Fission studies at ISS

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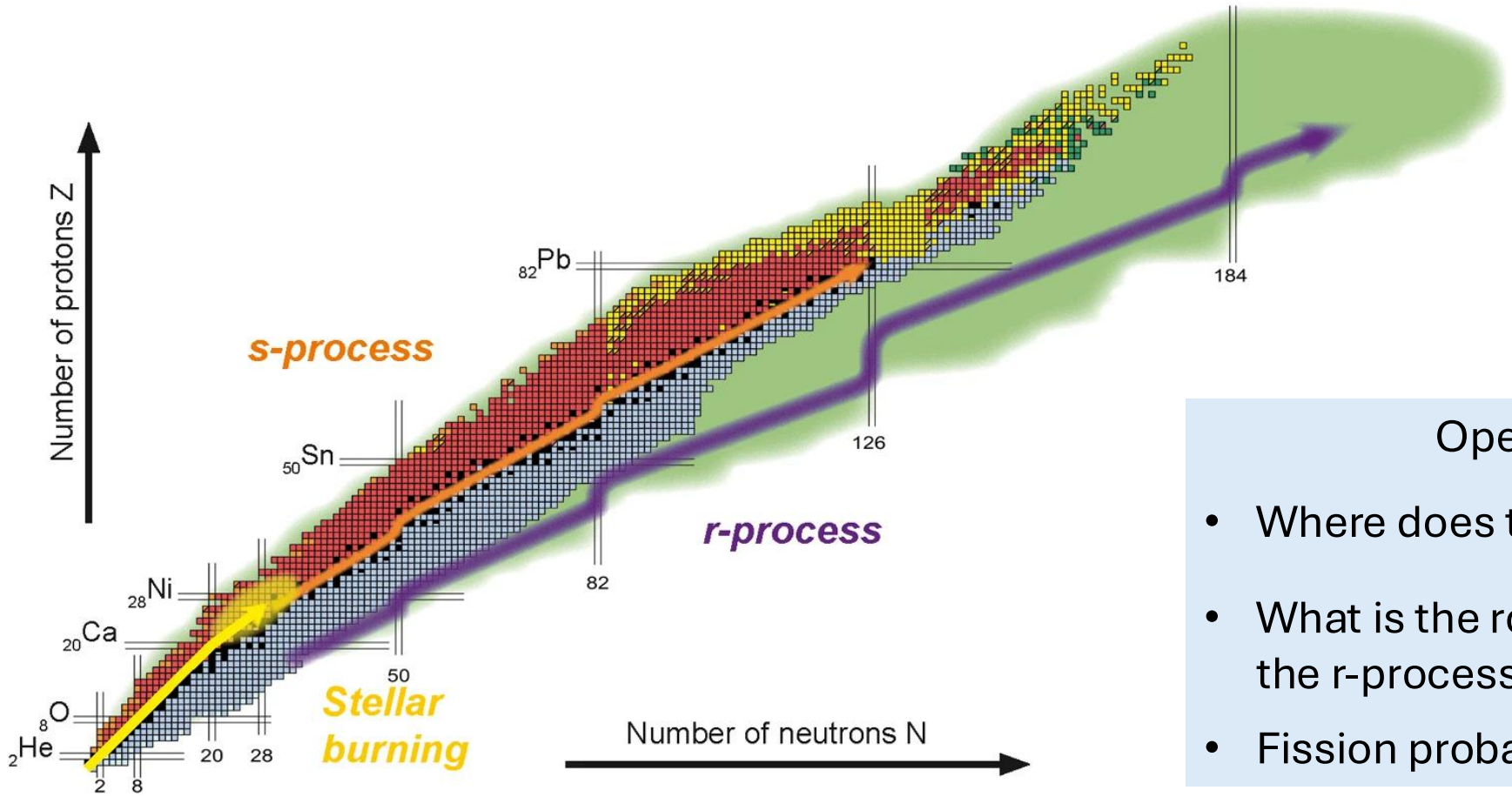
Chalmers University of Technology

ISOLDE Workshop and Users meeting 2025

Nuclear fission and the r-process

s-process (slow)
r-process (rapid)



Open questions:

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

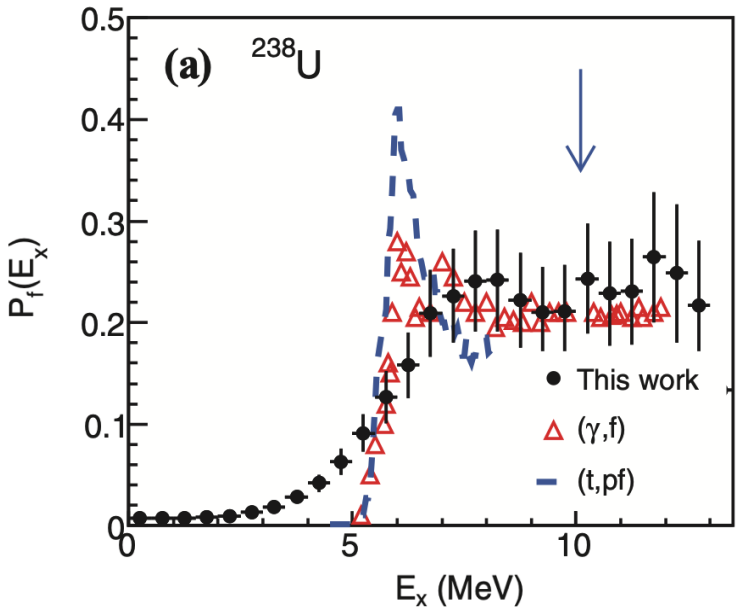
FK Thielemann, Eur. Phys. J. A 59, 12 (2023)

Probing fission of n-rich nuclei

Key <u>fission observables</u>:

- **Fission probability as a function of the excitation energy.**

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

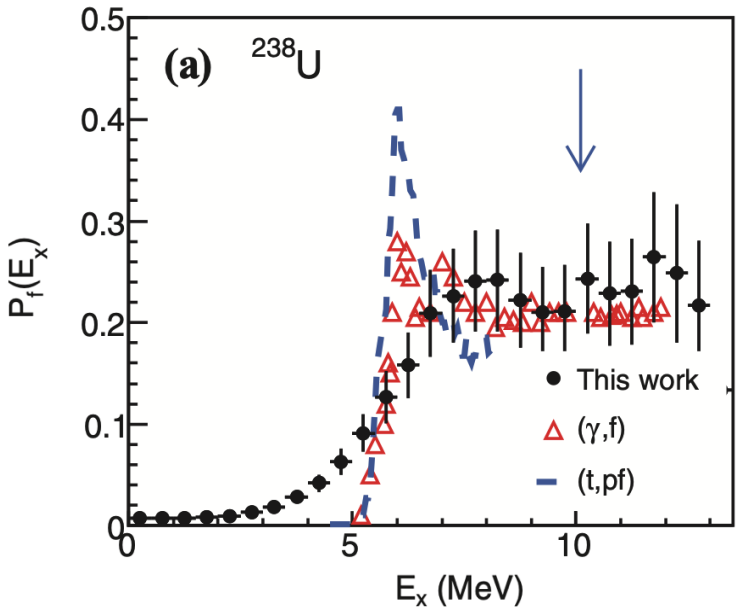


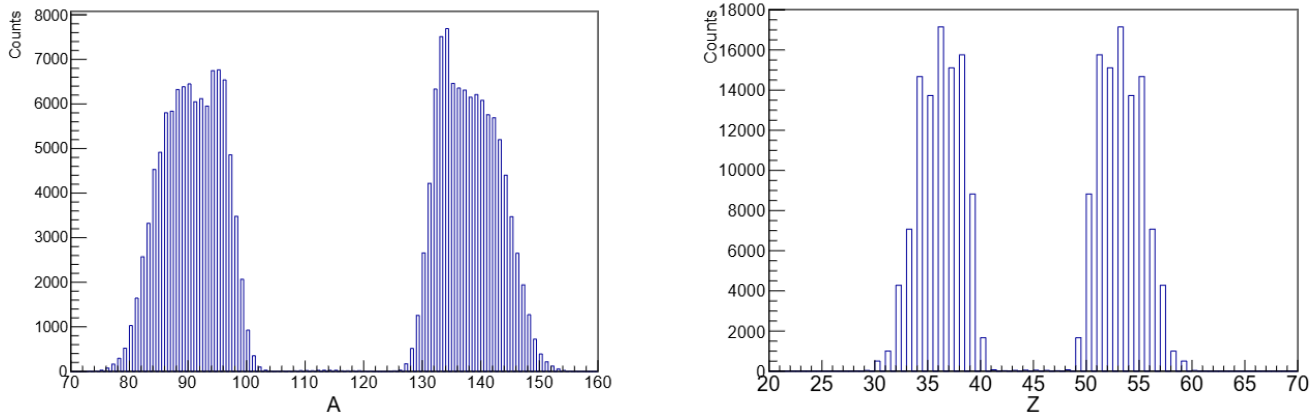
Probing fission of n-rich nuclei

Key <u>fission observables</u>:

- Fission probability as a function of the excitation energy.
- **Charge-mass distributions of fission fragments.**

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.

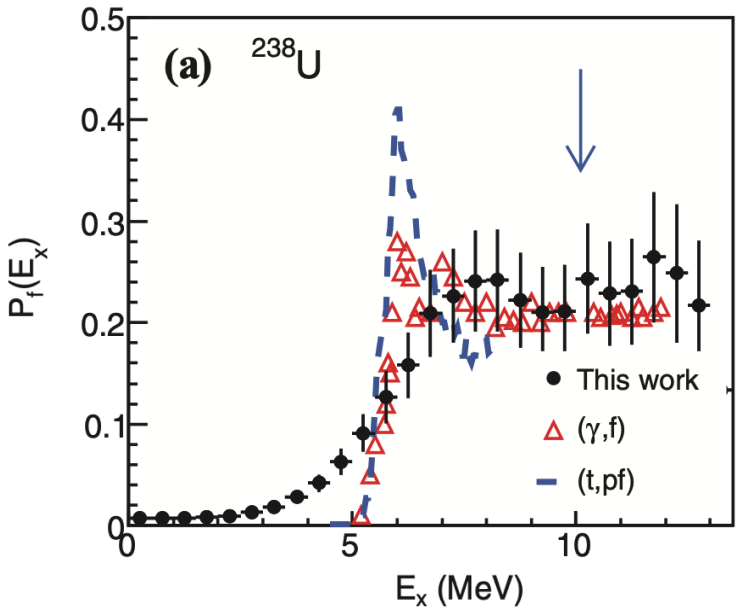
Probing fission of n-rich nuclei

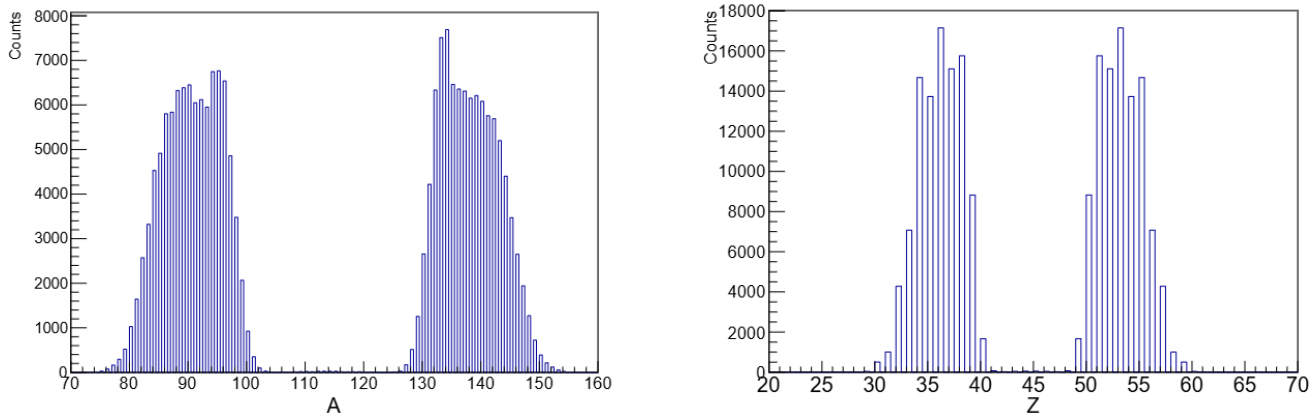
Key fission observables:

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

Experimentally challenging for n-rich nuclei!

