Probing the fission and radiative decay of the ^{235}U + n system using (d,pf) and (d,pγ) reactions

Following HIE-ISOLDE Letter of Intent I-224

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ISOLDE Solenoidal Spectrometer

Motivation

Nuclear physics properties of actinides are important for various fields and applications

Nuclear data inputs:

- Neutron induced fission cross sections
- Fission barriers
- Fission Yields
- Neutron induced capture cross sections

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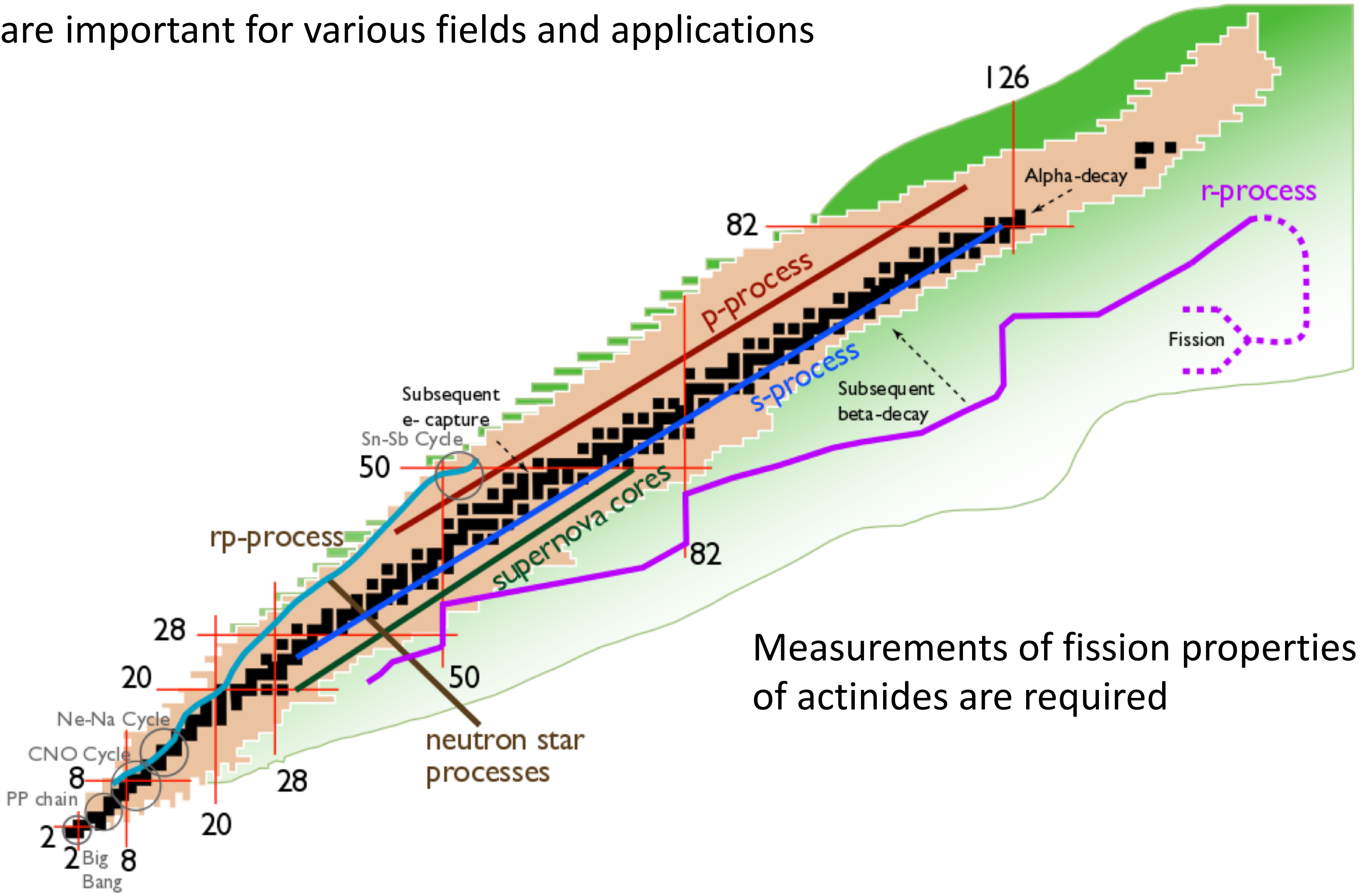
Applications and fields:

