Fission studies at the ISOLDE Solenoidal Spectrometer

Maria Vittoria Managlia
Chalmers University of Technology

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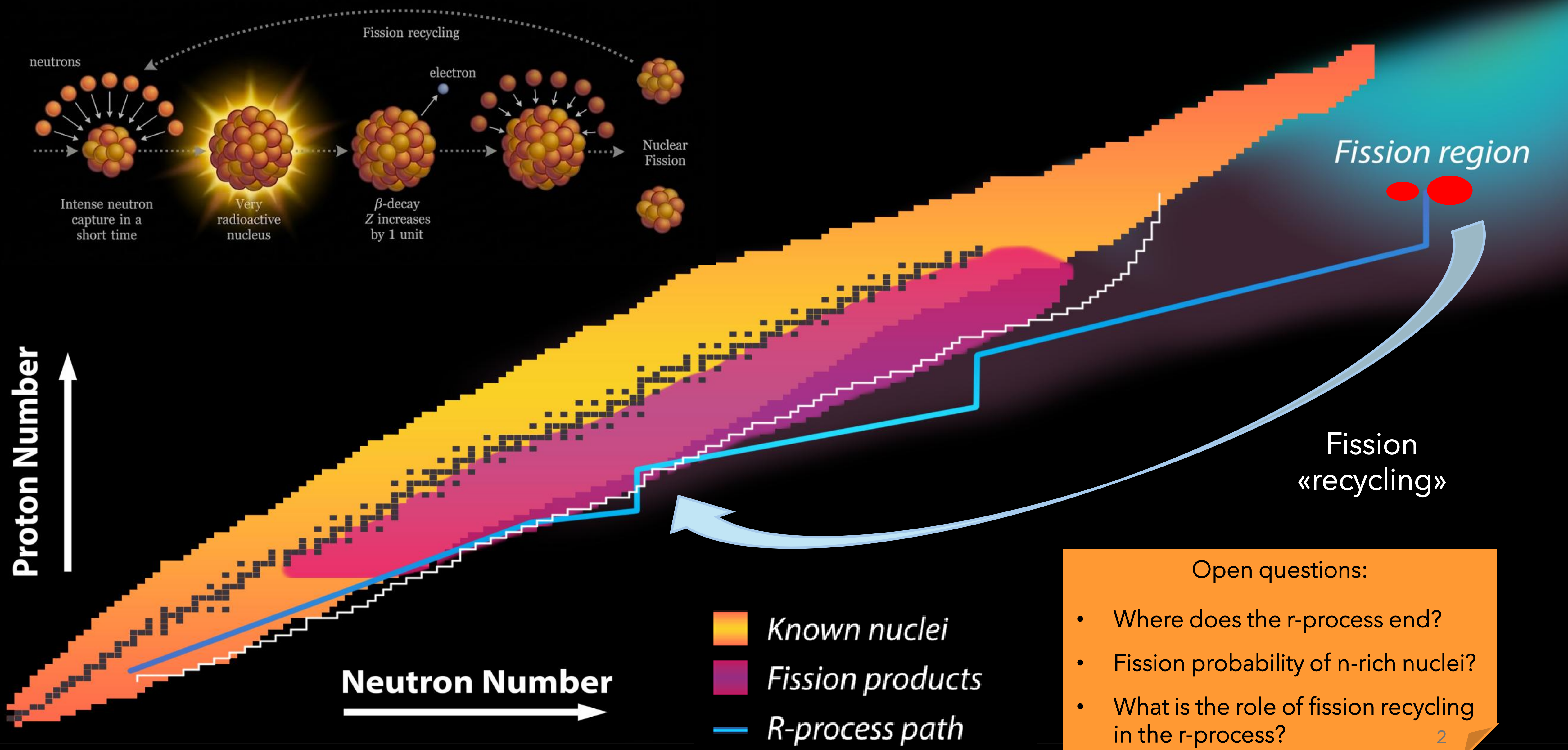
Knut and Alice Wallenberg Foundation
Swedish Research Council

Nuclear fission in the r-process



Open questions:

- Where does the r-process end?
- Fission probability of n-rich nuclei?
- What is the role of fission recycling in the r-process?

Matthew Mumpower©

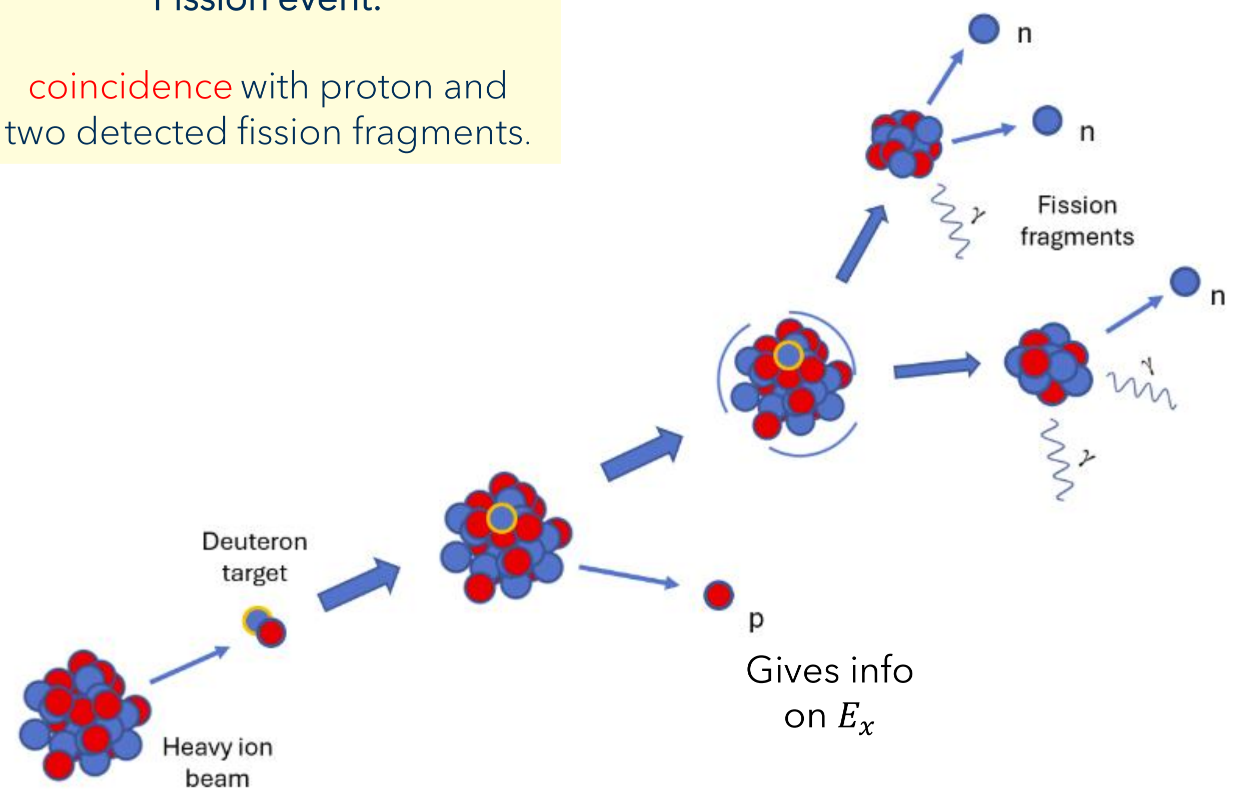
Probing fission of n-rich nuclei

Inverse kinematics using radioactive ion beams (RIBs)

Surrogate reaction: (d,pf) in inverse kinematics

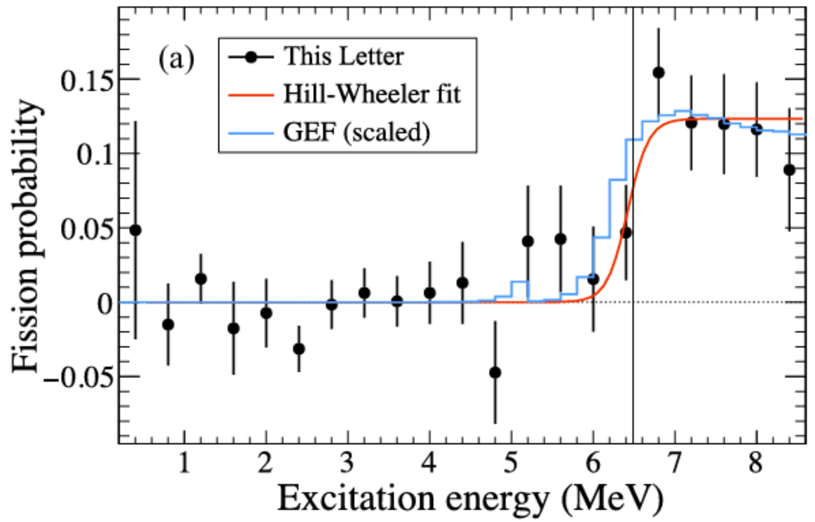
Fission event:

coincidence with proton and two detected fission fragments.



Key fission observables:

- Fission probability as a function of the excitation energy.
- Charge-mass distribution of fission fragments.
- Energy released in γ radiation during fission.



^{239}U

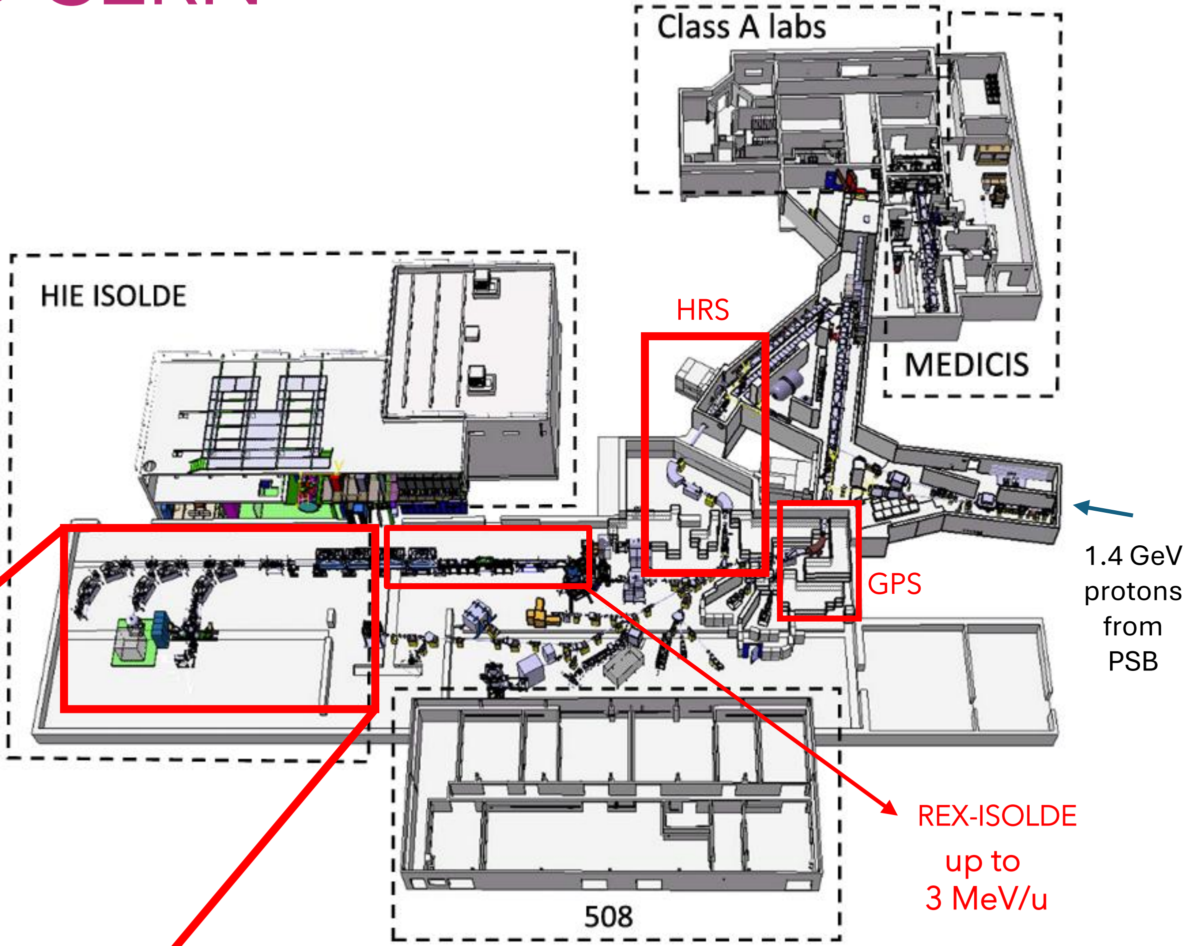
S.A. Bennet et al., *Phys.Rev.Lett.* 130 (2023) 20, 202501.

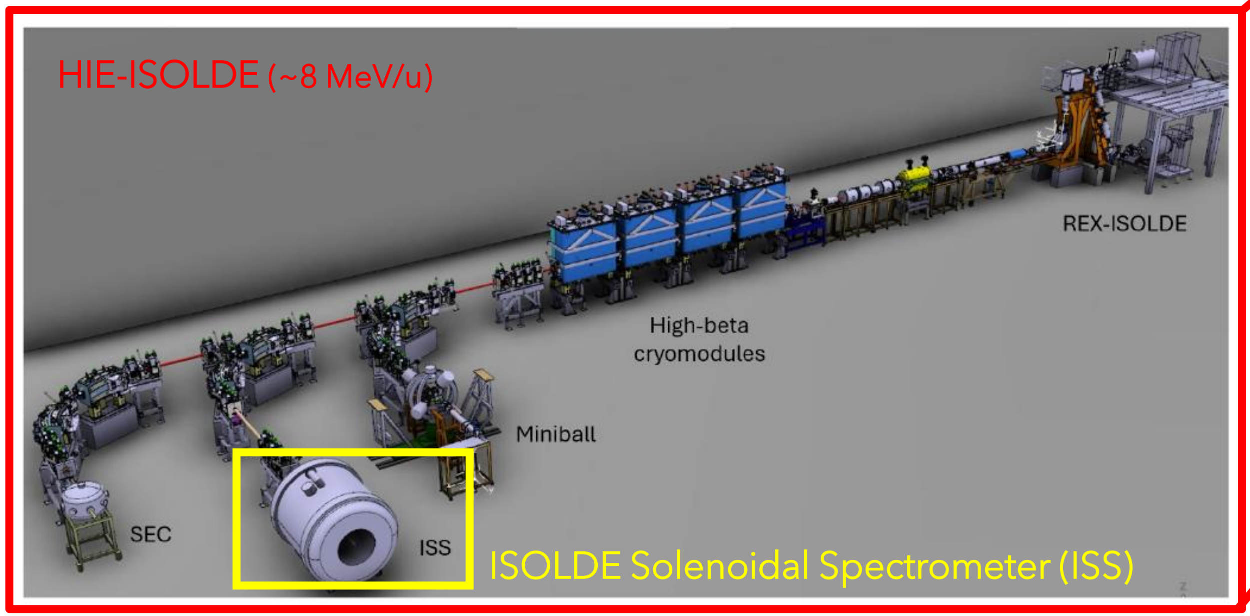
How?

ISOLDE @ CERN

ISOLDE: on-line isotope mass separator.

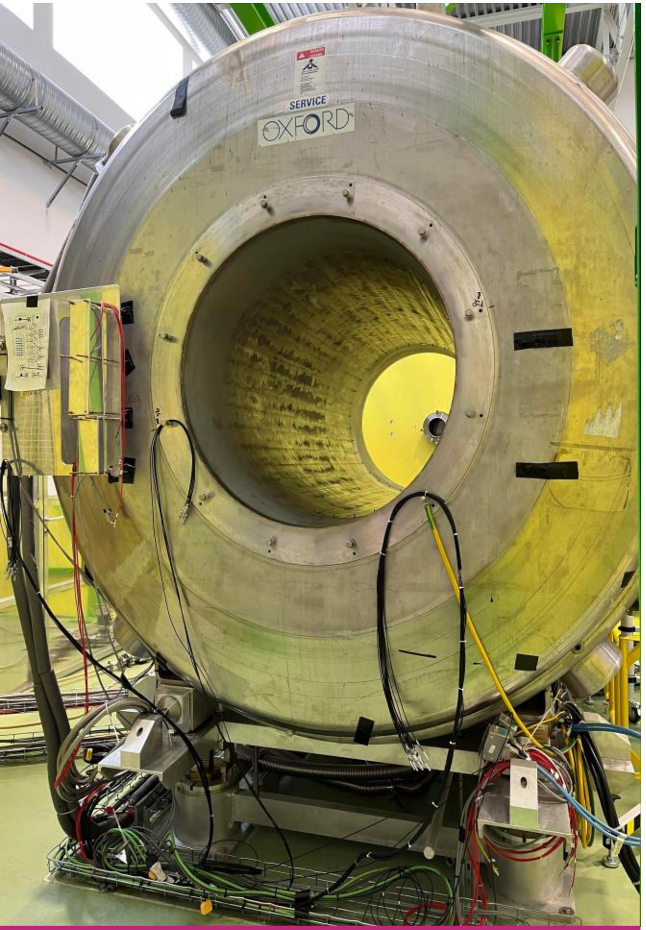
PS Booster proton beam on thick target → production and separation of exotic radioactive nuclides.



