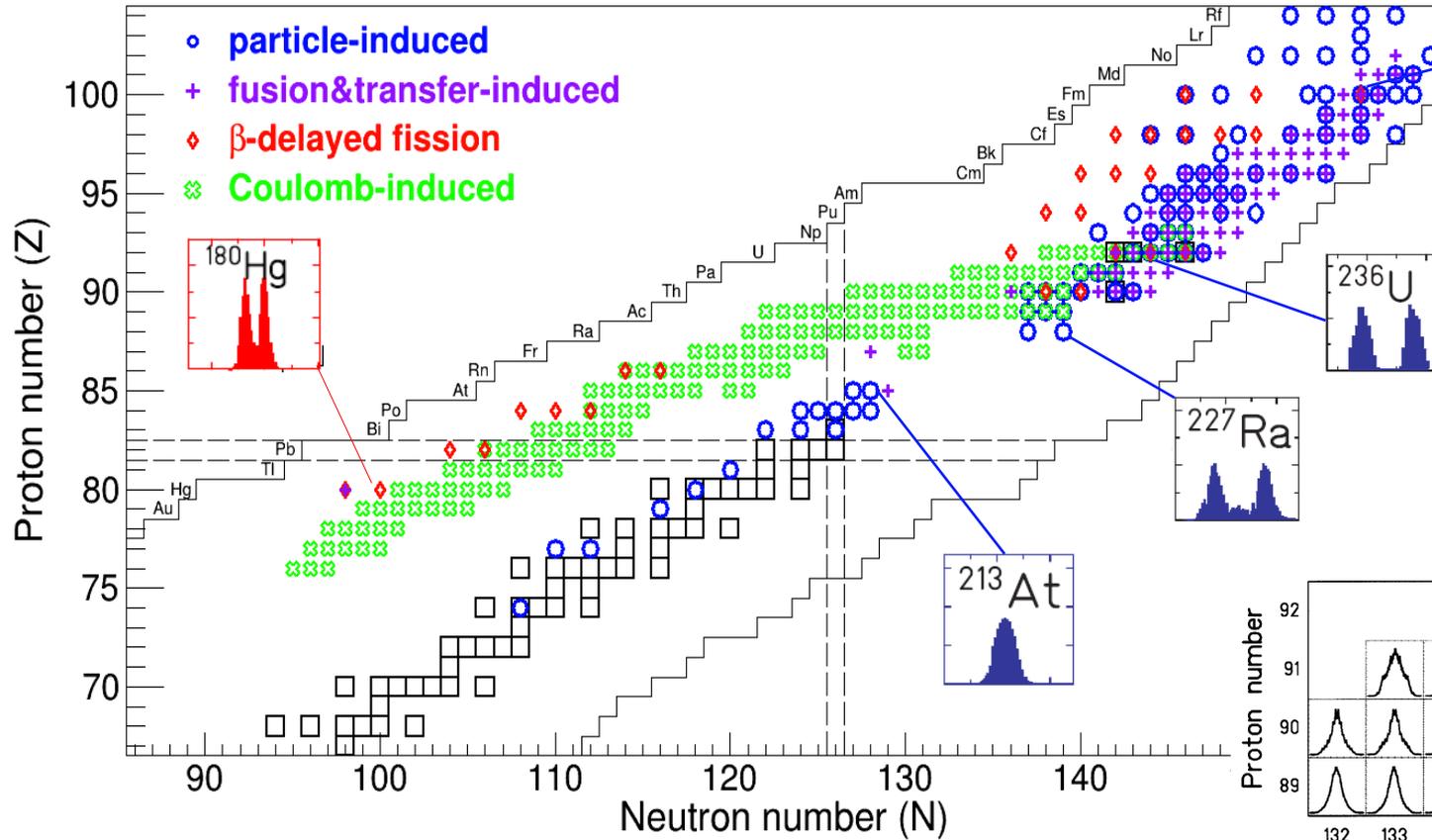


Fission yields



K. Nishio, Handbook of Nuclear Physics (2023)
*K. Miernik et al, PRC **108**, 054608 (2023)*
*M.J. Vermeulen et al, PRC **102**, 054610 (2020)*
*D. Ramos et al, PRC **101**, 034609 (2020)*
*D. Ramos et al, PRC **97**, 054612 (2018)*
*A.N. Andreyev et al, RPP **81**, 016301 (2018)*
*K. Hirose et al, PRL **119**, 222501 (2017)*
*R. Léguillon et al, PLB **761**, 125 (2016)*
*L. Ghys et al, PRC **90**, 041301(R) (2014)*
*A. Andreyev et al, PRL **105**, 252502 (2010)*
*M. Itkis et al, SJPNP **19**, 301 (1988)*
*H.C. Britt et al, PRC **30**, 559 (1984)*
*W. Lang et al, NPA **345**, 34 (1980)*
*J. Weber et al, PRC **13**, 2413 (1976)*

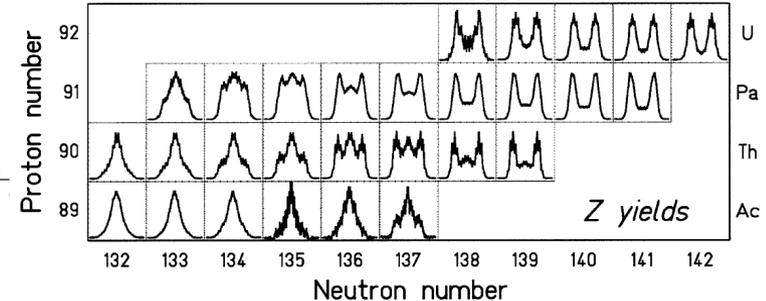
Fission yields



^{256}Fm
P. Morfouace et al, Nature **641**, 339 (2025)
A. Chatillon et al, PRC **106**, 024618 (2022)
J.F. Martin et al, PRC **104**, 044602 (2021)
A. Chatillon et al, PRL **124**, 202502 (2020)
A. Chatillon et al, PRC **99**, 054628 (2019)
E. Pellereau et al, PRC **95**, 054603 (2017)

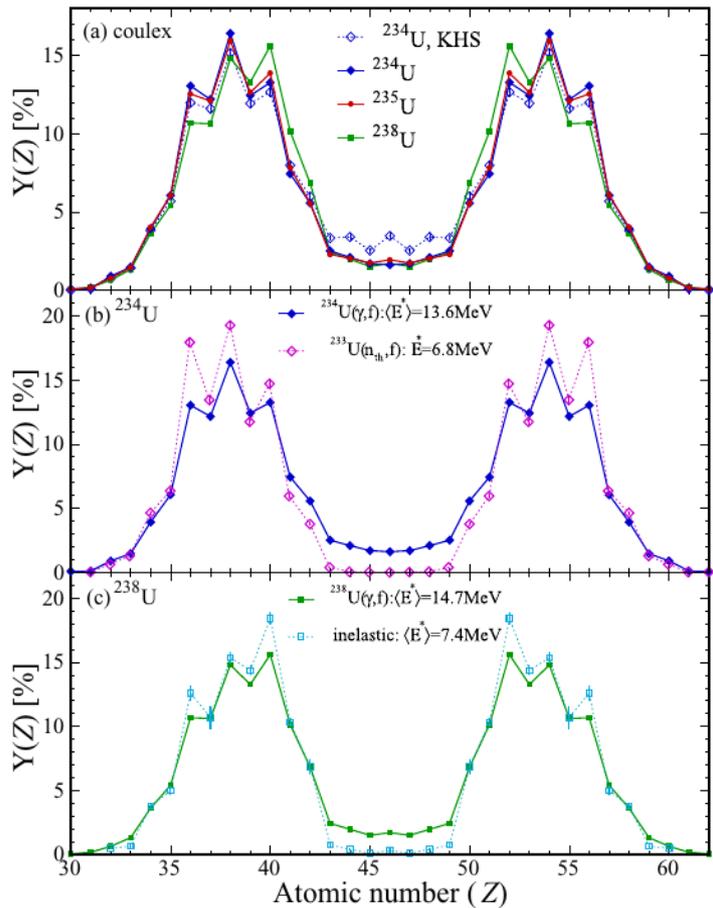
Z yields for 144 fissioning systems
A yields for ~20 fissioning systems

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

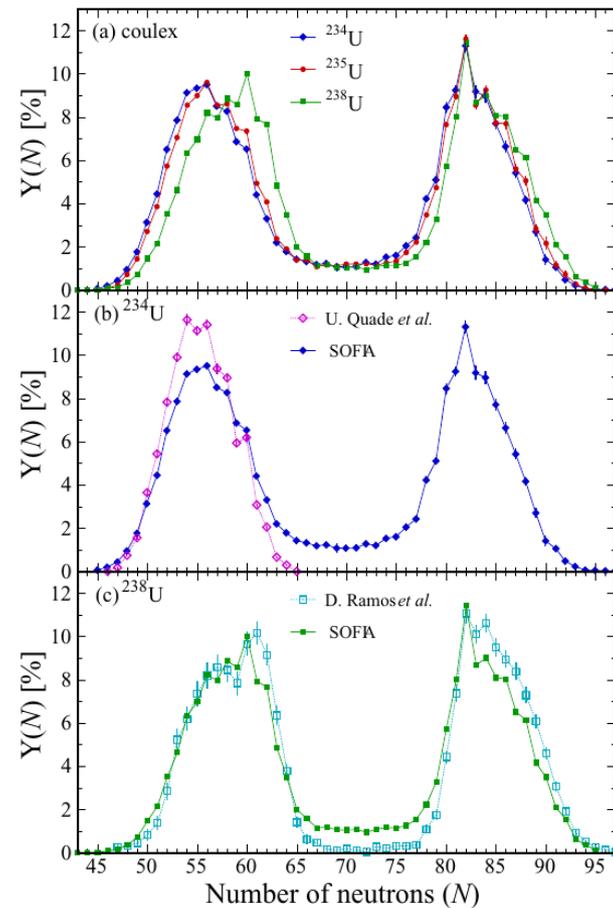
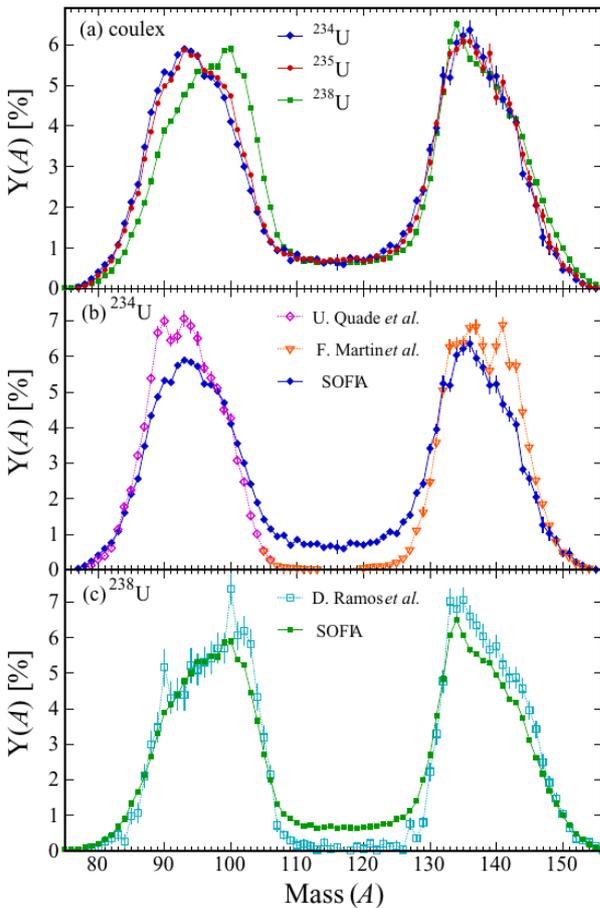