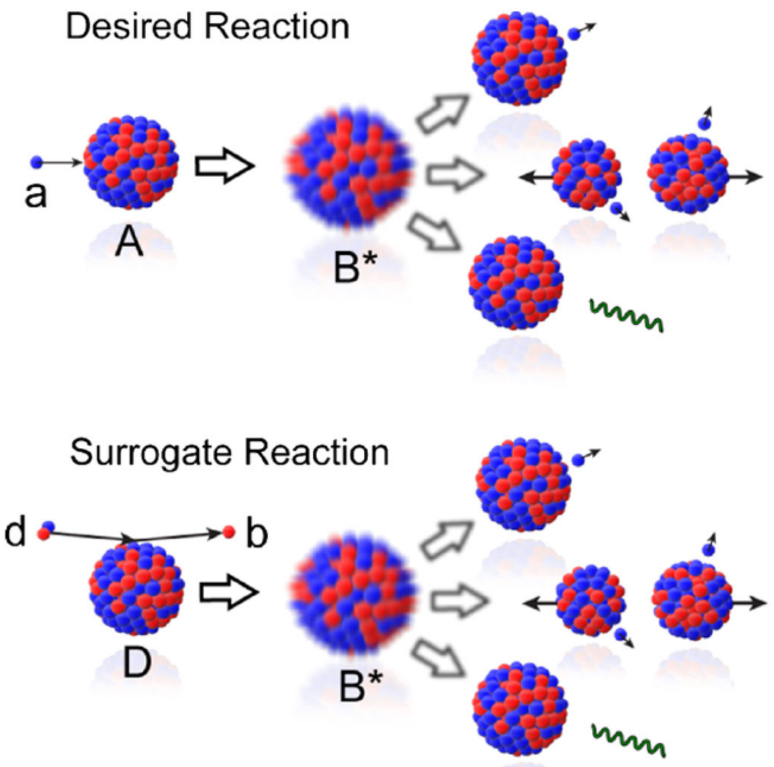
- r-process and fission recycling -> isotopic abundancies
- Nuclear technologies
- Fundamental understanding



Measurements of fission properties of actinides are required

Transfer induced fission in inverse kinematics

- Fixed target not possible – use radioactive beam
- Replicate neutron addition by (d,p) reaction



Escher et al., REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

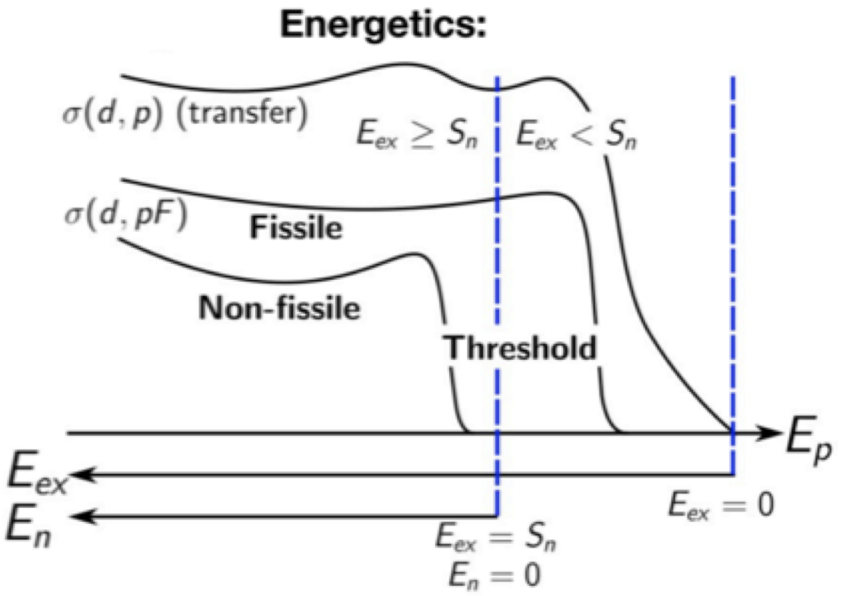
Aim to produce similar Compound Nucleus (CN) state to neutron absorption; can extract reaction cross section σ