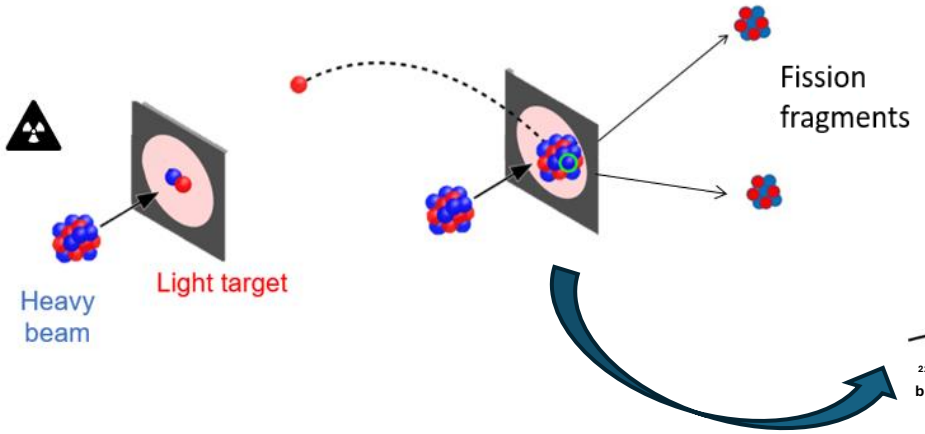
C. Rodríguez-Tajes et al., PRC 89, 024614 (2014).



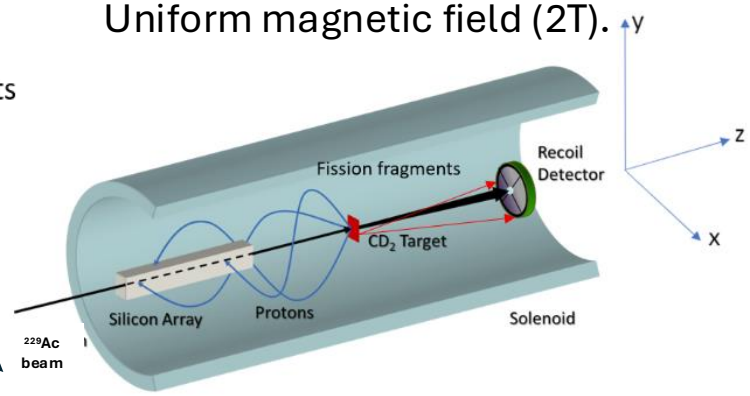


GEF-simulated mass and charge fission fragment distributions for ^{230}Ac with E_x=7 MeV.

(d,pf) surrogate reactions in inverse kinematics



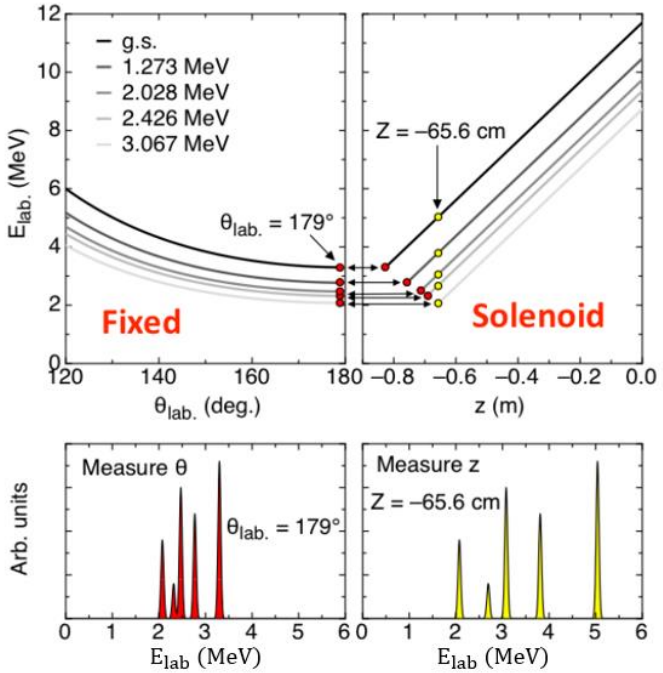
Uniform magnetic field (2T).



Experimental challenges:

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

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



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

Fission event:
coincidence with proton and two detected fission fragments.

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

Measured:

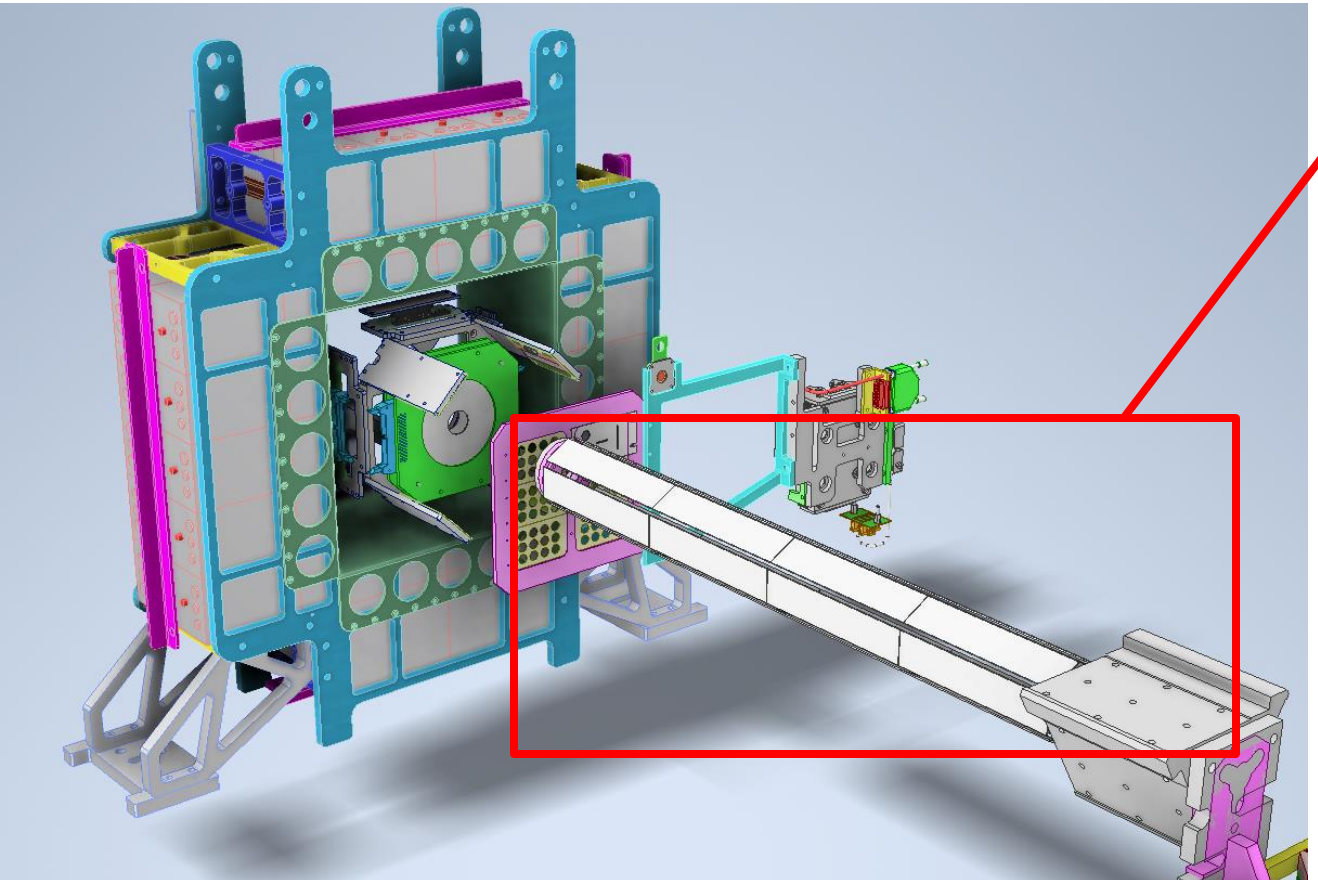
- **Protons.**
- Fission fragments (FFs).
- Scattered deuterons.
- γ-rays from FFs.

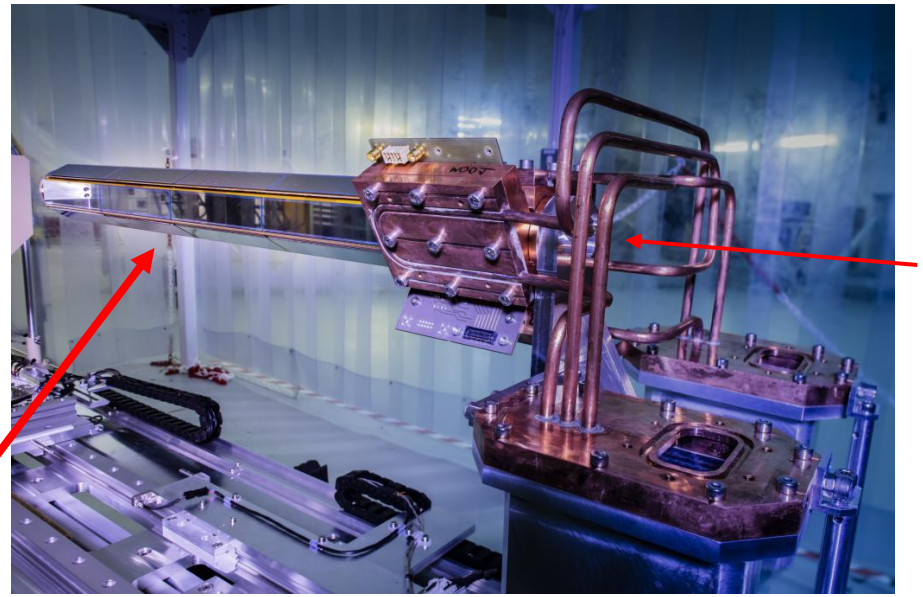
Beam tuning:

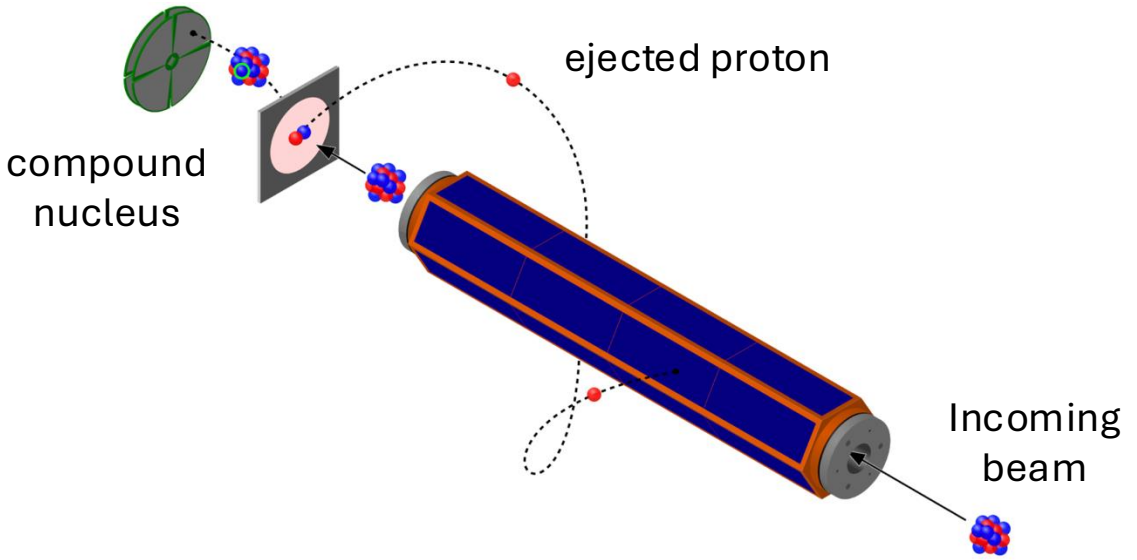
- Beam monitor detectors.