Fission yields

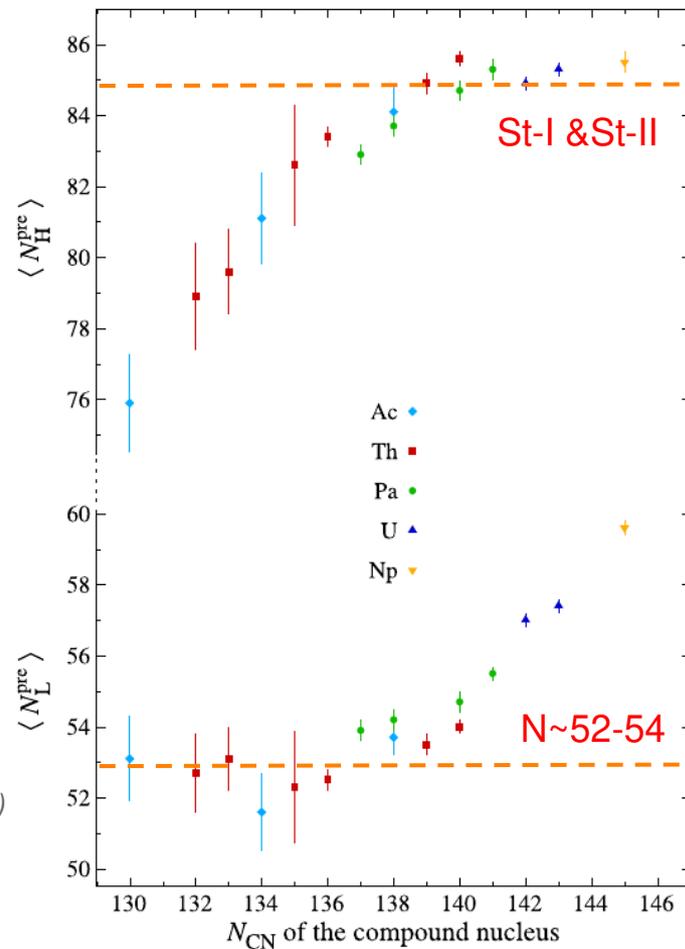
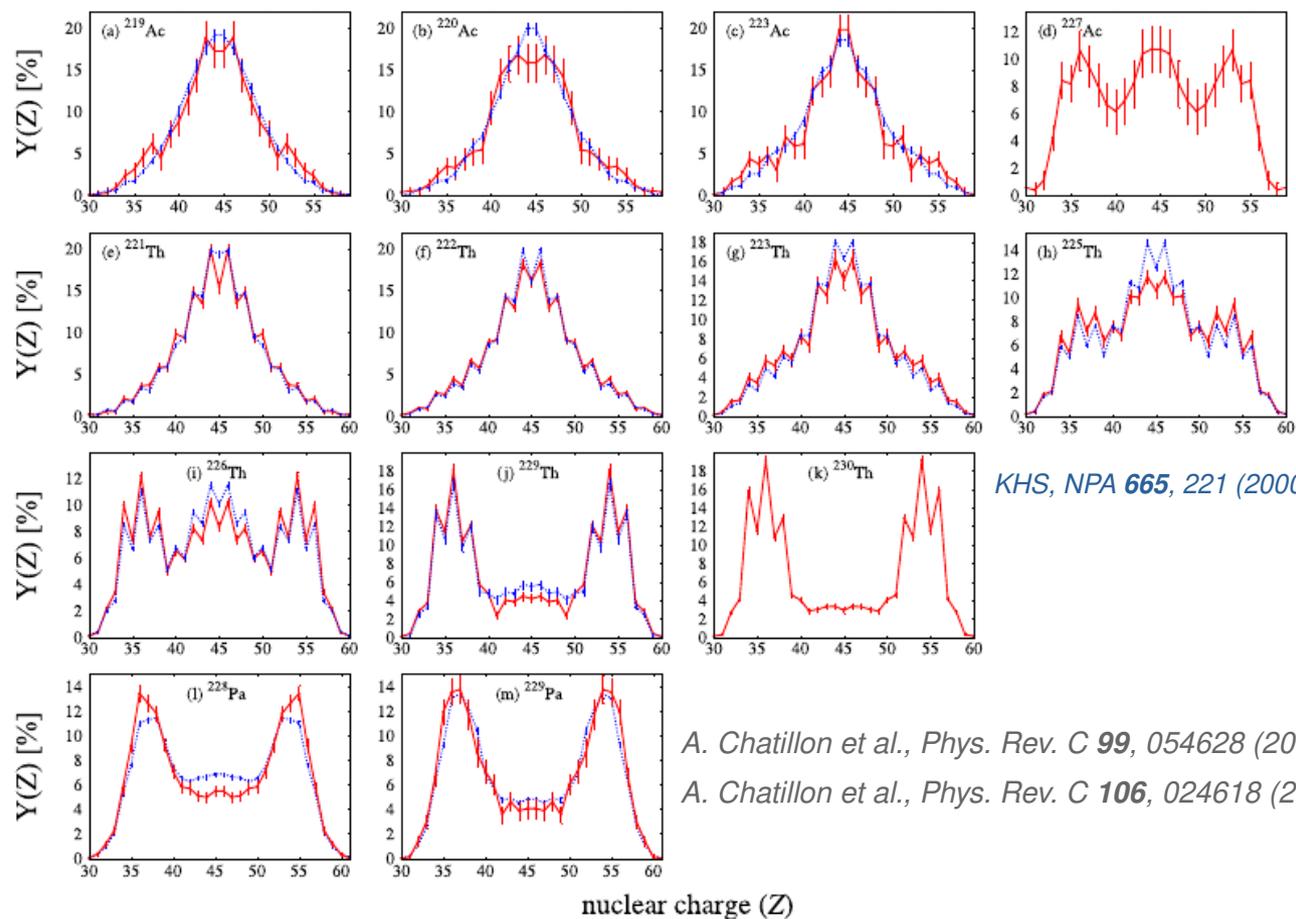
J.F. Martin et al., *Phys. Rev. C* **104**, 044602 (2021)



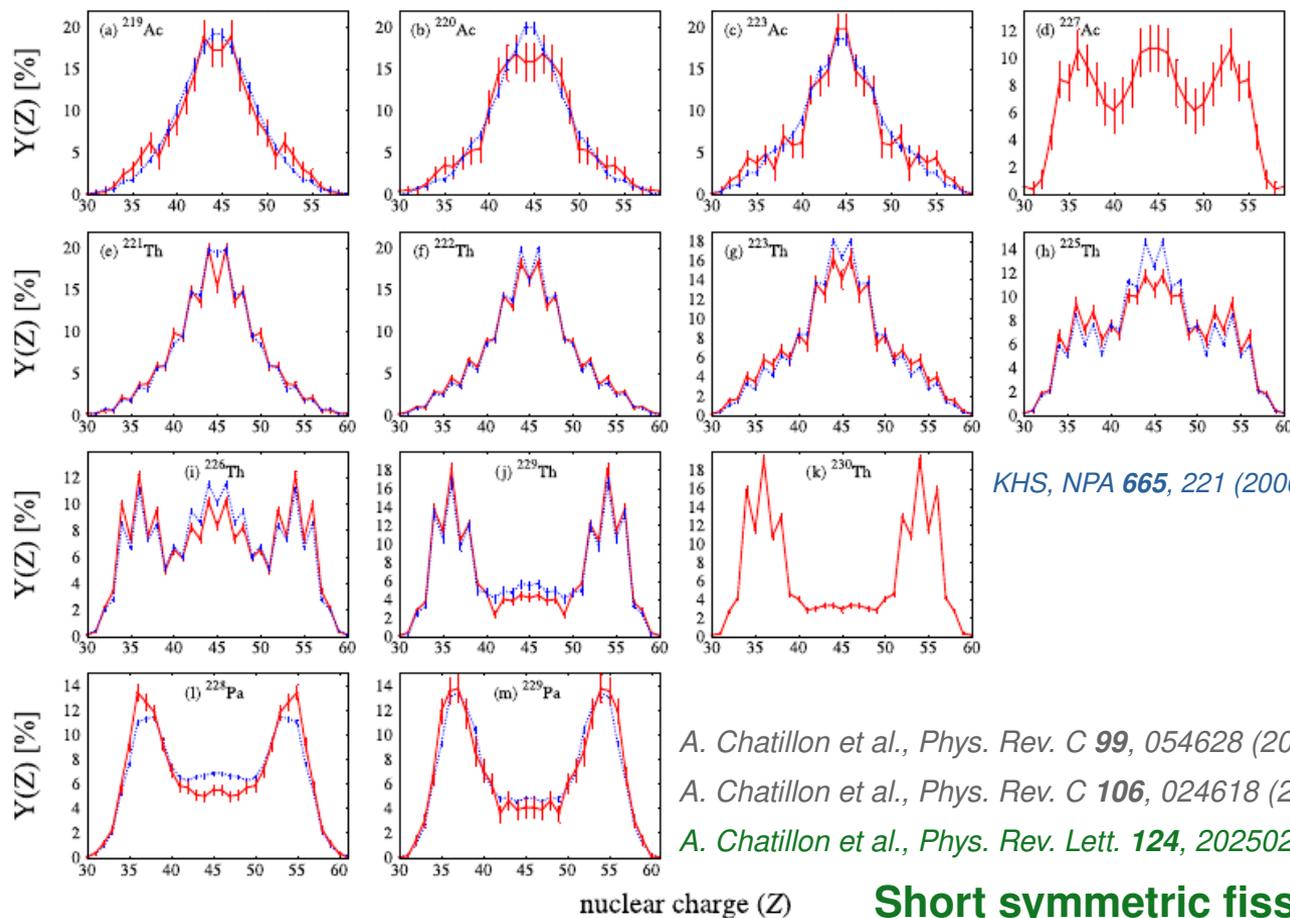
E. Pellereau et al, *PRC* **95**, 054603 (2017)