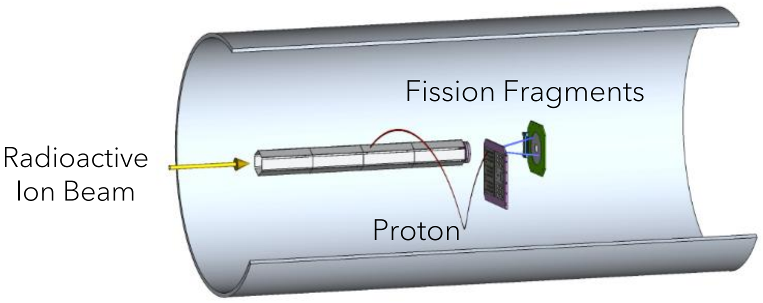


Why a solenoidal spectrometer?

(d,p f) in inverse kinematics:

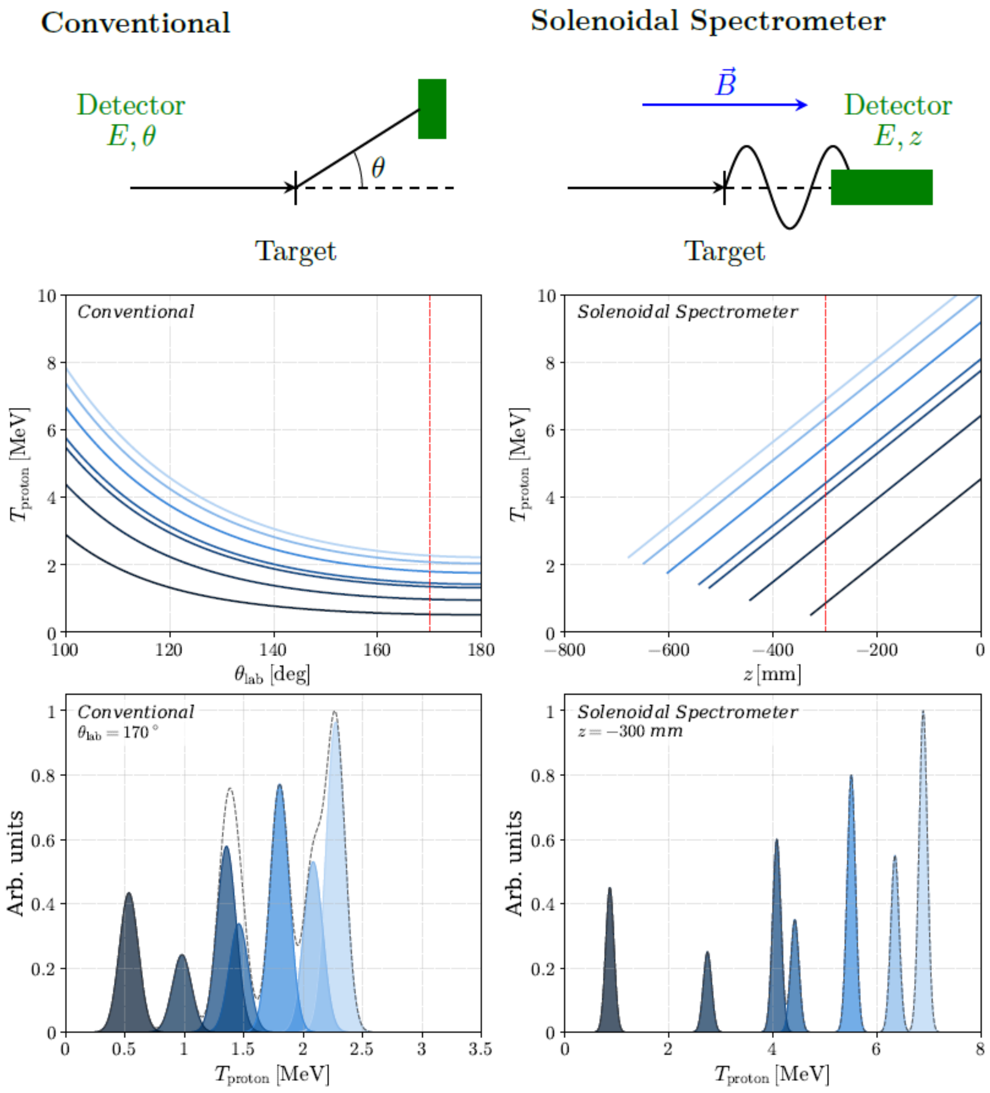


ISOLDE Solenoidal Spectrometer



- Uniform magnetic field (2T).
- Target and detectors inside the solenoid.
- Charged particles follow helical trajectories.
- Particles detected along the magnet axis.

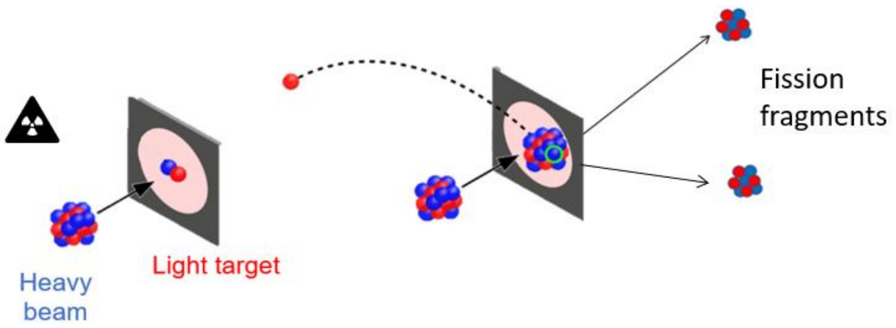
- <u>Considerably better</u> energy resolution of the populated state in the compound nucleus.

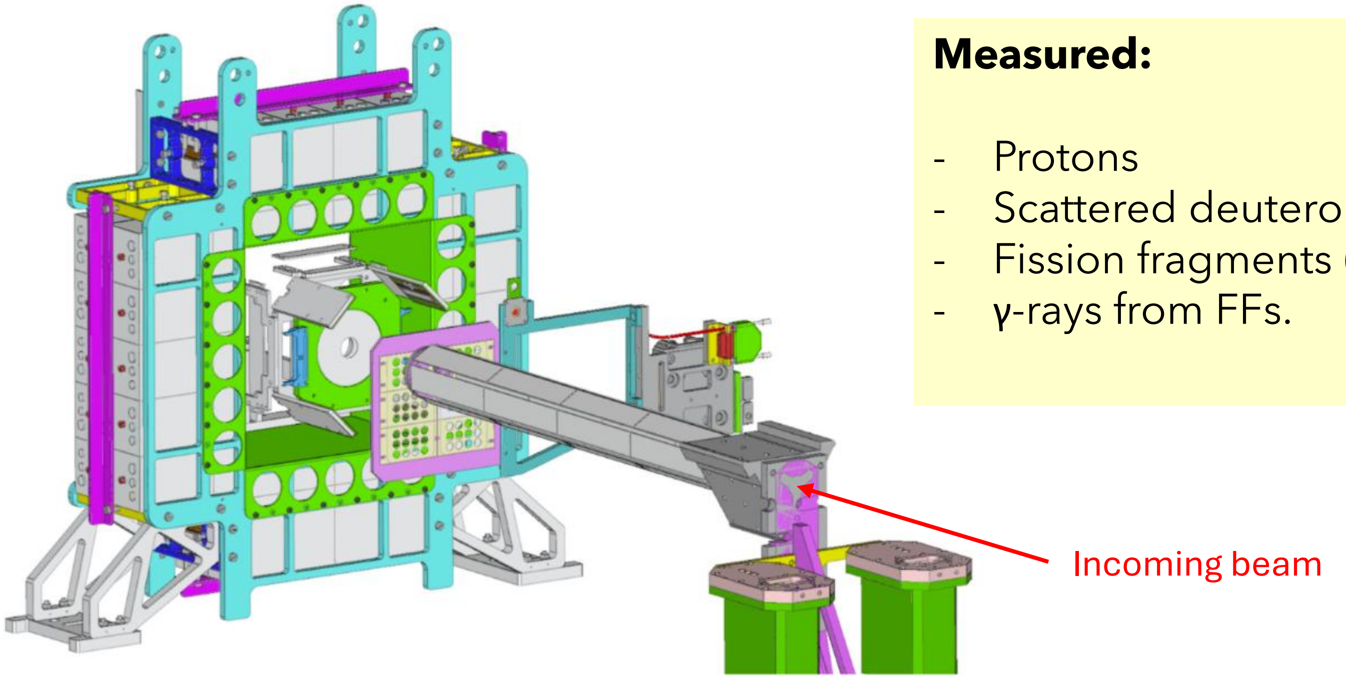


Experimental Setup

A novel setup for studying (d,pf) reactions at ISS

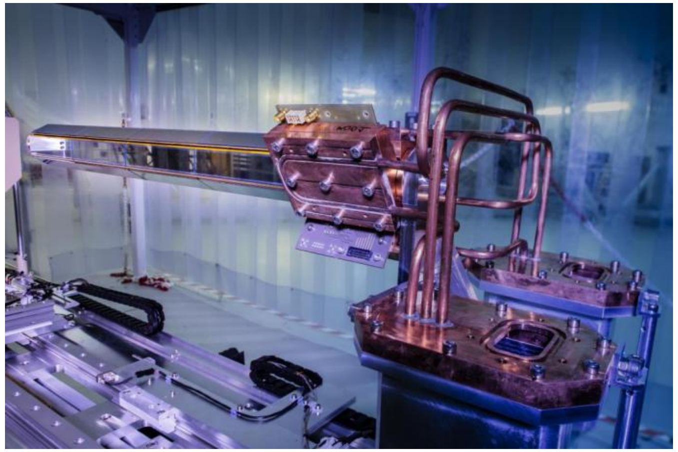
(d,pf) in inverse kinematics:



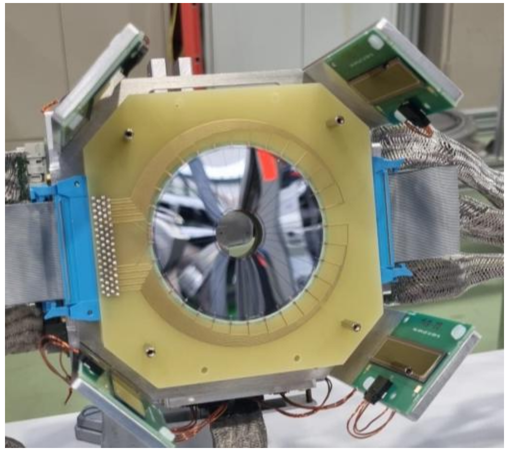


Measured:

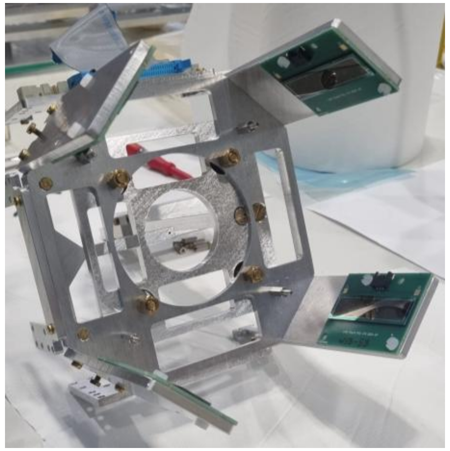
- Protons
- Scattered deuterons
- Fission fragments (FFs)
- γ-rays from FFs.



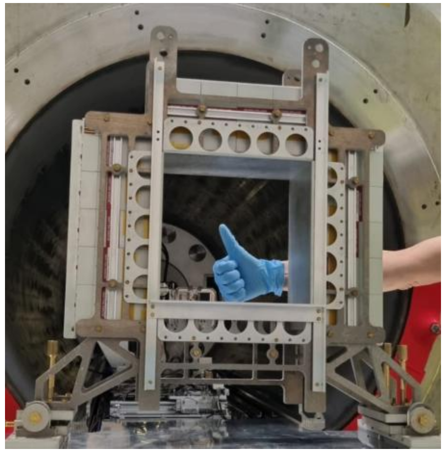
Protons: array of position-sensitive silicon detectors.



Fission Fragments: ΔE – E Double Sided Silicon Detectors.



Deuterons: Luminosity monitor with 4 position-sensitive silicon detectors.

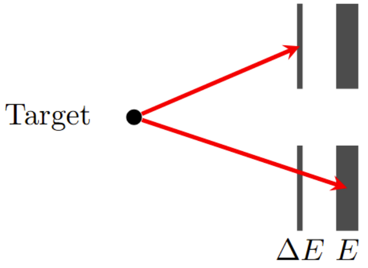


γ-rays: 28 $CeBr_3$.