Targets:

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



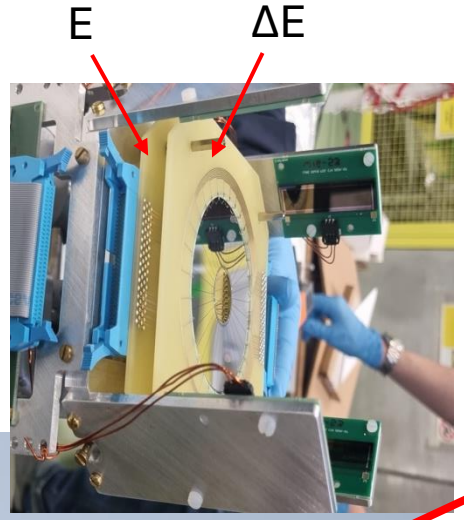


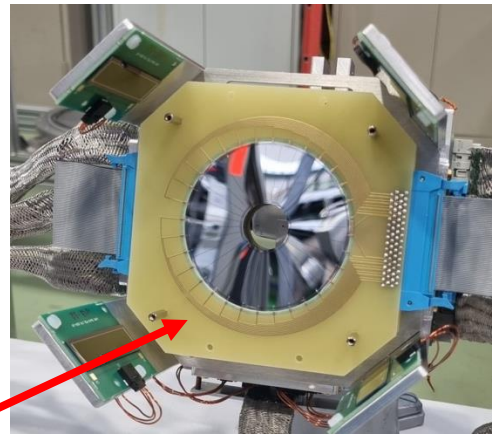


A novel setup for studying (d,pf) reactions at ISS – fission fragments

Measured:

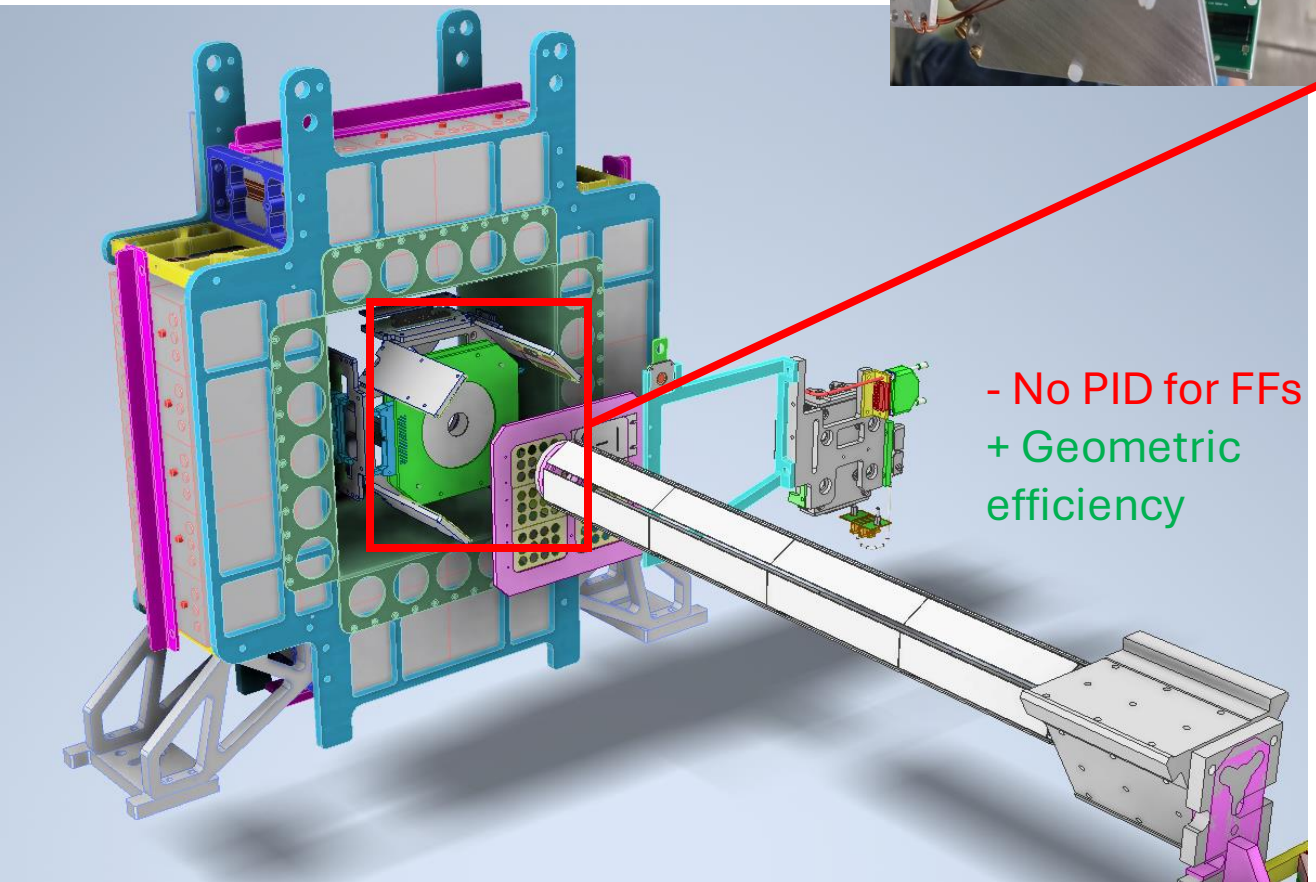
- Protons.
- **Fission fragments (FFs).**
- Scattered deuterons.
- γ-rays from FFs.

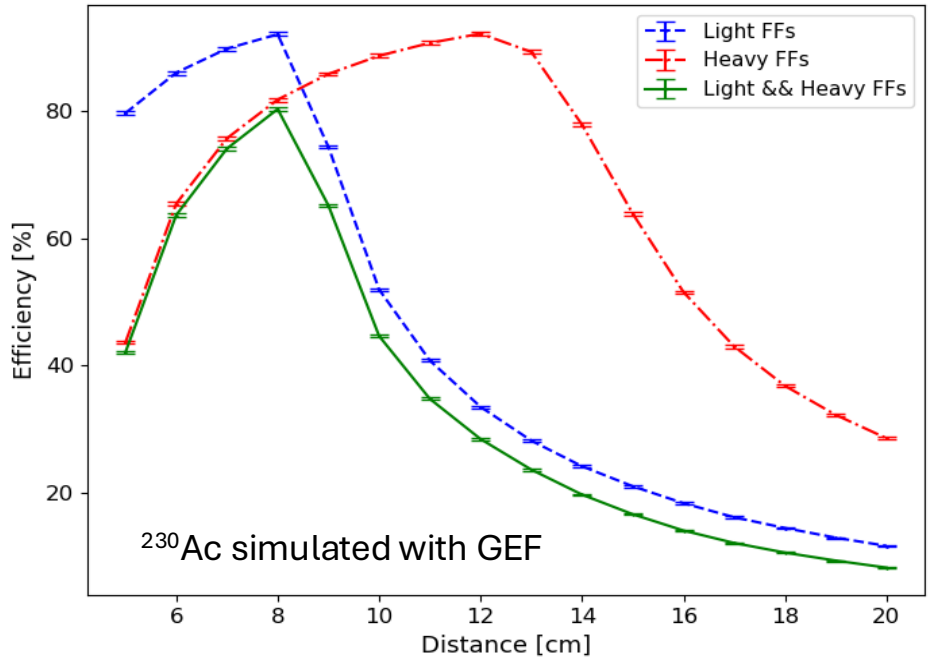




CD-shaped Si detector
Micron Semiconductor S3

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





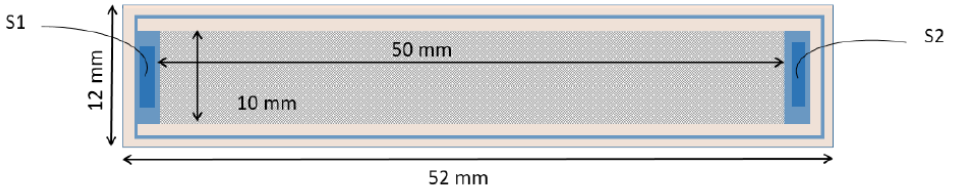
A novel setup for studying (d,pf) reactions at ISS – normalisation

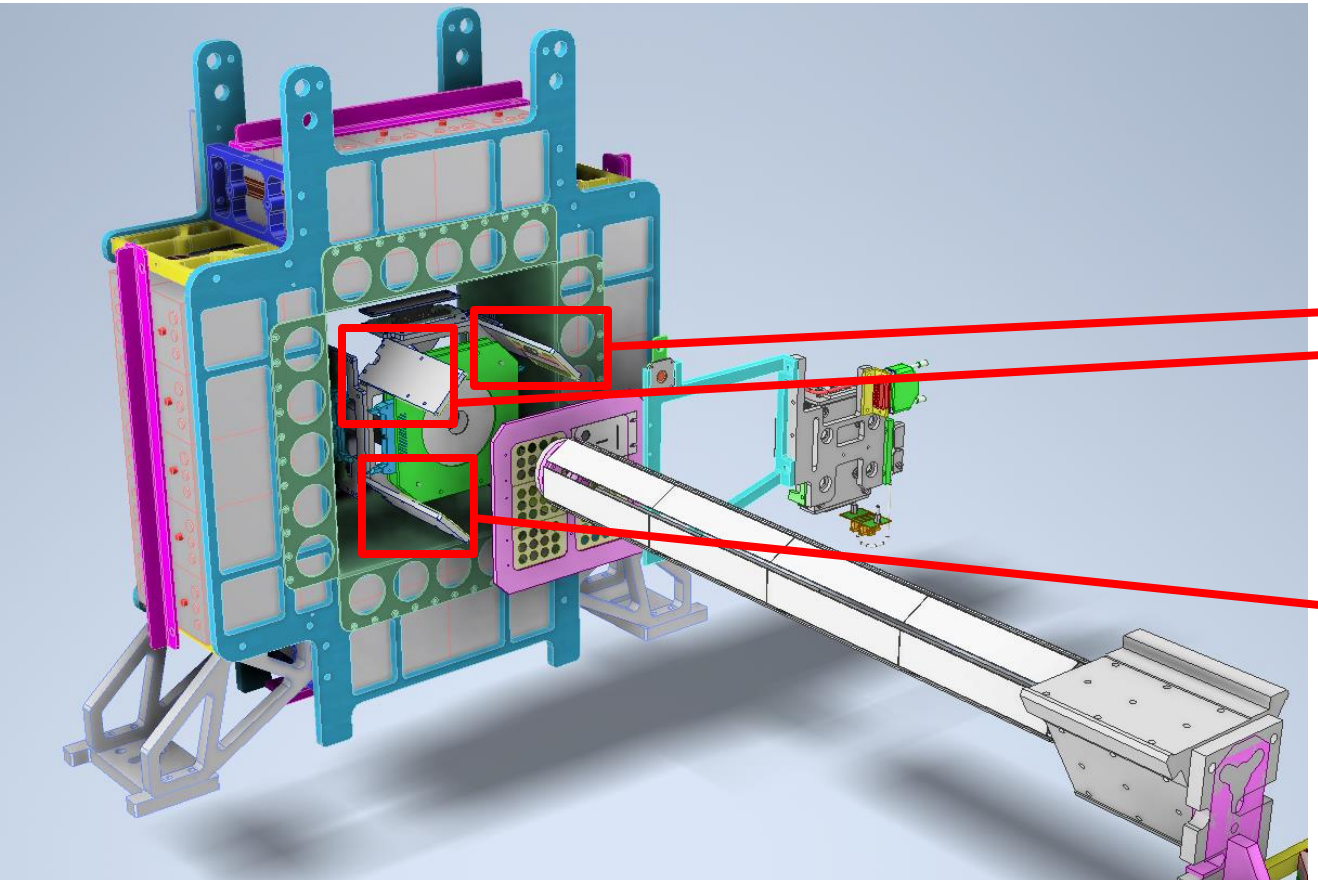
Measured:

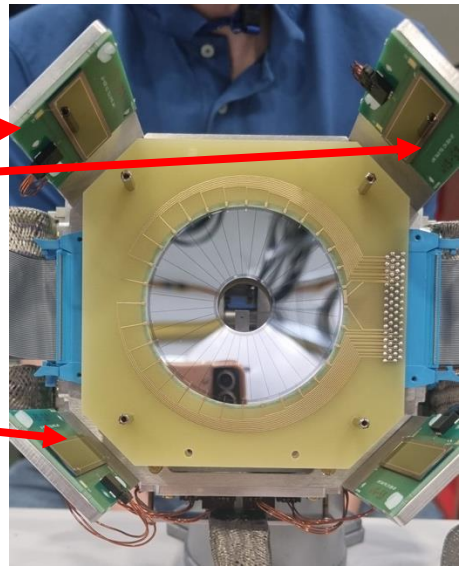
- Protons.
- Fission fragments (FFs).
- **Scattered deuterons.**
- γ-rays from FFs.

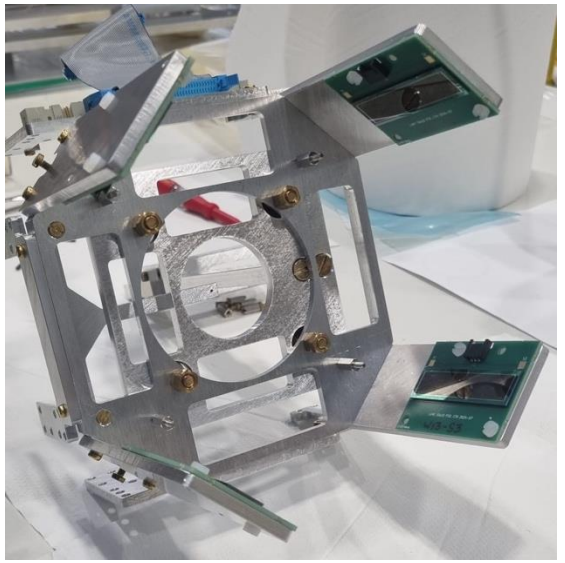
Many thanks to B. Kay!

LUME (luminosity) detectors
4 **position-sensitive** silicon detectors





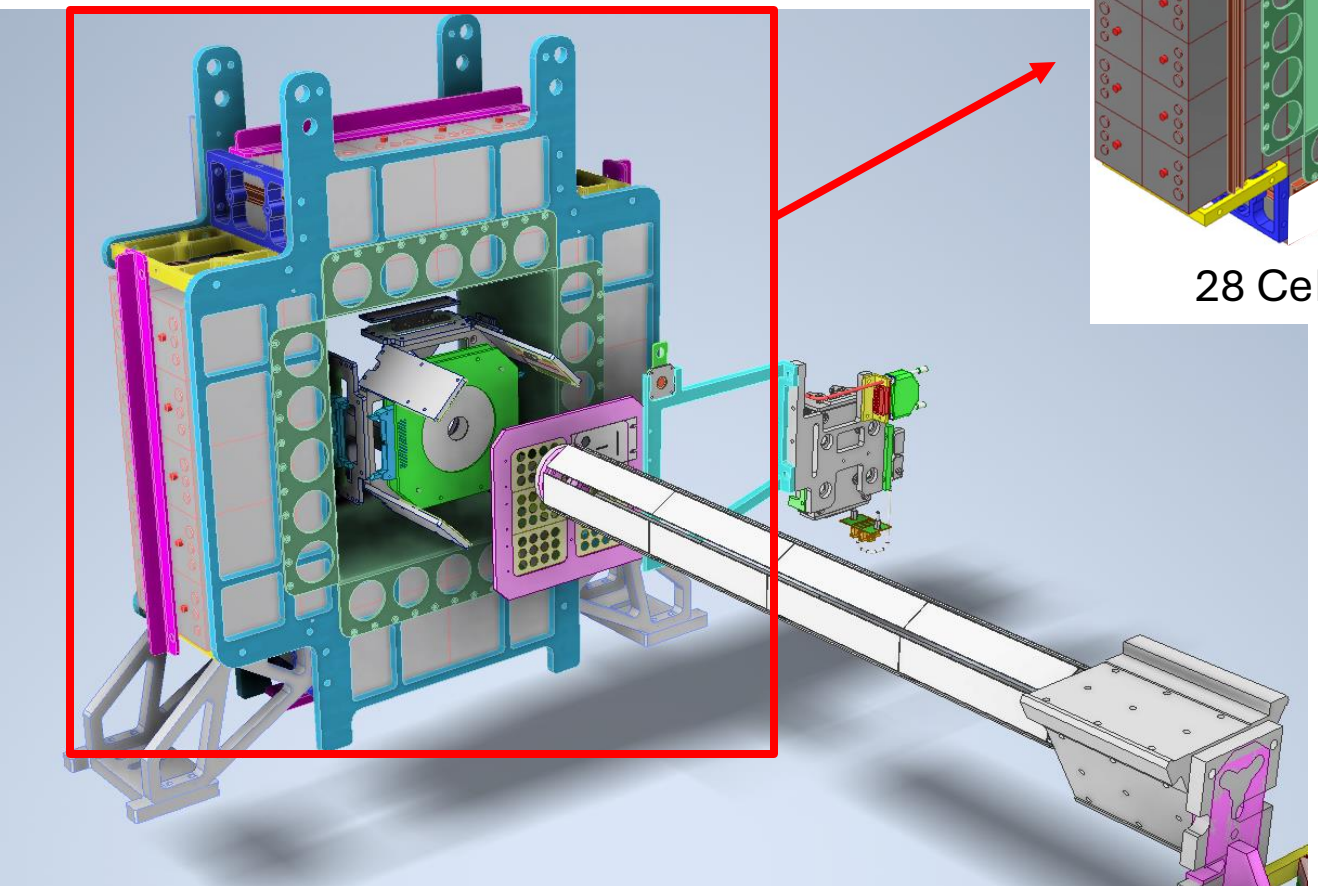


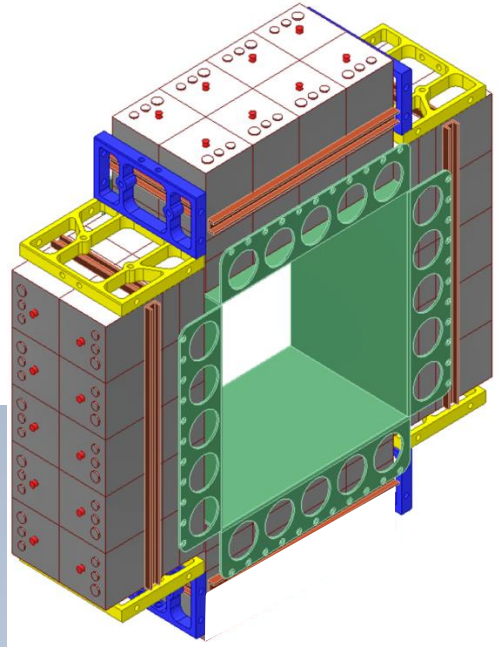


A novel setup for studying (d,pf) reactions at ISS – gammas

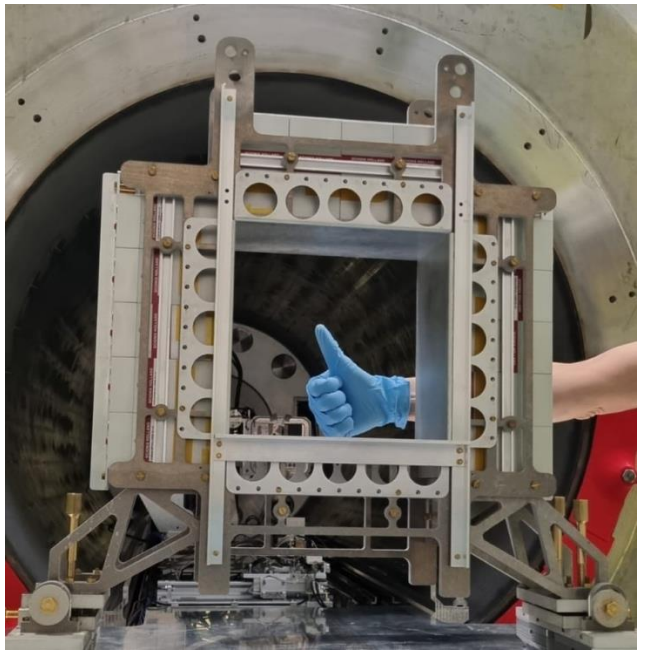
Measured:

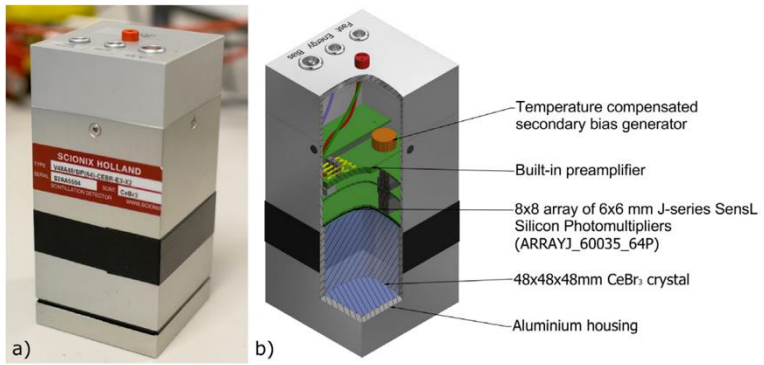
- Protons.
- Fission fragments (FFs).
- Scattered deuterons.
- **γ-rays from FFs.**





28 $CeBr_3$ crystals



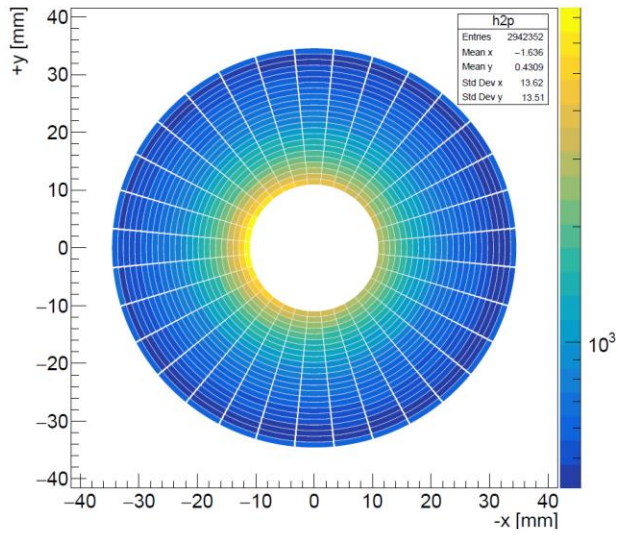


O. Poleshchuk *et al.*, "The SpecMAT active target," Nucl. Instrum. Methods A **1015**, (2021).

Commissioning with stable beam

^{22}Ne(d,p)^{23}Ne at 6 MeV/u, June 2025, ISOLDE

Preliminary!



