Transfer-induced fission at the ISOLDE Solenoidal Spectrometer

Annual Swedish Nuclear Physics and SFAIR meeting 2025

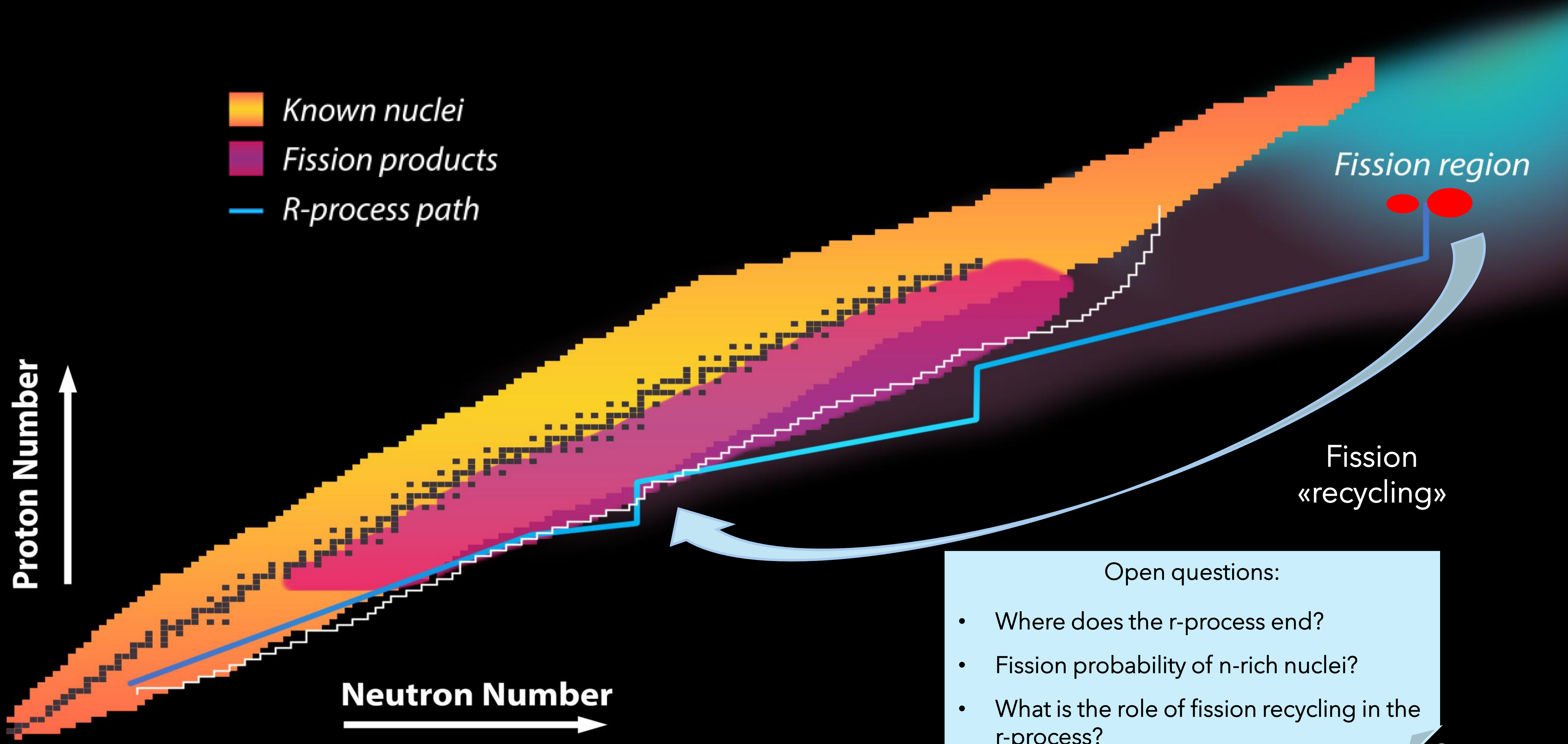
October 28th-30th, 2025, Göteborg

Maria Vittoria Managlia

Chalmers University of Technology

Why?

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 (2007-2025).

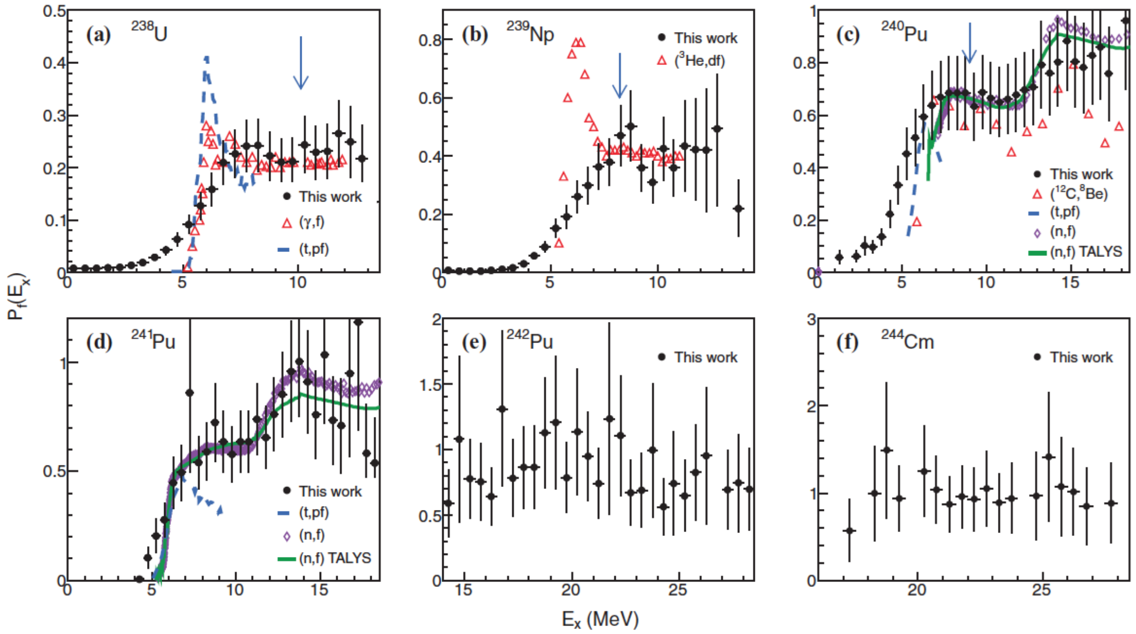
Goal

Key fission observables:

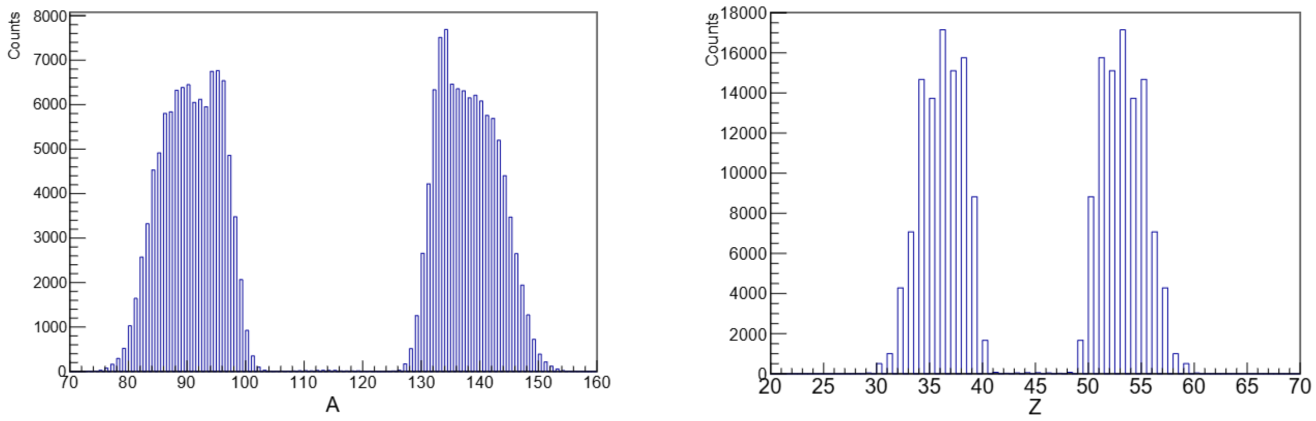
- Fission probability as a function of the excitation energy.
- Charge-mass distribution of fission fragments.
- Energy released in γ radiation during fission.

Experimentally challenging for n-rich nuclei!

C. Rodríguez-Tajes et al., PRC 89, 024614 (2014).



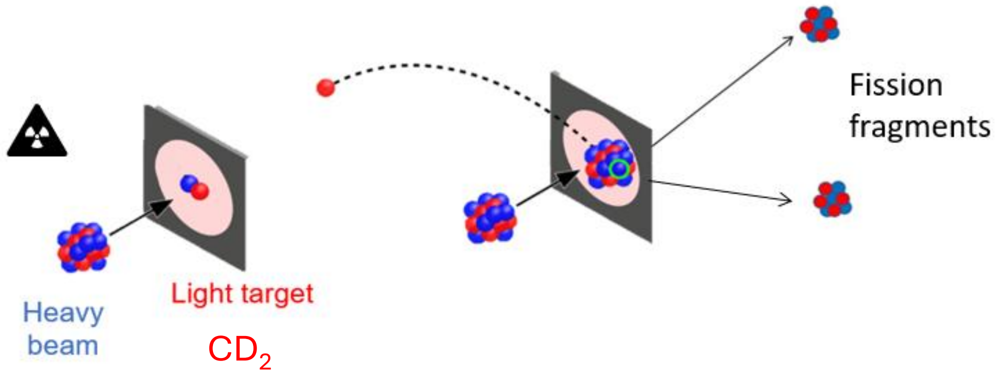
GEF-simulated mass and charge fission fragment distributions for ^{230}Ac with E_x=7 MeV.



K.-H, Schmidt et al. Nucl. Data Sheets 131, 107 (2016).

How?