Experiment IS739

ISOLDE, CERN
July 10 - 20, 2025

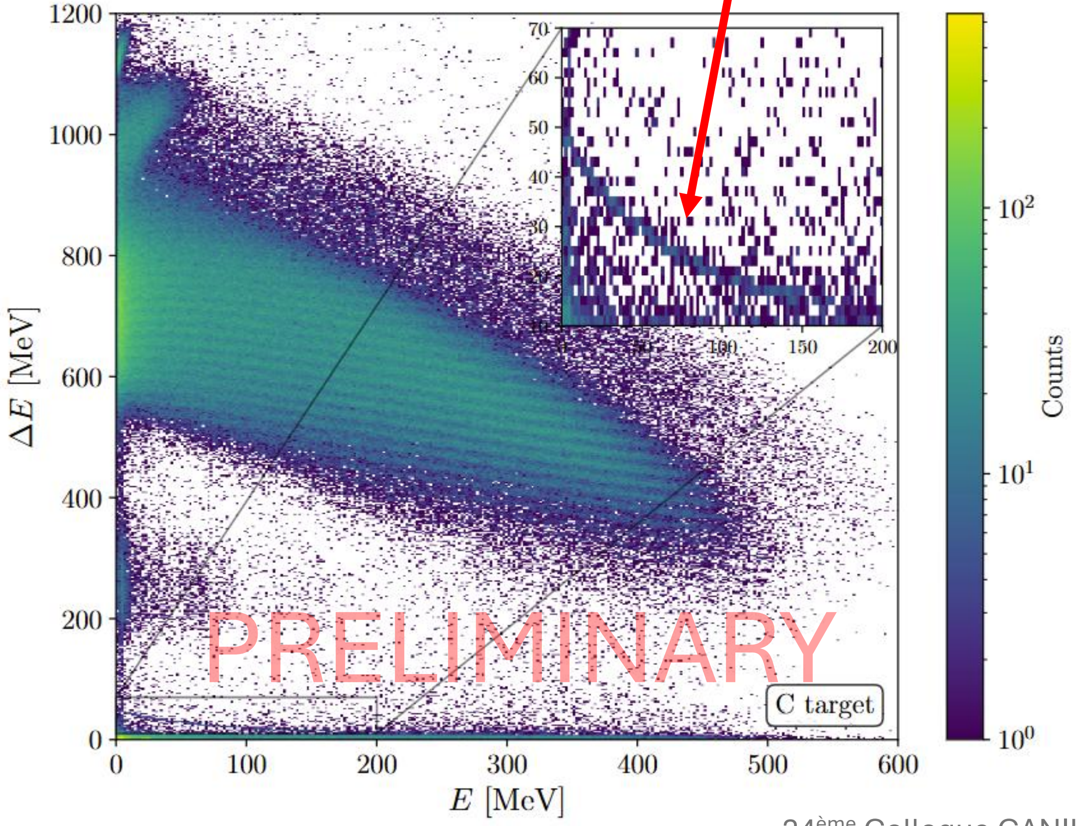
IS739: ^{232}U(d,pf) at 7.34 MeV/u

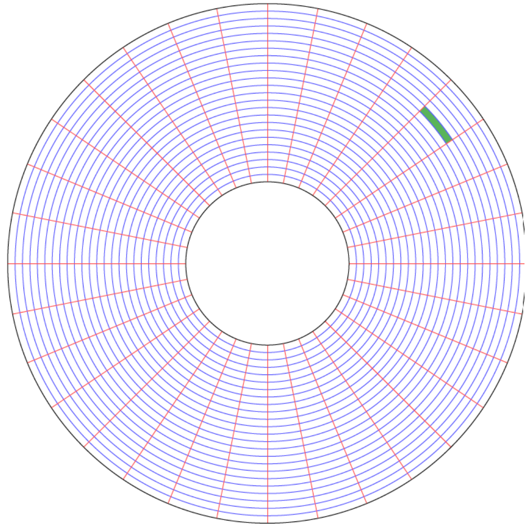


Fission detectors

CD_2 target

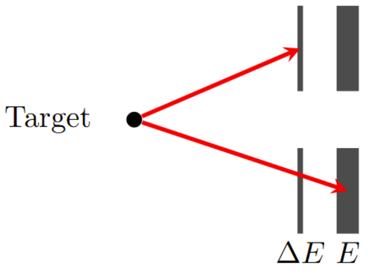
Scattered C





IS739: $^{232}U(d,pf)$ at 7.34 MeV/u

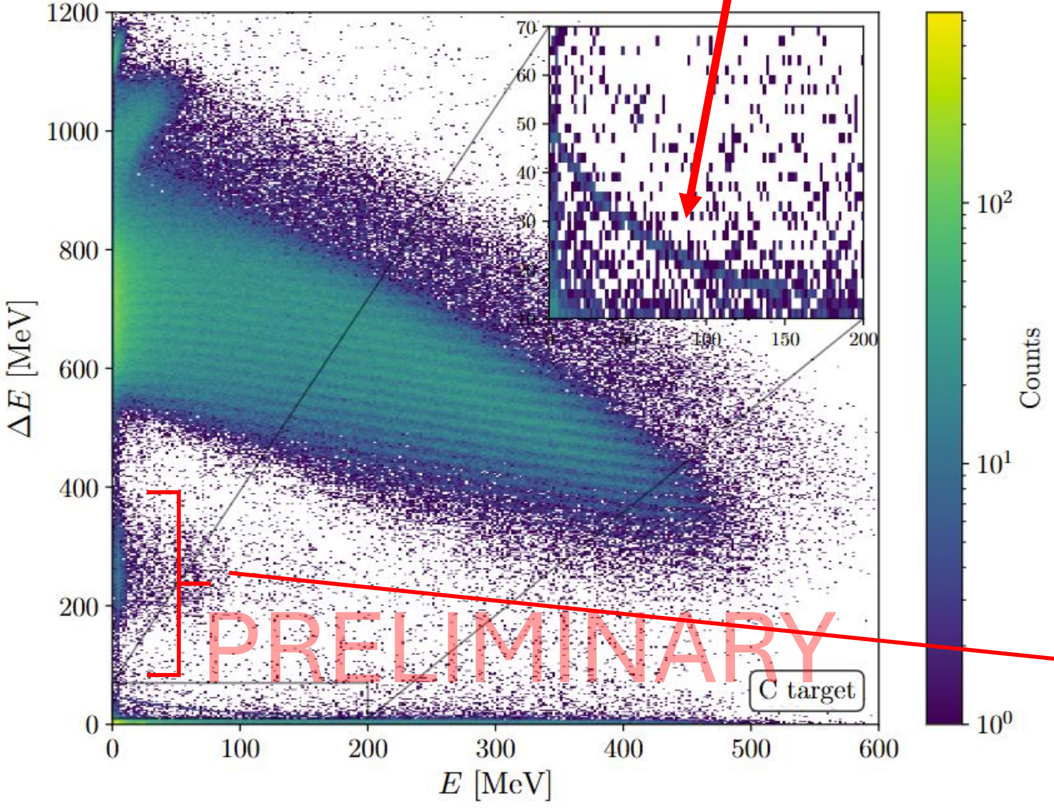
Fission detectors



CD$_2$ target

Find average A per Z to use as reference: GEF simulation.

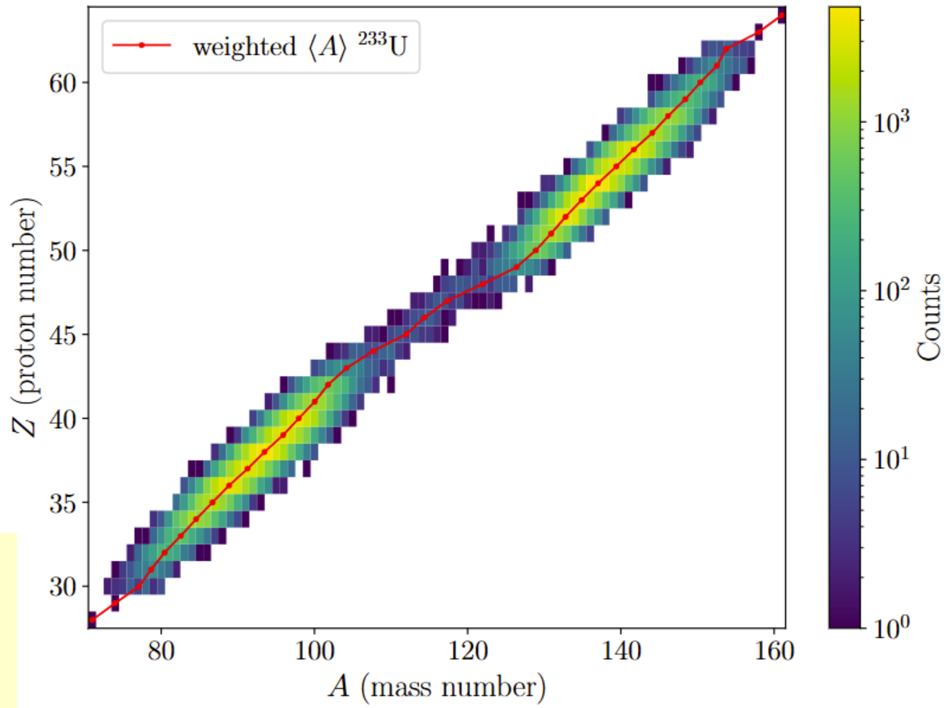
Scattered C



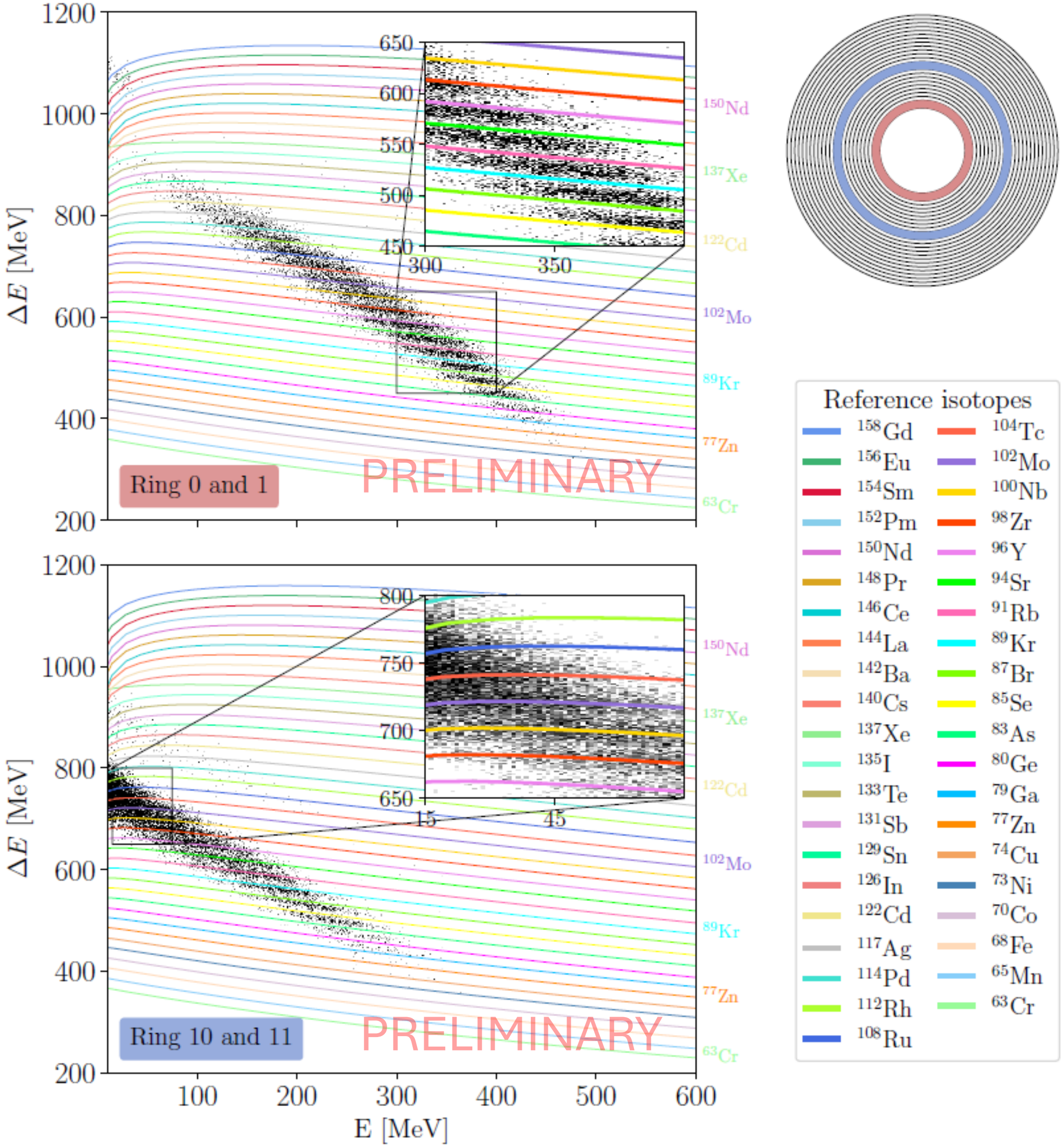
Large gap.

Far extrapolation from C

GEF predictions



Charge identification of fission fragments



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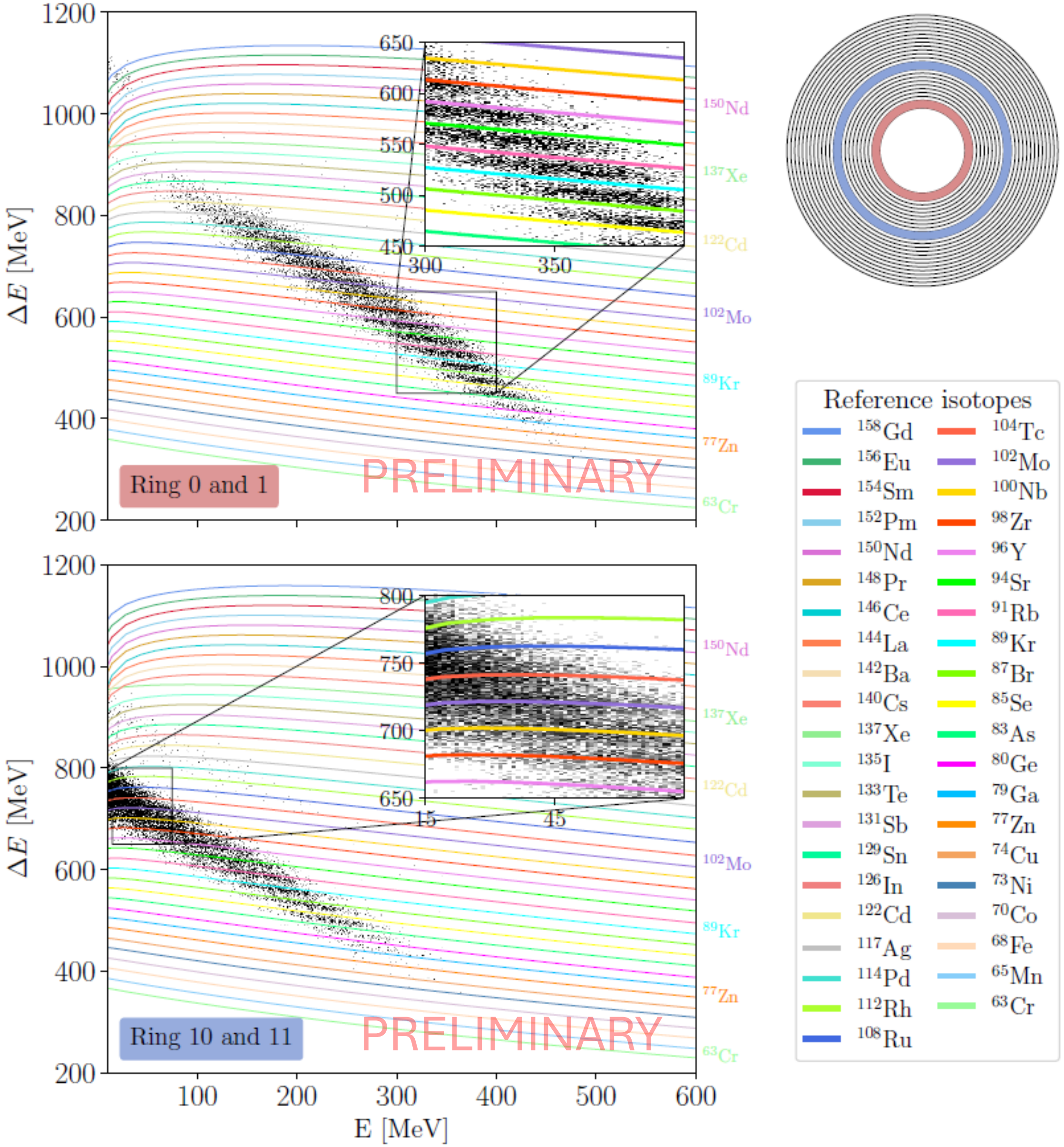
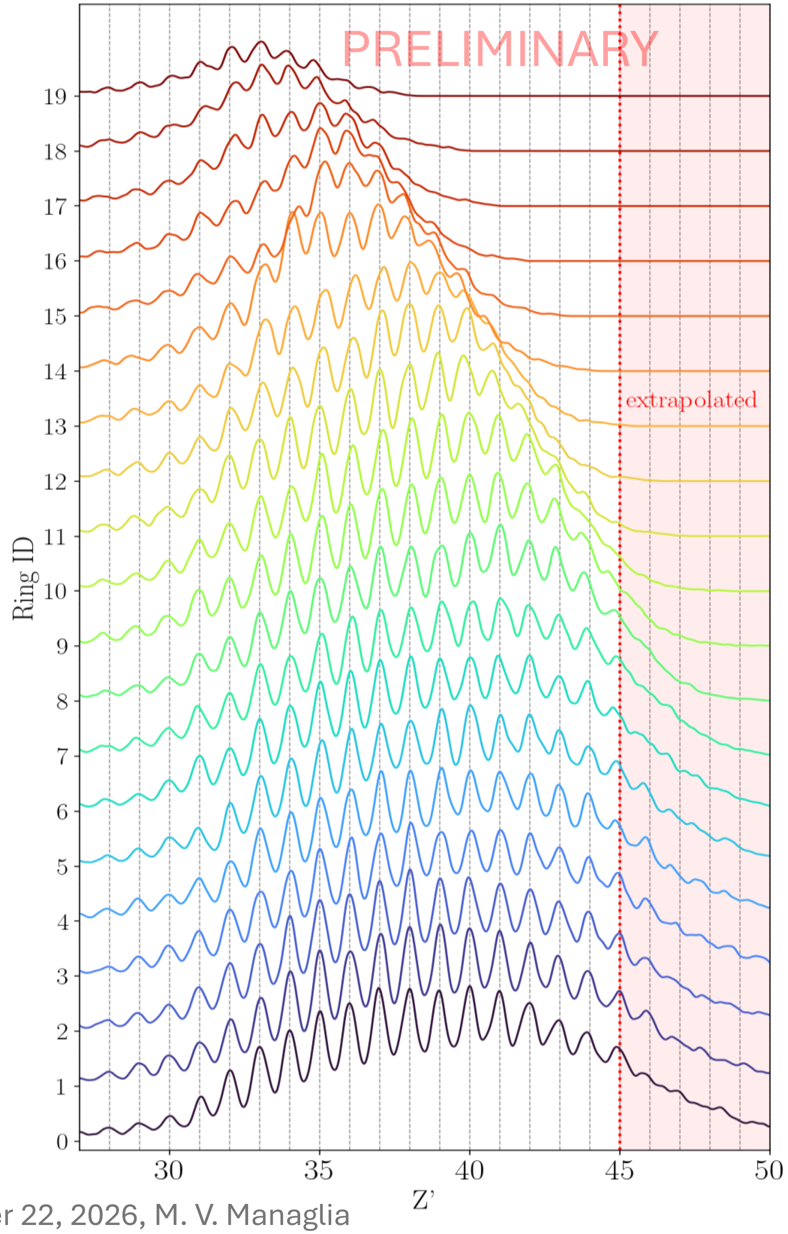




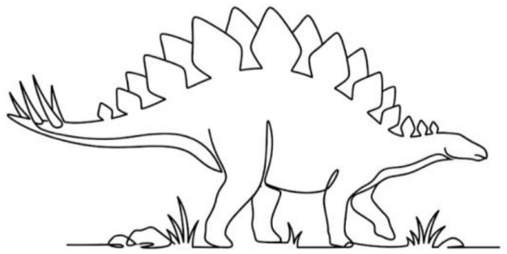
Extrapolation: Peak finding not possible.