Fission yields



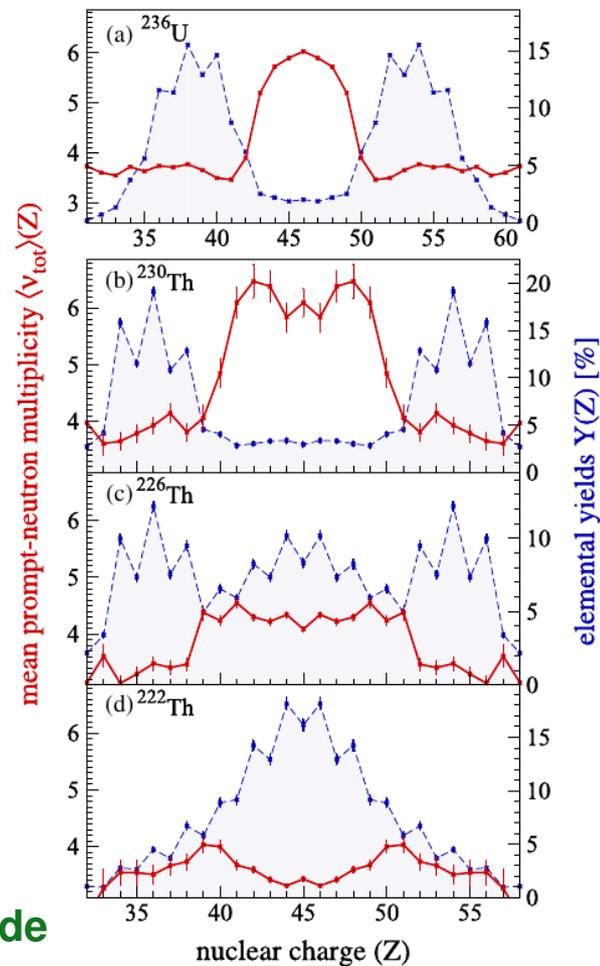
Fission yields



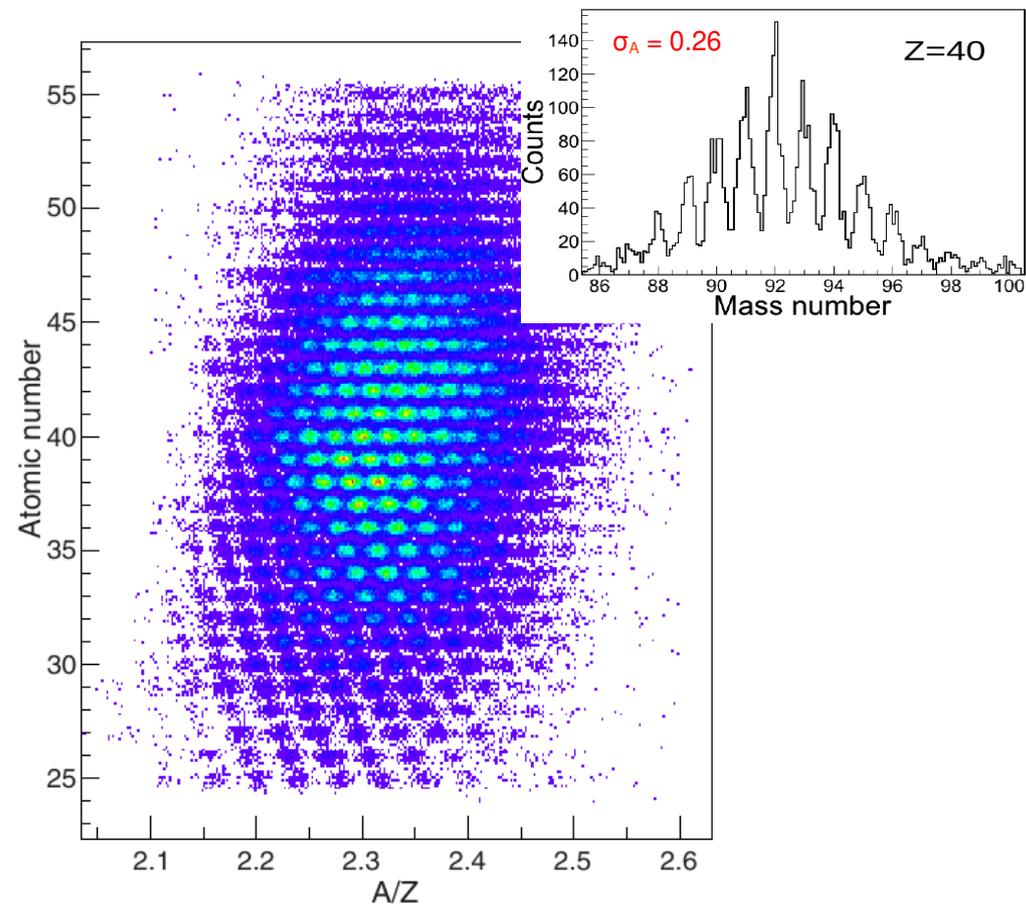
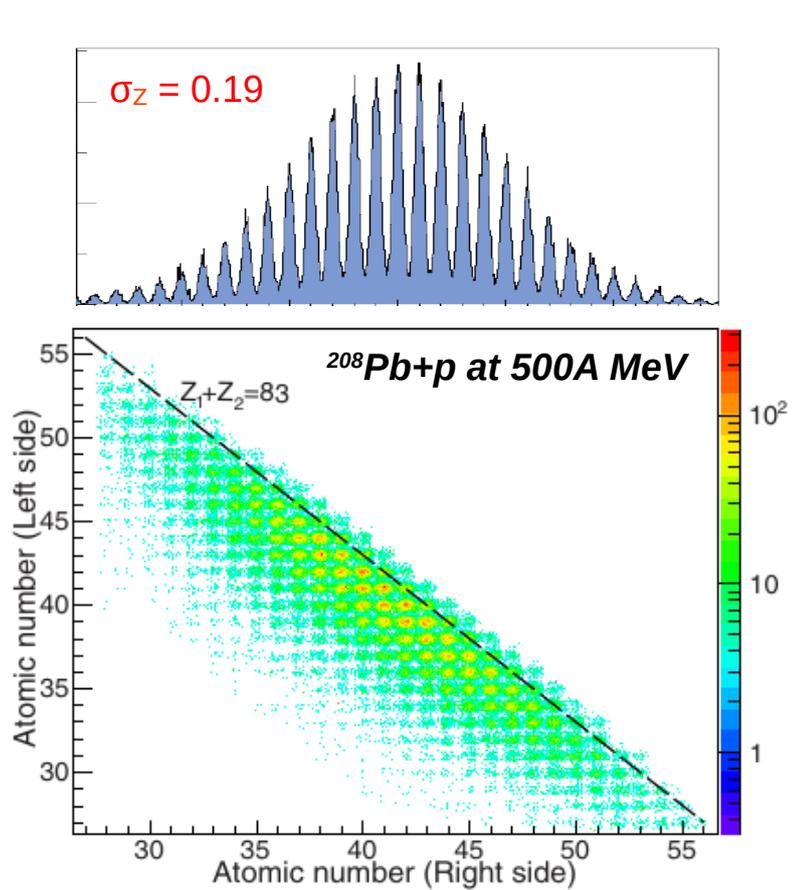
KHS, NPA 665, 221 (2000)

- A. Chatillon et al., Phys. Rev. C 99, 054628 (2019)*
- A. Chatillon et al., Phys. Rev. C 106, 024618 (2022)*
- A. Chatillon et al., Phys. Rev. Lett. 124, 202502 (2020)*

Short symmetric fission mode



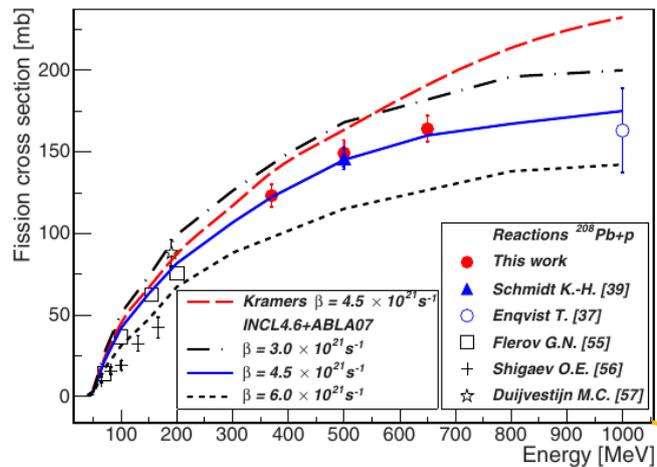
Fission dynamics using $^{208}\text{Pb}+p$ reactions



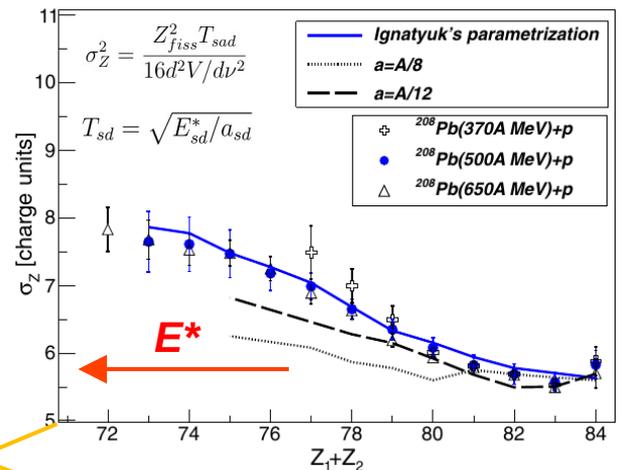
J.L. Rodríguez-Sánchez et al., *Phys. Rev. C* **91**, 064616 (2015)

Fission dynamics using $^{208}\text{Pb}+p$ reactions

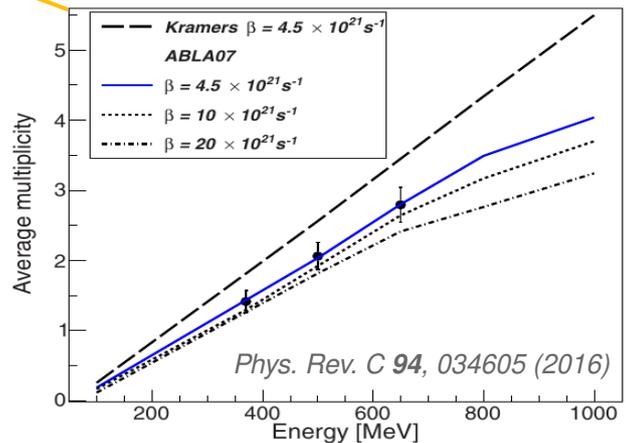
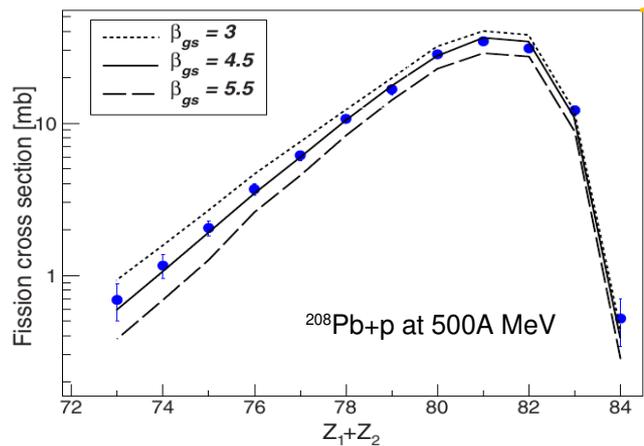
J.L. Rodríguez-Sánchez et al., *Phys. Rev. C* **90**, 064606 (2014)



Phys. Rev. C **92**, 044612 (2015)



$$\beta_{gs} = 4.5 \cdot 10^{21} \text{ s}^{-1}$$

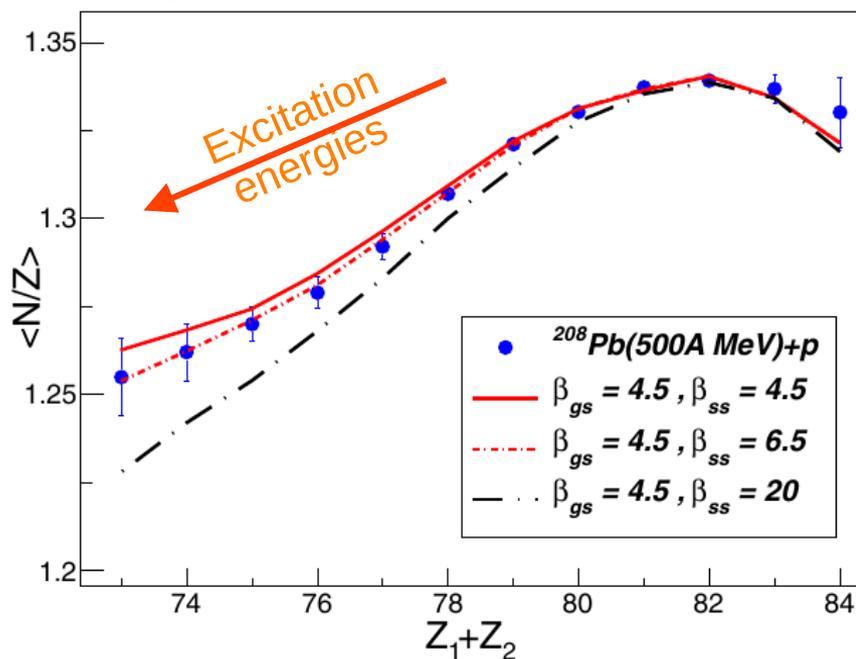


Constraint of the dissipation coefficient at large deformations (saddle-scission)