(d,pF) surrogate reactions in inverse kinematics



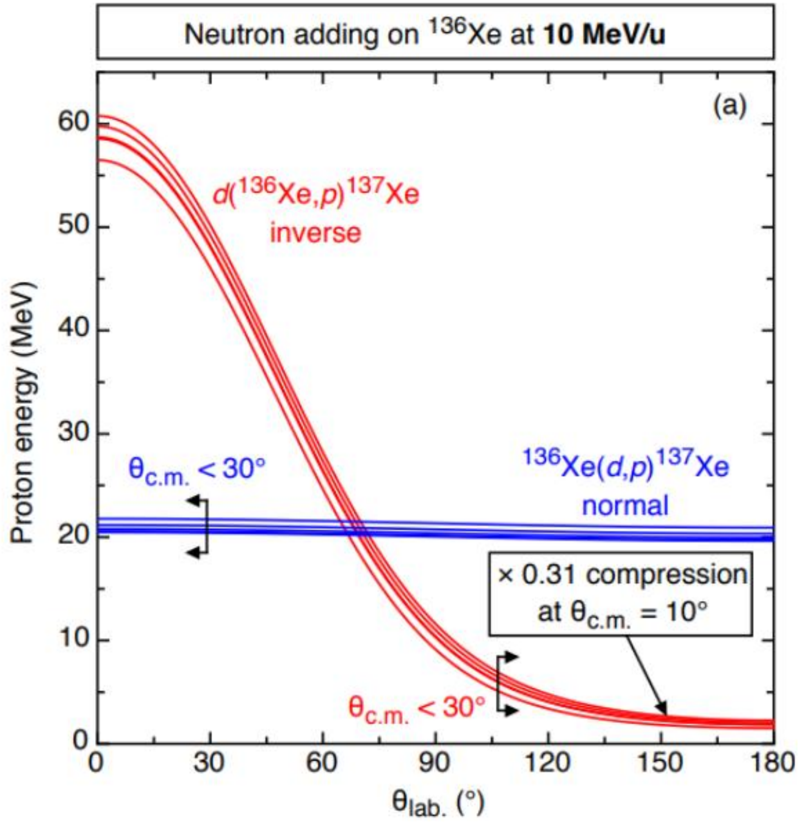
Fission event:

coincidence with proton and two detected fission fragments.

$$P_f(E_{ex}) = \frac{N_{d,pF}(E_{ex})}{N_{d,p}(E_{ex}) \cdot e_f}$$

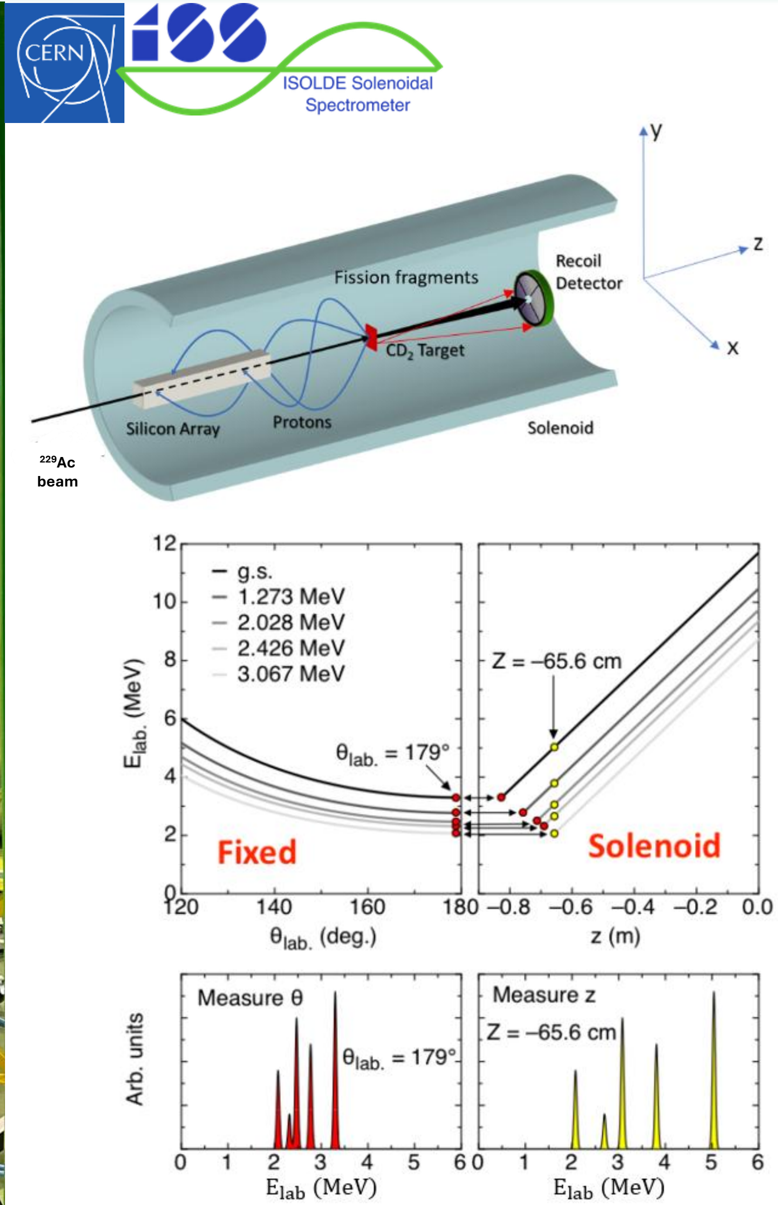
Experimental challenges:

- Strong angular dependence of proton energy on the LAB angle, i.e. *kinematic shift*.
- *Kinematic compression* → much worse resolution in backward angles.
- Low intensity beams (detection efficiency).



J.S. Winfield, NIM A, 396(1-2):147-164, 1997

The solenoidal spectrometer method



A. Wuosmaa *et al*. NIMA **580** (2007) 1290

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

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

- Considerably better energy resolution of the populated state in the compound nucleus.
    - Solution for kinematics compression.
- Background reduction in having the proton detector placed upstream.

Experimental Setup

A novel setup for studying (d,pF) reactions at ISS - I

Measured:

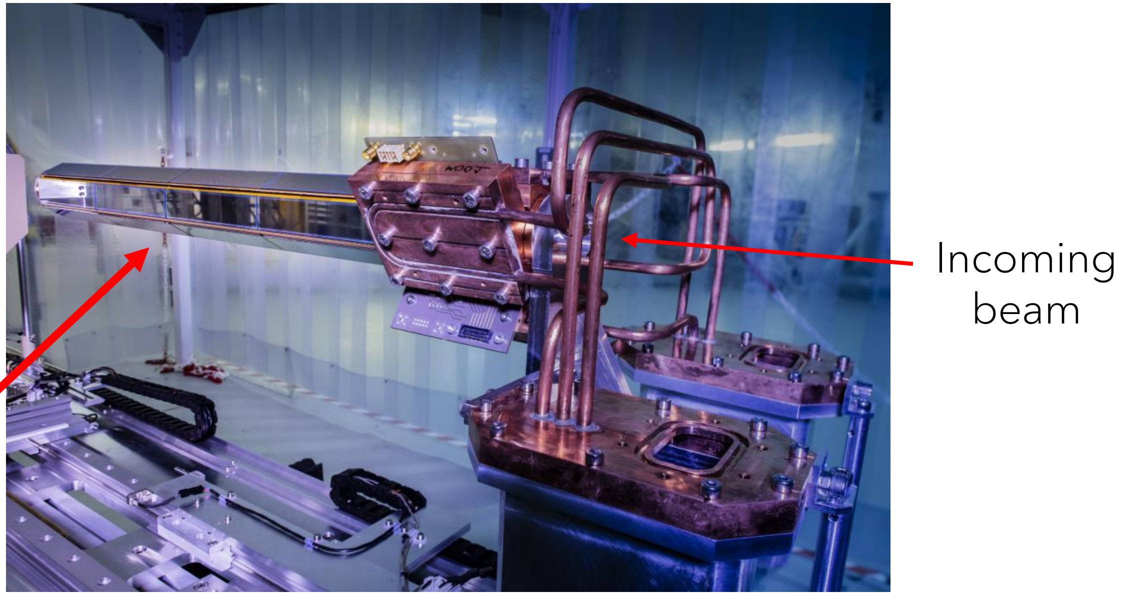
- **Protons.**
- Fission fragments (FFs).
- Scattered deuterons.
- γ-rays from FFs.

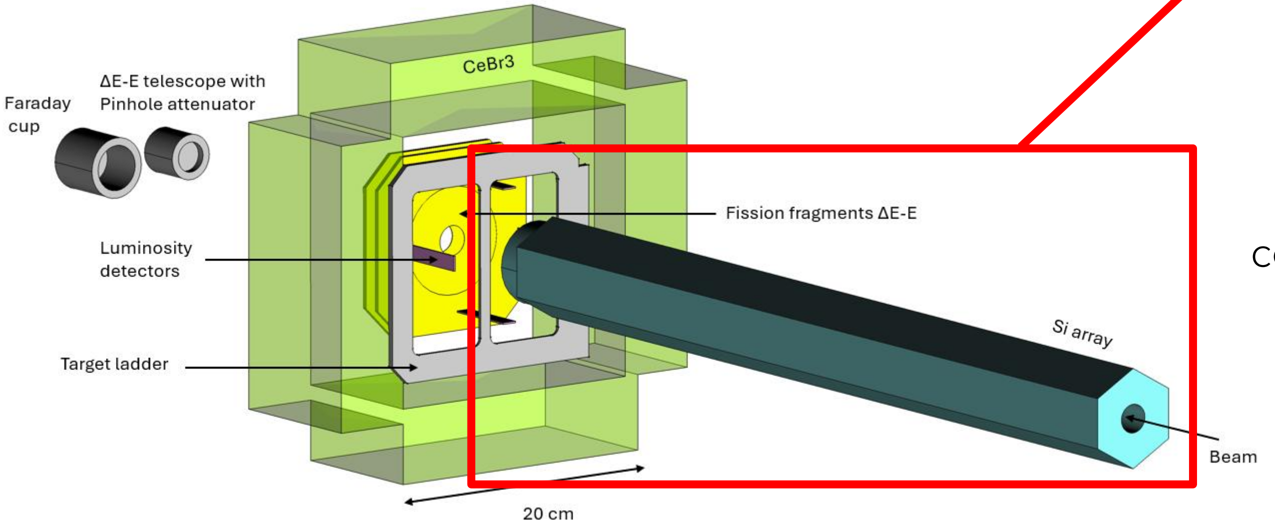
Beam tuning:

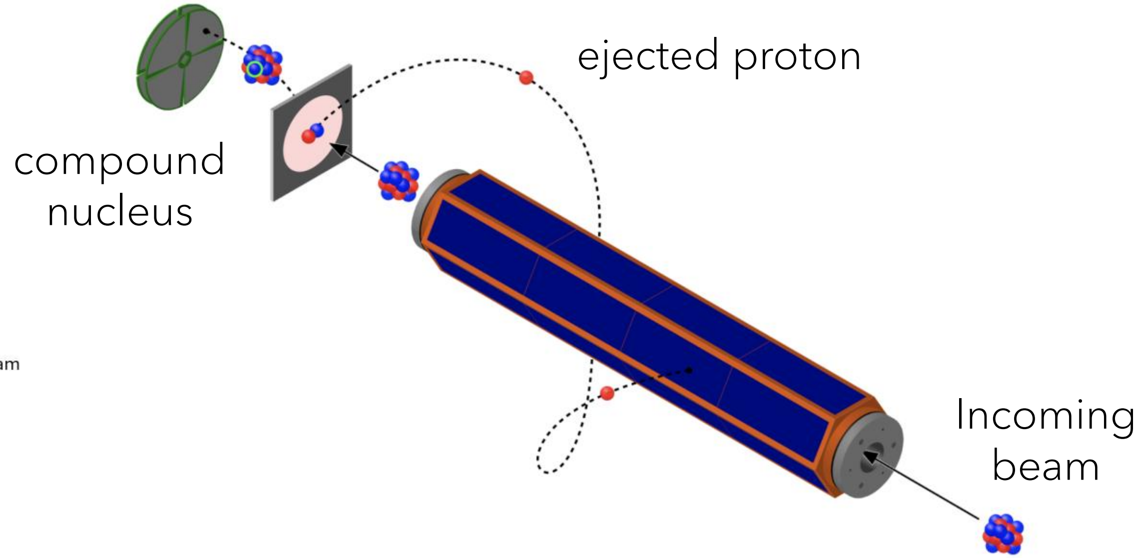
- Beam monitor detectors.