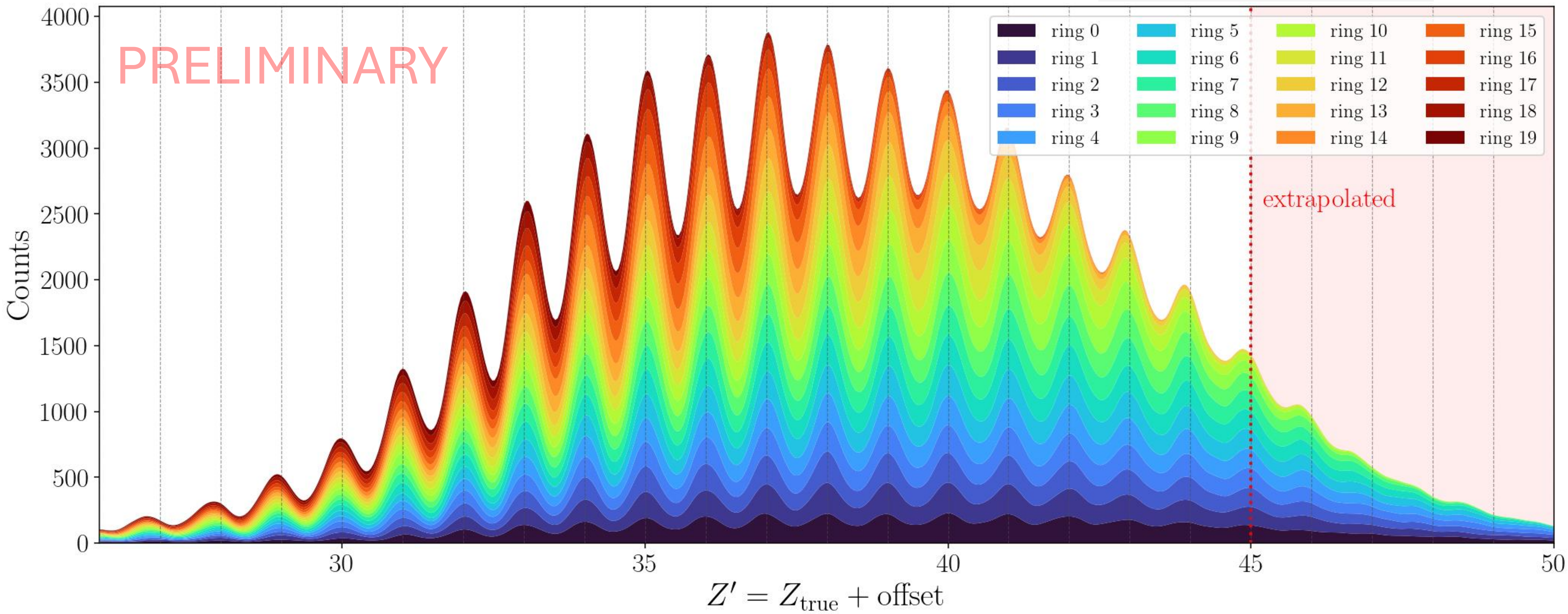
Align (stretch) to tentative integer Z

$Z' = Z_{true} + \text{offset}$

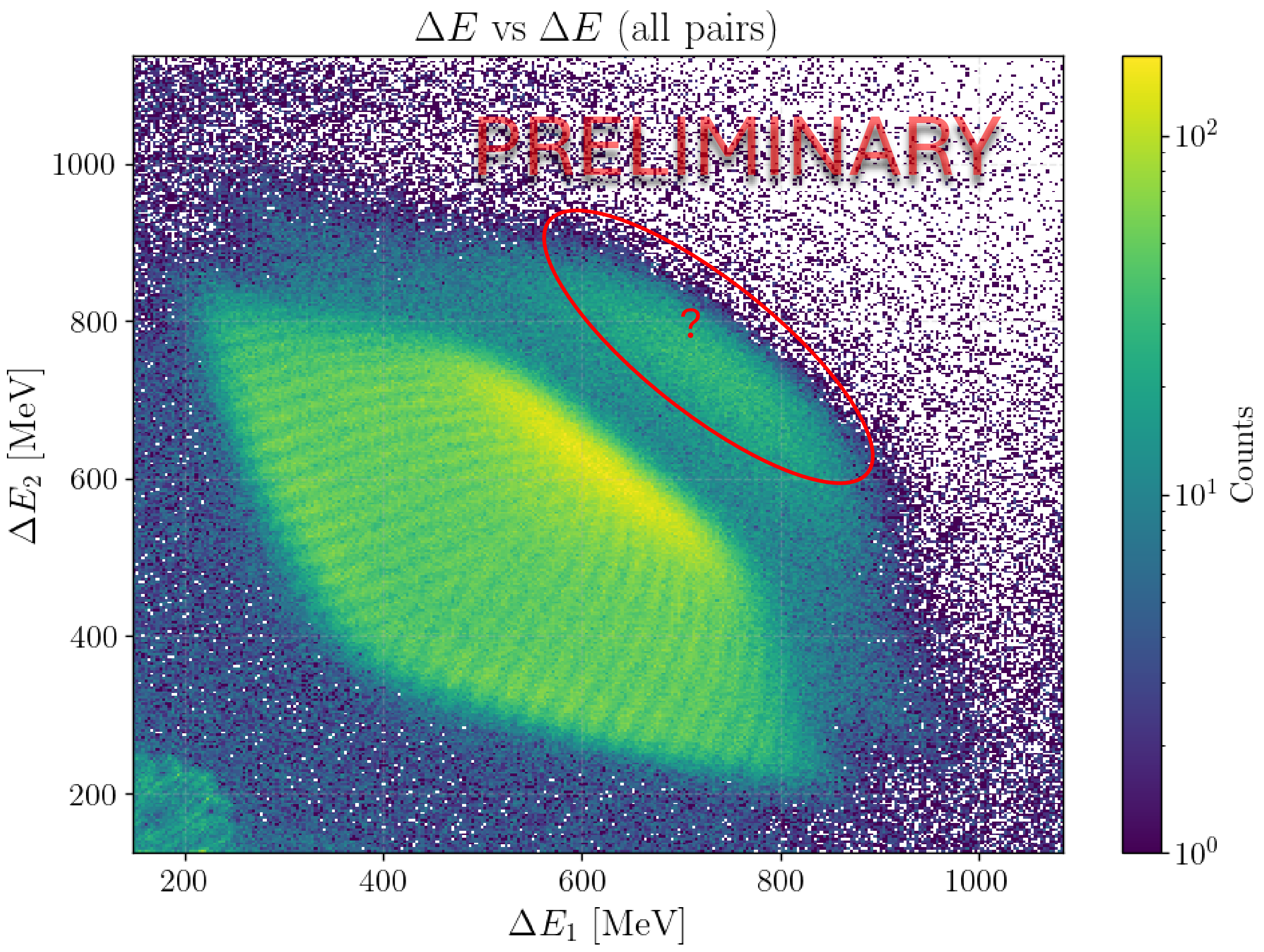
Charge identification of fission fragments

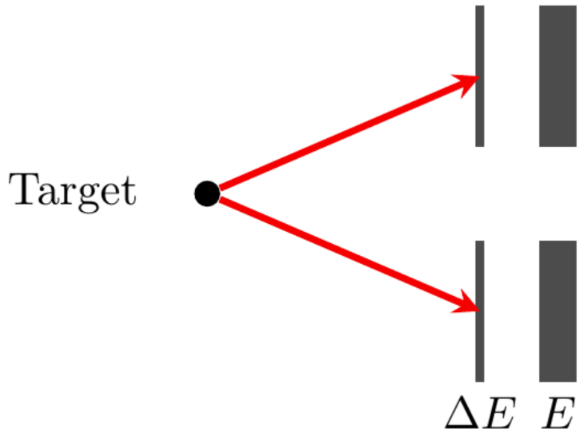
"Dino" plot:
Z' for all rings combined.





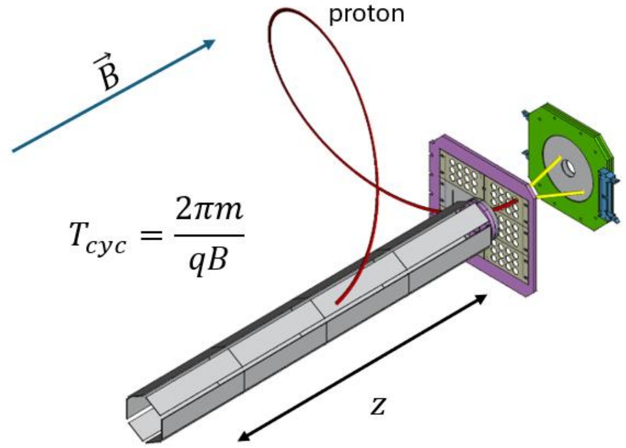
Second component



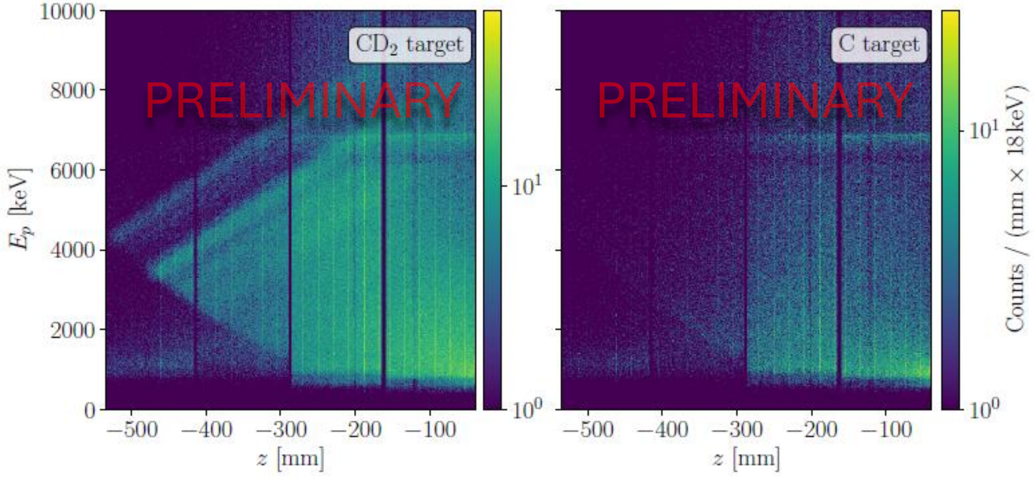


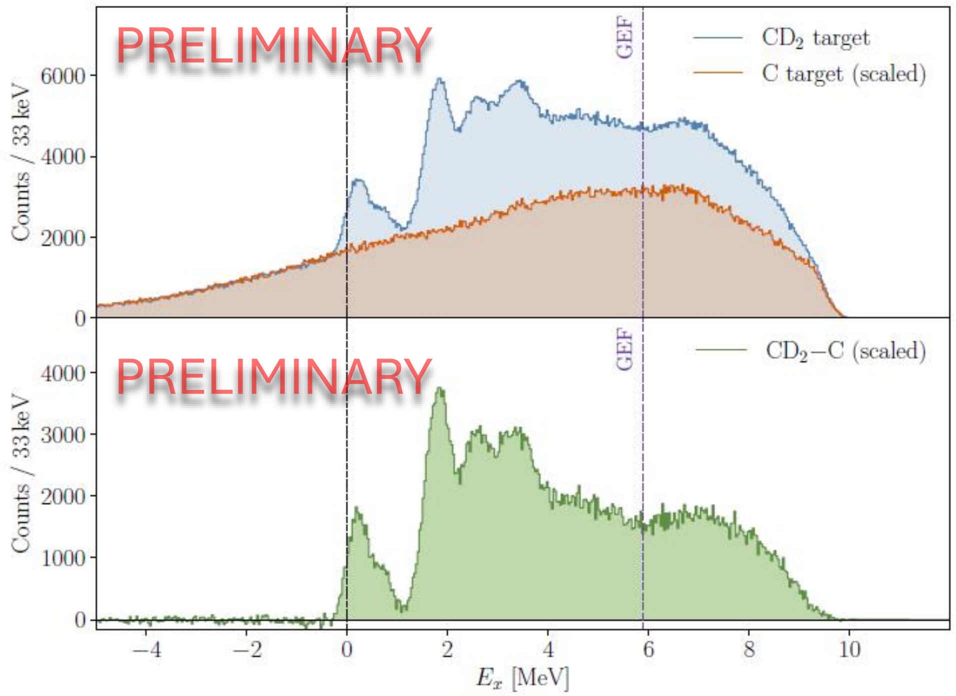
- Due to beam contamination?
- Indication of ^{209}Rn and ^{209}At from gamma rays.
- Unlikely due to heavier beam component.
- Potentially an artifact.

Fission barrier

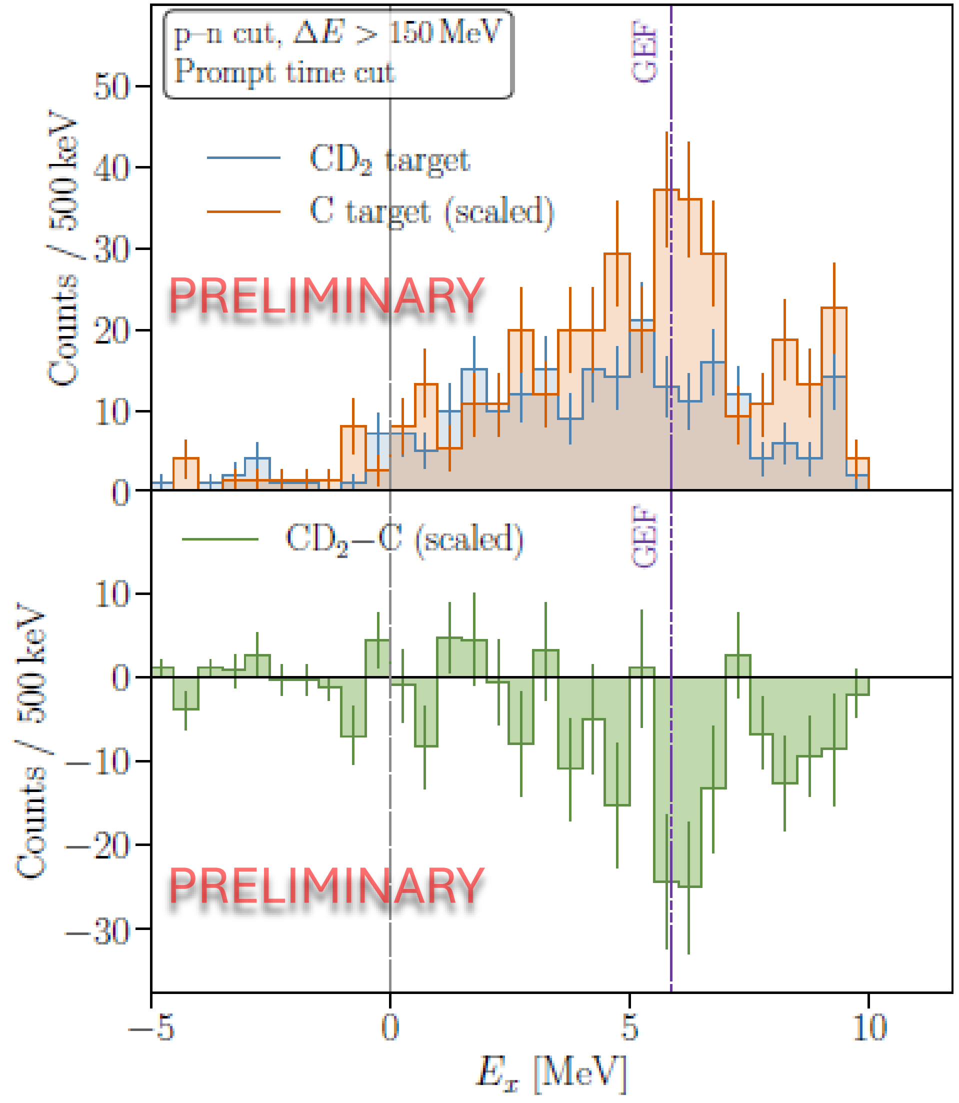


$$E_X = -m_2 + \sqrt{M_C^2 + m_1^2 - 2\gamma M_C(E - \alpha\beta z_{hit})}$$





Fission barrier: the puzzle



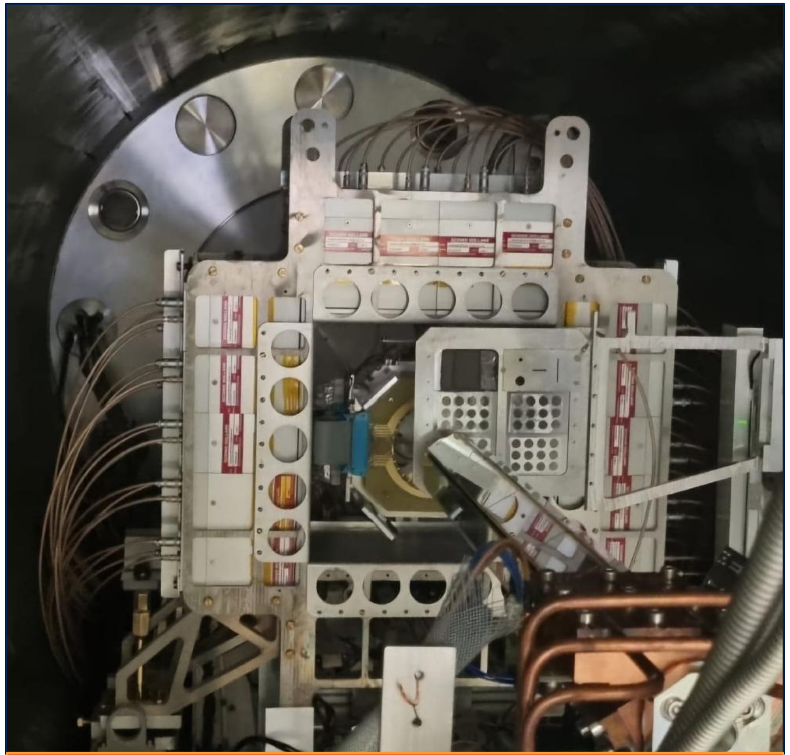
Outlook

The setup works:

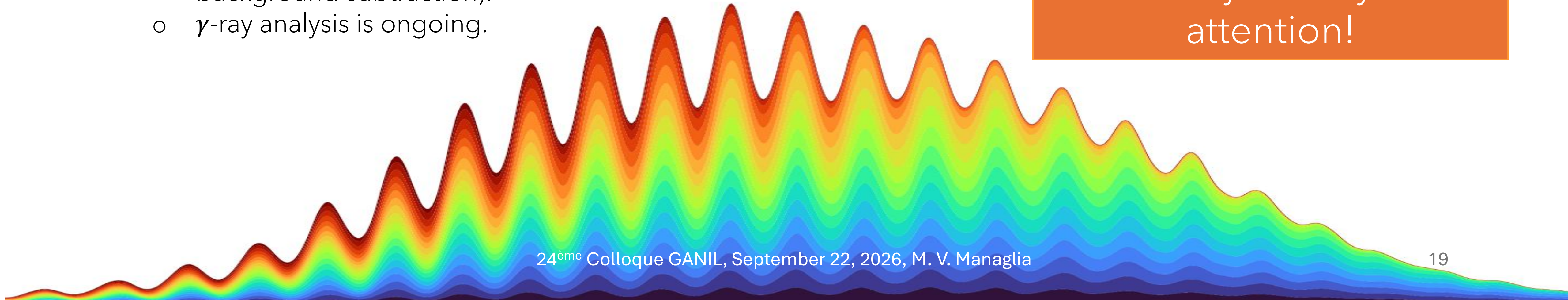
- Detectors performed well!
- First (d,p) measurement on ^{232}U.
- Calibration done ✅
- Resolve individual charges from fission fragments.

Open questions:

- Calculation of efficiencies and comparison with simulations.
- Nature of second structure.
- Extraction of P_f (after beam contaminant background subtraction).
- γ-ray analysis is ongoing.



Thank you for your attention!



Thanks to

A. Kawęcka, H. T. Törnqvist, A. Heinz, H. T. Johansson, T. Nilsson, B. Jonson, E. A. M. Jensen, H. Joukainen, B. Johansson, A. Svärdström, S. Persson, P. MacGregor, F. Rowntree, G. Willmott, C. Porzio, D. K. Sharp, A. G. Smith, T. Wright, M. Wlodarczyk, N. Sosnin, M. Au, F. Browne, P. A. Butler, A. Camaiani, A. Ceulemans, D. J. Clarke, A. J. Dolan, S. J. Freeman, L. P. Gaffney, S. A. Giuliani, B. R. Jones, B. P. Kay, J. Klimo, M. Labiche, I. Lazarus, J. Ojala, B. Olaizola, R. D. Page, G. Martínez-Pinedo, O. Poleshchuk, R. Raabe, S. Reeve, A. Rodriguez, S. Rothe, T. Beck, H. Agarwal, A-C. Larsen, V. W. Ingeberg, J. Henderson, Y. Kucuk, I. Boztosun, H. Dapo, H. Sansar, J.S. Nielsen.

CHALMERS

Knut and Alice Wallenberg Foundation

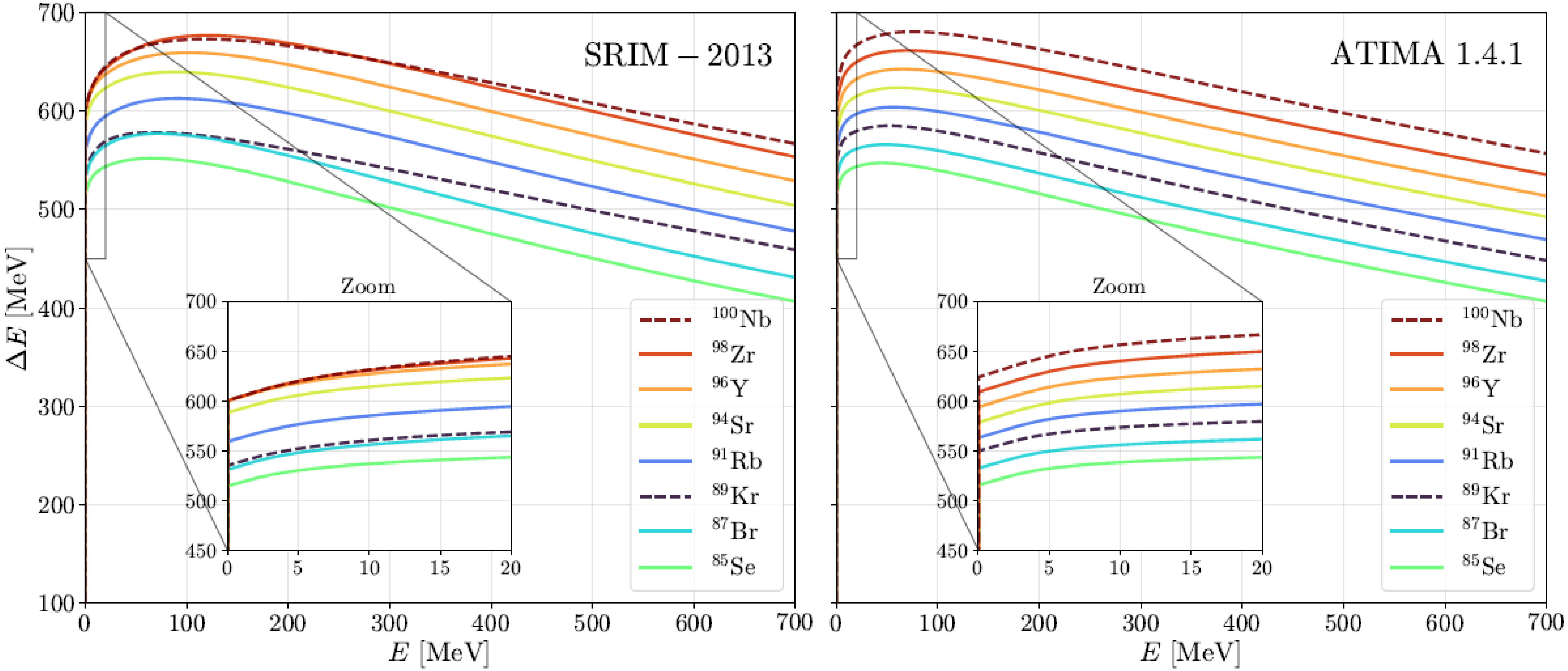
Swedish Research Council

ISOLDE Solenoidal Spectrometer

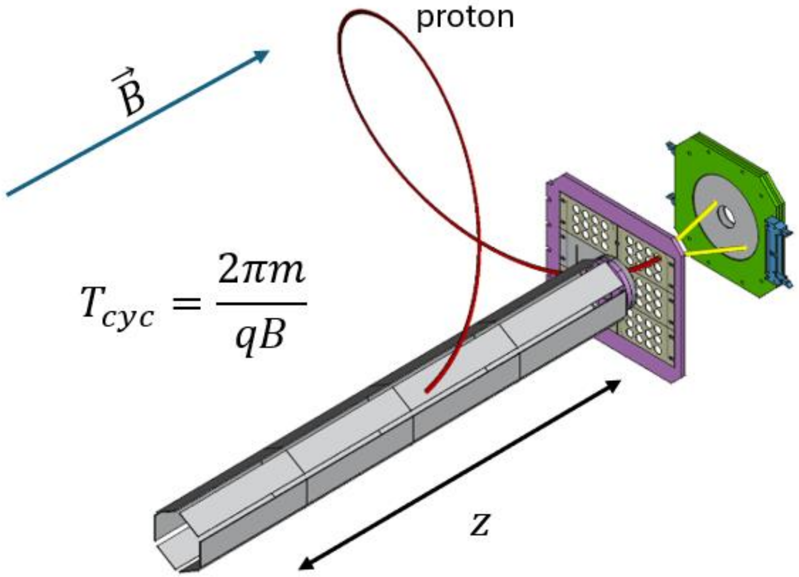
CERN

Backup slides

SRIM vs ATIMA



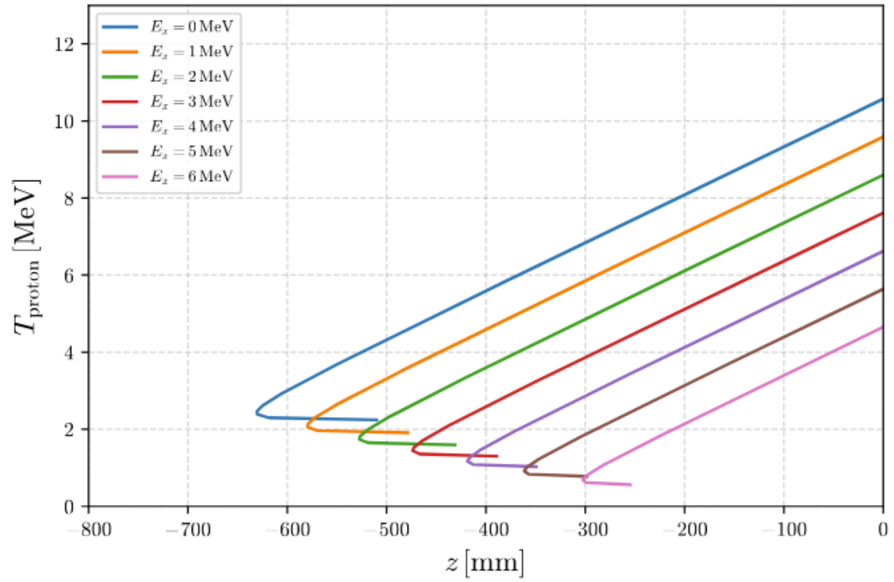
The kinematics of (d,p) reactions in solenoidal spectrometers



$$T_{cyc} = \frac{2\pi m}{qB}$$

We measure:
- E_p
- z

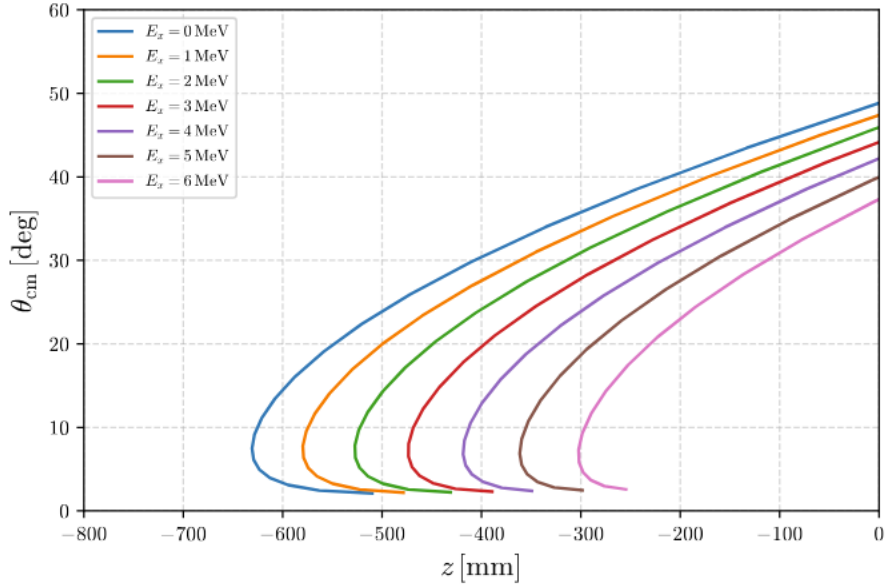
We are interested in:
- E_x
- θ_{cm}



$$\alpha = \frac{ZB}{2\pi}$$

$$\boxed{E_X = -m_2 + \sqrt{M_C^2 + m_1^2 - 2\gamma M_C(E - \alpha\beta z_{hit})}}$$

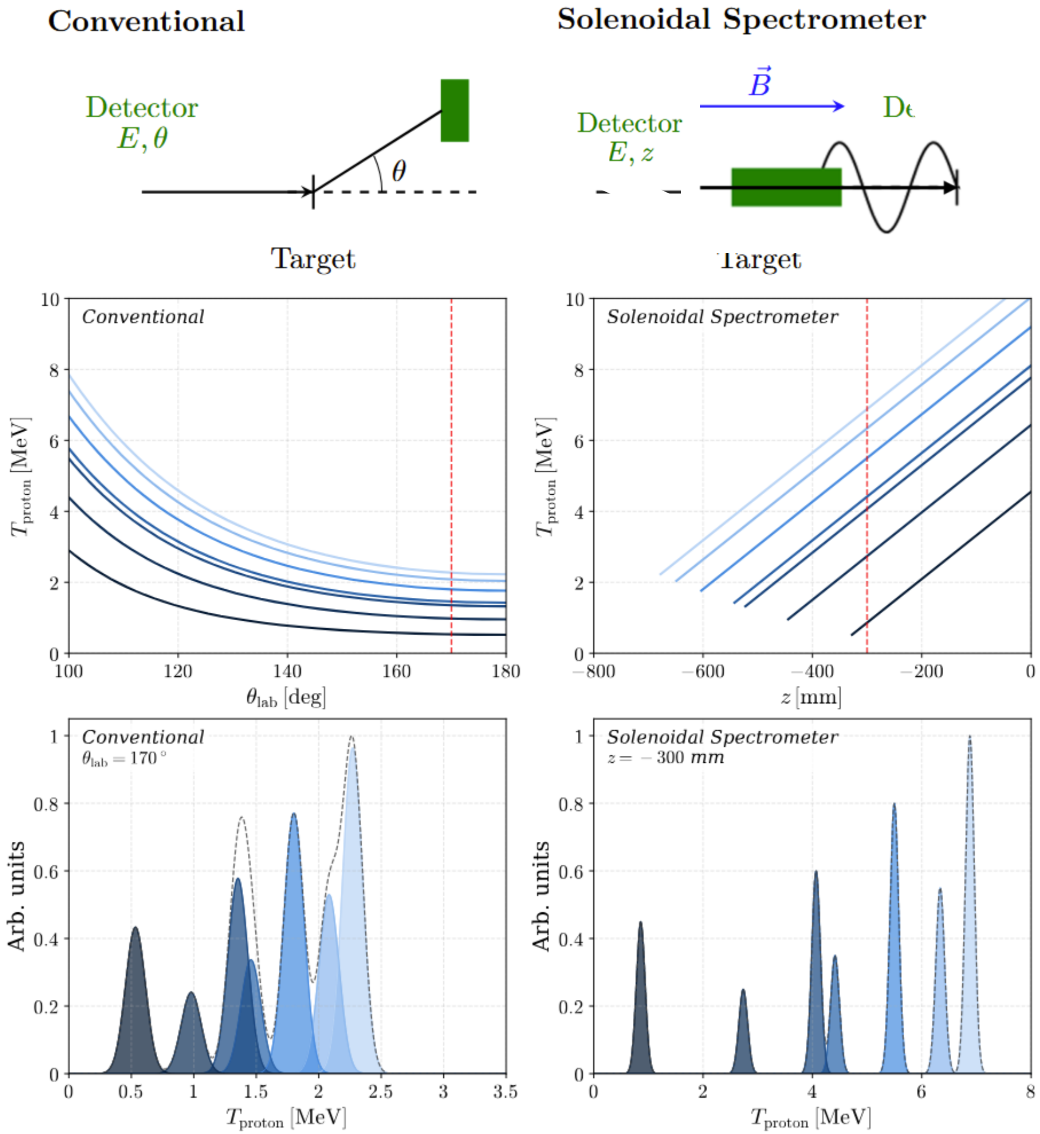
$$\boxed{\cos\theta_{cm} = \frac{\gamma(E\beta - \alpha z_{hit})}{\sqrt{\gamma^2(E - \alpha\beta z_{hit})^2 - m_1^2}}}$$