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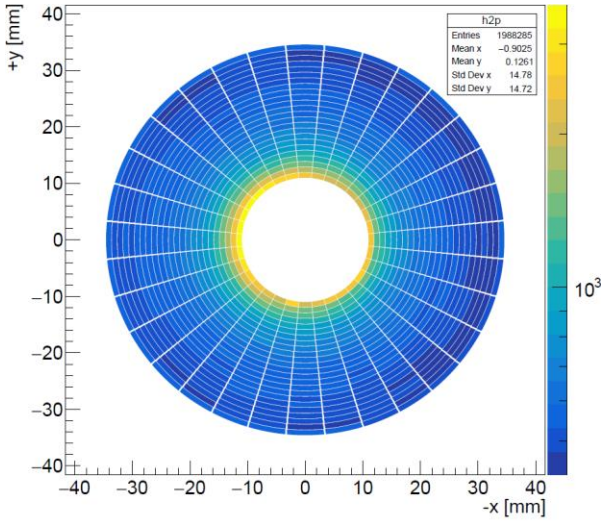
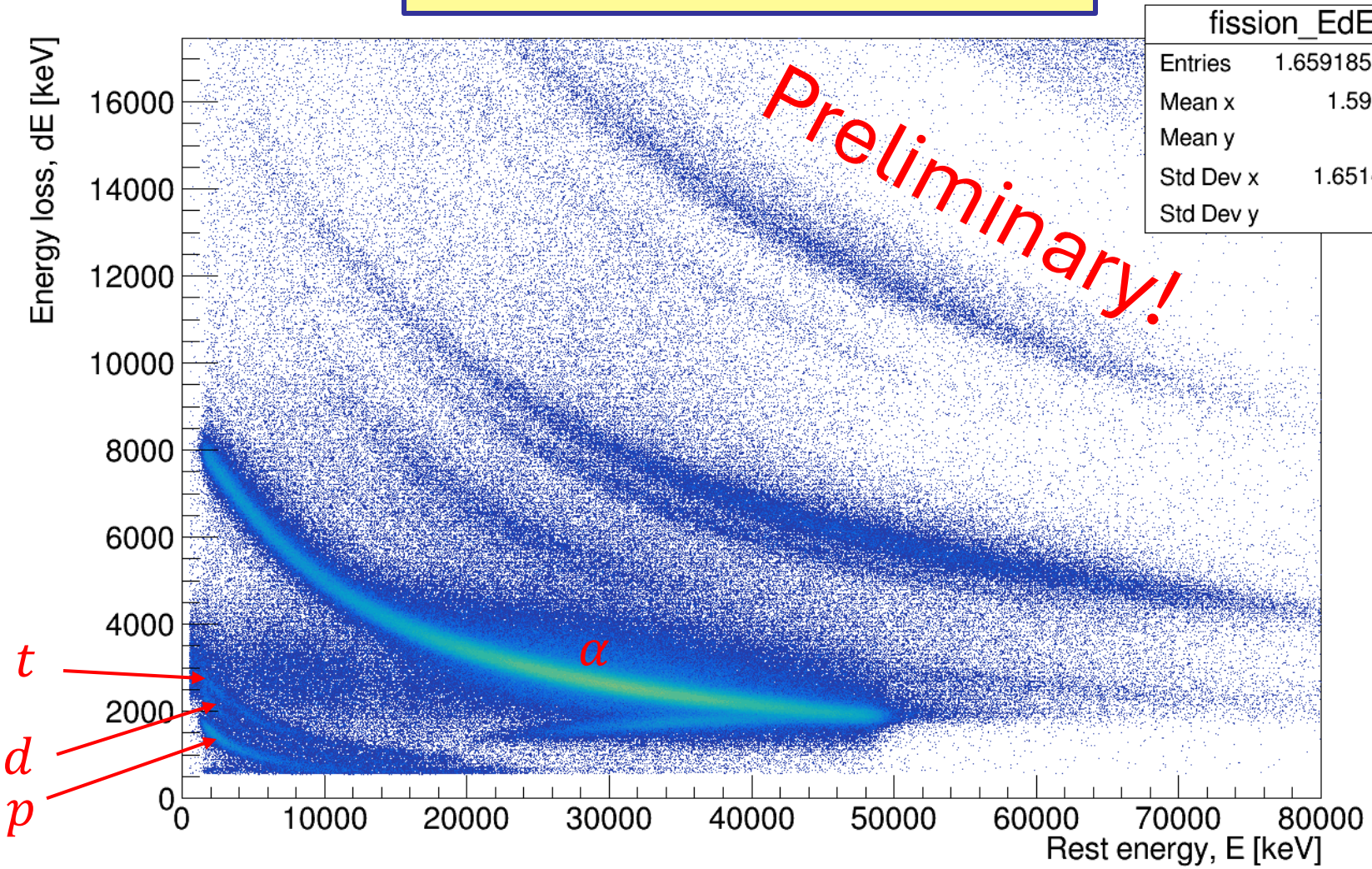
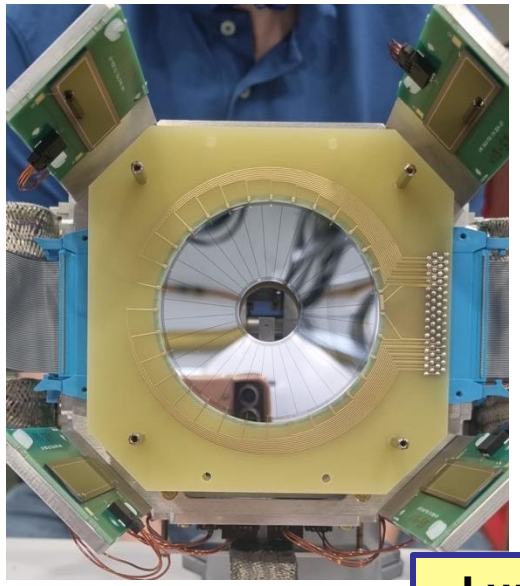


Test of fission detectors



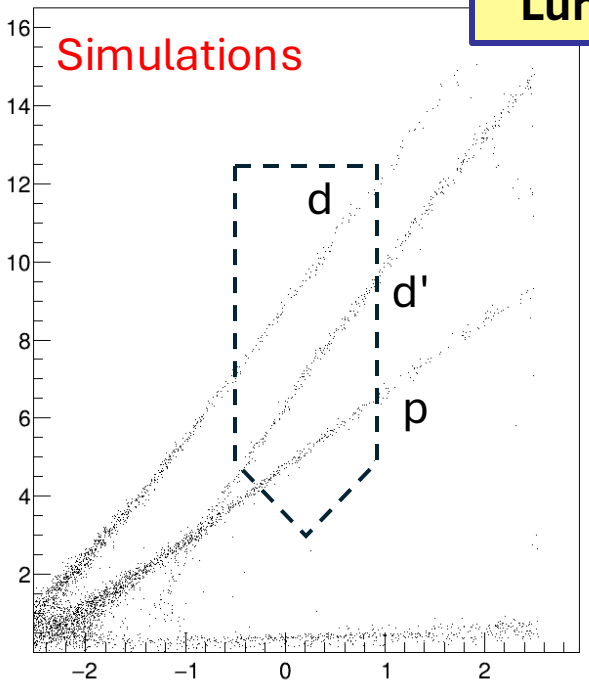
Commissioning with stable beam

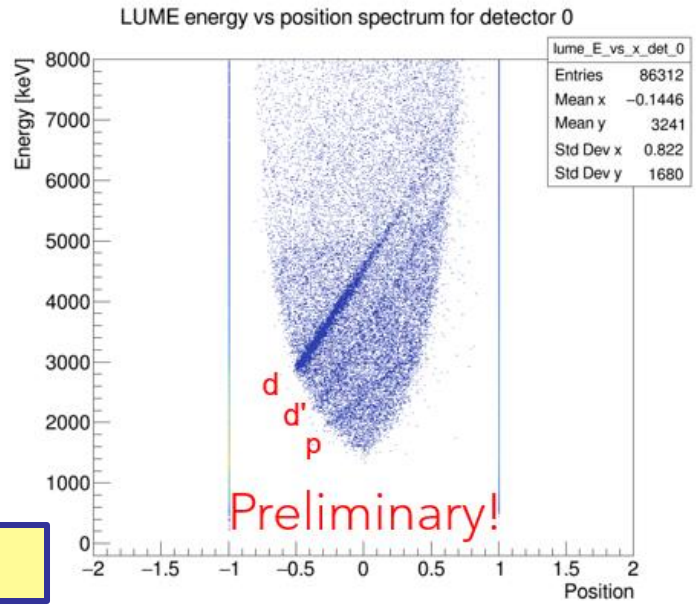
$^{22}Ne(d,p)^{23}Ne$ at 6 MeV/u, June 2025, ISOLDE