Targets:

- CD_2: 0.5 – 1 mg/cm^2
- C: 0.38 – 0-75 mg/cm^2



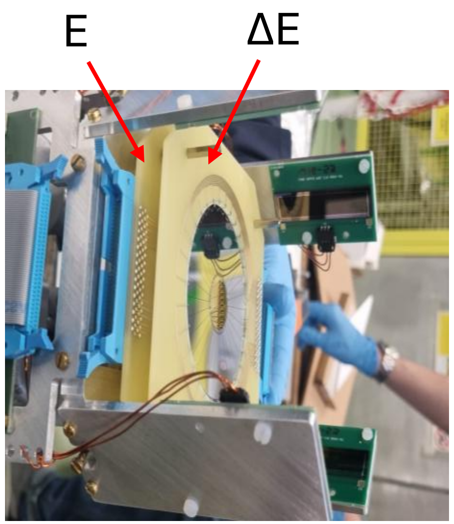


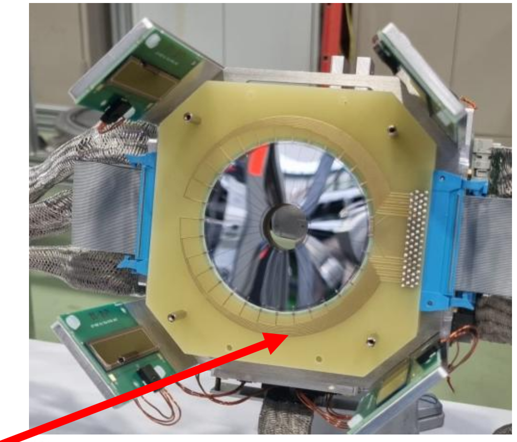


A novel setup for studying (d,pF) reactions at ISS - II

Measured:

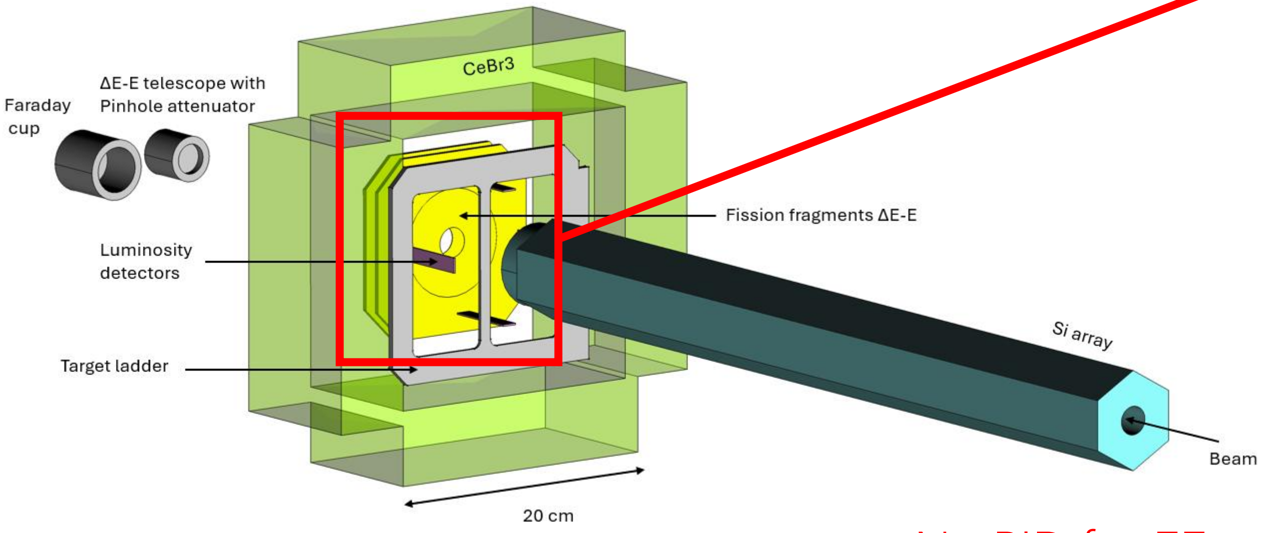
- Protons.
- **Fission fragments (FFs).**
- Scattered deuterons.
- γ-rays from FFs.



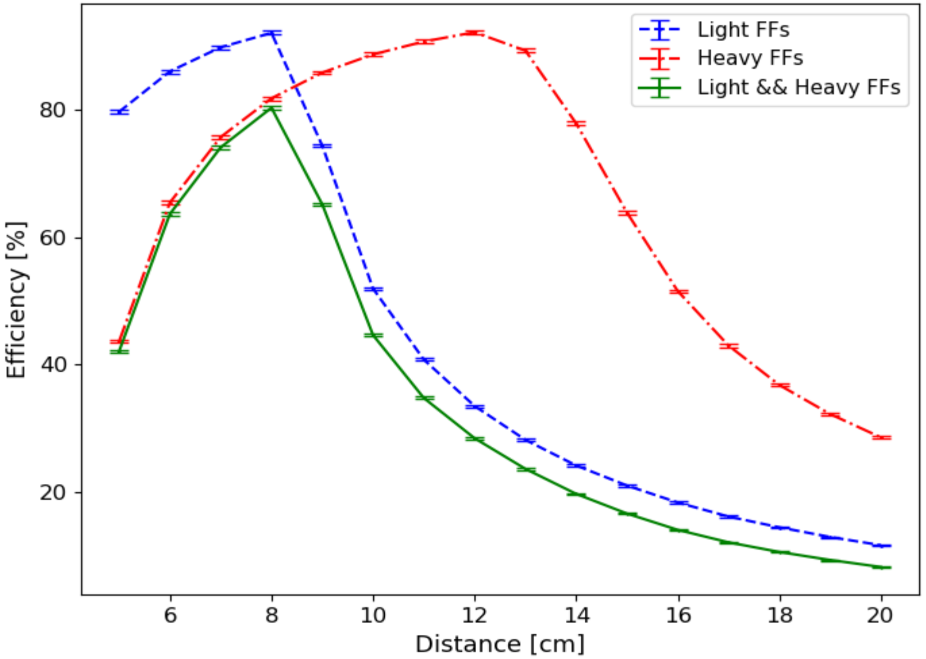


CD-shaped Si detector
Micron Semiconductor S3

Junction number of elements	24 rings
Ohmic number of elements	32 sectors
Active area Ø - inner (mm)	22
Active area Ø - outer (mm)	70



- No PID for FFs
+ Angular acceptance

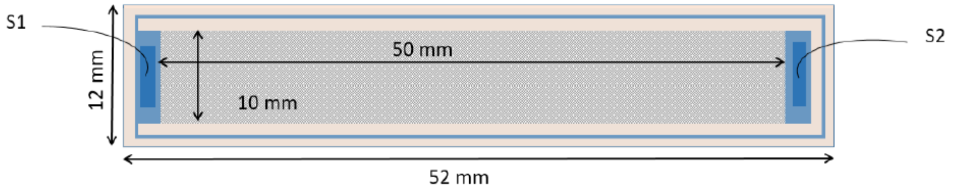


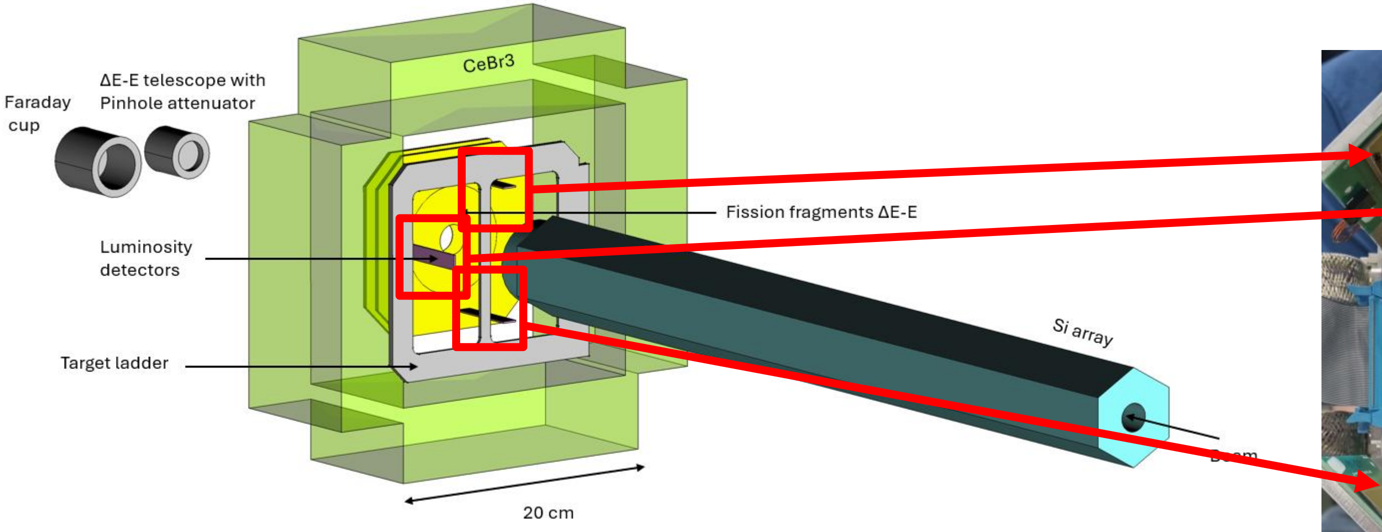
Measured:

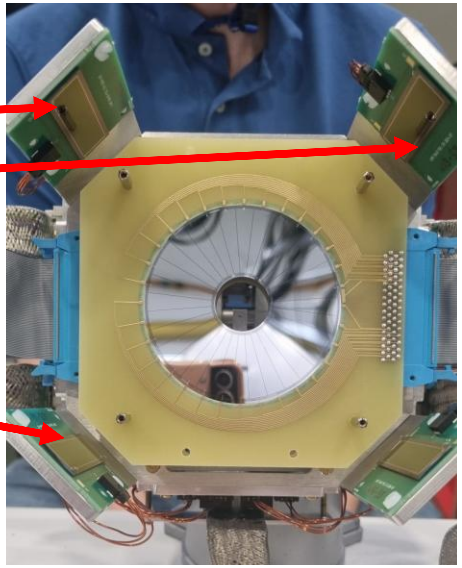
- Protons.
- Fission fragments (FFs).
- **Scattered deuterons.**
- γ-rays from FFs.

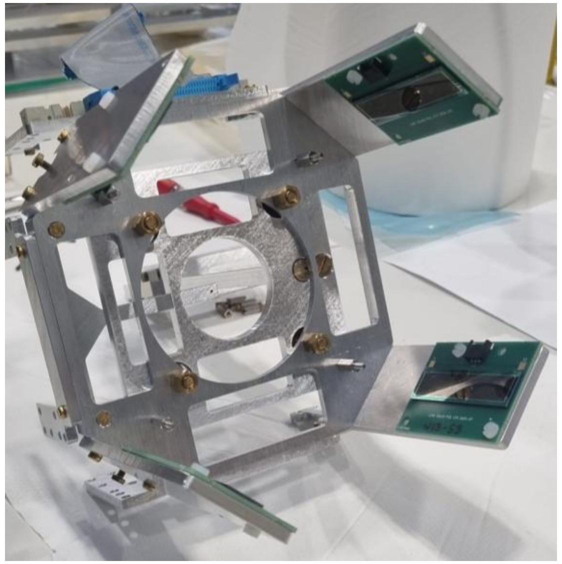
Many thanks to B. Kay!