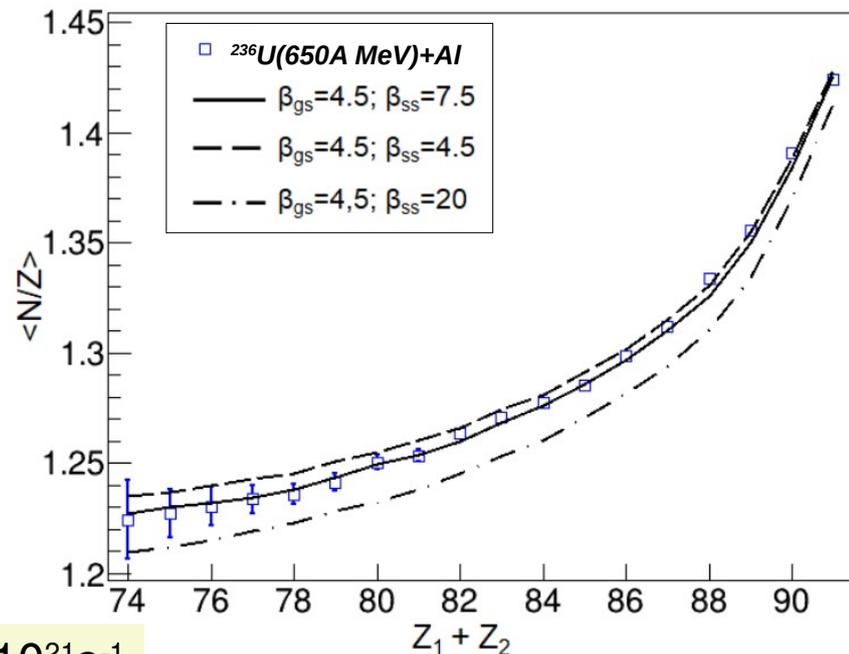
Using the average N/Z of fission fragments as a complementary observable of neutron evaporation

High excitation energies \rightarrow larger neutron evaporation \rightarrow smaller $\langle N/Z \rangle$ for fission fragments

J.L. Rodríguez-Sánchez et al., Phys. Rev. C **94**, 061601(R) (2016)

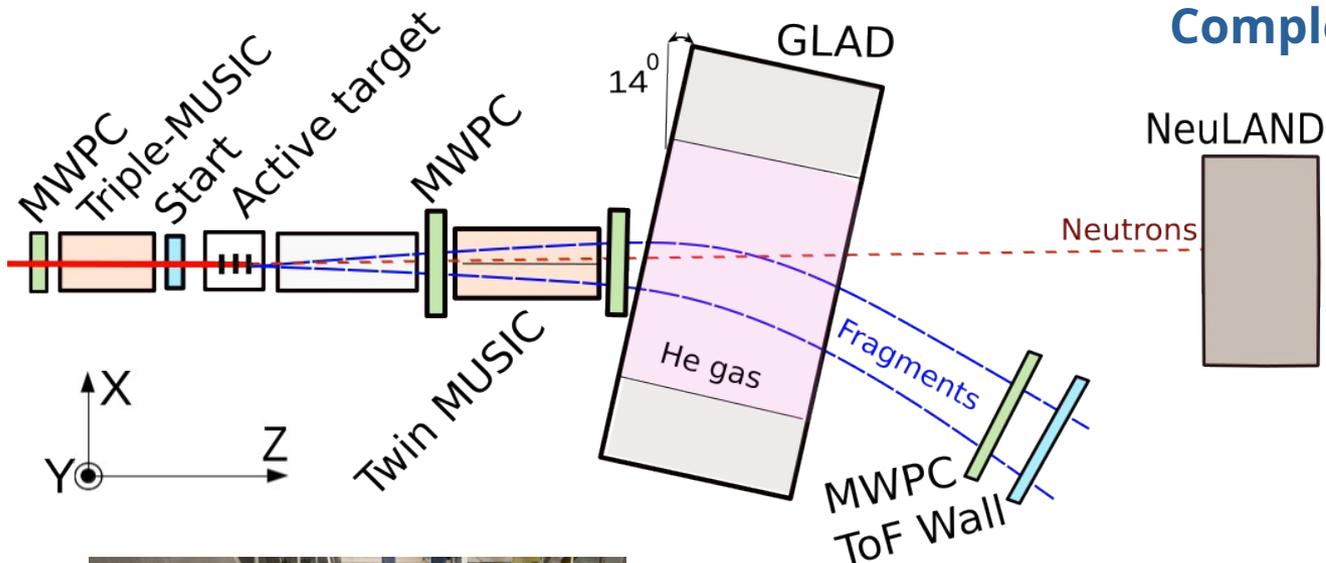


M. Feijoo, PhD thesis, University of Santiago de Compostela (2021)



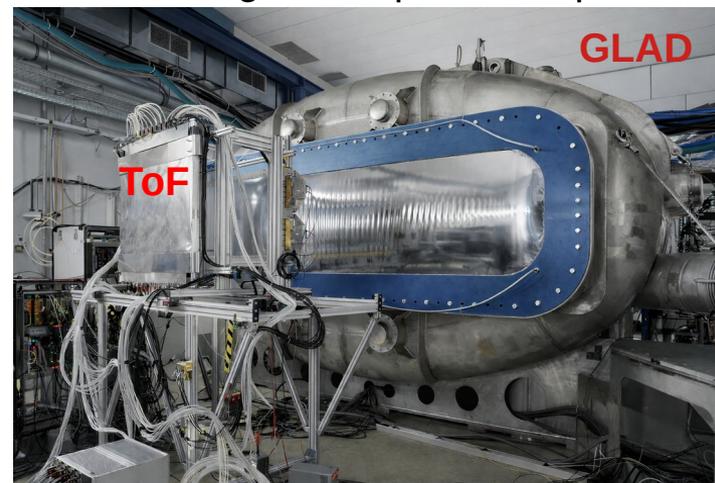
$$\beta_{ss} \sim 7 \cdot 10^{21} \text{s}^{-1}$$

SOFIA/R³B experimental setup (2021)



Complete kinematics measurements

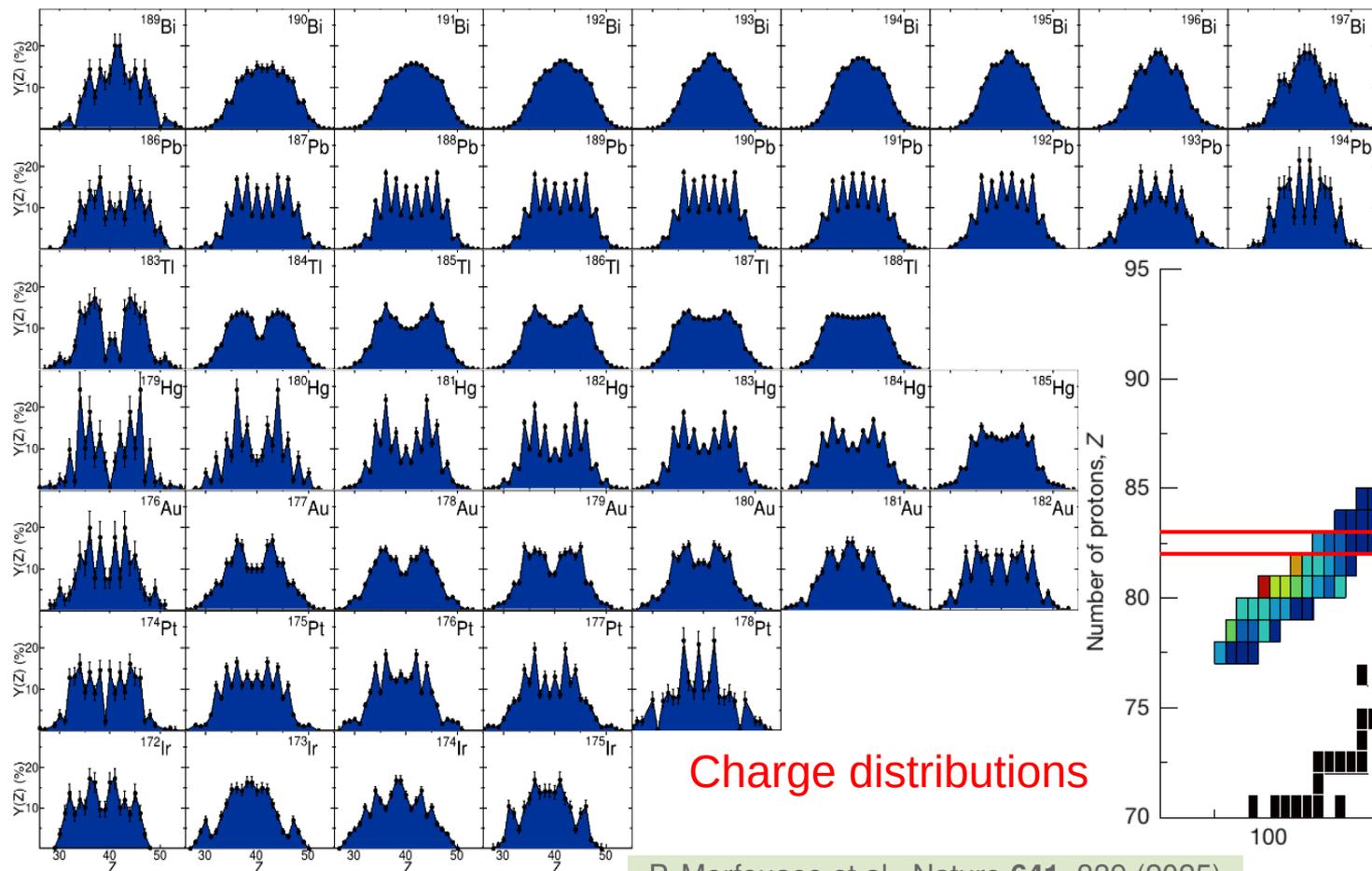
GSI Large-Acceptance Dipole



Spokesperson: J. Taïeb (CEA)

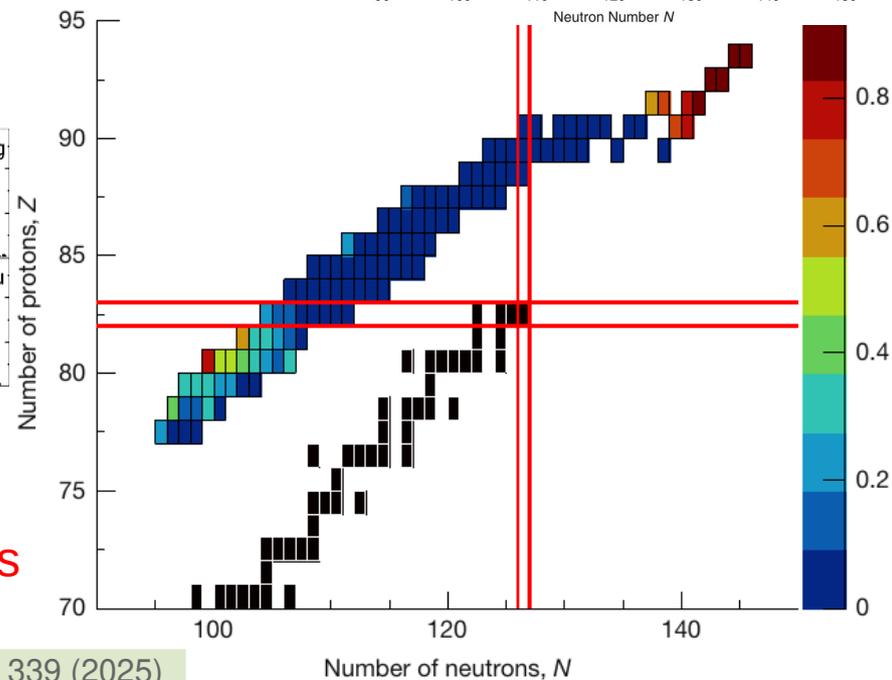
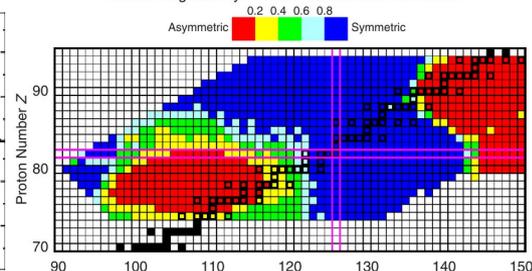
- **Magnetic field:** ~4.5 Tm
- **MUSIC, ToF wall and MWPC detectors:** Fission fragments
 $\Delta Z \sim 0.31$, ToF ~ 40 ps, Position res. $250 \mu\text{m}$ (FWHM)
- **NeuLAND:** Neutron multiplicities (max. 4-5 neutrons)