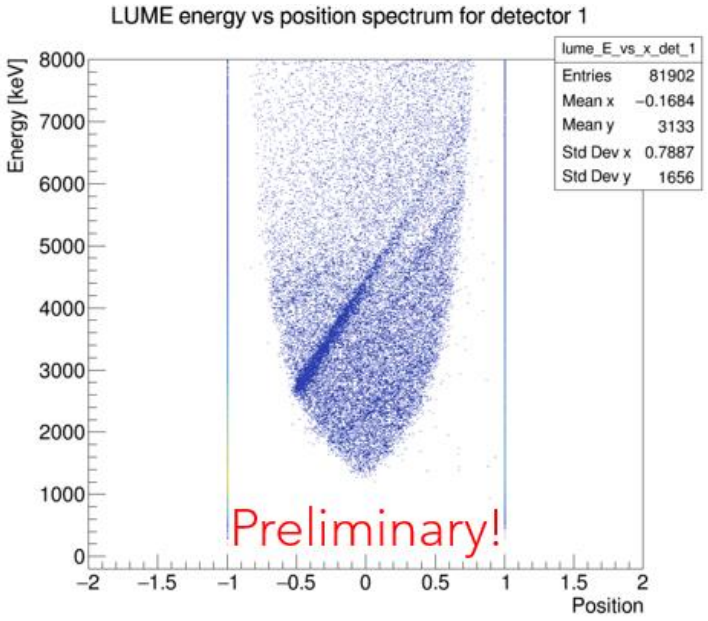


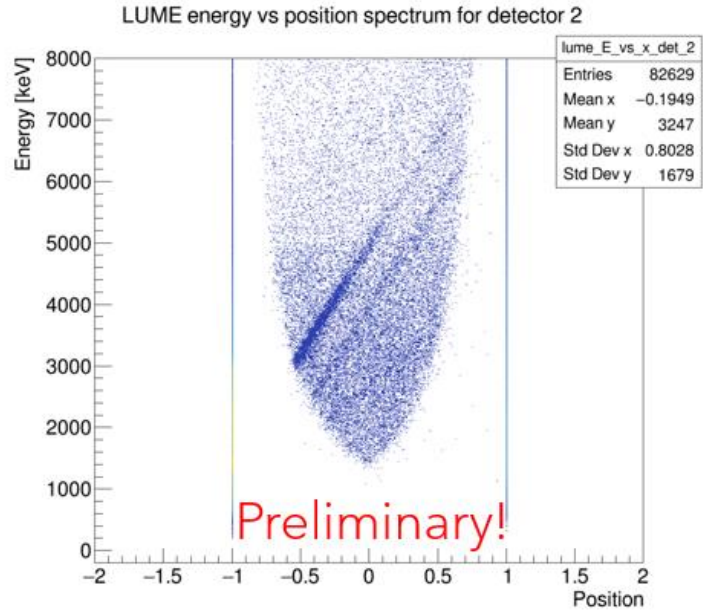
Luminosity monitor

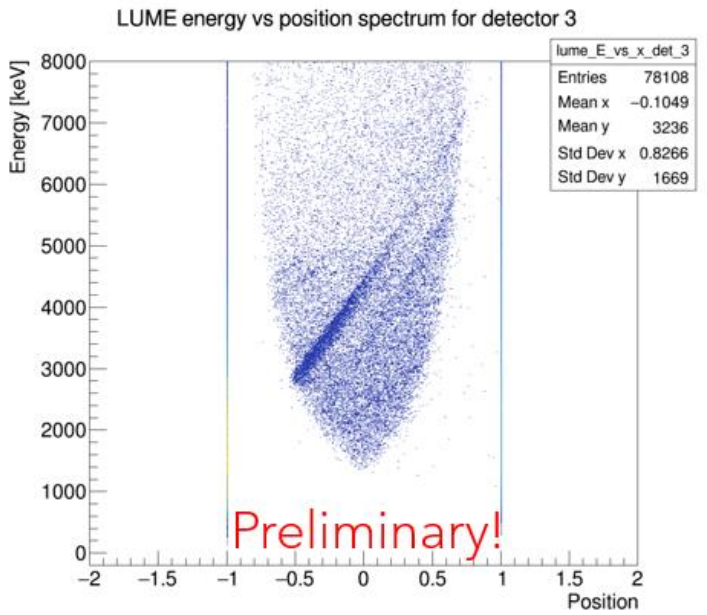
Simulations







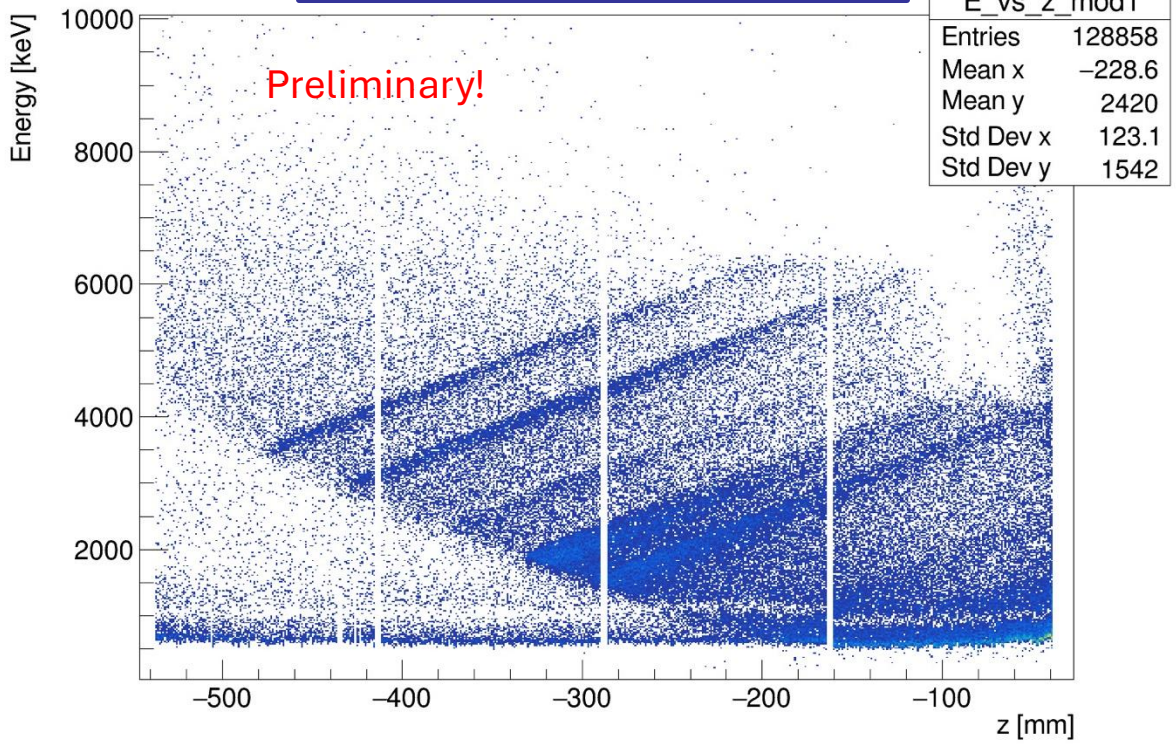


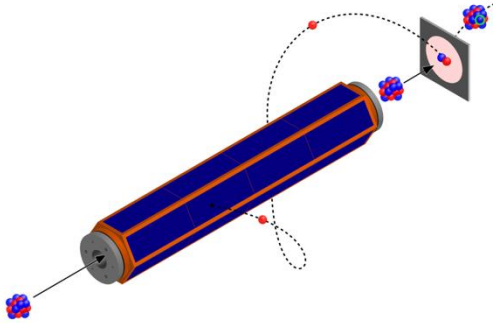


Commissioning with stable beam

$^{22}Ne(d,p)^{23}Ne$ at 6 MeV/u, June 2025, ISOLDE

Si array





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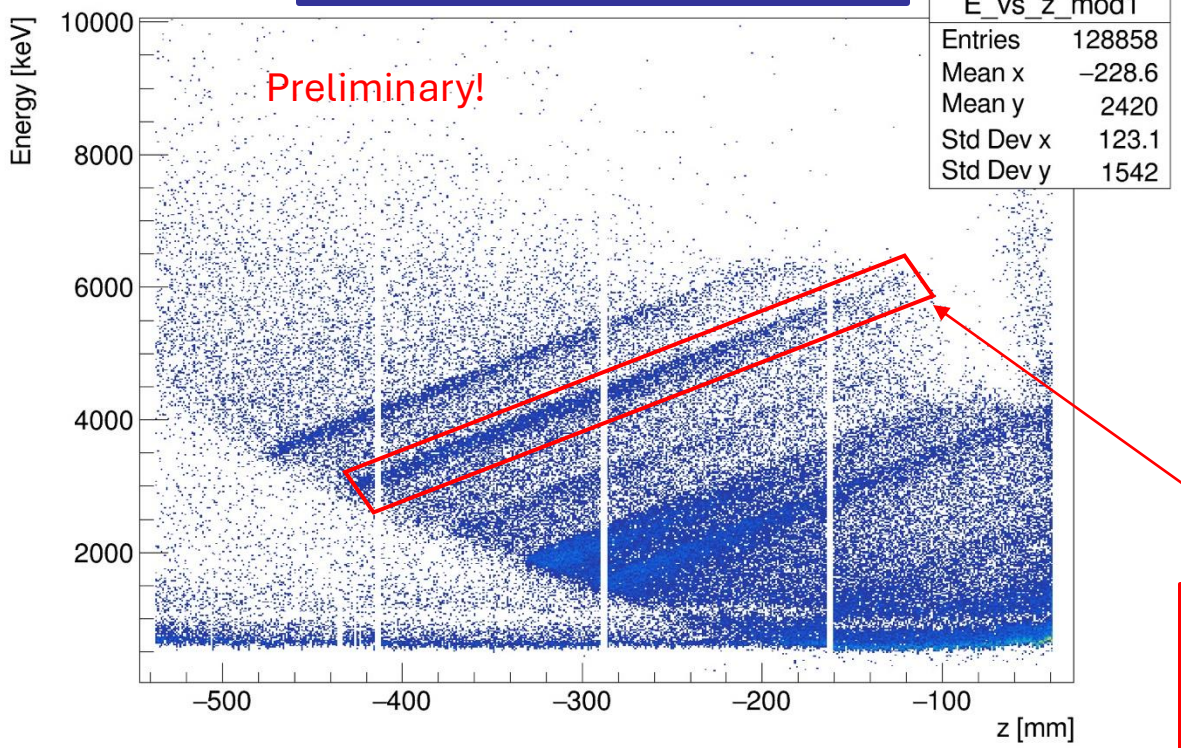
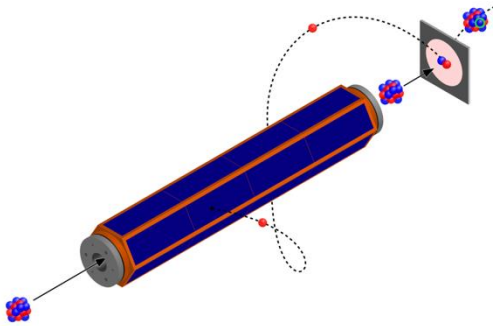
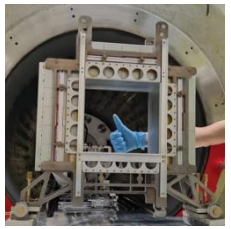
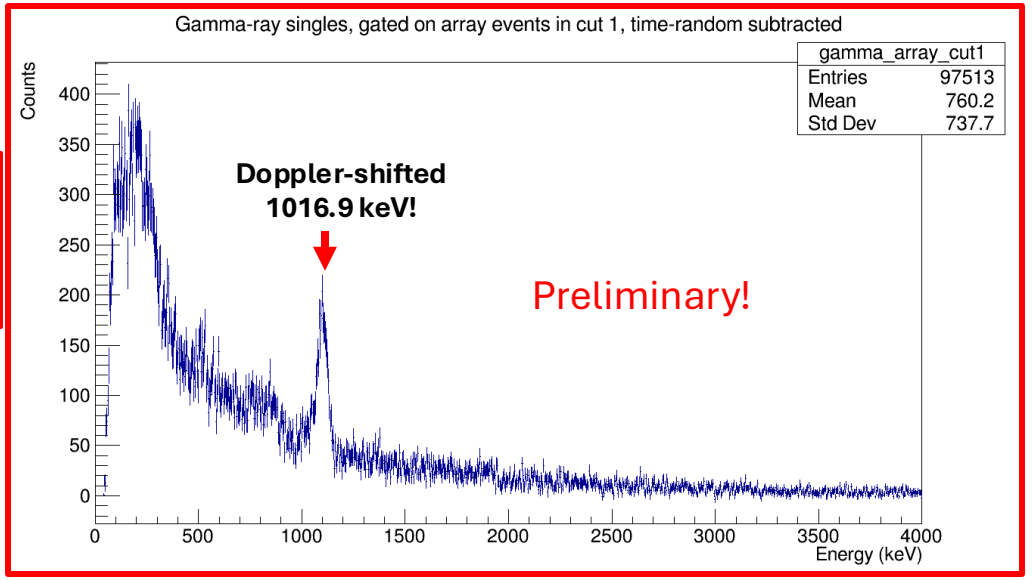