LUME (luminosity) detectors
4 position-sensitive silicon detectors





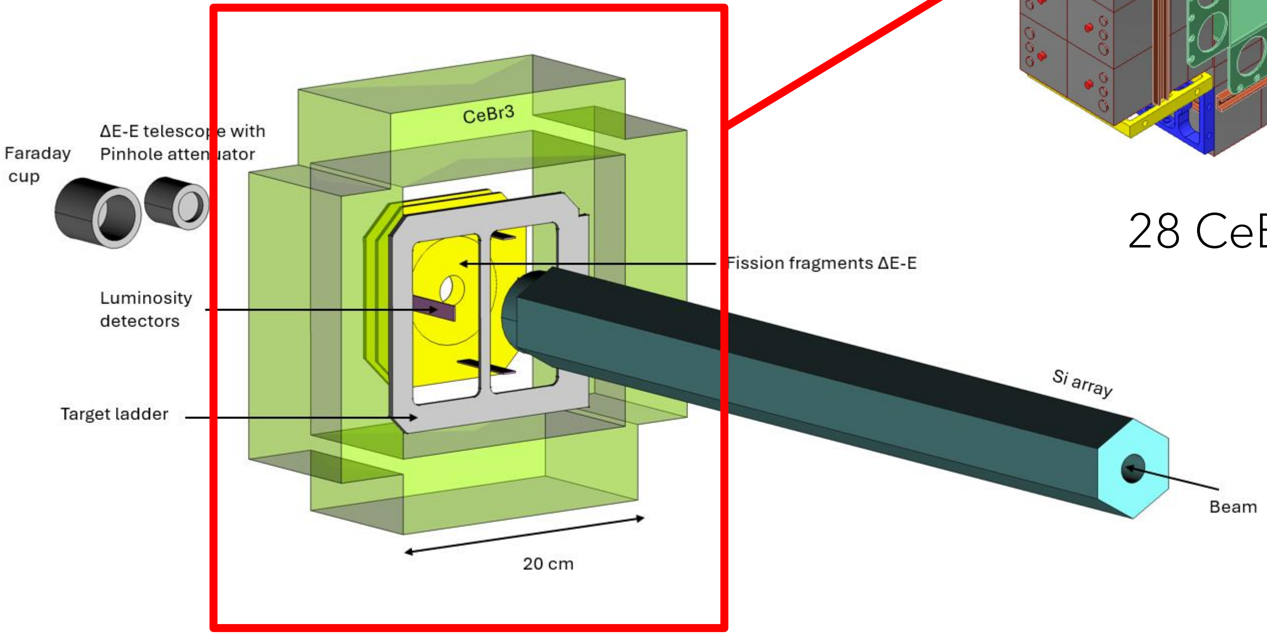


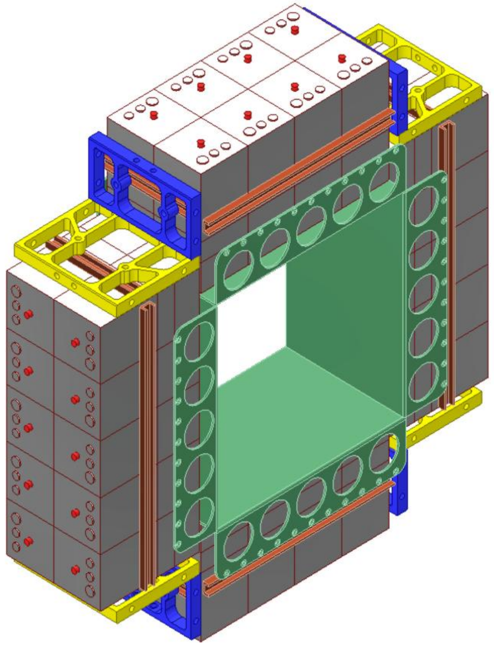


A novel setup for studying (d,pF) reactions at ISS - IV

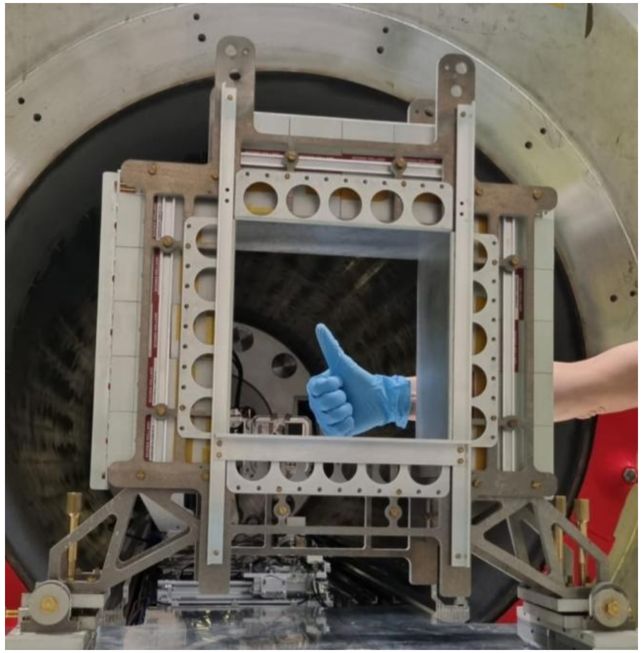
Measured:

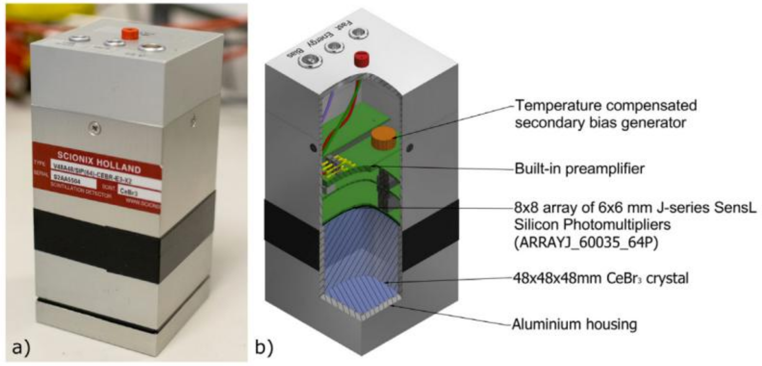
- Protons.
- Fission fragments (FFs).
- Scattered deuterons.
- **γ-rays from FFs.**





28 $CeBr_3$ crystals





O. Poleshchuk *et al.*, "The SpecMAT active target," Nucl. Instrum. Methods A **1015**, (2021).

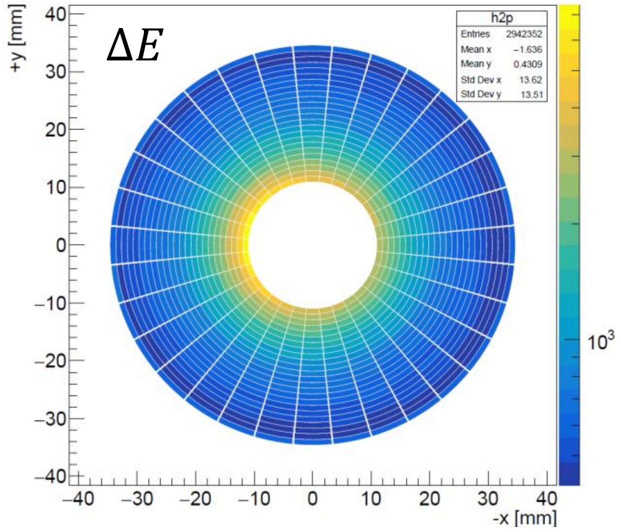
Commissioning with stable beam

$^{22}Ne(d,p)^{23}Ne$ 6 MeV/u

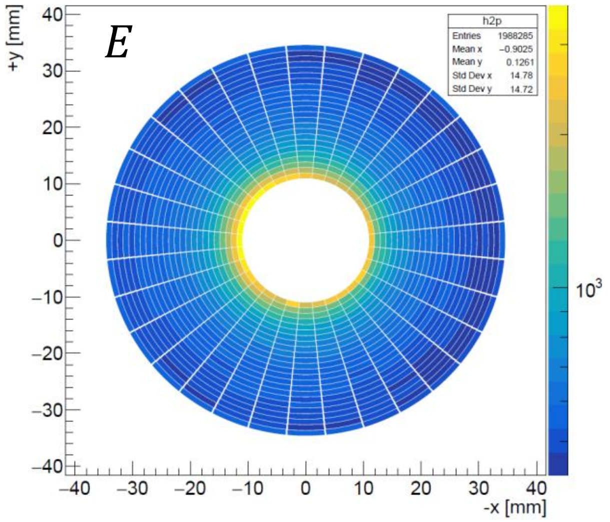
ISOLDE, CERN

June 3 -10, 2025

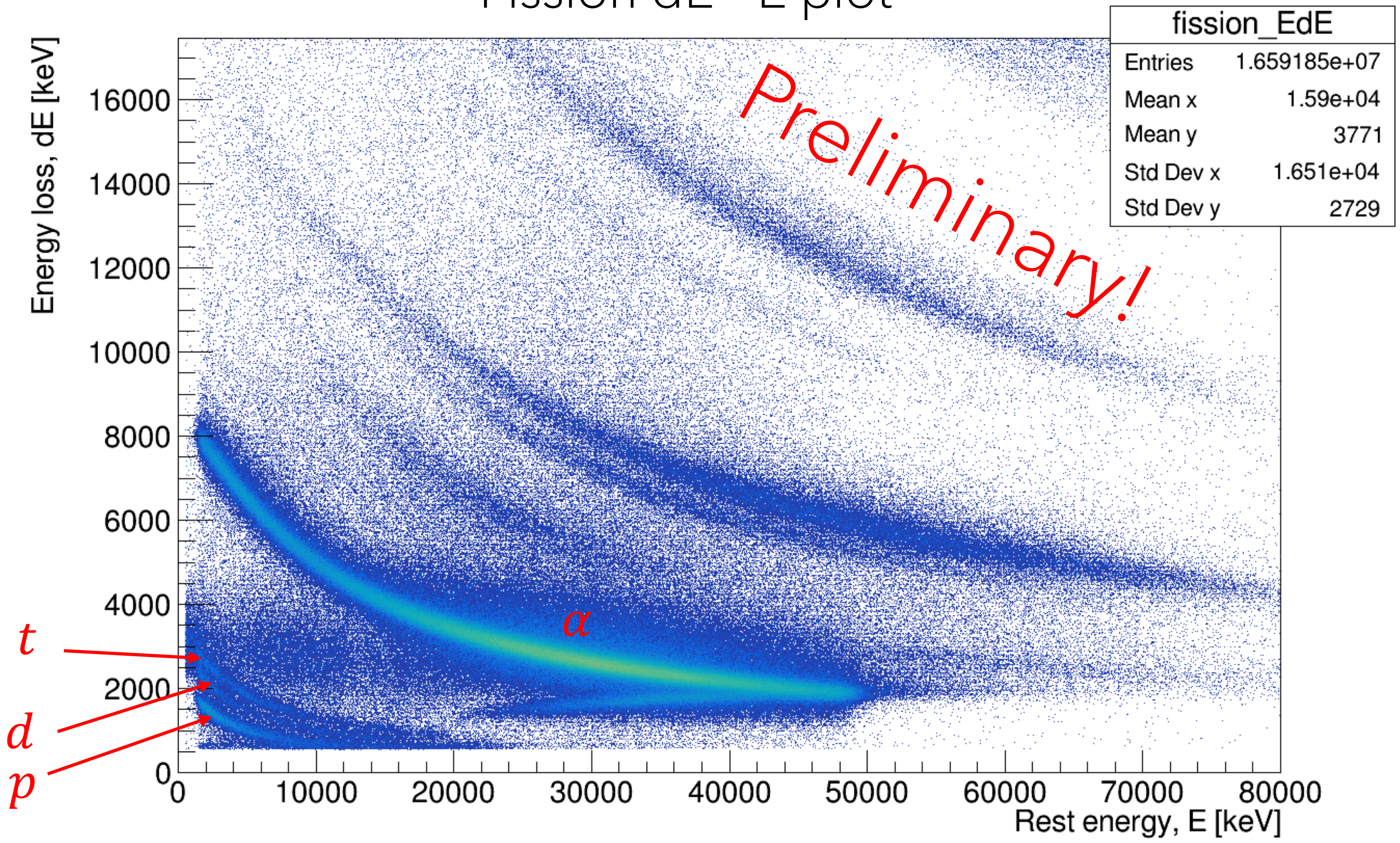
Preliminary!