Fission yields for pre-actinides



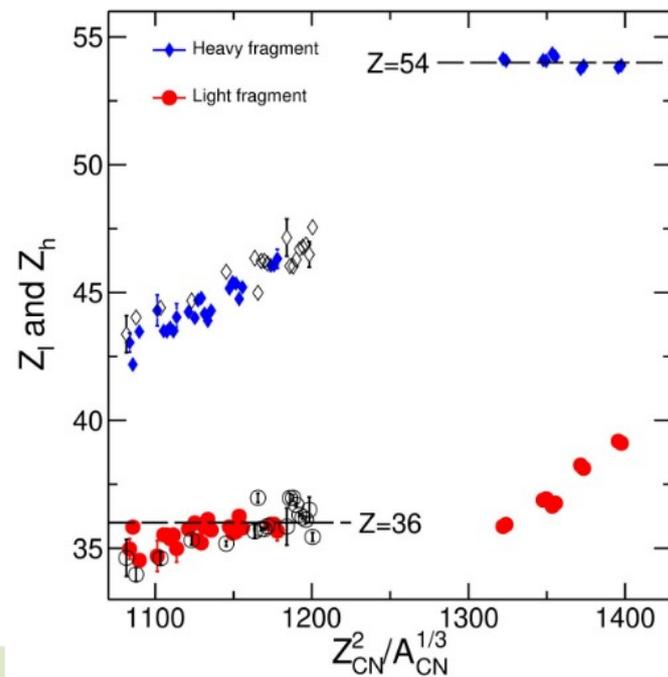
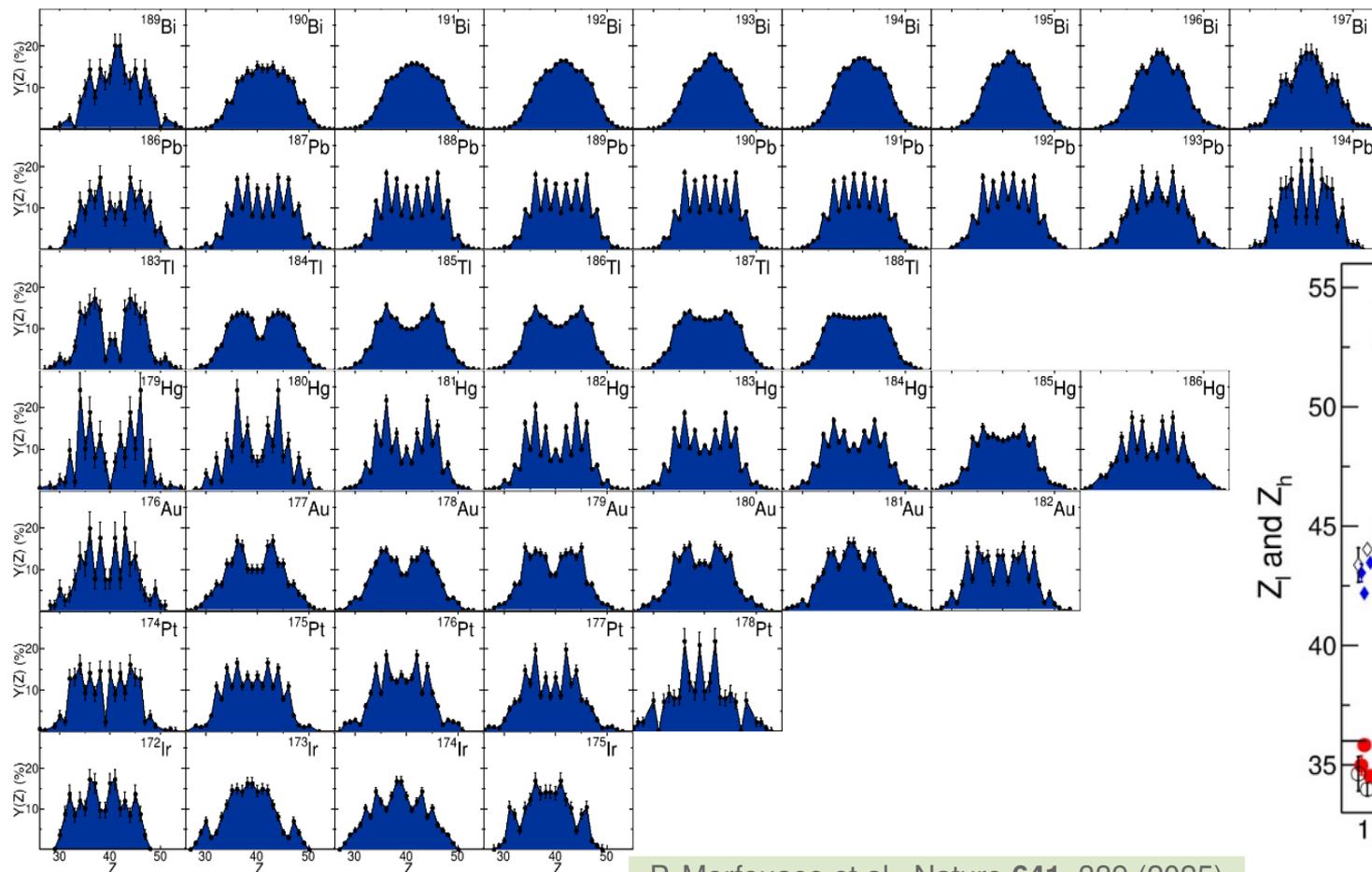
Charge distributions

Fission-Fragment Symmetric-Yield to Peak-Yield Ratio



P. Morfouace et al., Nature 641, 339 (2025)

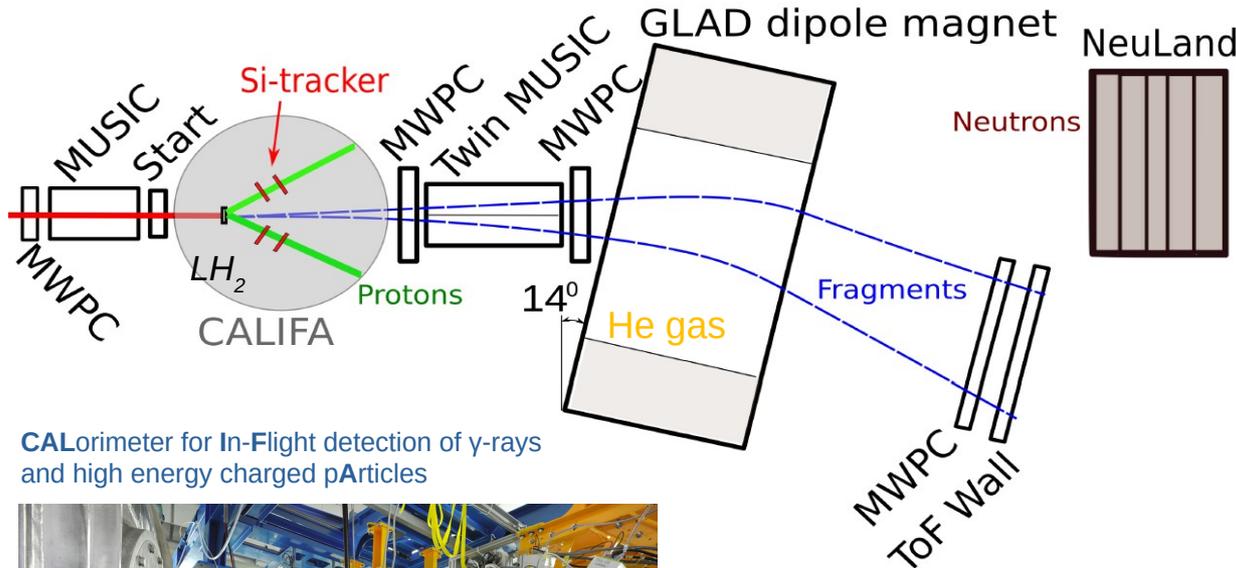
Fission yields for pre-actinides



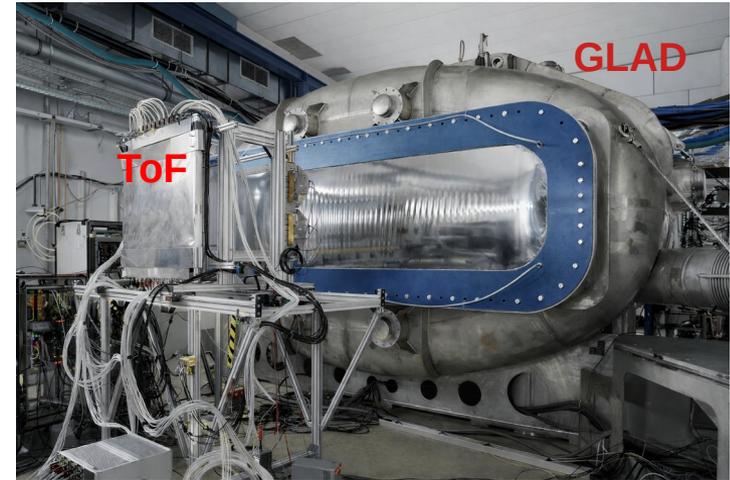
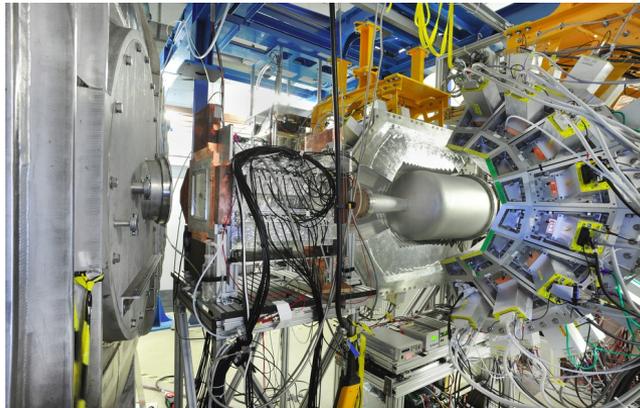
P. Morfouace et al., Nature **641**, 339 (2025)

First quasi-free (p,2p)-induced fission experiment (2021)