$$\sigma_{n,f}^{A-1}(E_n) = \sigma_{CN}^{A}(E_n)P_f^{A}(E^*)$$

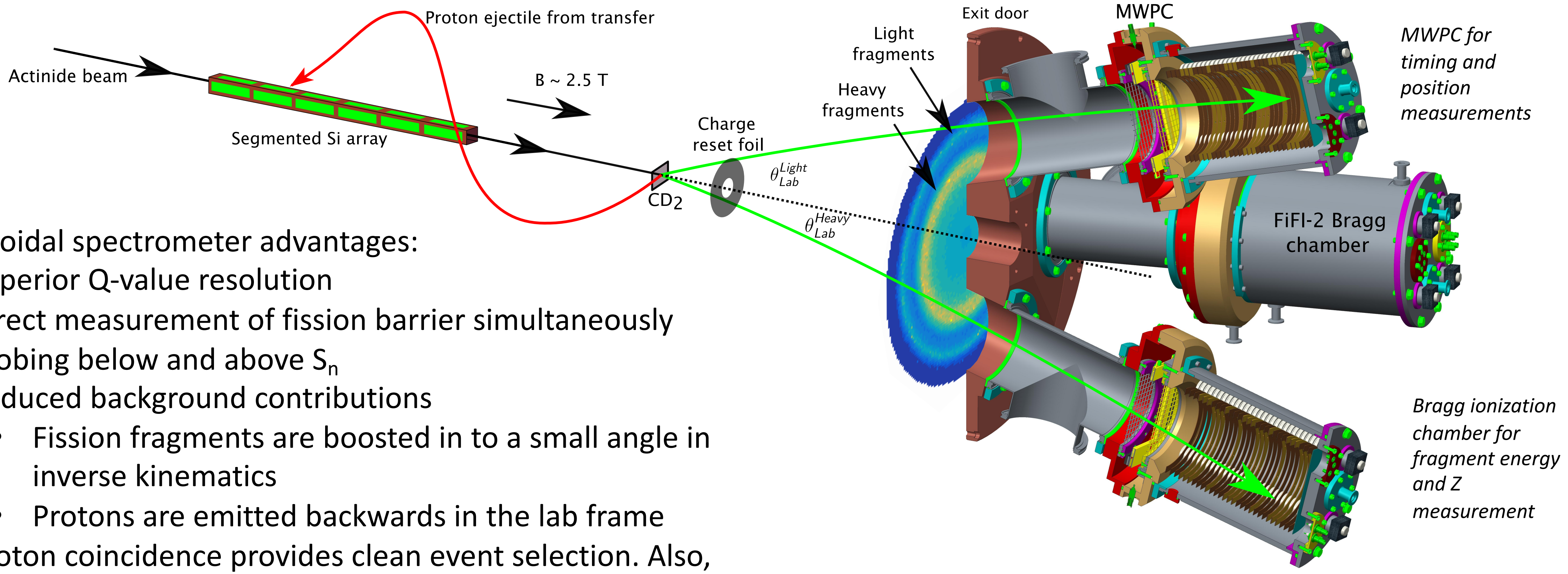
Can experimentally determine the probability of the compound nucleus undergoing fission $P_f(E_{ex})$

$$P_f(E_{ex}) = \frac{N_{d,pf}(E_{ex})}{\epsilon_f N_{d,p}(E_{ex})}$$

Example energetics of the compound nucleus and protons – the fission barrier is probed above and below in terms of E_{ex} regardless of S_n