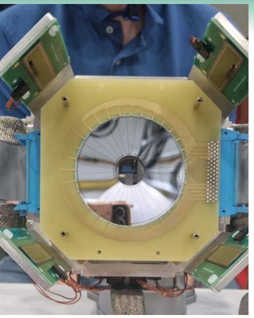
Preliminary!



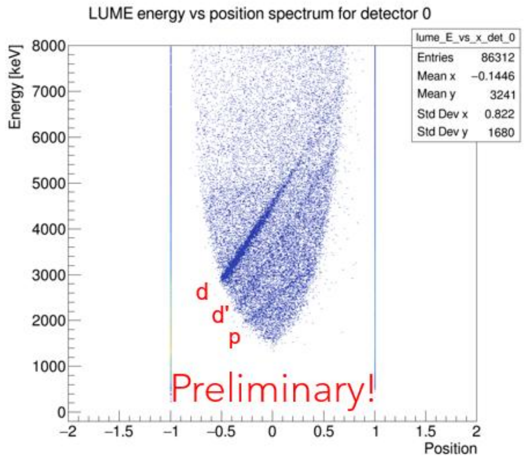
Fission dE - E plot

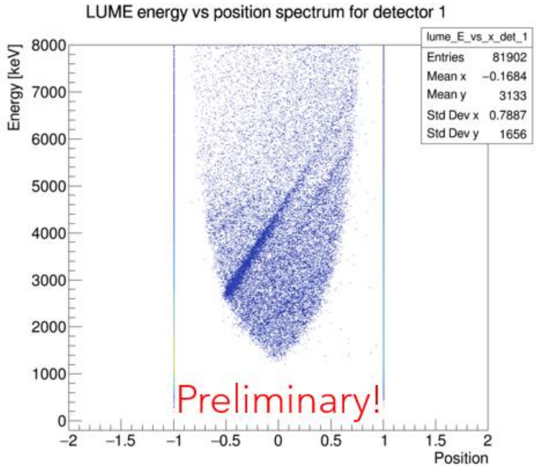


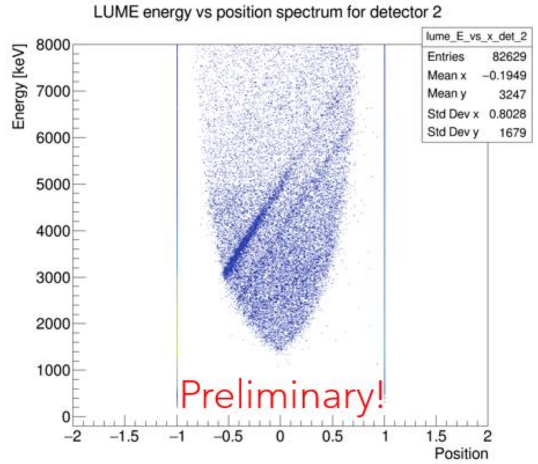
Other detectors

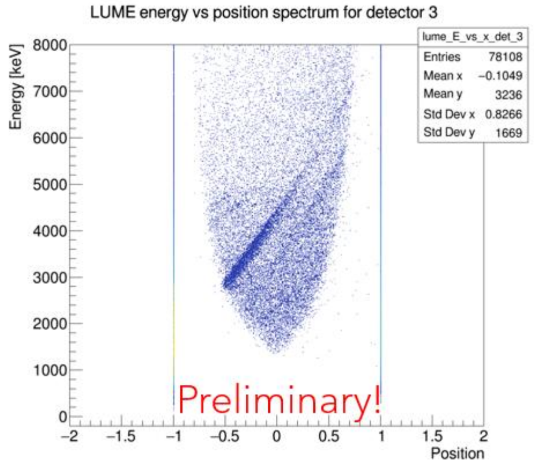


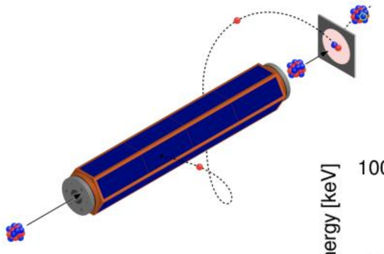
Luminosity monitor



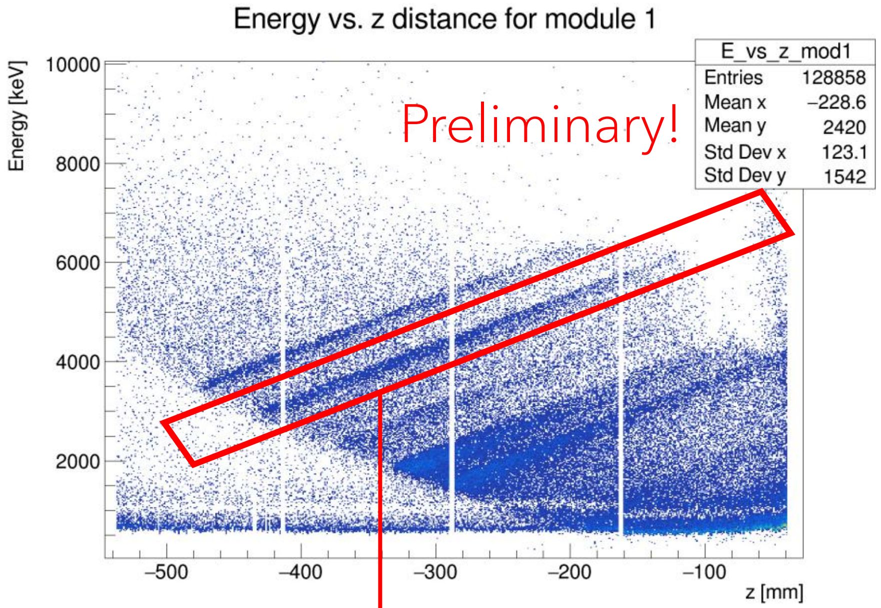


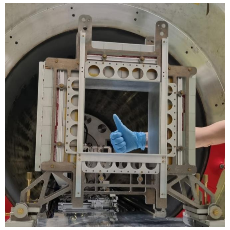


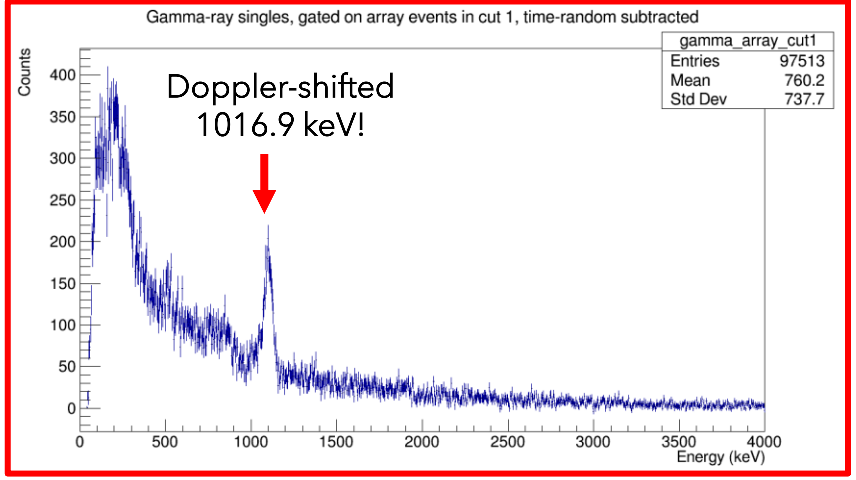




$p - \gamma$ coincidences







Why is it hard to measure fission of n-rich nuclei?

- Going neutron-rich:

$$\downarrow S_n \qquad \uparrow B_f$$

- Radioactive beam requirements:
  - Sufficient beam intensity.
  - no contaminant with higher fission probability.

- Radioactive beam energy: limits available excitation energy in (d,pF).

$$E^* > B_f$$

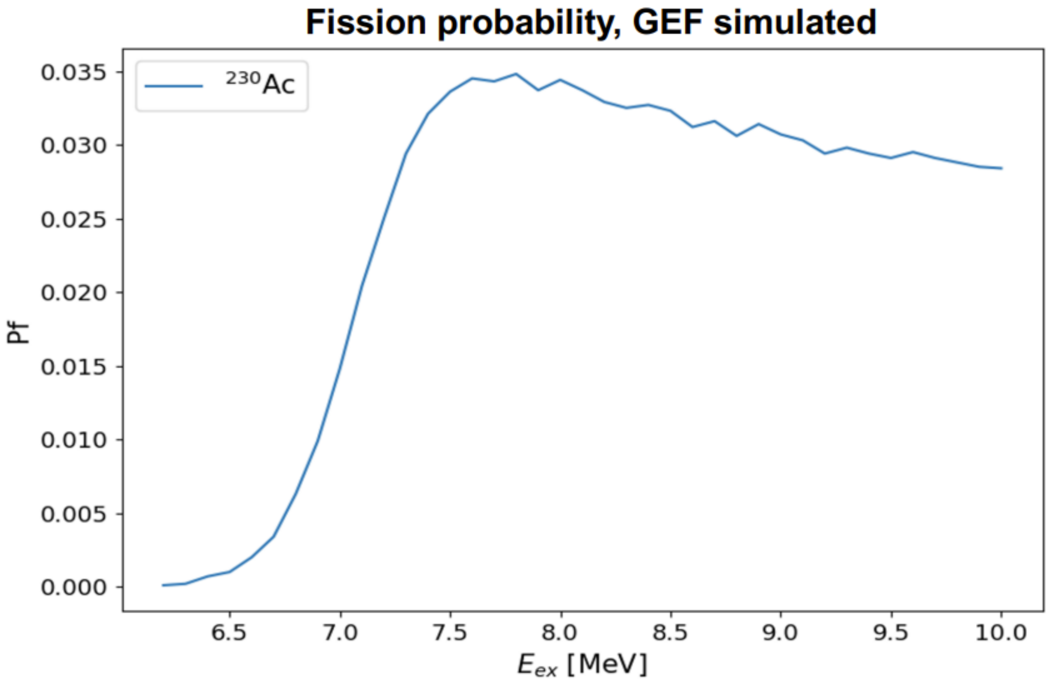
A good candidate to study:

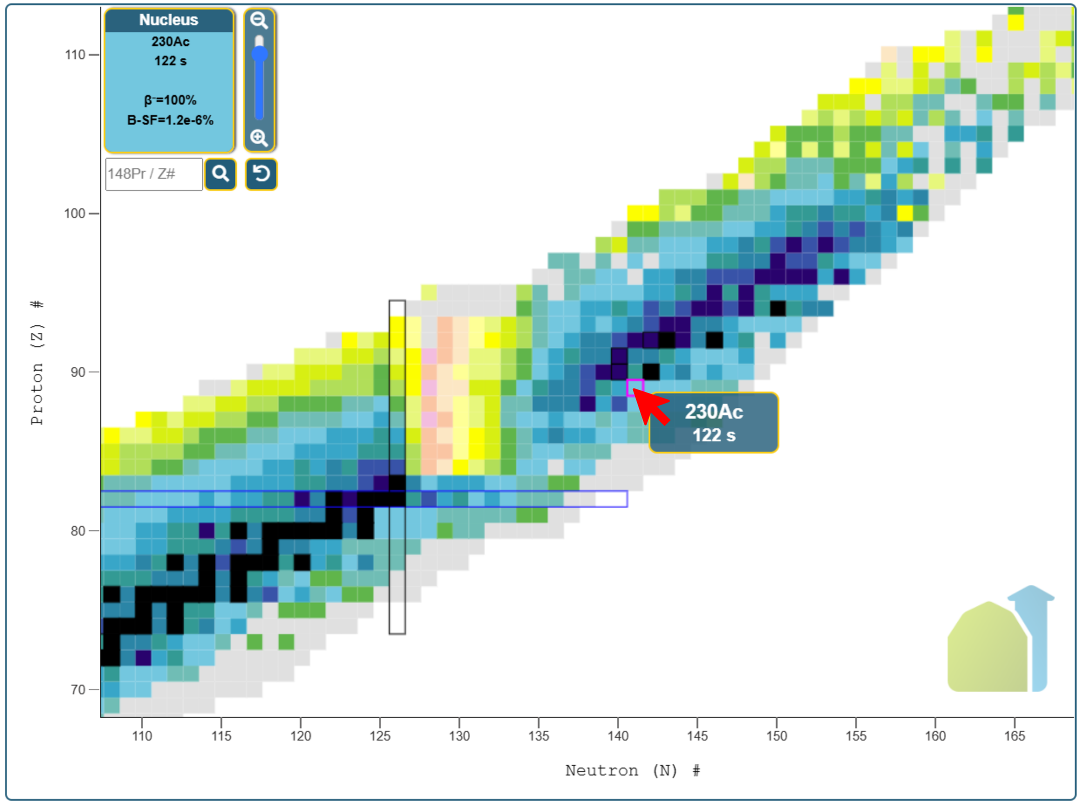
beam ^{229}Ac → fission of ^{230}Ac compound nucleus

No conclusive data on fission at low excitation energies of such nucleus.

A good candidate: ^{230}Ac

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





https://www.nndc.bnl.gov/nudat3/

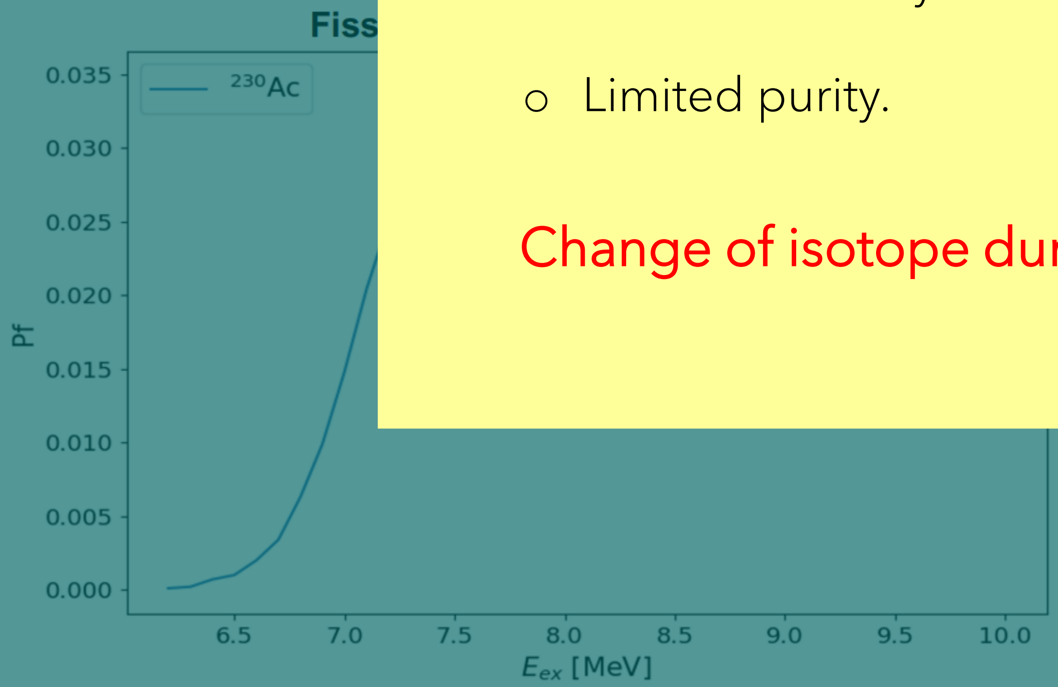
^{230}Ac	
Sn [1]	4.923 MeV
Fission barrier height [2]	7.01 MeV
P_f (1st chance) [2]	3%

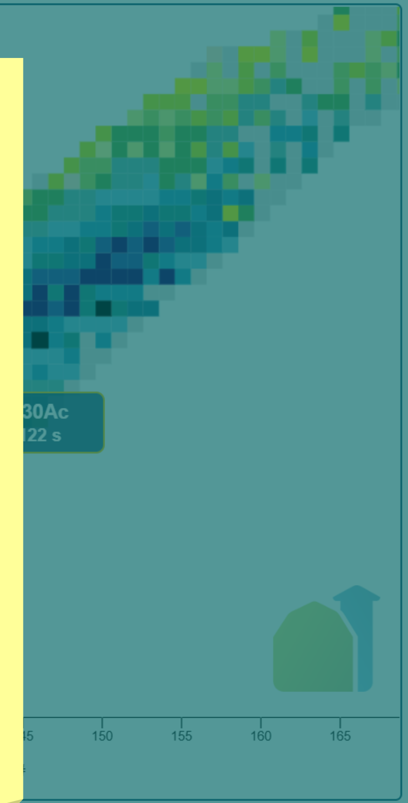
[1] M. Wang at al. Chinese Physics C 45, 030003 (2021).
[2] K.-H, Schmidt et al. Nucl. Data Sheets 131, 107 (2016).

A good candidate: ^{230}Ac

Approve

Beam ti
optimized t





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

Technical challenges during the experiment:

- Limited beam energy (< 8 MeV/u).
- Limited intensity.
- Limited purity.

Change of isotope during the experiment ⚠️

Experiment IS739

ISOLDE, CERN
July 10 - 20, 2025

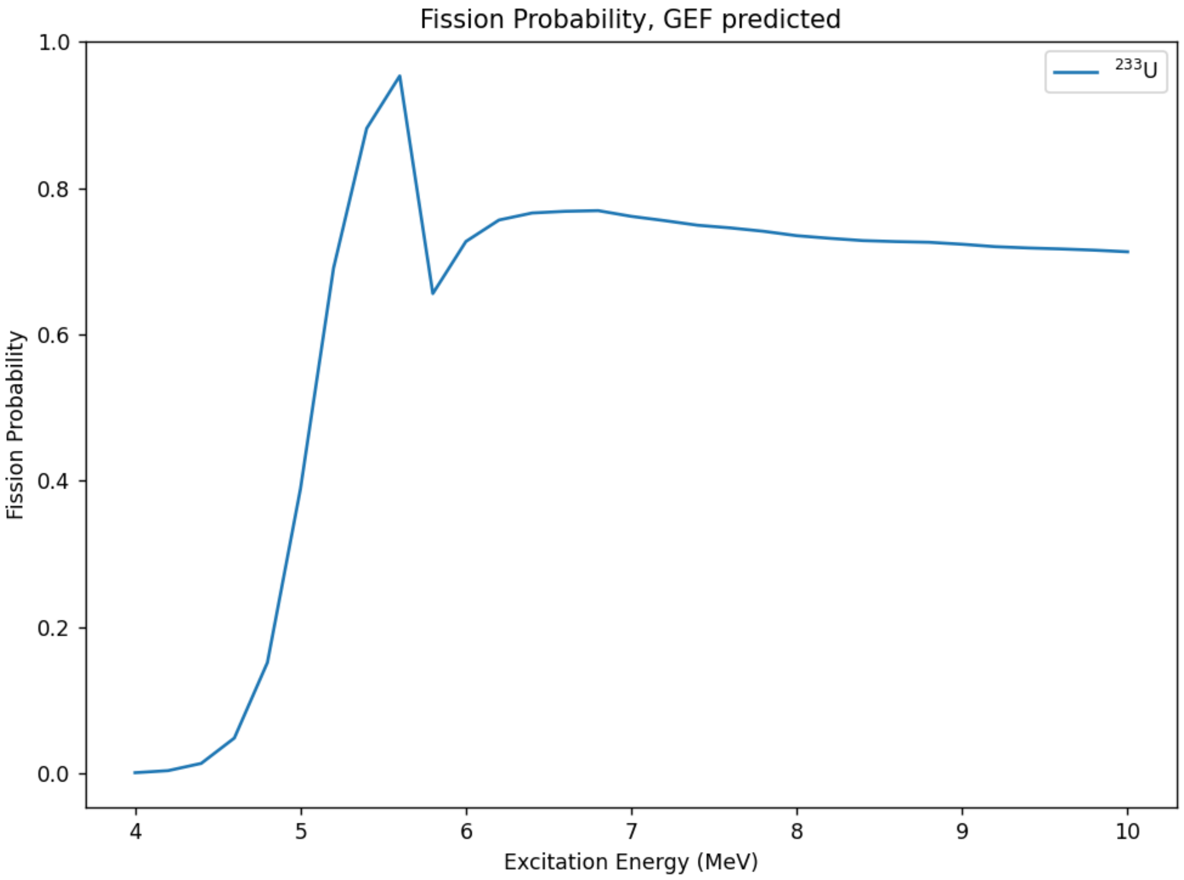
Fission of ^{233}U

Why is ^{233}U a good candidate?

- Higher production yield for ^{232}U beam (UCx primary target).
- $S_n > B_f$
- Higher fission probability.
- Smaller fission barrier of any possible beam contaminant.
- Important for Th-fuel cycle.

Cons:

- Experimental setup geometry not optimized for ^{233}U fission.



^{233}U	
Sn [1]	5.76 MeV
Fission barrier height [1]	4.34 MeV
P_f (1st chance) [1]	~ 90%

[1] K.-H, Schmidt et al. Nucl. Data Sheets 131, 107 (2016).

What's in the literature?

2.A.1:
2.J

Nuclear Physics **55** (1964) 517—522; © *North-Holland Publishing Co., Amsterdam*
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THE FISSION CROSS SECTION OF U^{232} FROM 4 eV TO 400 eV

G. D. JAMES
Nuclear Physics Division, U.K.A.E.A. Research Group, Atomic Energy Research Establishment, Harwell

Received 17 February 1964

Abstract: The fission cross section of U^{232} from 4 eV to 400 eV has been measured by time-of-flight experiment. The distribution of fission widths for eight resonances below 100 eV fits a chi-squared distribution with $\nu = 1.9 \pm 0.8$ degrees of freedom. The level spacing D is 7.6 ± 1.5 eV and the strength function $\overline{\Gamma^0}/D$ is $(1.0 \pm 0.5)10^{-4}$.