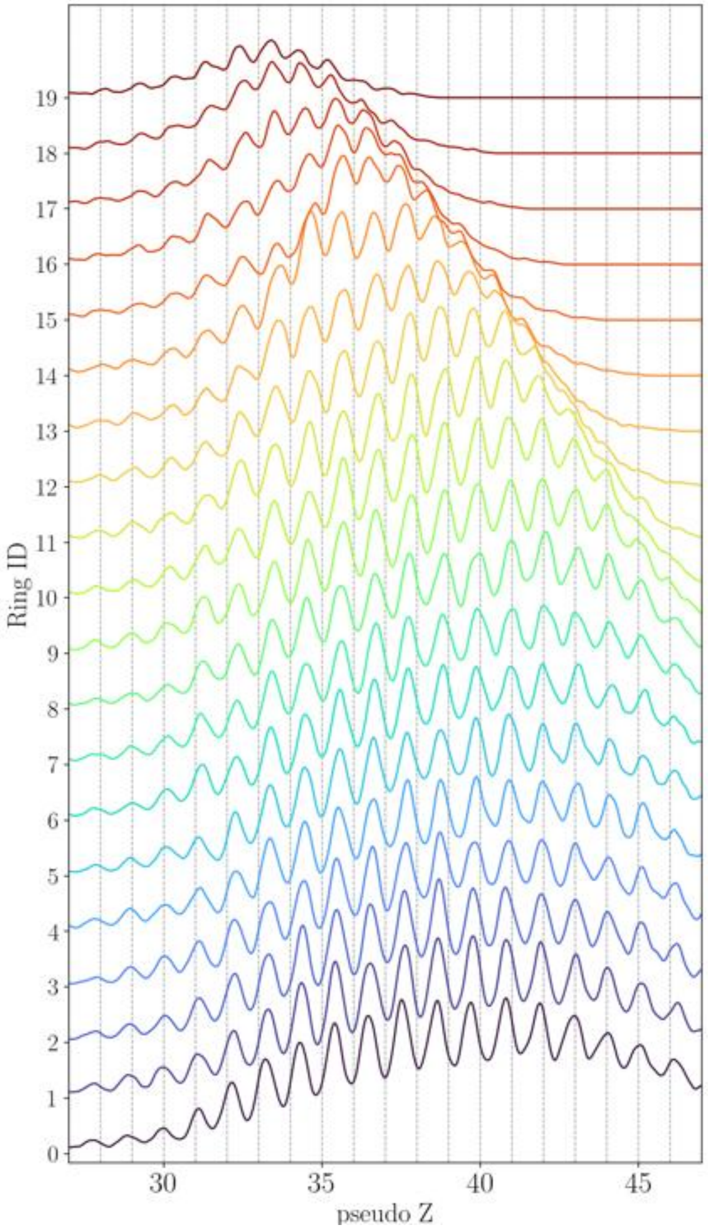
Solenoidal field approach

- Solution for kinematics compression.
- <u>Considerably better excitation energy resolution.</u>
- Background reduction in having the proton detector placed upstream.

$$E_{\mathrm{cm}} = E_{\mathrm{lab}} + \frac{mV_{\mathrm{cm}}^2}{2} - \frac{mzV_{\mathrm{cm}}}{T_{\mathrm{cyc}}}$$



Charge identification of fission fragments



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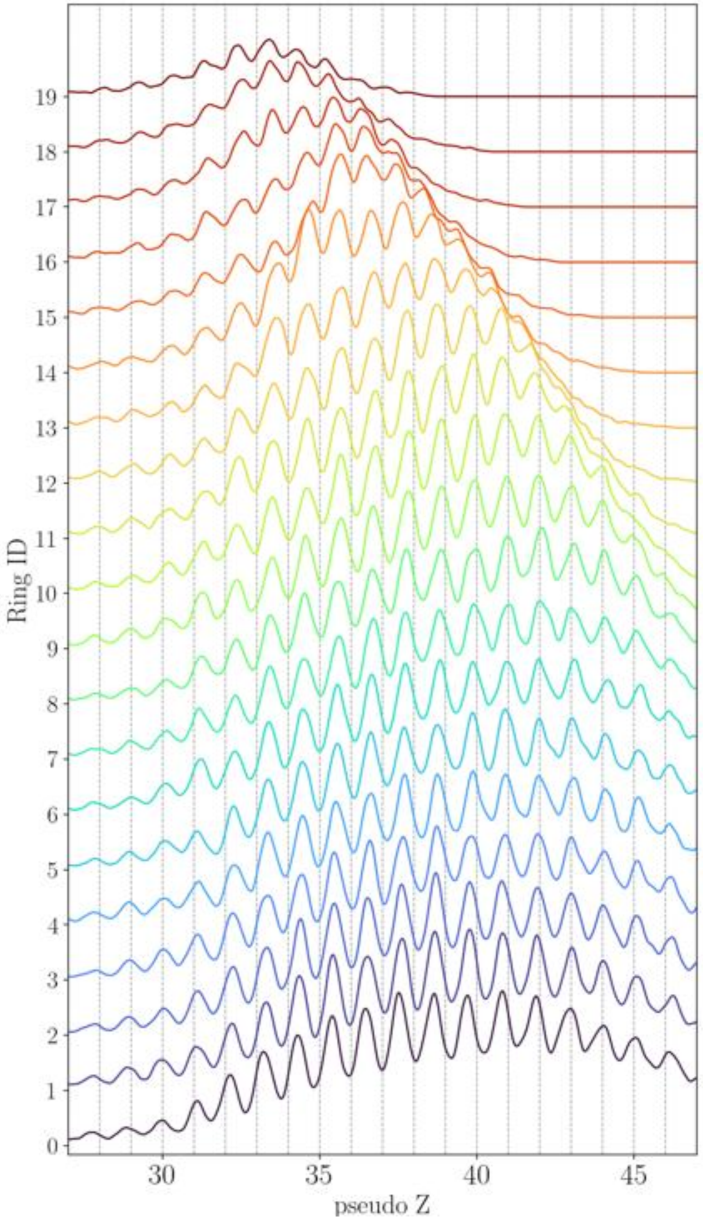
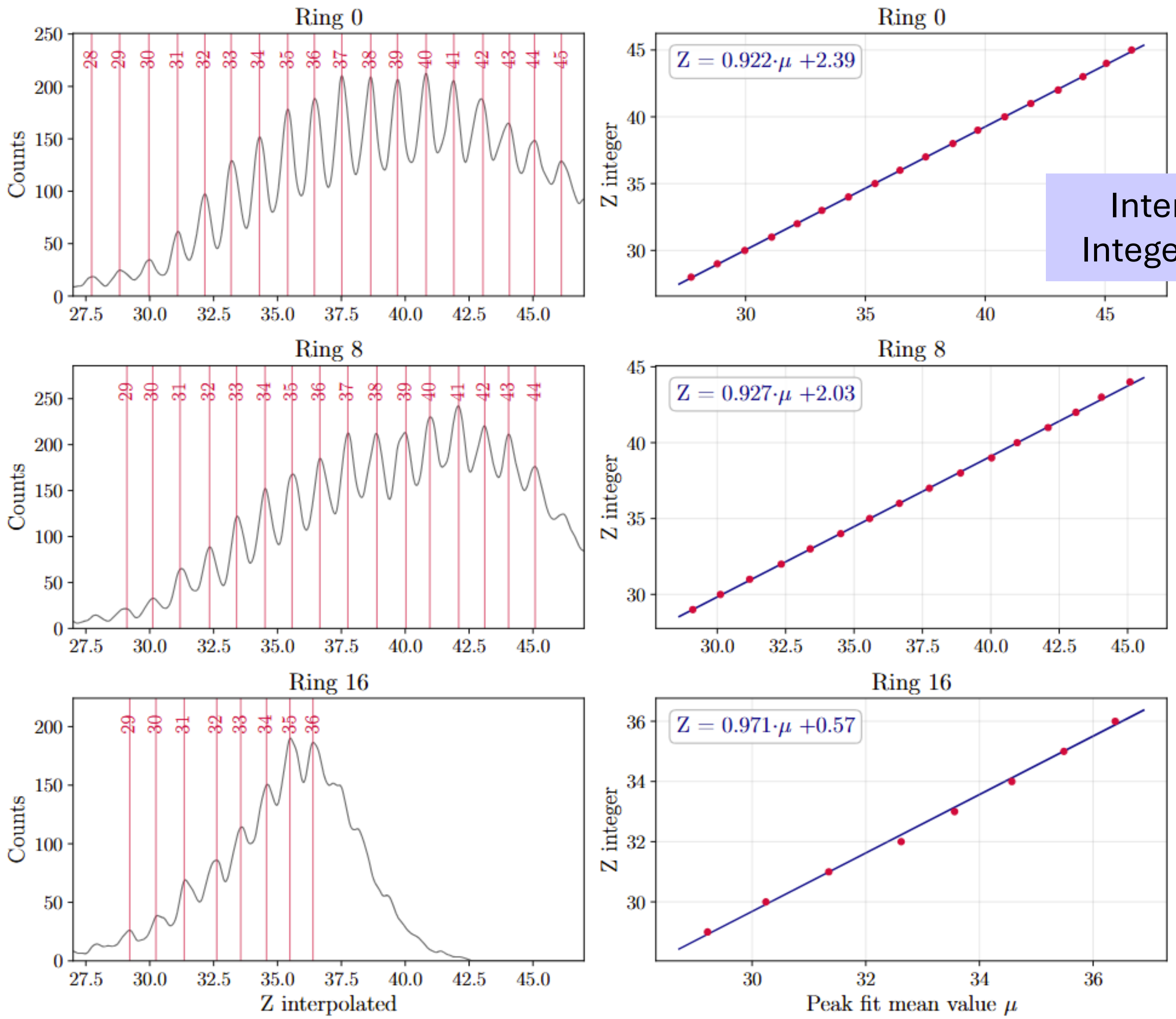
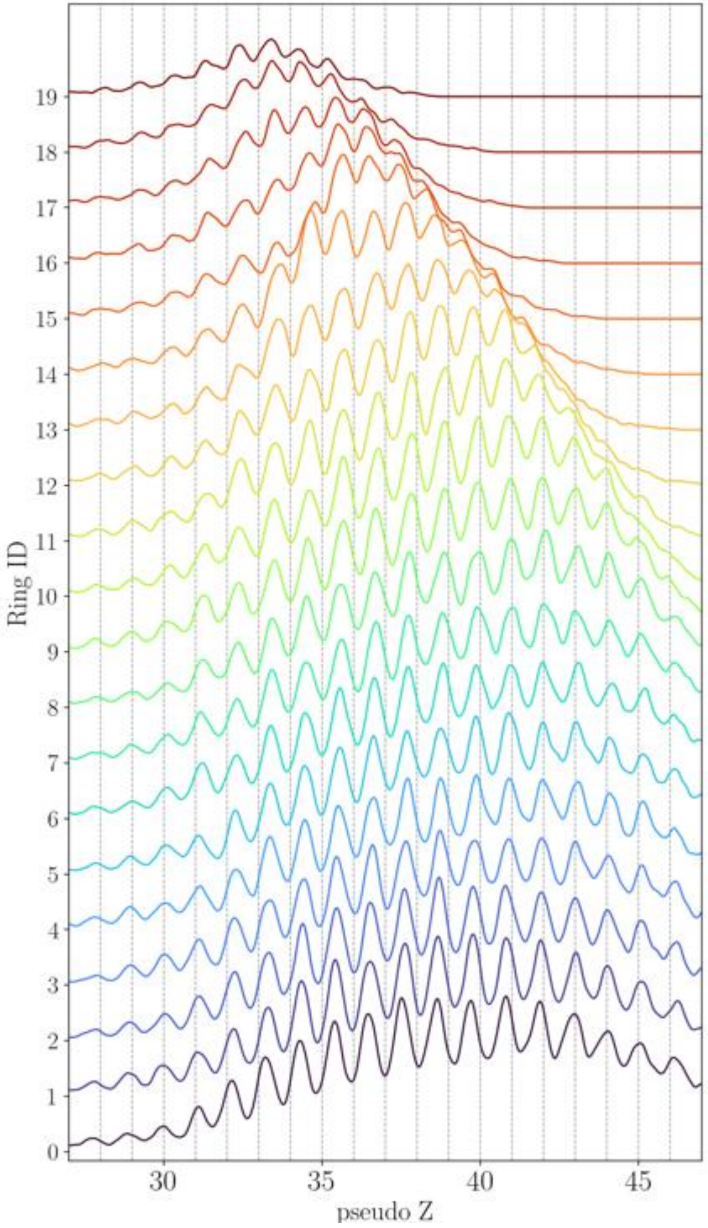
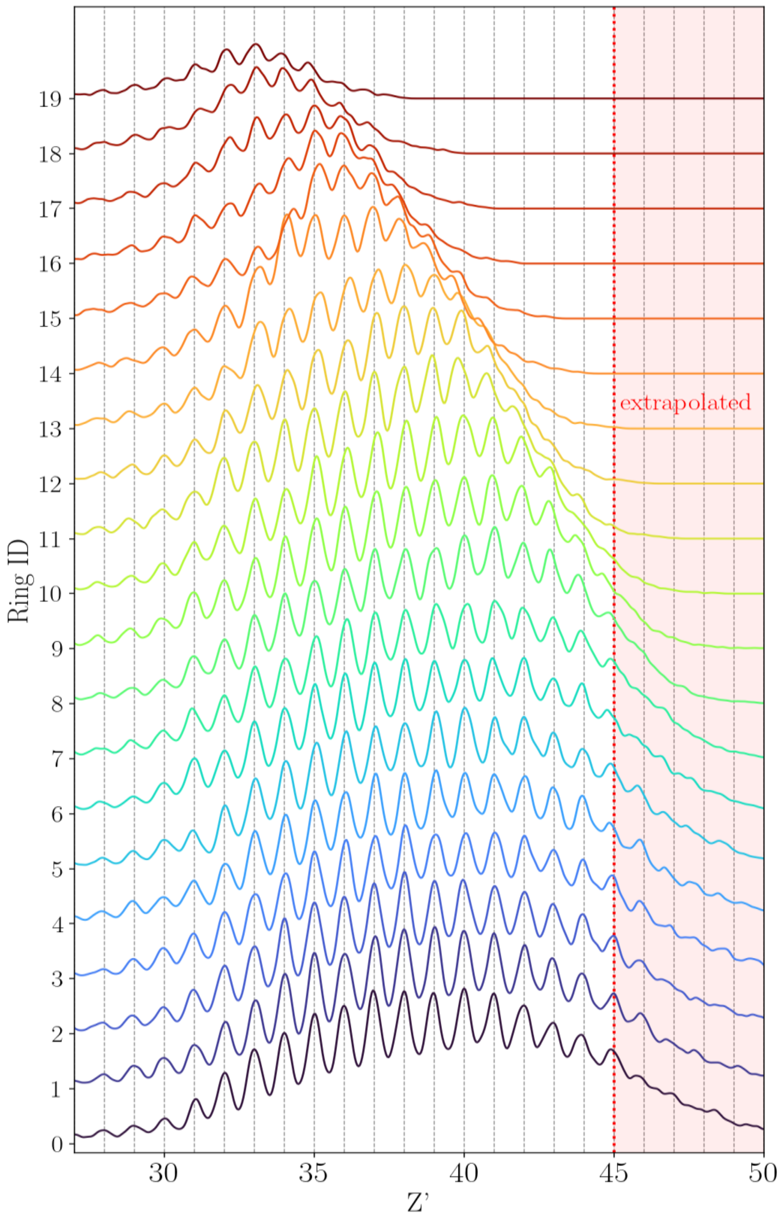




Interpolation → Integer (tentative) Z

Charge identification of fission fragments



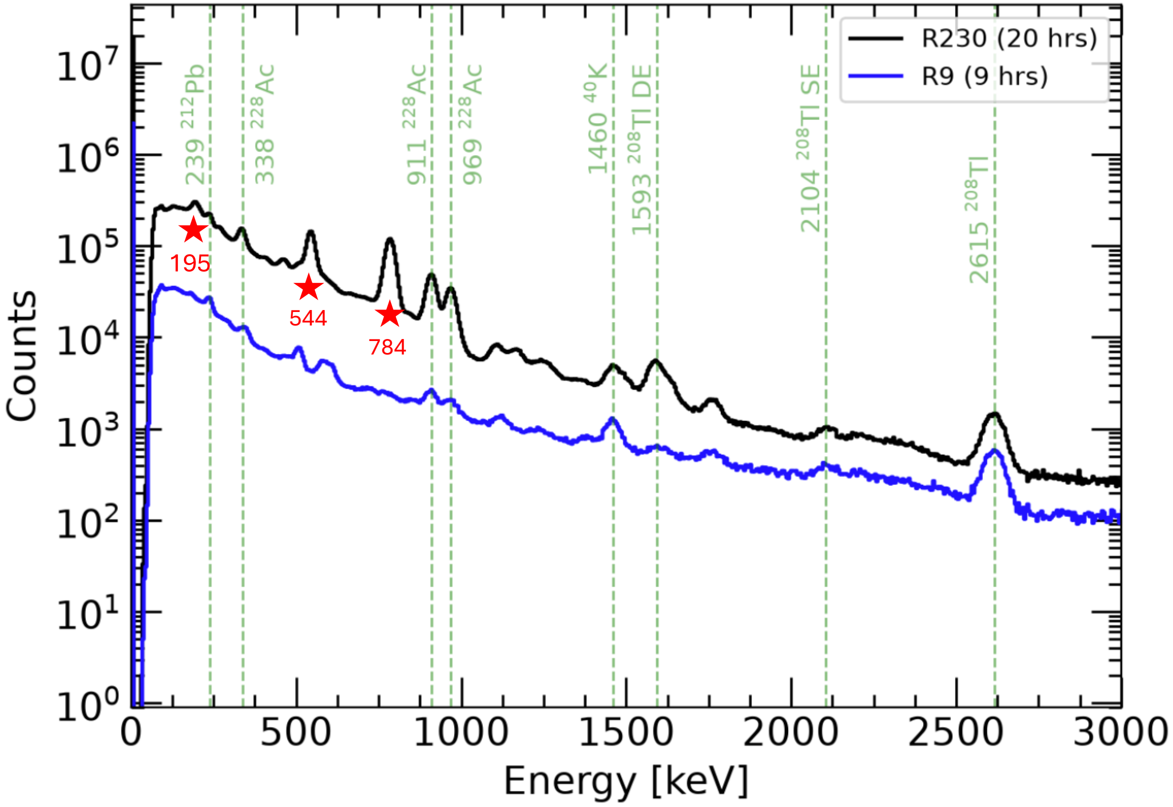


Extrapolation:
Peak finding
not possible.