Beam of ^{238}U at 540 MeV/u



CALorimeter for In-Flight detection of γ -rays and high energy charged pArticles

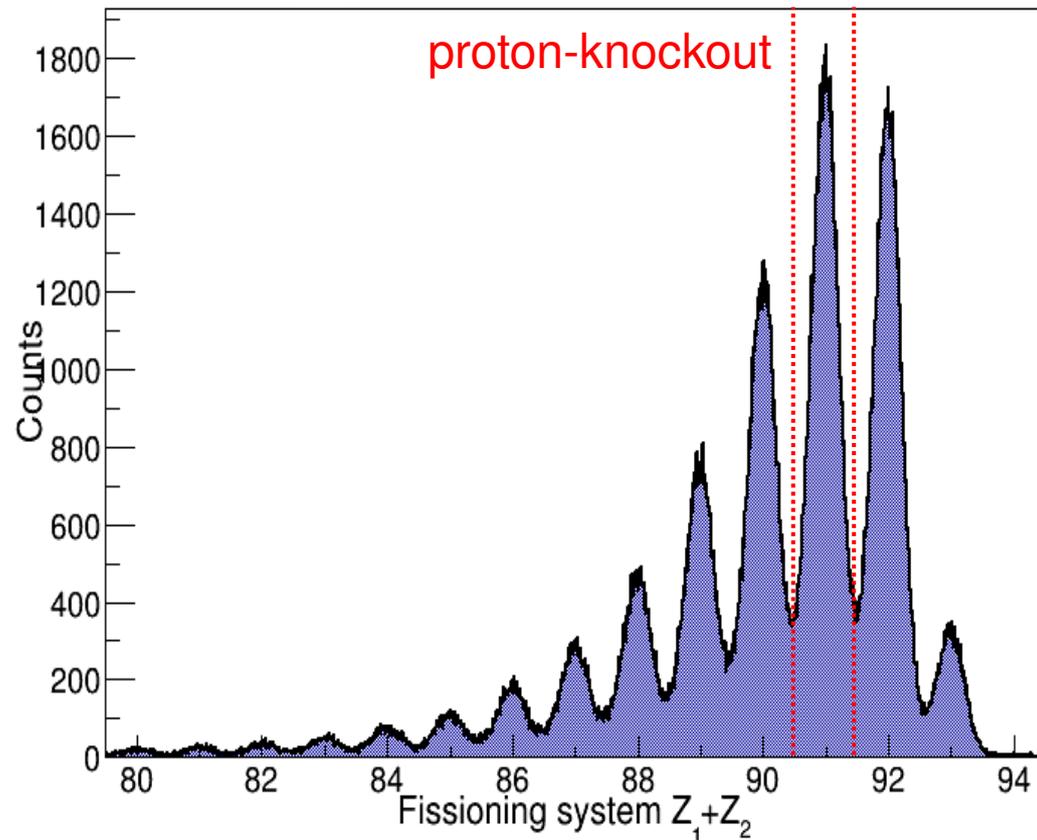
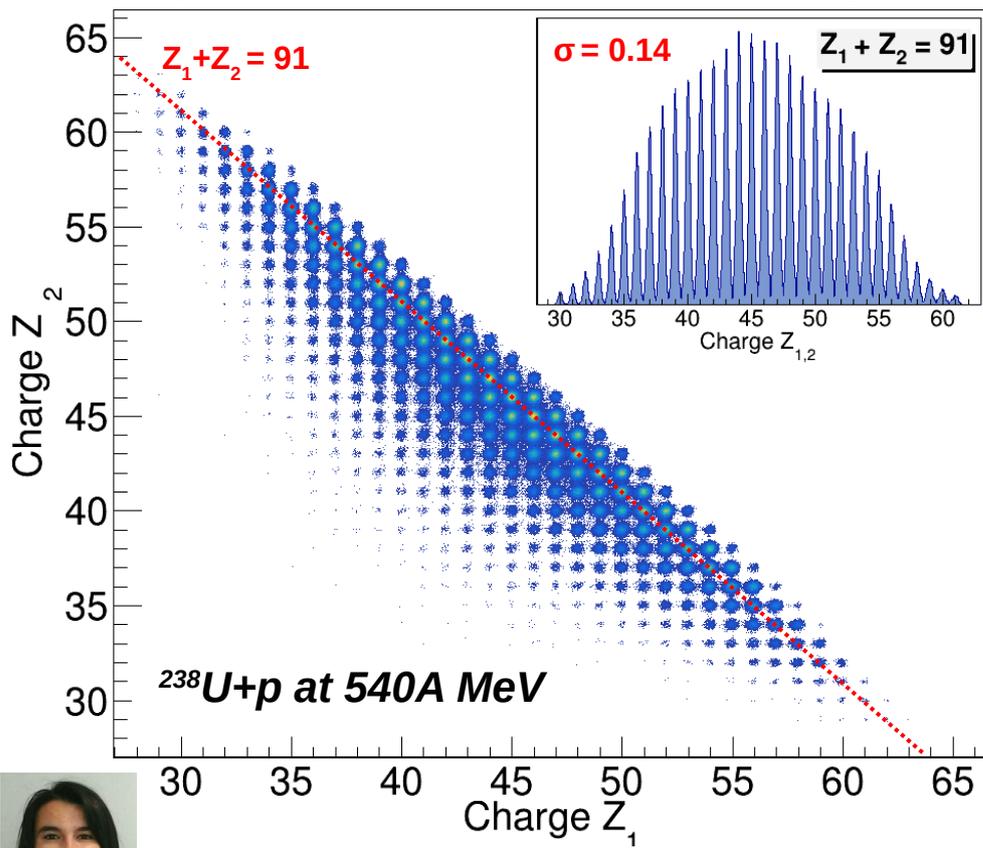


• Magnetic field: ~ 4.5 Tm

- CALIFA and Si-tracker: Proton momenta and γ -rays
Energy res. protons(gamma) 1%(5% at 1 MeV), Position res. 70 μm
- MUSIC, ToF wall and MWPC detectors: Fission fragments
 $\Delta Z \sim 0.34$, ToF ~ 40 ps, Position res. 250 μm (FWHM)
- NeuLAND: Neutron multiplicities (max. 4-5 neutrons)

First quasi-free (p,2p)-induced fission experiment

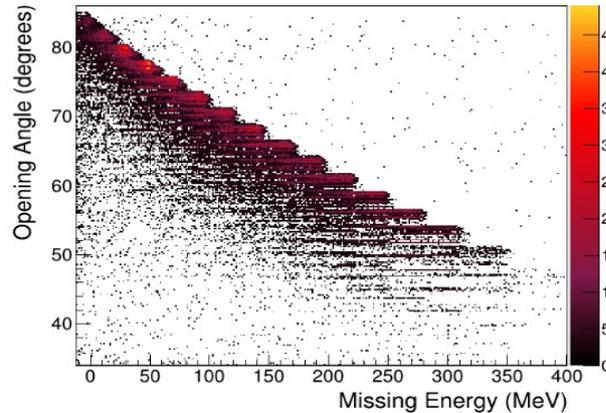
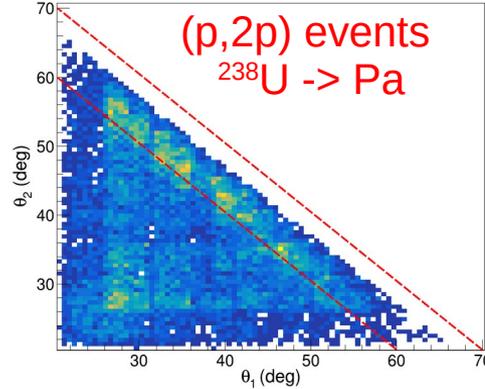
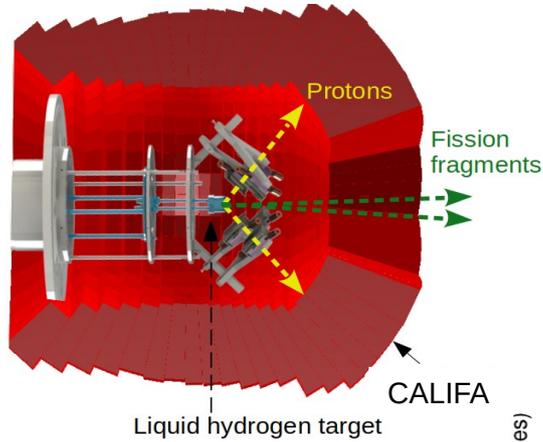
Charge identification of fission fragments & fissioning systems



• A. Graña, PhD thesis 2024

First quasi-free (p,2p)-induced fission experiment

Quasi-free nucleon-knockout collisions, such as (p,2p), in inverse kinematics are used for the first time to induce fission and measure the E^* of the compound nuclei



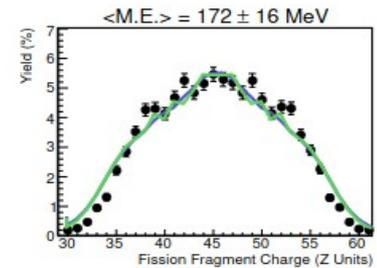
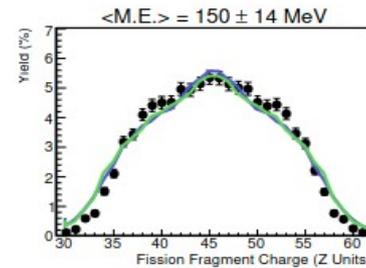
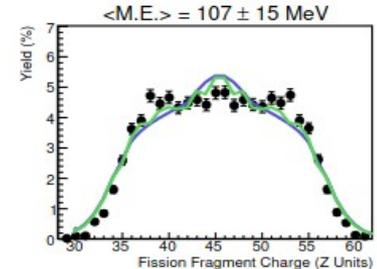
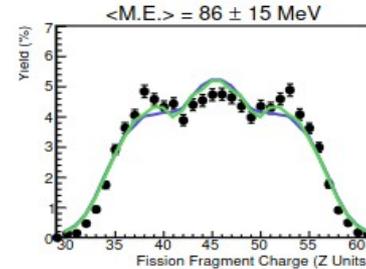
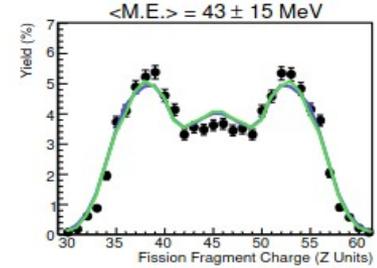
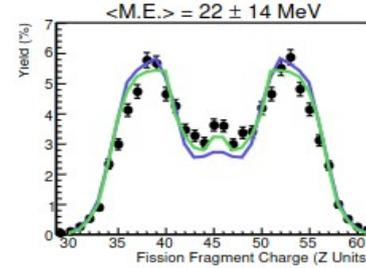
Invariant mass method