Experimental technique: Radioactive beams in inverse kinematics with HELIOS/ISS



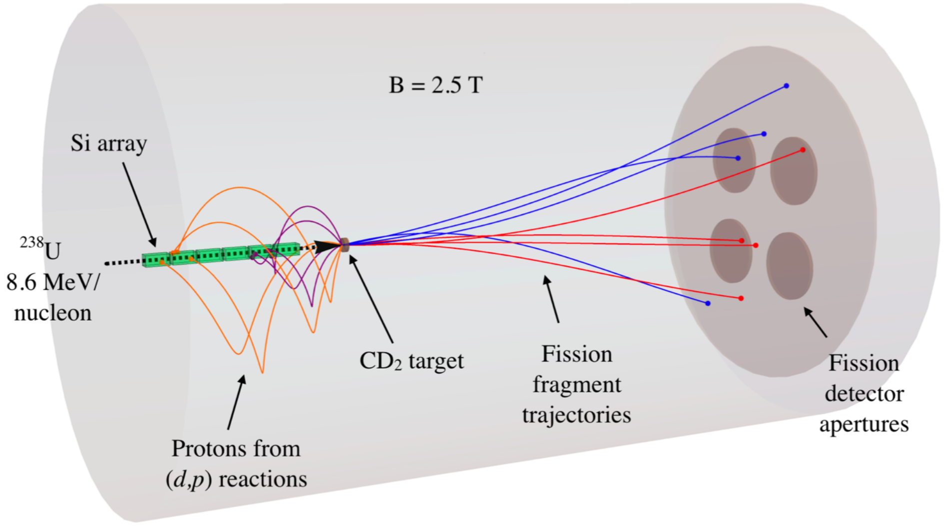
MWPC for timing and position measurements

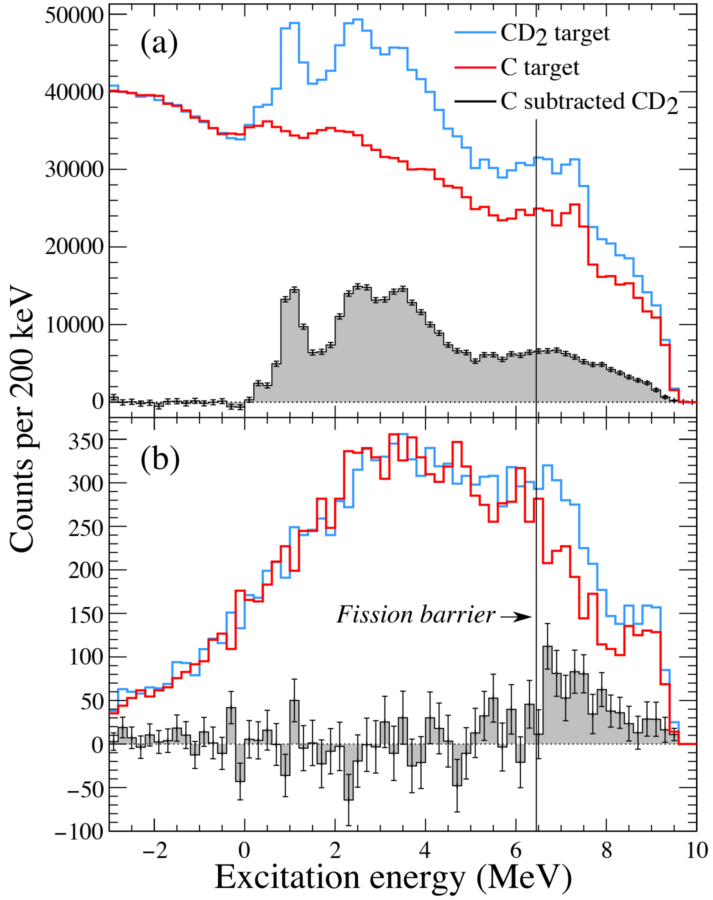
Bragg ionization chamber for fragment energy and Z measurement