Data from US

2.J

Nuclear Physics **A112** (1968) 329—336; © *North-Holland Publishing Co., Amsterdam*
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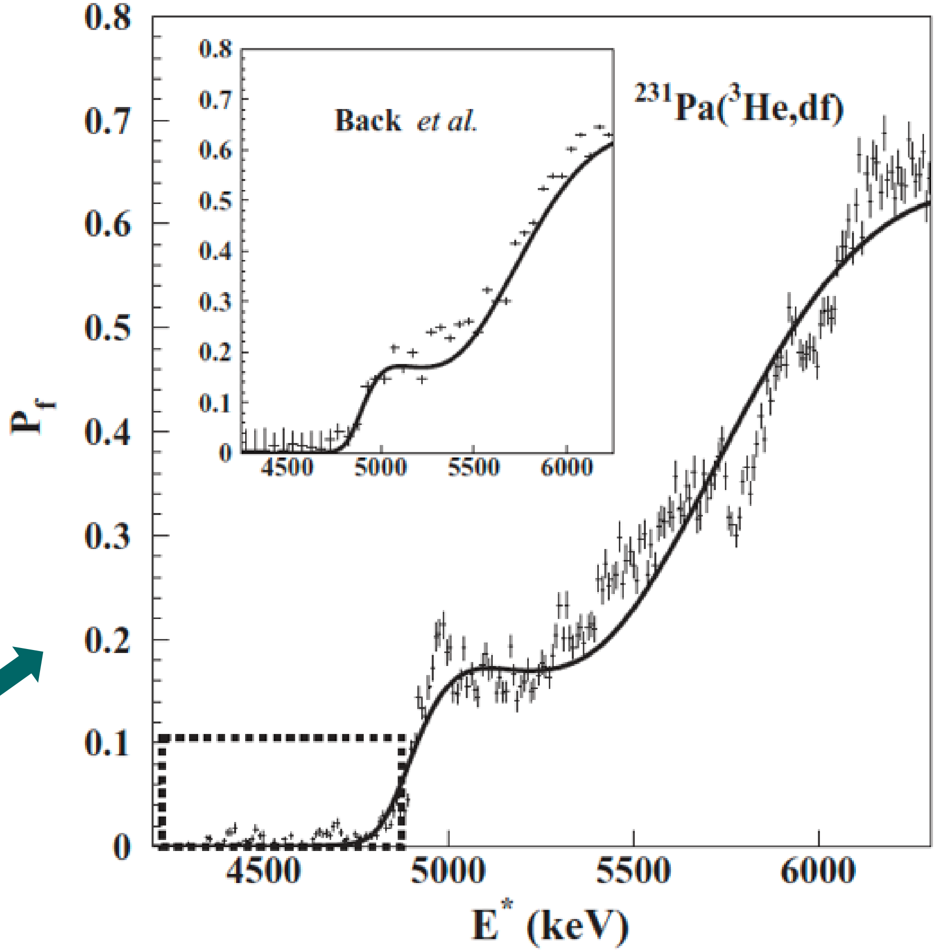
NEUTRON-INDUCED FISSION CROSS SECTION OF ^{232}U

G. F. AUCHAMPAUGH, C. D. BOWMAN and J. E. EVANS
Lawrence Radiation Laboratory, University of California, Livermore, California †

Received 26 February 1968

Abstract: The neutron-induced fission cross section of ^{232}U has been measured from 5 to 1900 eV. This is the only doubly even target known which undergoes substantial resonance fission. Only one spin state is excited, and only one open fission channel is expected. An attempt was made to fit the data using the Reich and Moore formula for a single-fission channel. The rather poor quality of the fit suggests that a one-channel theory for fission in ^{232}U is inadequate, which is in agreement with earlier conclusions from total cross-section measurements.

In **direct** kinematics:



Resolution: 11 keV FWHM!

Fission of ^{232}U*:

PHYSICAL REVIEW C **80**, 011301(R) (2009)

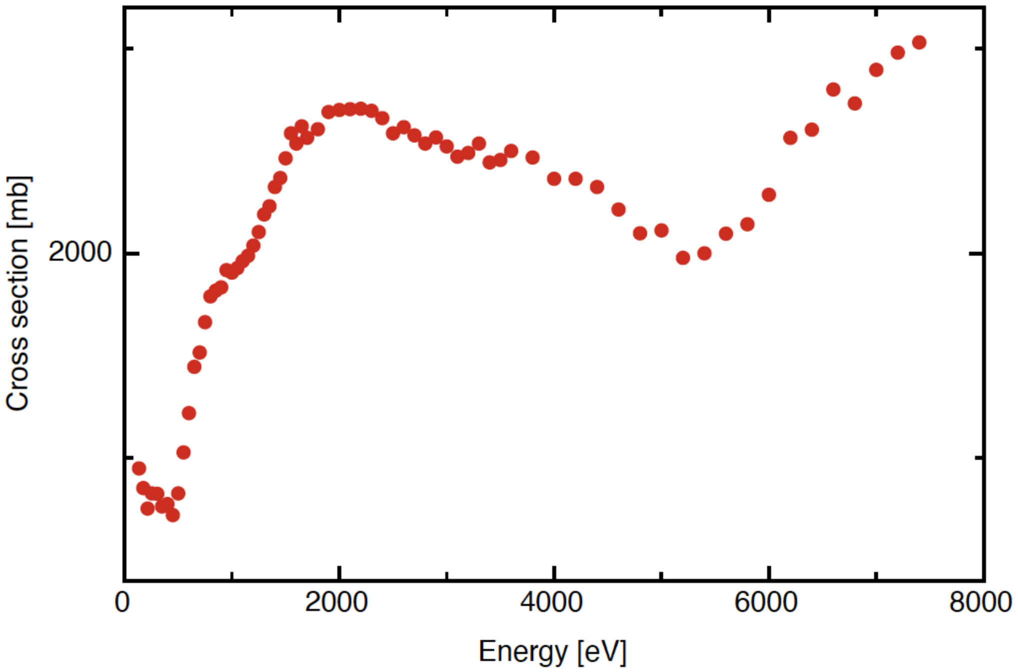
Hyperdeformed sub-barrier fission resonances observed in ^{232}U

L. Csige,[1,2] M. Csatlós,[1] T. Faestermann,[3] Z. Gácsi,[1] J. Gulyás,[1] D. Habs,[2] R. Hertenberger,[2] A. Krasznahorkay,[1] R. Lutter,[2] H. J. Maier,[2] P. G. Thirolf,[2] and H.-F. Wirth[3]
[1]*Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), Post Office Box 51, H-4001 Debrecen, Hungary*
[2]*Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*
[3]*Technische Universität München, D-85748 Garching, Germany*
(Received 27 February 2009; revised manuscript received 18 June 2009; published 2 July 2009)

What's in the literature? Fission of $^{233}U^*$

Data from SU: $^{232}U(n,F)$

- B. I Fursov *et al*., Atomnaya Energiya 61, 383 (1986).



- P. E Vorotnikov *et al*., Kurchatov Inst. 32 (1970).

- Other: E. K. Hultet et al., Wash. AEC Office Reports 1033, 28 (1961).

Experiment IS739:

First measurement of (d,pF) of ^{233}U.

Collaboration

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, 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, A-C. Larsen, V. W. Ingeberg, J. Henderson, Y. Kucuk, I. Boztosun, H. Dapo, H. Sansar.

CHALMERS

Knut and Alice Wallenberg Foundation

Swedish Research Council

ISOLDE Solenoidal Spectrometer

CERN

Status

- The method works.
- Detectors performed well!
- First (d,p) measurement on ^{232}U.
- Analysis in progress:
  - Calibration.
  - Next: quantify efficiencies and compare with simulations.
  - Gamma ray analysis.

Next:

After CERN long shutdown: higher beam energy available at ISOLDE → beam development.

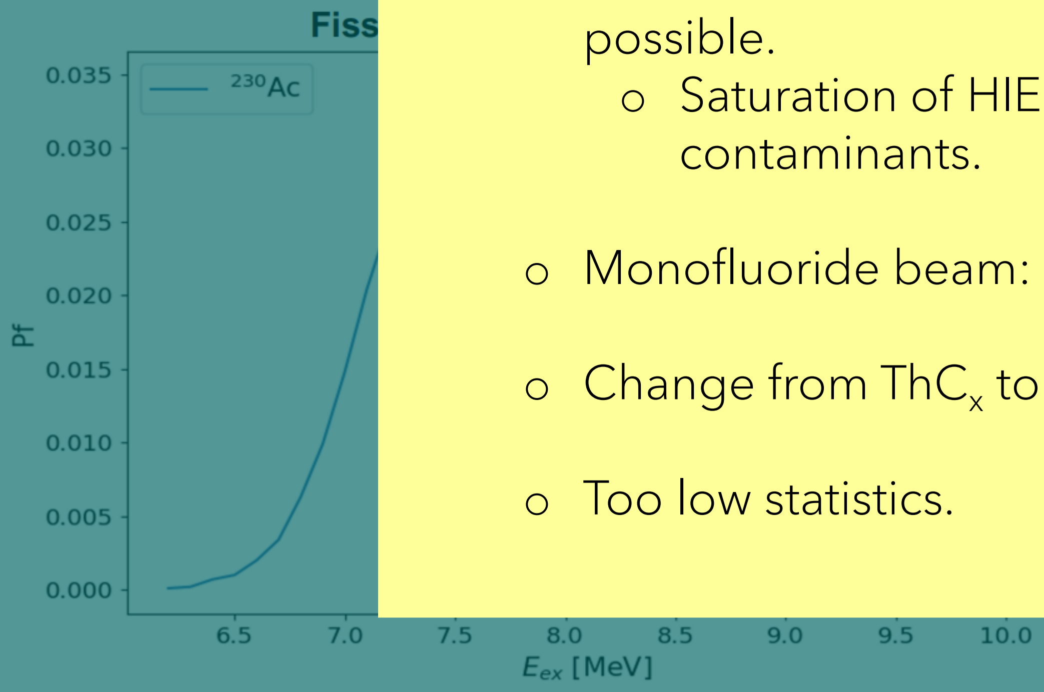
  - Try once more ^{230}Ac case study.
  - Push further to heavier beams.

Thank you for your attention!

Backup slides

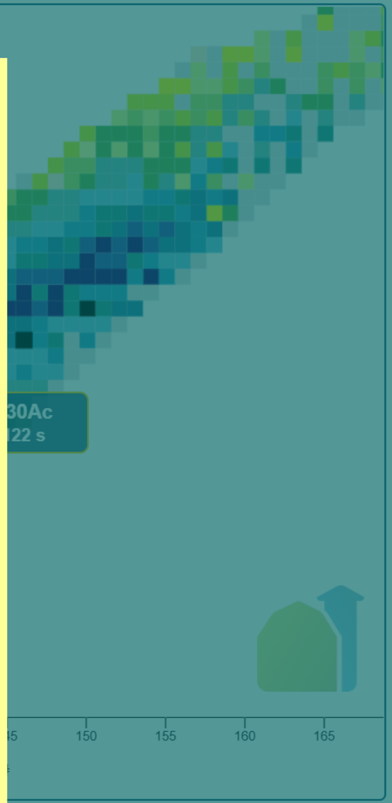
Approve

Beam ti
optimized t



Technical challenges during the experiment:

- Limited beam energy (< 8 MeV/u).
- Production of ^{229}Ac beam in difluoride form not possible.
  - Saturation of HIE-ISOLDE trap likely due to contaminants.
- Monofluoride beam: production yield too low.
- Change from ThC_x to UC_x primary target required.
- Too low statistics.