$$E^* = I_M - m_{A-1} c^2$$

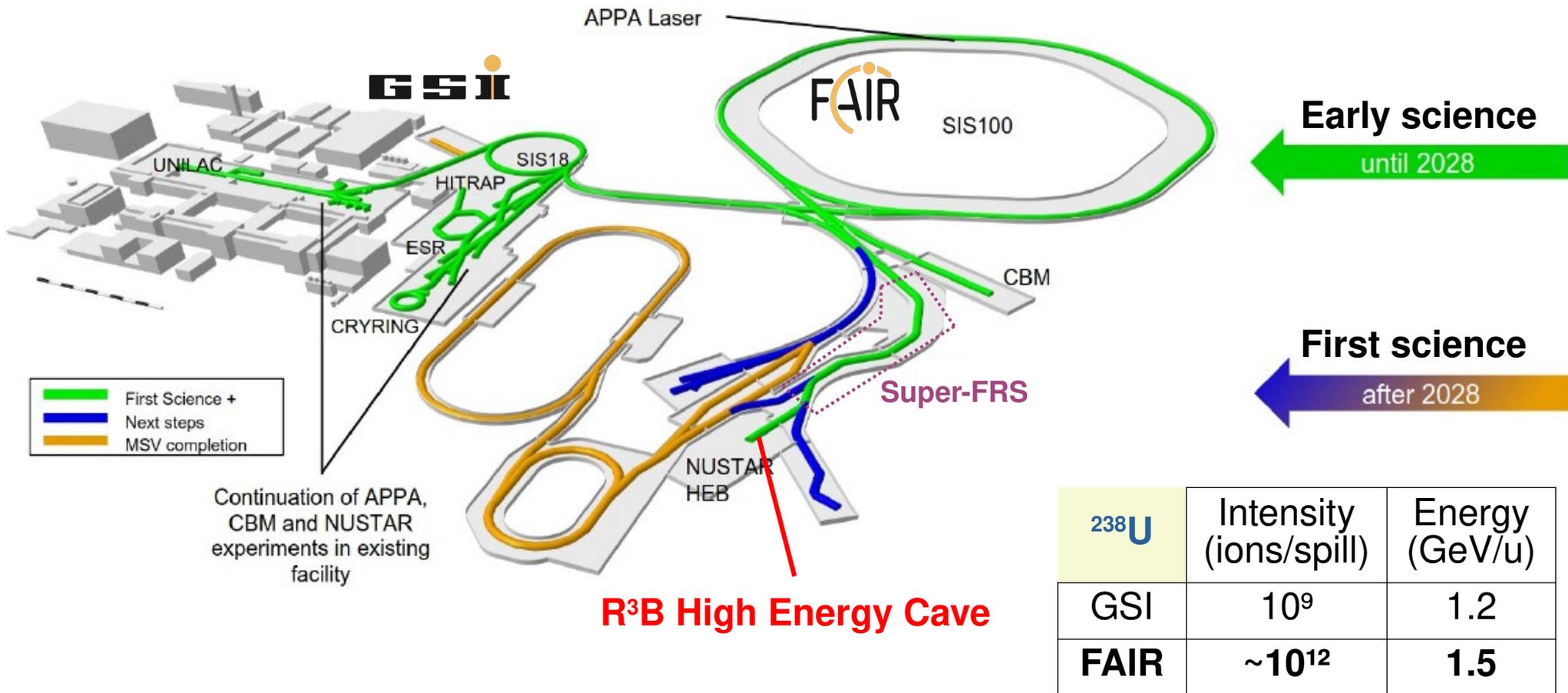
Invariant mass Rest mass



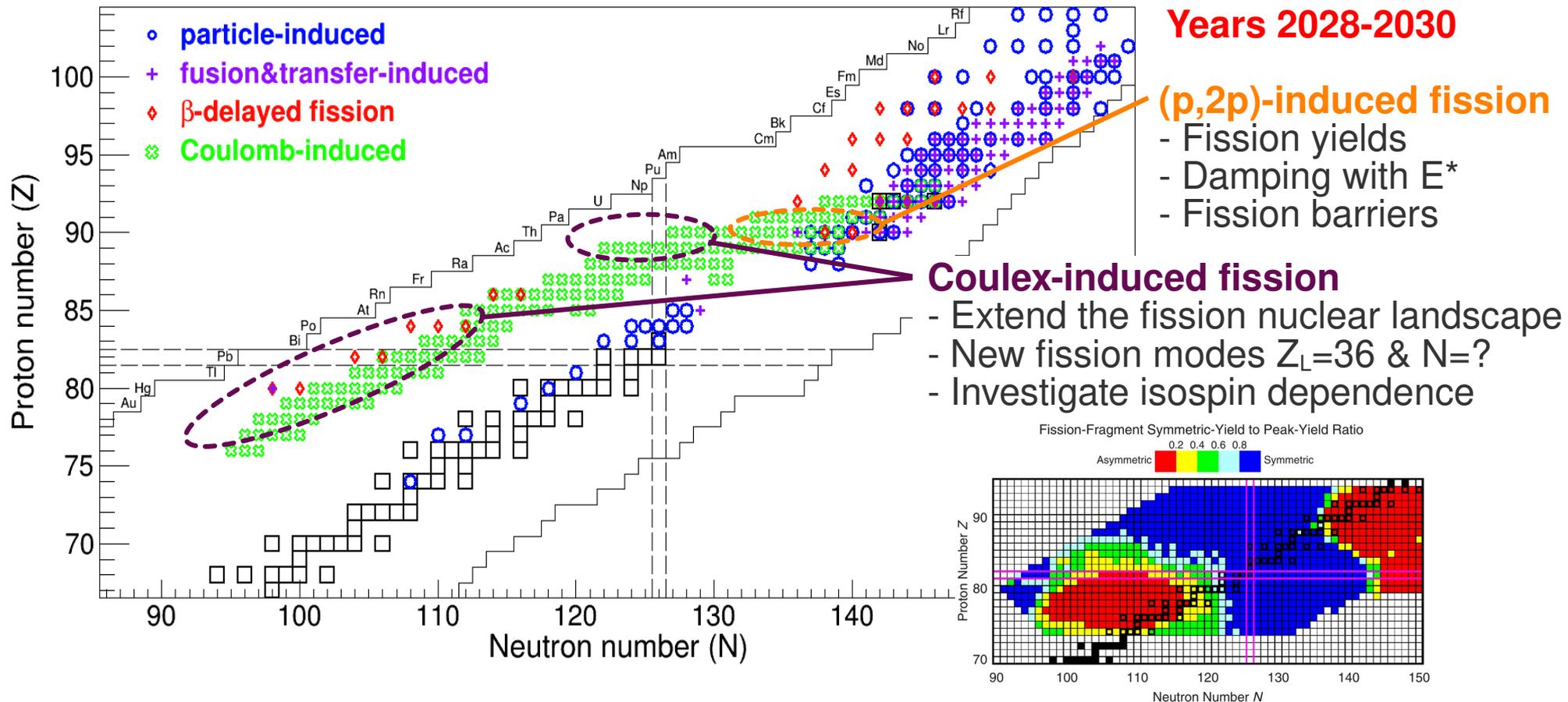
• G. García, PhD thesis 2024



Future SOFIA/R³B fission experiments at GSI/FAIR



Future SOFIA/R³B fission experiments at GSI/FAIR



15 years of SOFIA/R³B experiments at the GSI facility

- Measurement of fission yields for around 144 fissioning systems
- Discovery of a short symmetric fission mode in the thorium region
- First exploration of the fission island in the pre-actinide region
- Stabilization of charge fission yields around $Z_L=36$ for pre-actinides
- Constraint of the dissipation coefficient at small and large deformations
- First quasi-free (p,2p)-induced fission experiment with ^{238}U

Future fission experiments at the GSI/FAIR facility

- Extend the study of the new fission island in the pre-actinide and actinide regions
- First quasi-free (p,2p)-induced fission experiments with exotic nuclei

Acknowledgments



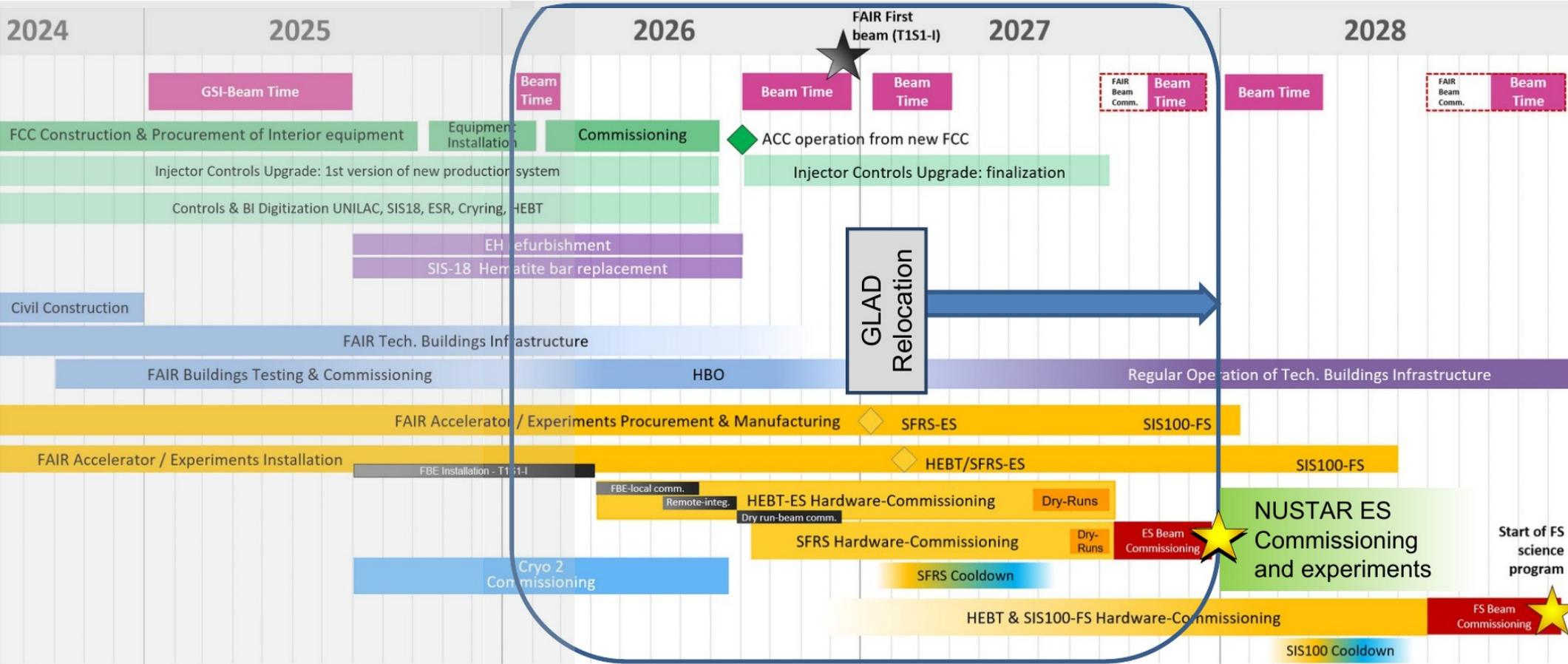
Special thanks to:

Hector Alvarez, Laurent Audouin, Jose Benlliure, Audrey Chatillon, Gabriel García-Jiménez, Andreas Heinz, Thomas Gorbinet, Antía Graña-González, Pierre Morfouace, Julien Taïeb et al.