Gate on proton line populating the first excited state of ^{23}Ne



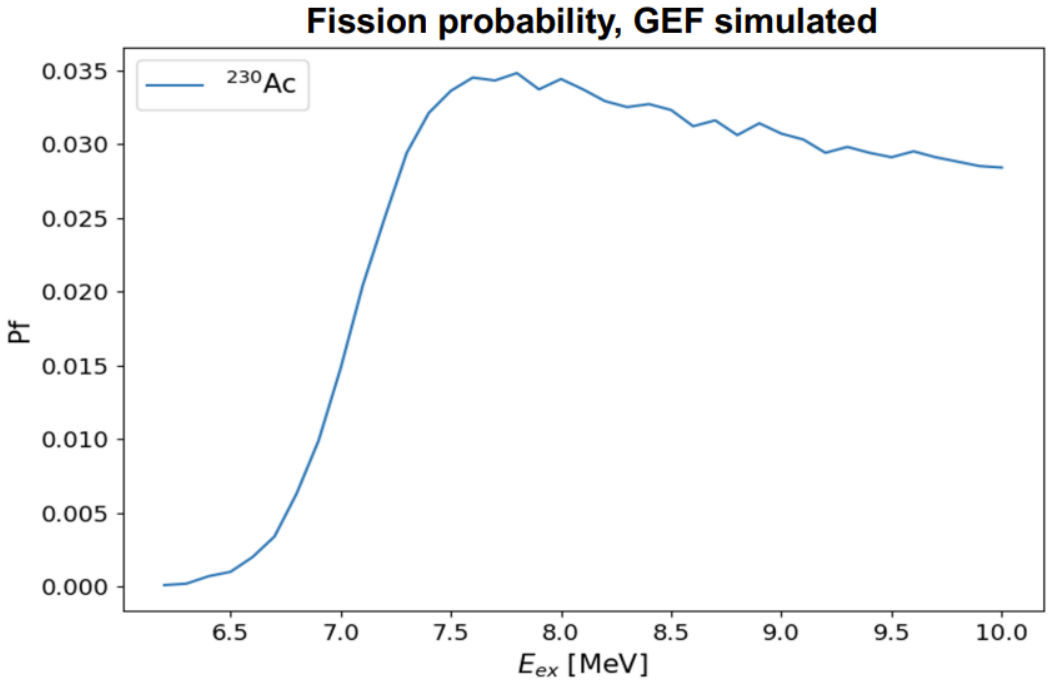
Si array + $CeBr_3$'s: $p-\gamma$ coincidences

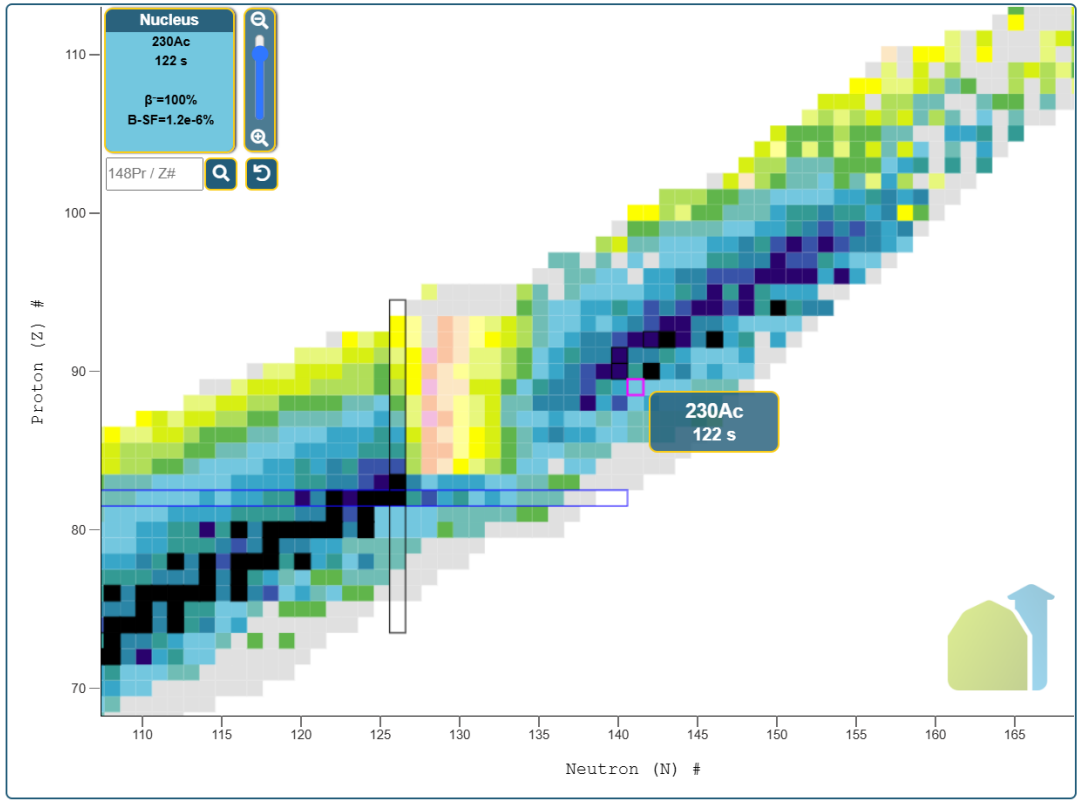


Experiment IS739

Why ^{230}Ac?

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





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

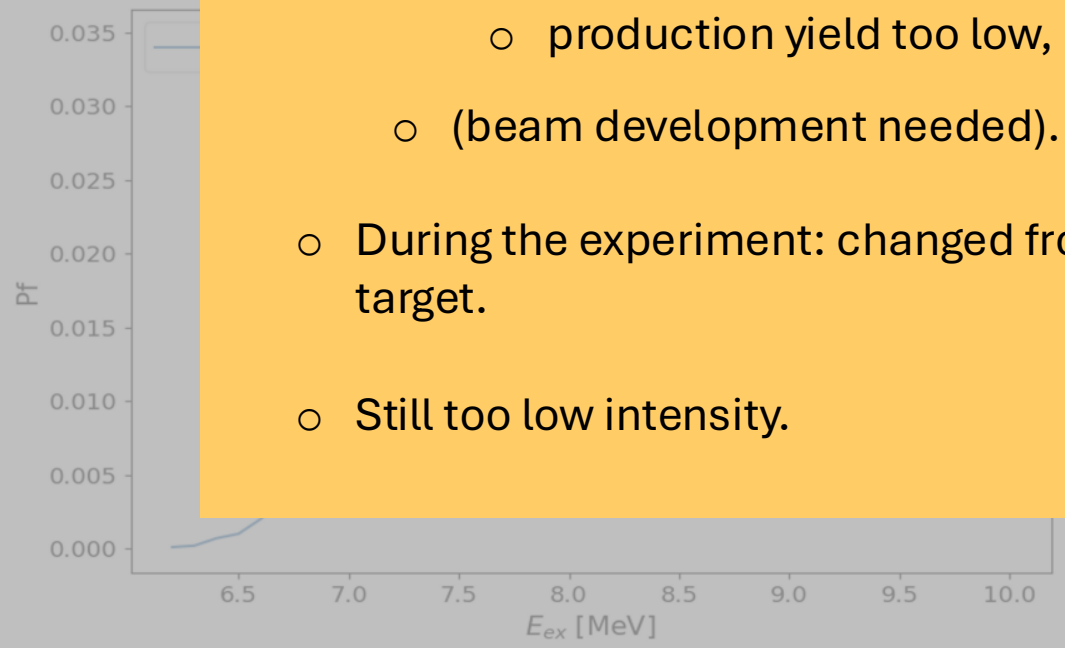
^{230}Ac	
Sn [1]	4.923 MeV
Fission barrier height [2]	7.01 MeV
P_f (1st chance) [2]	3%

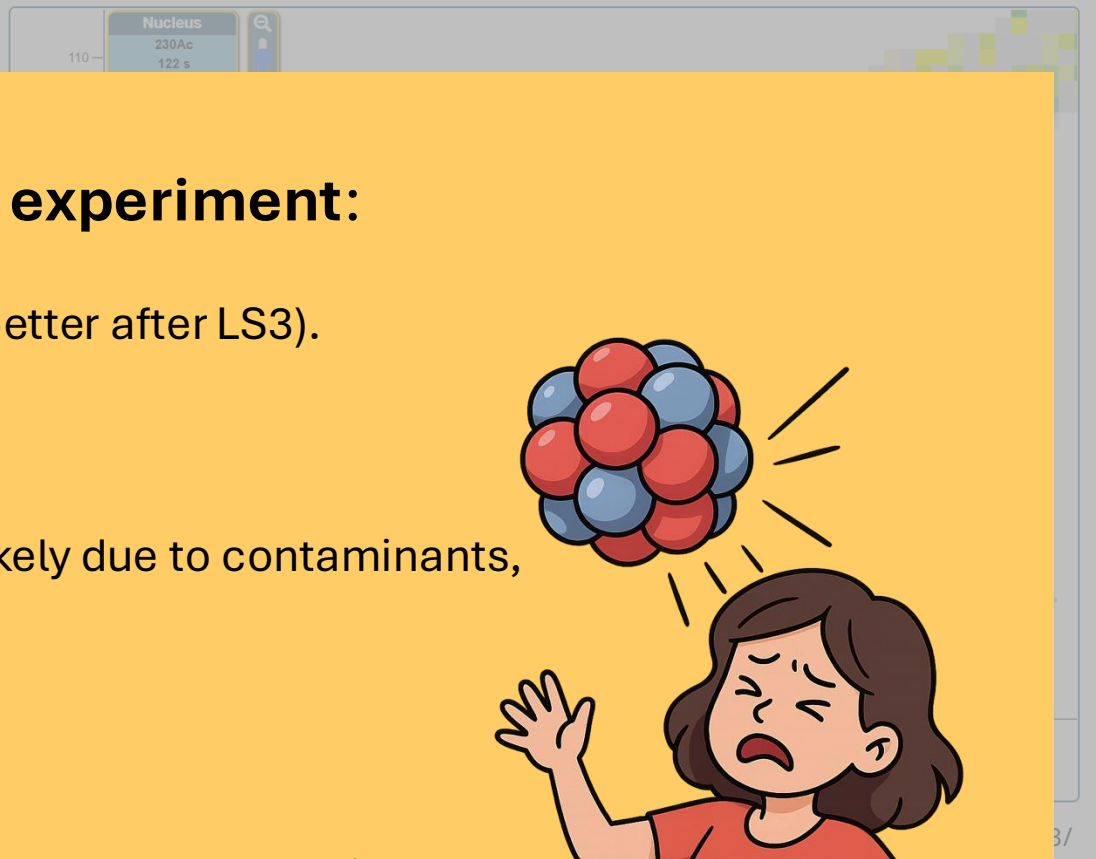
[1] M. Wang at al. Chinese Physics C 45, 030003 (2021).
[2] K.-H, Schmidt et al. Nucl. Data Sheets 131, 107 (2016).

Experiment IS739

Why 230Ac?

- **Practical ch**
  estimated b
  (available in
- **No conclus**
- The **first stu**
  kinematics





Technical challenges during the experiment:

- Limited beam energy (< 8 MeV/u) (will be better after LS3).
- Production of ^{229}Ac beam:
  - in difluoride form:
    - saturation of HIE-ISOLDE trap, likely due to contaminants,
  - in monofluoride form:
    - production yield too low,
  - (beam development needed).
- During the experiment: changed from ThC_x to UC_x (used) primary target.
- Still too low intensity.