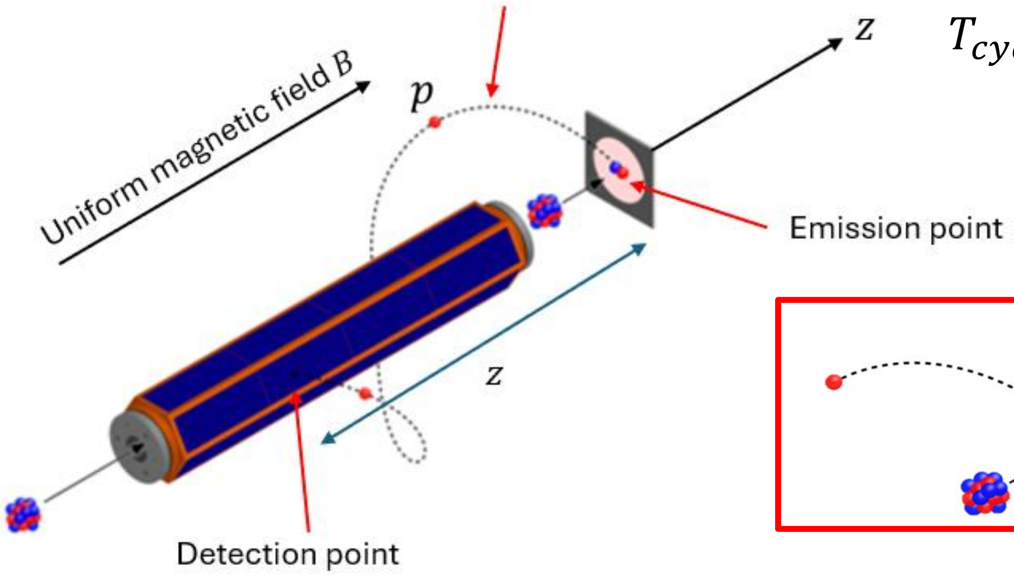


s://www.nndc.bnl.gov/nudat3/

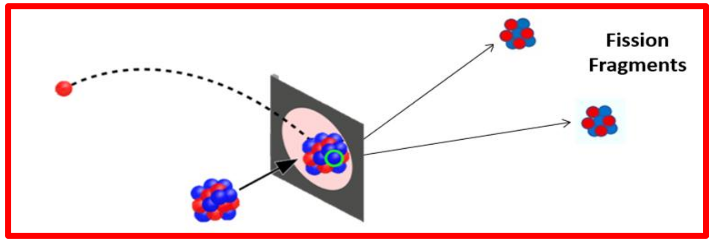
	.923 MeV
	7.01 MeV
	3%

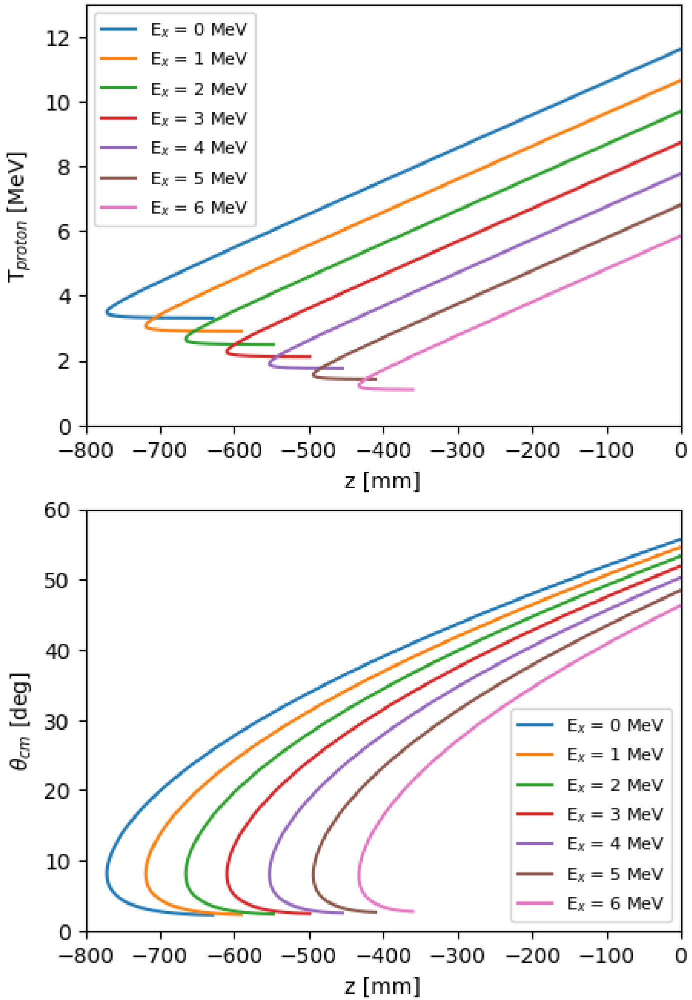
[1] M. Wang at al. Chinese Physics C 45, 030003 (2021).
[2] K.-H, Schmidt et al. Nucl. Data Sheets 131, 107 (2016).

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



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





Analytical calculations for ^{28}Si(d,p)^{29}Si at 6 MeV/u.

We measure:

- E_p,
- z,
- T_{cyc}.

We we are interested in:

- E_x,
- θ_{cm}

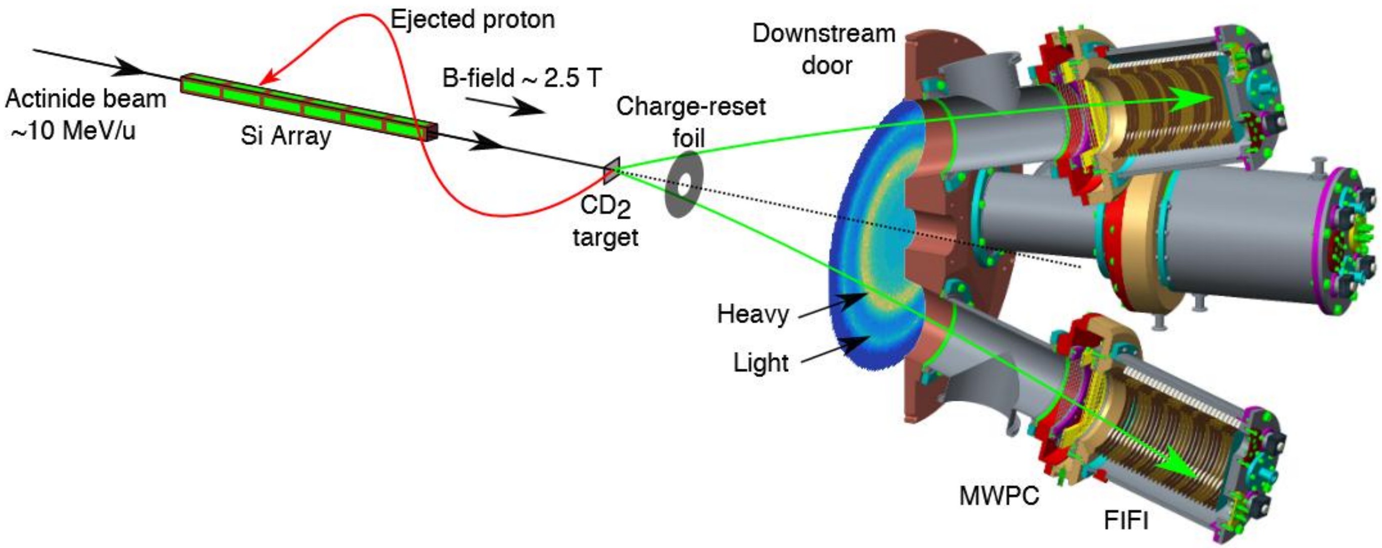
$$\alpha = \frac{ZB}{2\pi}$$

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

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

Proof-of-principle experiment at ANL – HELIOS

^{238}U(d,pF) @8.6 MeV/u

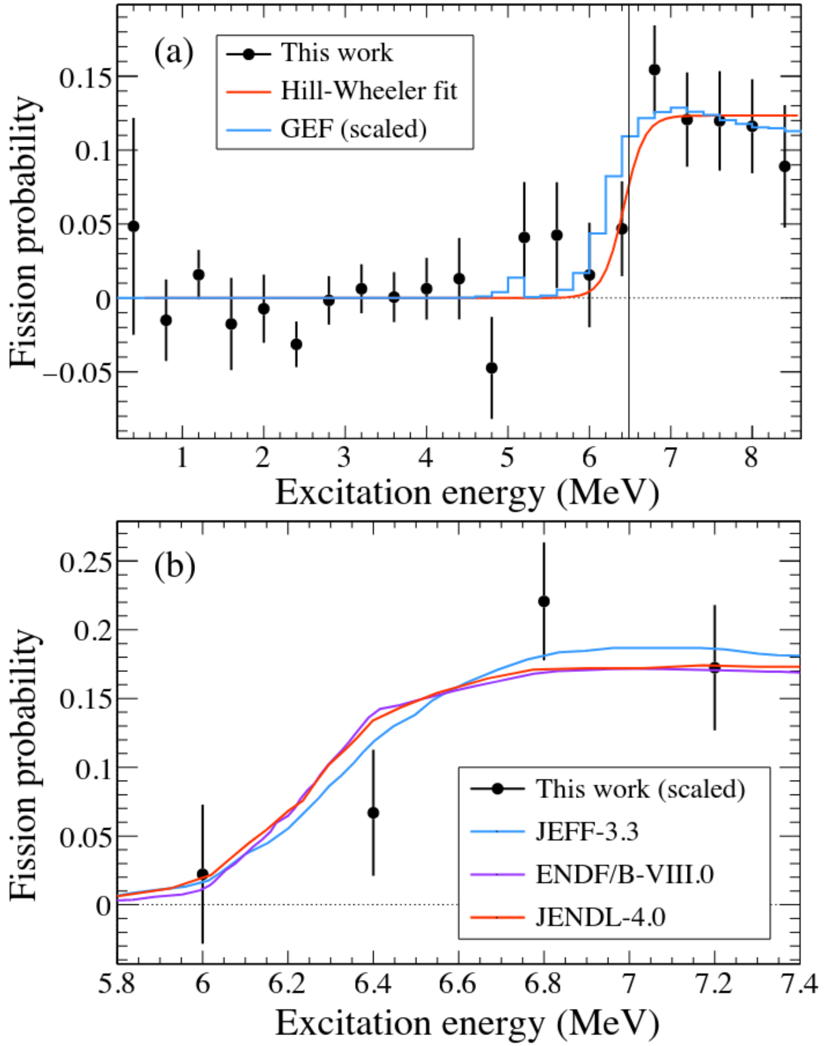


(LoI, INTC-I-224)

Very promising for ISS, BUT.... Geometrical efficiency of the setup is limited:

- ~10% for the detection of one or more FF,
- ~1% for the coincident detection of light and heavy fragments

Commissioning experiment for ISS is planned (IS224).



S. A. Bennett et al., Phys. Rev. Lett. 130, 202501

Fission barrier of beam contaminants