Align (stretch) to tentative integer Z

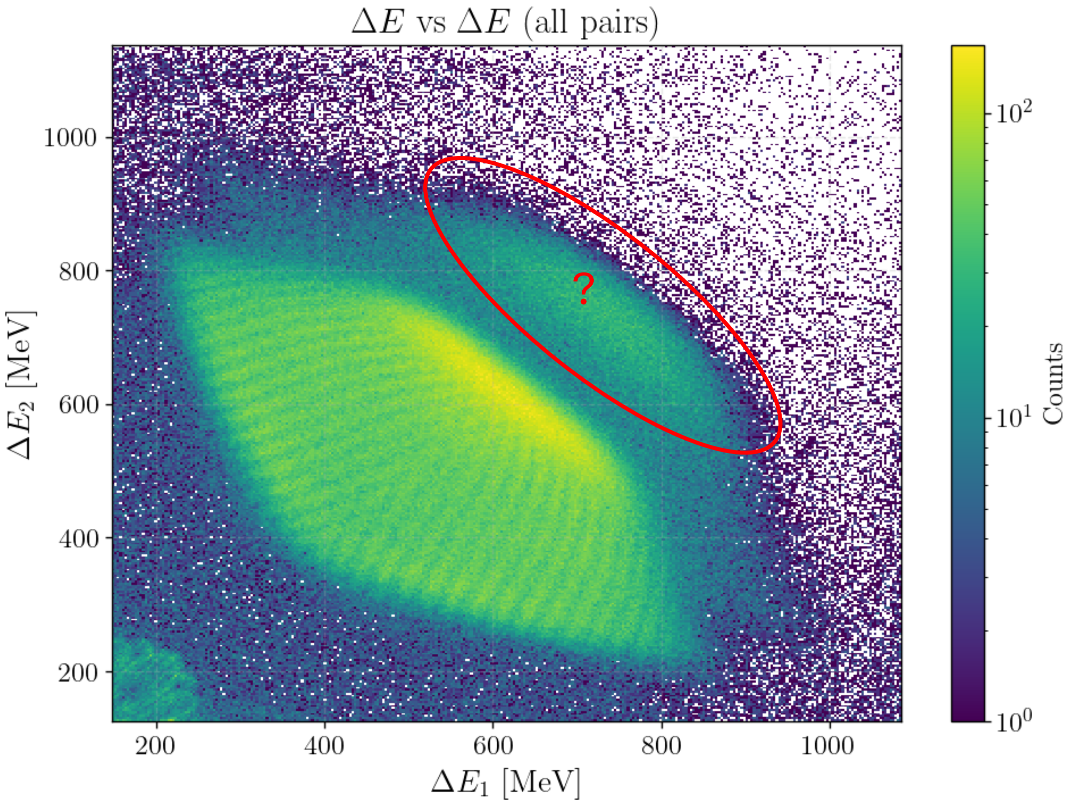
$Z' = Z_{true} + \text{offset}$

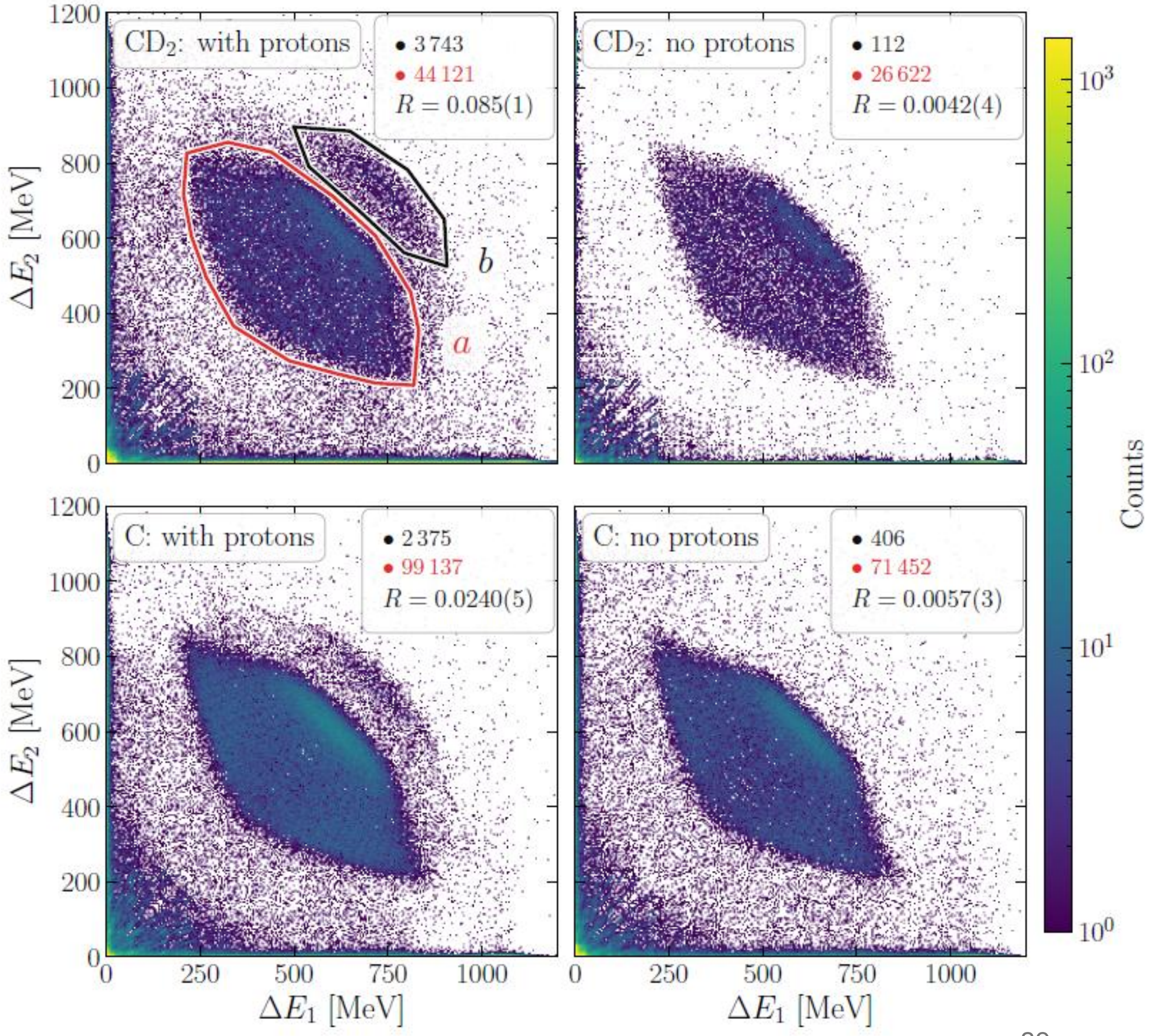
What γ rays tell us



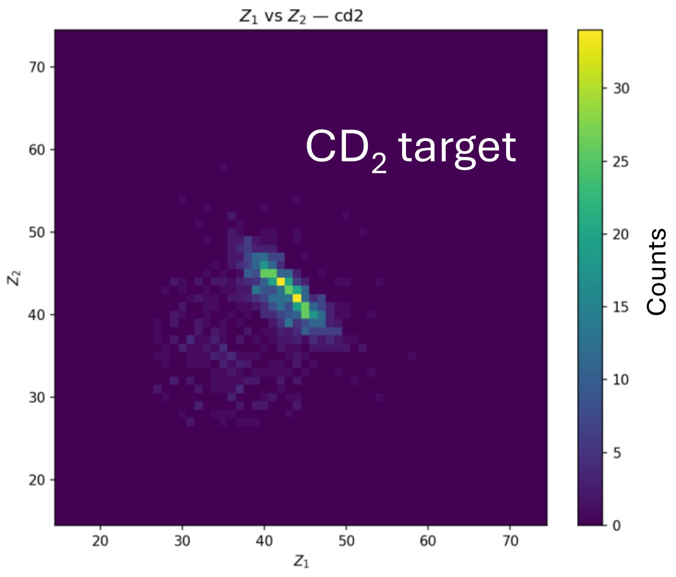
Courtesy of Henna Joukainen

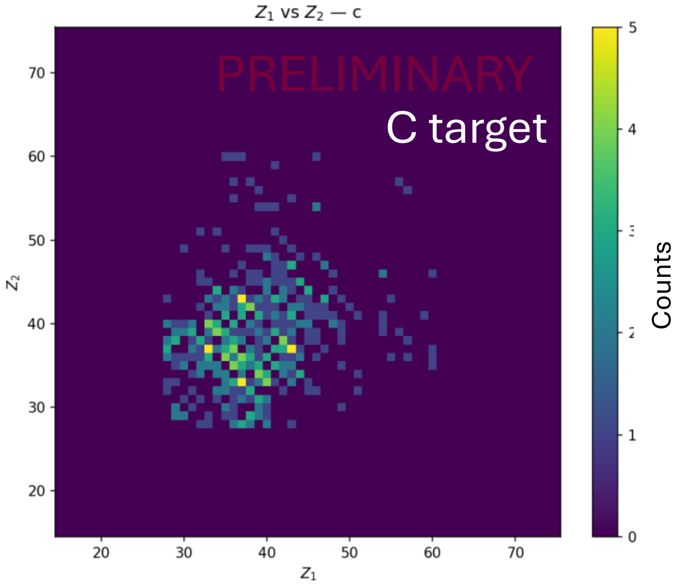
Second component

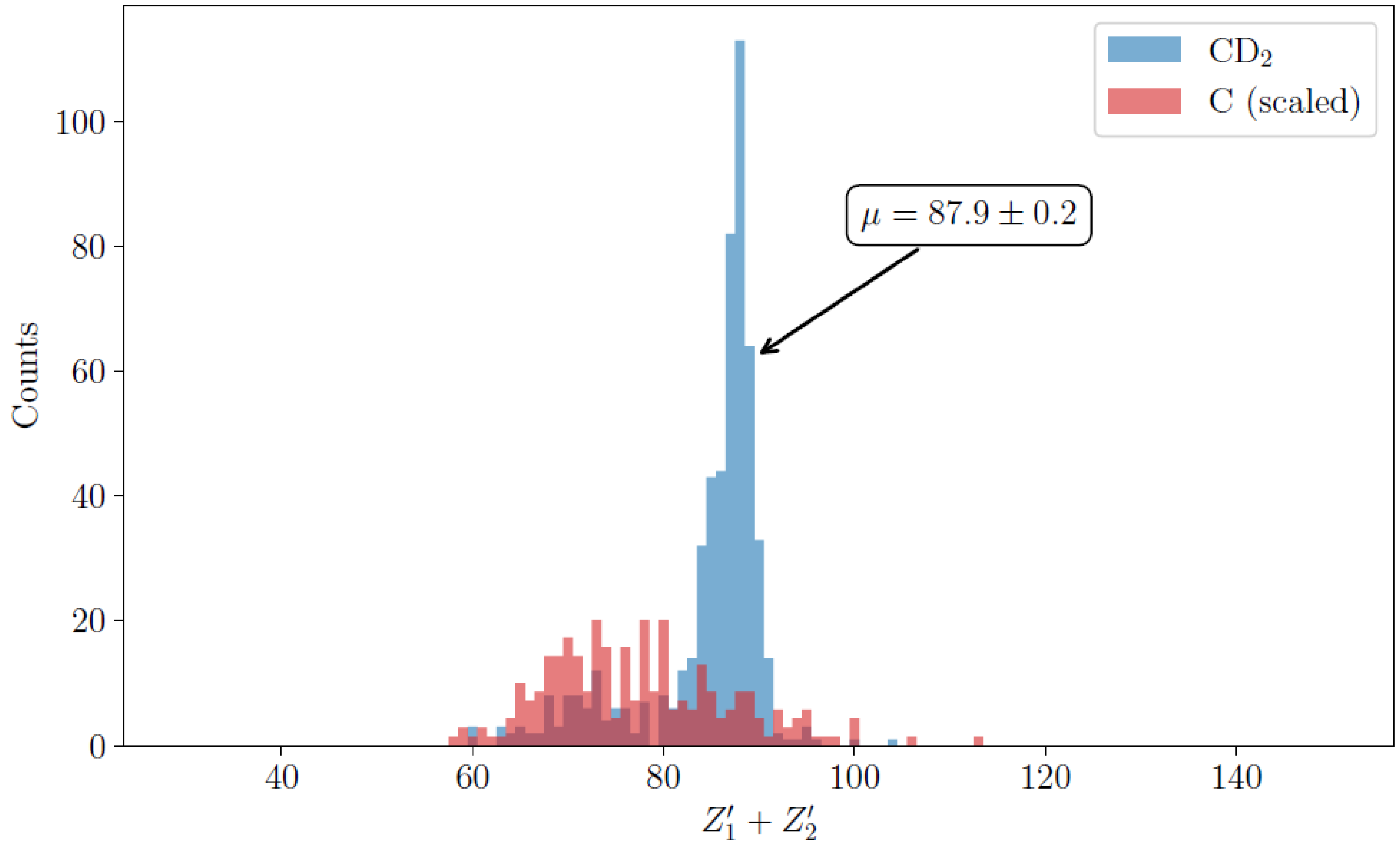




Charge identification of fissioning system

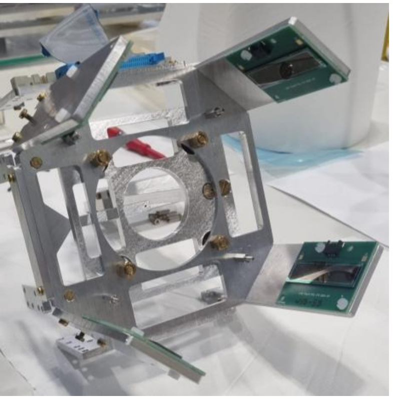




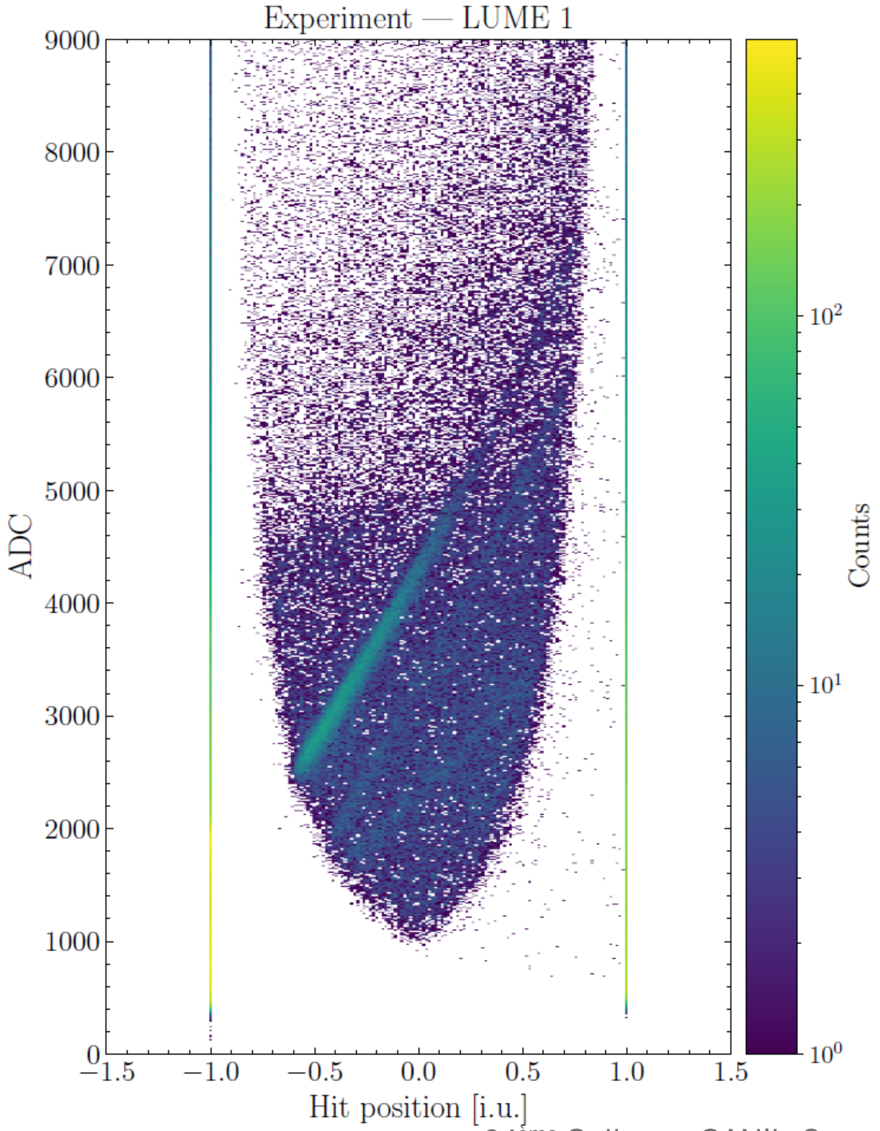


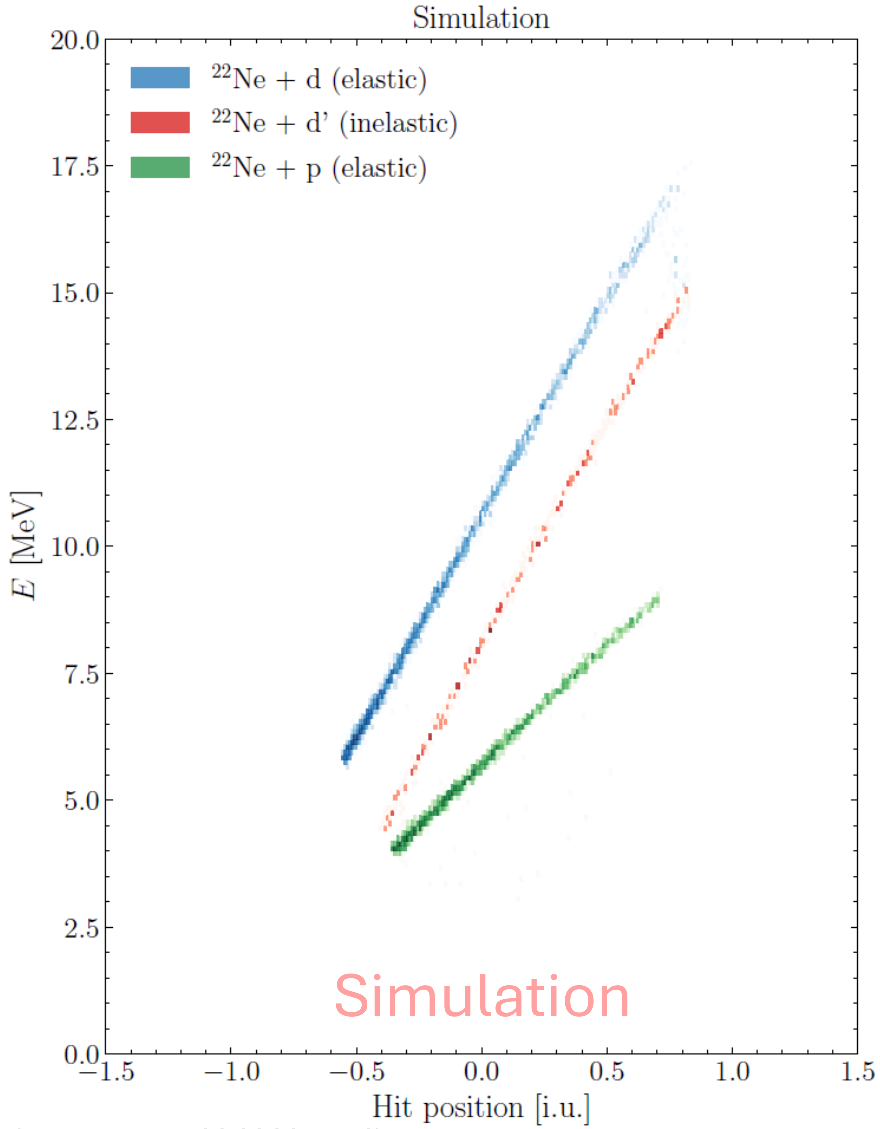
With Z_{offset} = 2,
this would give $Z_{fission}$ = 92.

Commissioning with stable beam: $^{22}Ne(d,p)^{23}Ne$



Luminosity Monitor



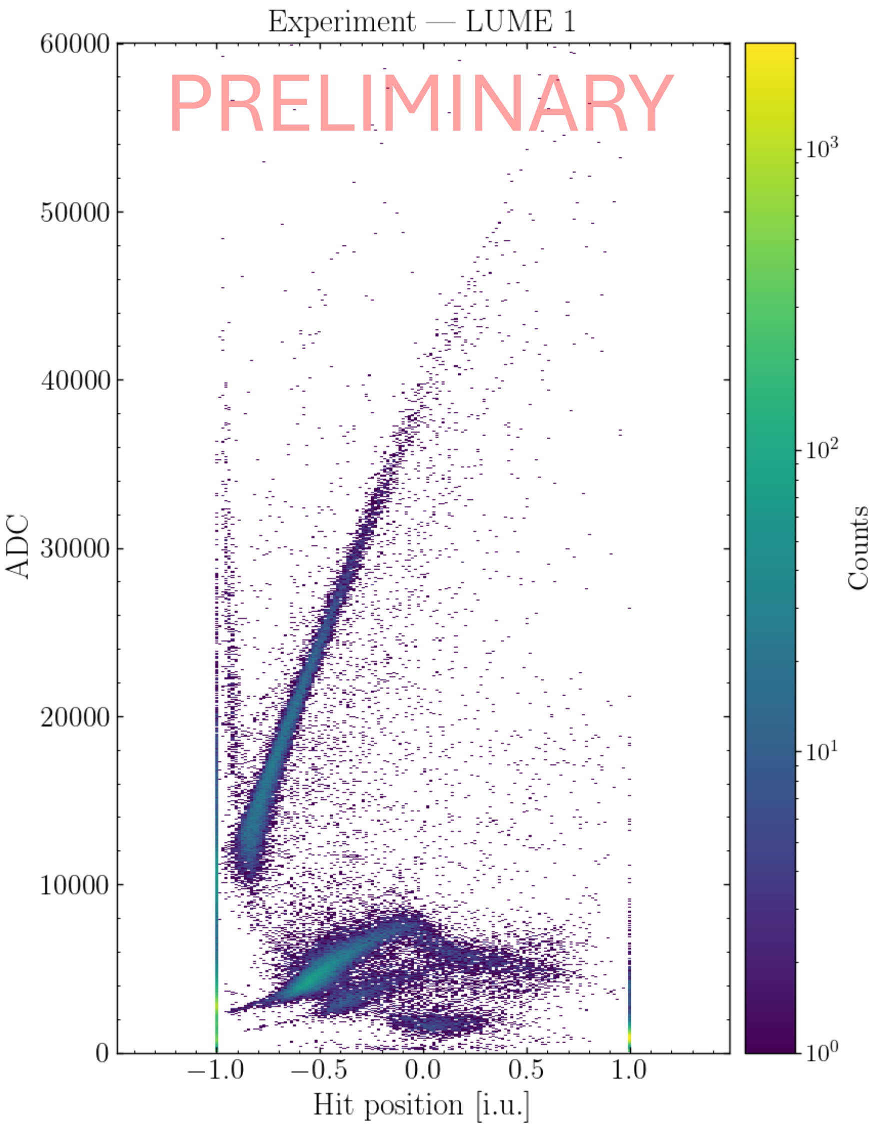


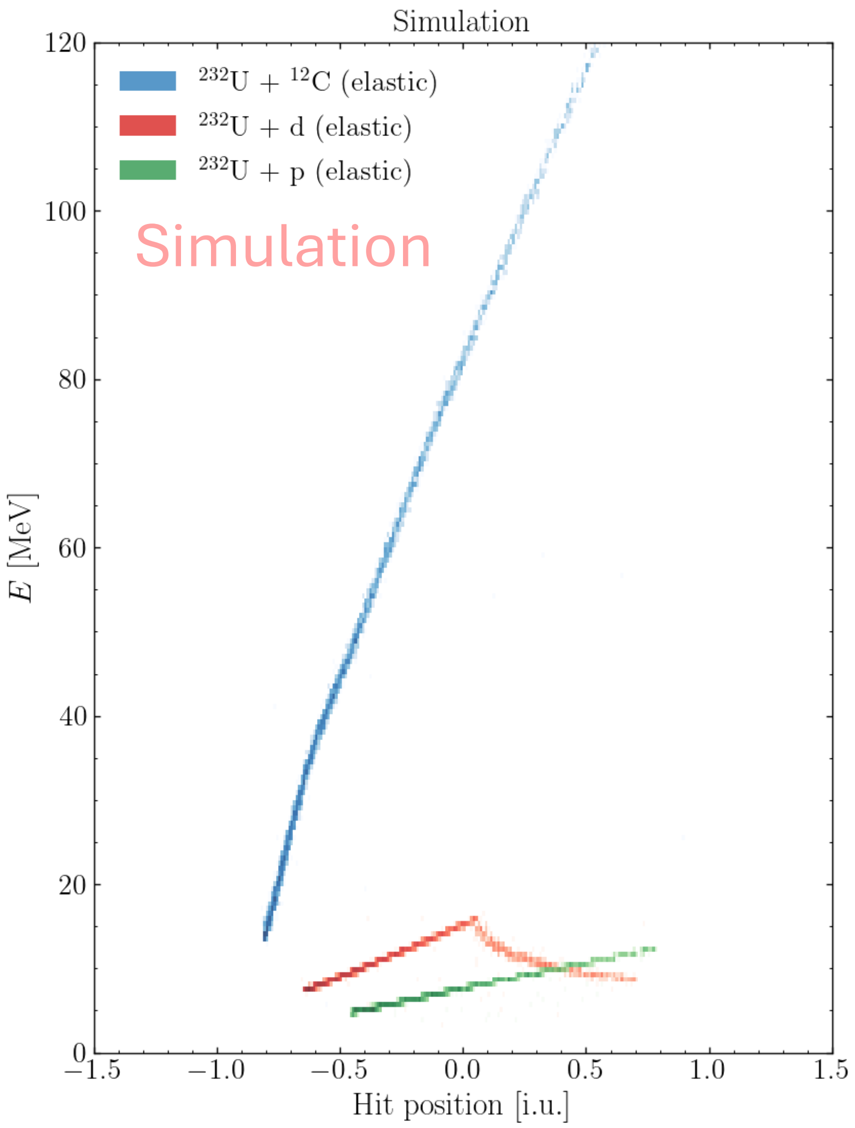
CD_2 target

IS739: ^{232}U(d,pf) at 7.34 MeV/u

Luminosity monitors

CD$_2$ target



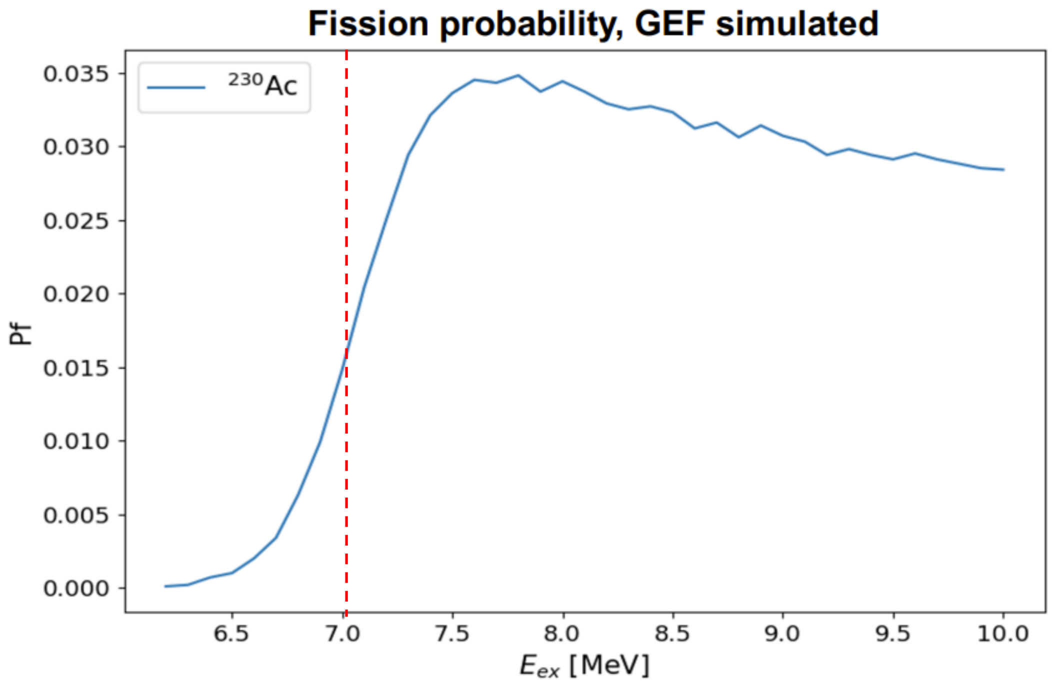


IS739: Fission of ^{230}Ac

- <u>Practical choice</u> for investigation: based on the fission barrier estimated by GEF, it lies within the capabilities of the facility (available intensity and energy of the beam).
- <u>No conclusive data</u> on fission at low excitation energies.
- The <u>first study</u> of fission using <u>radioactive</u> beams in inverse kinematics with a solenoidal spectrometer.

^{230}Ac	
Sn [1]	4.923 MeV