Picture generated by ChatGPT

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

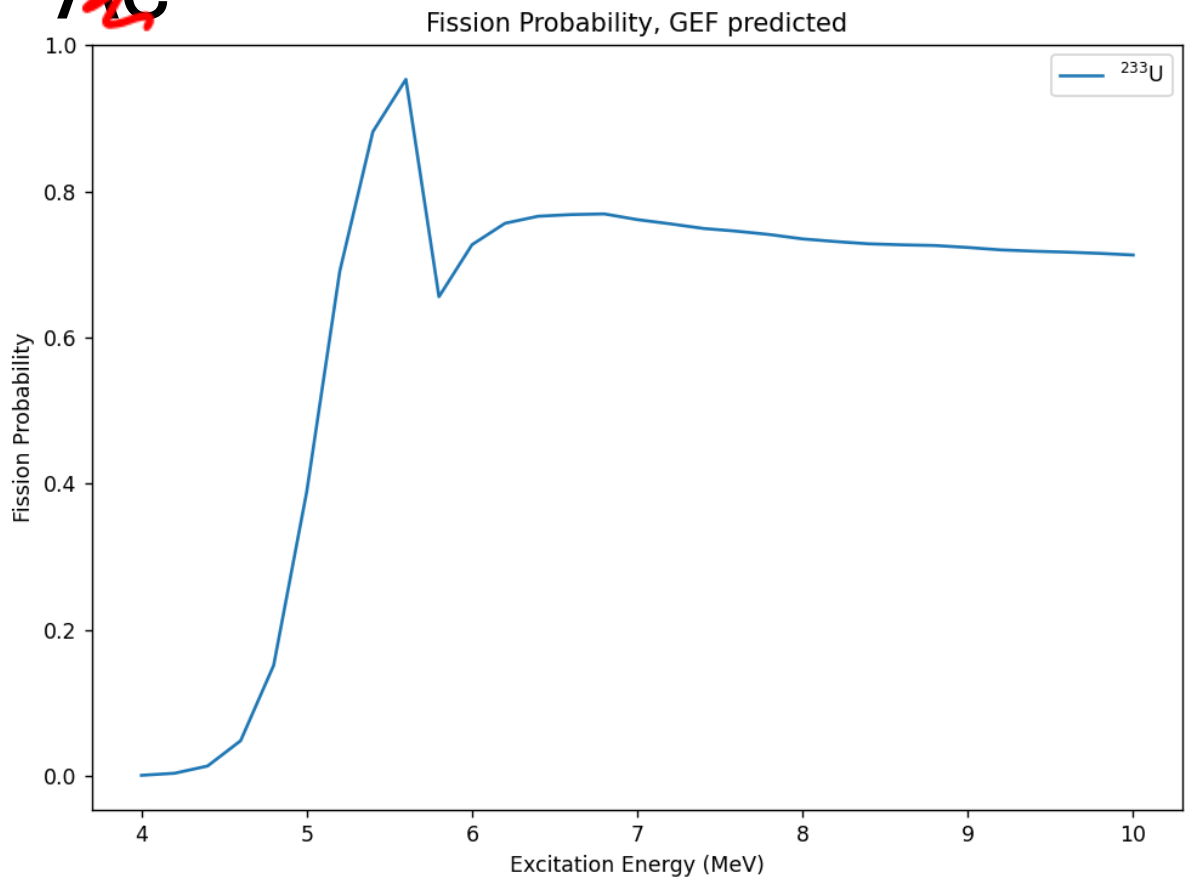
Fission of ~~^{230}Ac~~ ^{233}U

Why is ^{233}U a good candidate?

- Higher production yield for ^{232}U beam (UC_x 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 do we know about fission of ^{233}U?

Discovery:

G.T. Seaborg, J.W. Gofman, R.W. Stoughton, Phys. Rev. 71, 378 (1947)

Nuclear Properties of U^{233}: A New Fissionable Isotope of Uranium*

G. T. SEABORG, J. W. GOFMAN, AND R. W. STOUGHTON
Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California
April 13, 1942
(Received February 11, 1947)

A first fission cross section estimate:

R. Elson et al., Phys. Rev. 89, 320 (1953)

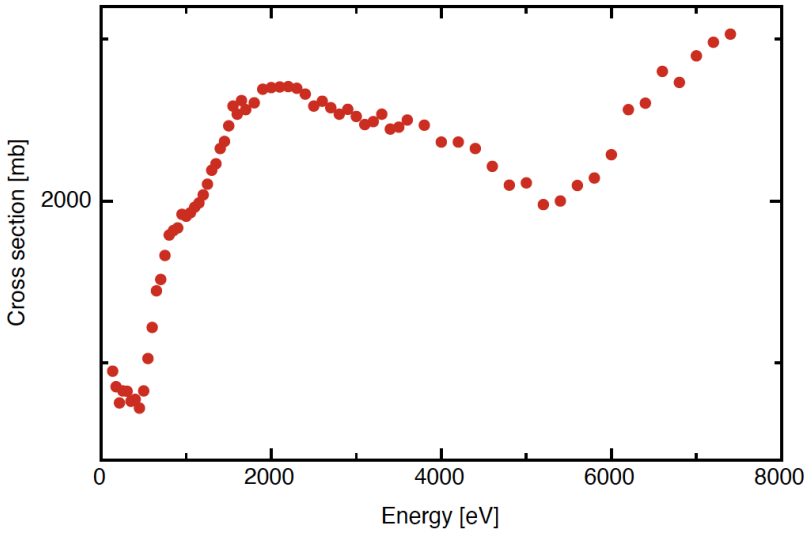
The Thermal Neutron Fission and Capture Cross Section of U^{232}

R. ELSON,* W. BENTLEY, A. GHIORSO, AND Q. VAN WINKLE
Argonne National Laboratory, Lemont, Illinois
(Received November 19, 1952)

Fission of ^{233}U – data from the SU

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

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



$^{232}U(n,f)$

$T_{1/2}$ (^{232}U) = 68.9 years → difficult to produce enriched targets for neutron-induced fission experiments.

Fission of ^{233}U – data from the US

2.A.1:
2.J

Nuclear Physics **55** (1964) 517—522; © *North-Holland Publishing Co., Amsterdam*

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 $(1.0 \pm 0.5)10^{-4}$.

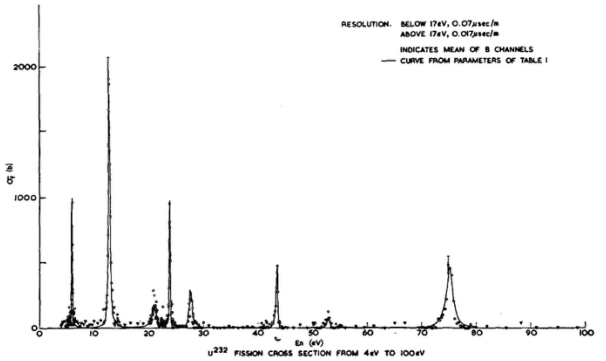


Fig. 1. The fission cross section of U^{232} from 4 eV to 100 eV.

2.J

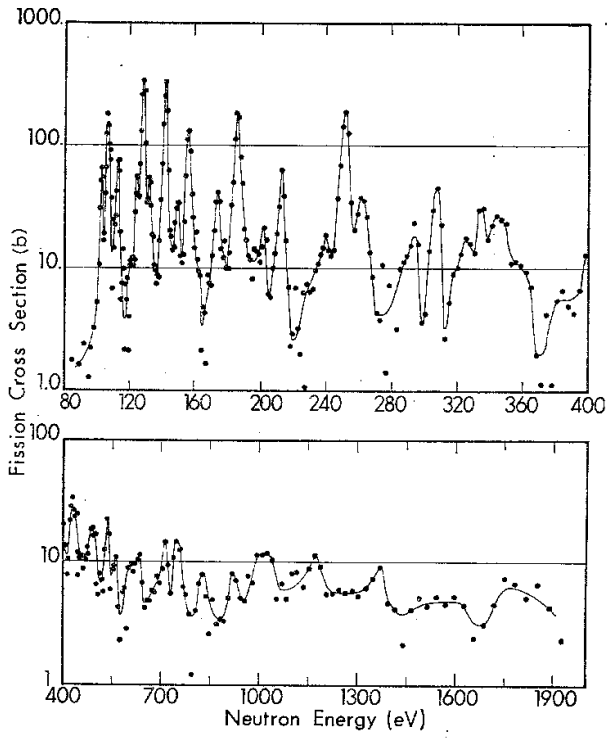
Nuclear Physics **A112** (1968) 329—336; © *North-Holland Publishing Co., Amsterdam*

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.



Collaboration

M. V. Managlia, 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.

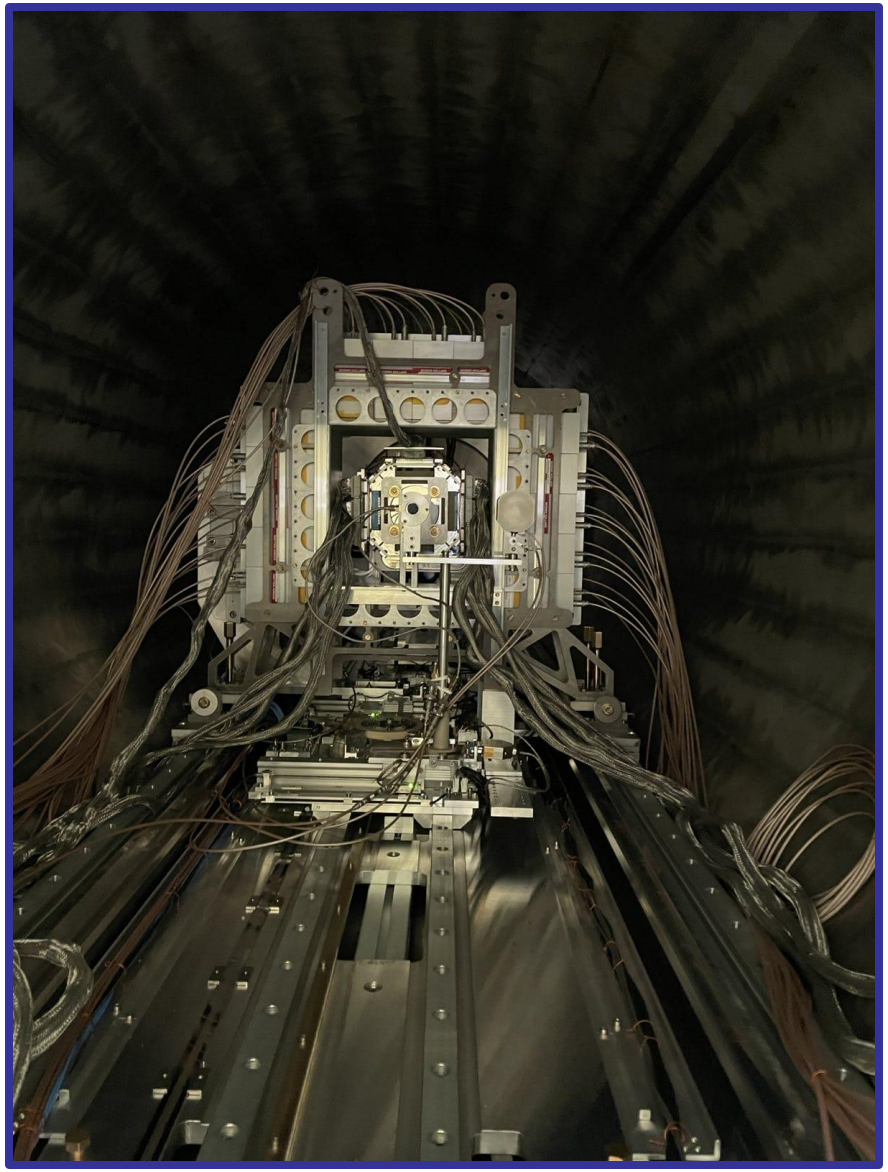
Status

- New detectors for ISS.
- The setup **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 towards **heavier beams**.



Status

Normalisation and $CeBr_3$ detectors used in 3 more ISS experiments since.

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Thank you for your attention!