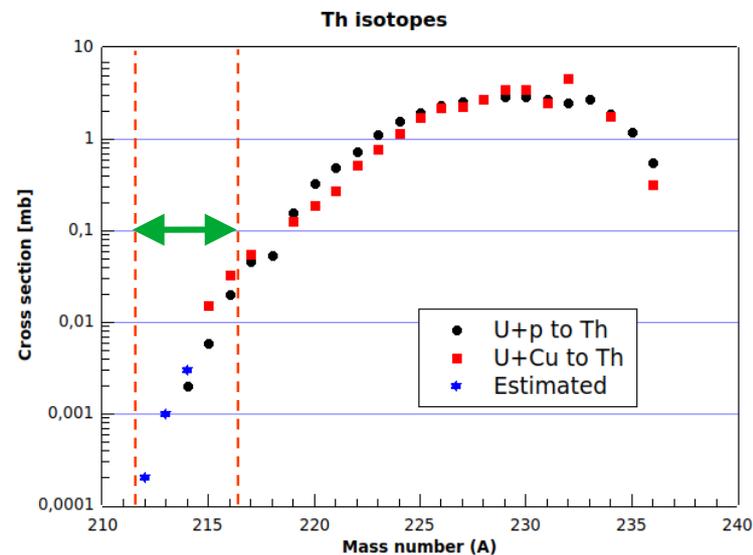
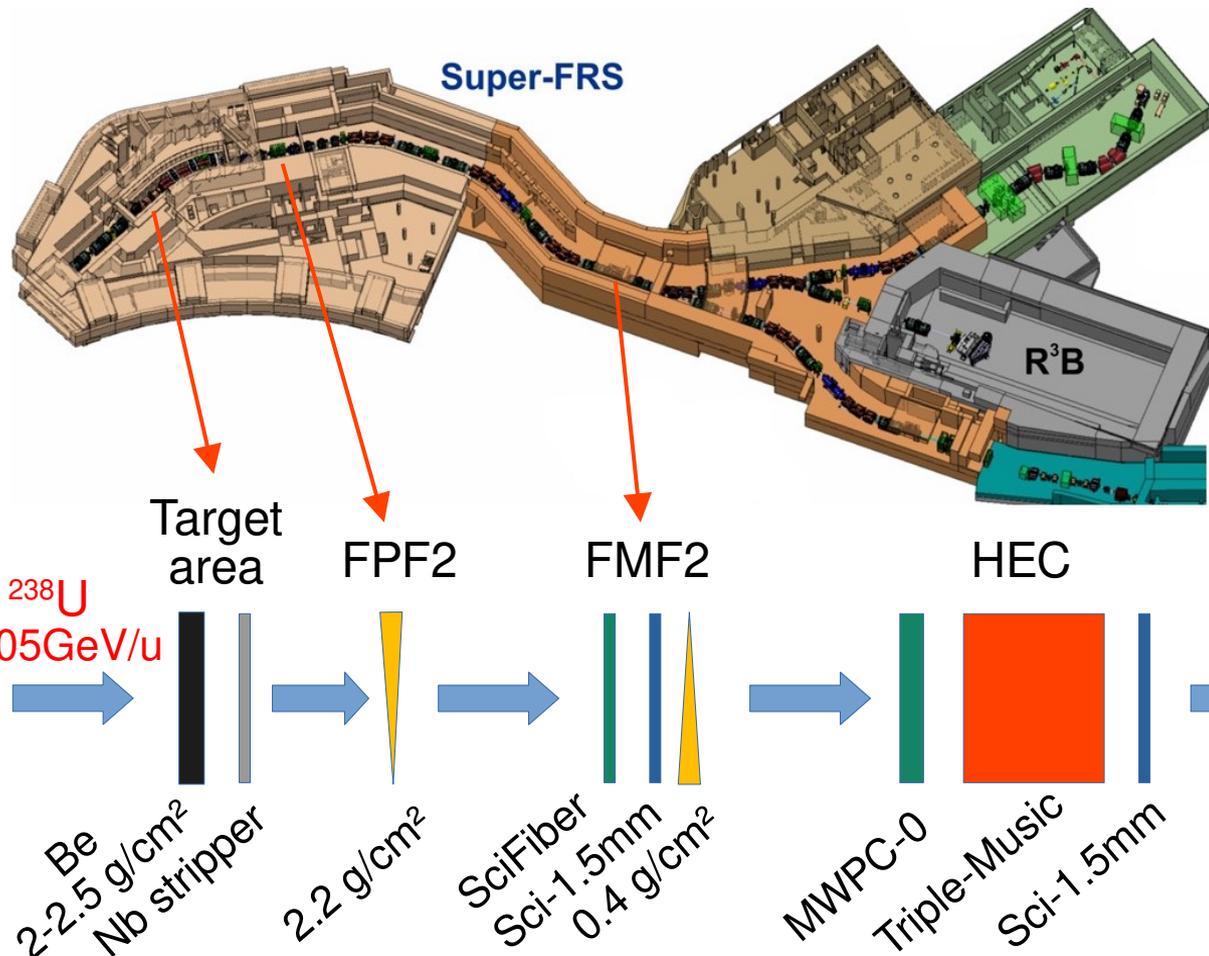
Backup

FAIR & GSI Integrated Schedule



https://www.gsi.de/work/gesamtprojektleitung_fair/project_management_office/integrated_campus_scheduling

Experimental setup at Super-FRS



212-216Th @ 670 MeV/u

209-214Ac

207-213Ra

174Au, 177,180Hg, 182Tl, 185Pb, 187Bi

Experimental setup

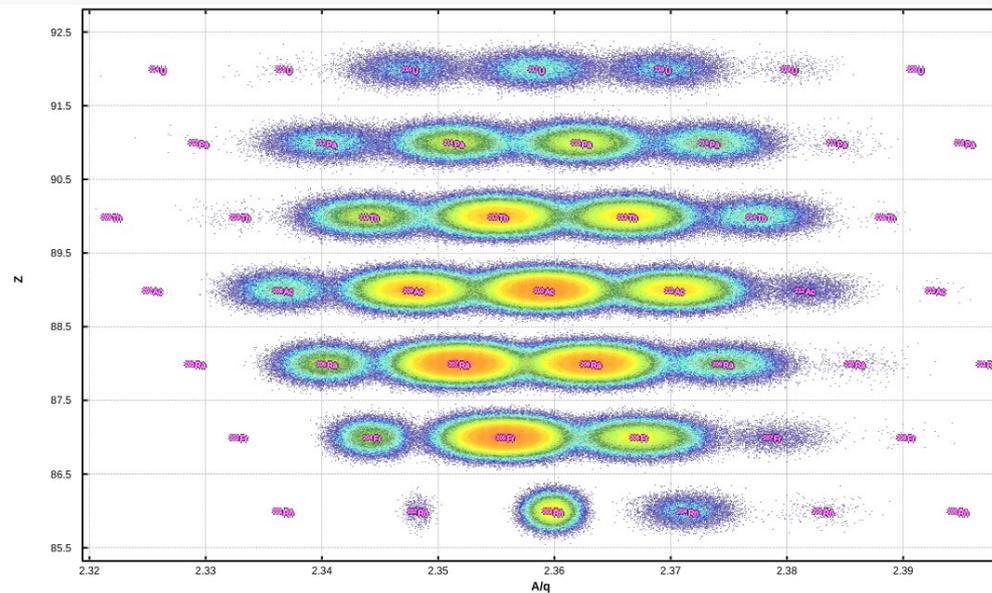
^{212}Th setting, transmission 48 %

It's PSEUDO
Monte Carlo!

Z vs. A/q

^{238}U (1000 MeV/u) + C (2.6 g/cm²), Nb (110 mg/cm²); Settings on ^{212}Th ; Config: D⁰⁰⁰⁰⁰D⁰D⁰D⁰...D⁰D⁰...
dP/P=1.59%; Wedge(s): Al (2.2 g/cm²); Bp (Tm): 11.3022, 11.3022, 11.3022, 11.3022, 9.2890....
constructed from ToF and dE1 measurements **

with
all



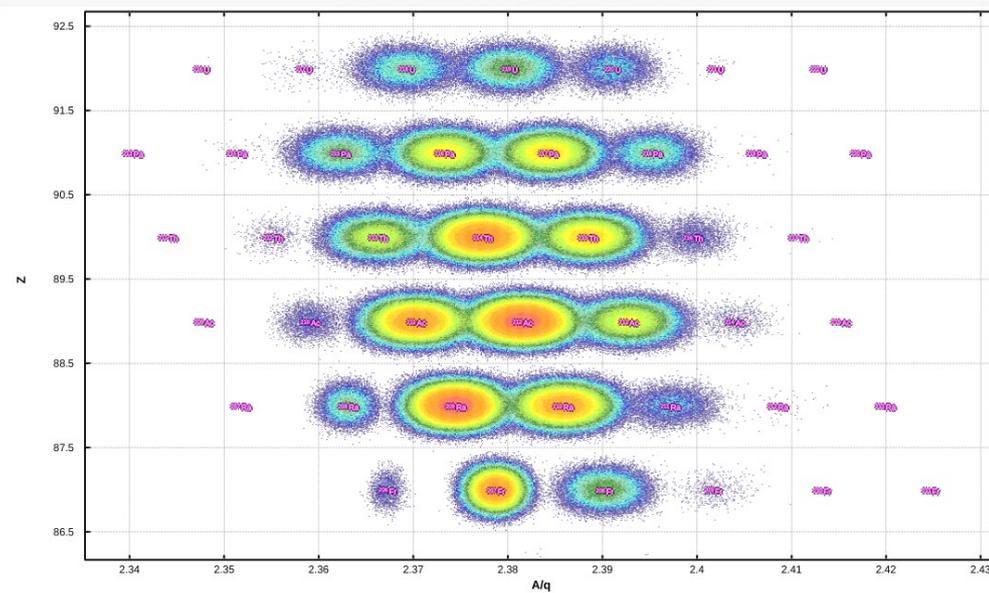
^{214}Th setting, transmission 44 %

with
all

Z vs. A/q

^{238}U (1.05 GeV/u) + C (2.6 g/cm²), Nb (110 mg/cm²); Settings on ^{214}Th ; Config: D⁰⁰⁰⁰⁰D⁰D⁰D⁰...D⁰D⁰...
dP/P=1.27%; Wedge(s): Al (2.2 g/cm²); Bp (Tm): 11.9177, 11.9177, 11.9177, 11.9177, 9.9723....
constructed from ToF and dE1 measurements **

with
all



Experimental setup

^{187}Bi setting, transmission 41 %

^{180}Hg setting, transmission 43 %

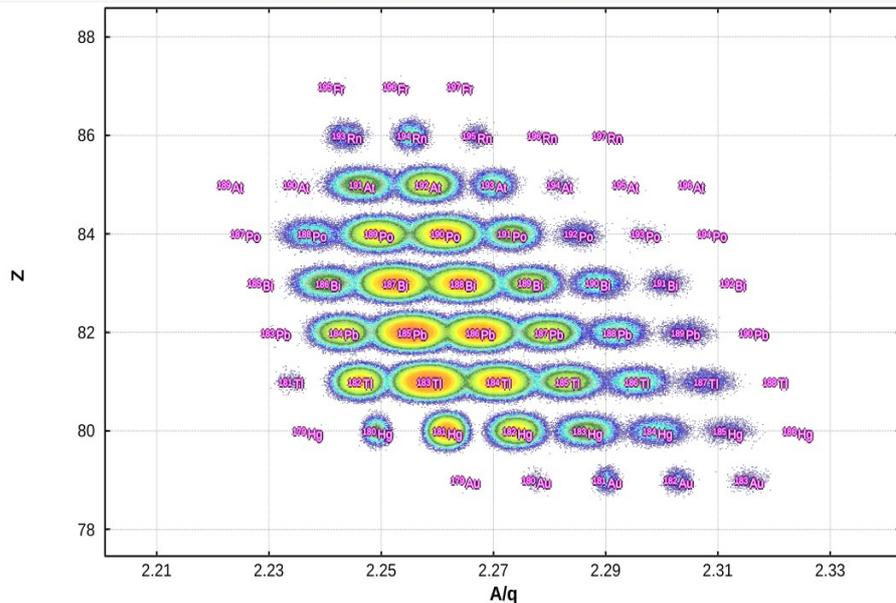
It's PSEUDO Monte Carlo!

Z vs. A/q

It's PSEUDO Monte Carlo!

^{238}U (1.05 GeV/u) + Be (2.5 g/cm²), Nb (110 mg/cm²); Settings on ^{187}Bi ; Config: D^{hhhh}D^hD^hD^h_{wm}D^hD^h_m
dP/P=1.21%; Wedge(s): Al (2.2 g/cm²); Bp (Tm): 11.5344, 11.5344, 11.5344, 9.7871....
constructed from ToF and dE1 measurements **

with all



Continue

^{238}U (1.05 GeV/u) + Be (2.5 g/cm²), Nb (110 mg/cm²); Settings on ^{180}Hg ; Config: D^{hhhh}D^hD^hD^h_{wm}D^hD^h_m
dP/P=1.25%; Wedge(s): Al (2.2 g/cm²); Bp (Tm): 11.5494, 11.5494, 11.5494, 9.8763....
constructed from ToF and dE1 measurements **

without charge states
all reactions separ.