Fission barrier height [2]	7.01 MeV
P_f (1st chance) [2]	3%

[1] M. Wang at al. Chinese Physics C 45, 030003 (2021).
[2] K.-H, Schmidt et al. Nucl. Data Sheets 131, 107 (2016).



✅ Approved INTC proposal.

✅ Beam time and setup geometry optimized to measure fission of ^{230}Ac.

IS739: Fission of ^{230}Ac

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[1] M. Wang at al.
[2] K.-H, Schmidt e

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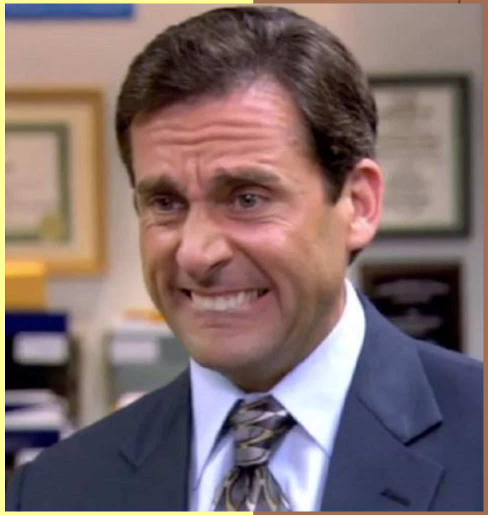
of ^{230}Ac.

Technical challenges during the experiment:

- Limited beam energy (< 8 MeV/u).
- Production of ^{229}Ac beam in difluoride form not possible.
- Monofluoride beam: production yield too low.
- Change from ThC_x to UC_x primary target.
- Too low rate.



IS739: Fission of ^{230}Ac

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Fission b

P_f(1st

[1] M. Wang at al.
[2] K.-H, Schmidt e

Fission probability ... ed

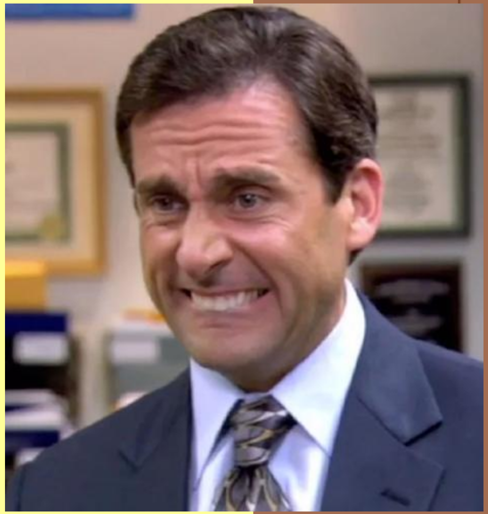
Ac.

Technical challenges during the experiment:

- Limited beam energy (< 8 MeV/u).
- Production of ^{229}Ac beam in difluoride form not possible.
- Monofluoride beam: production yield too low.
- Change from ThC_x to UC_x primary target.
- Too low rate.

↓

Change of isotope during the experiment ⚠️ →



Validation of Si array hits