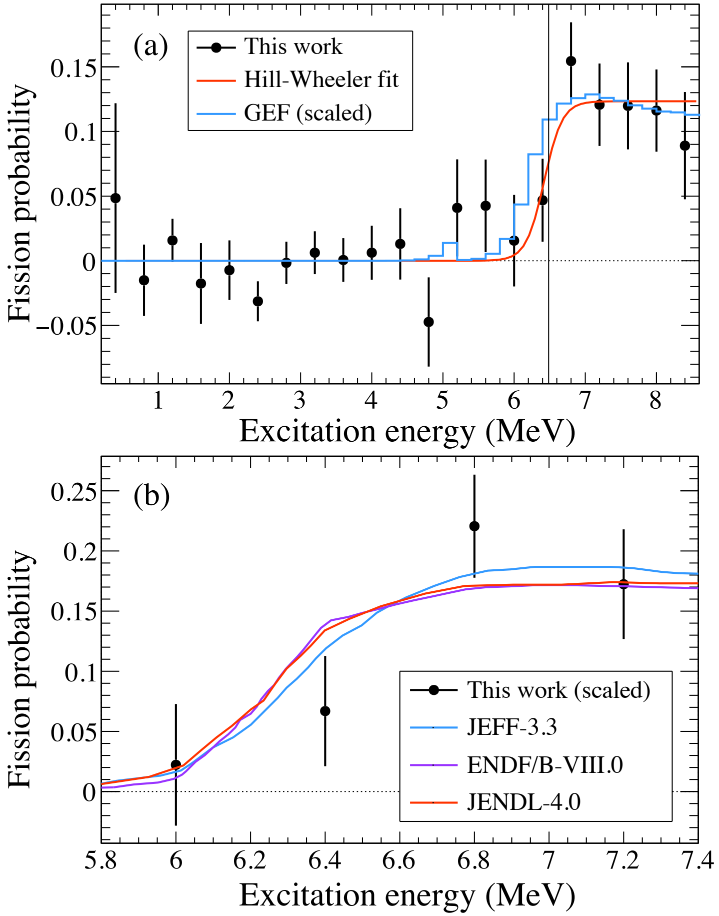
Solenoidal spectrometer advantages:

- Superior Q-value resolution
- Direct measurement of fission barrier simultaneously probing below and above S_n
- Reduced background contributions
  - Fission fragments are boosted in to a small angle in inverse kinematics
  - Protons are emitted backwards in the lab frame
- Proton coincidence provides clean event selection. Also, measured angular distributions -> ℓ of populated state

^{238}U(d,pf) with HELIOS, ANL





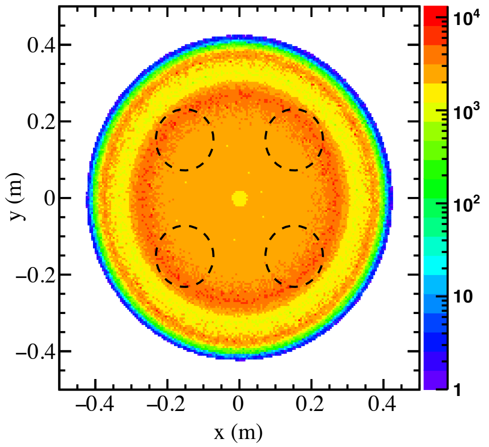


- Proof of principle experiment performed in 2022, PRL submitted *Bennett et al.*
- 840 (d,pf) events recorded
- Measured fission barrier consistent with neutron-induced measurements

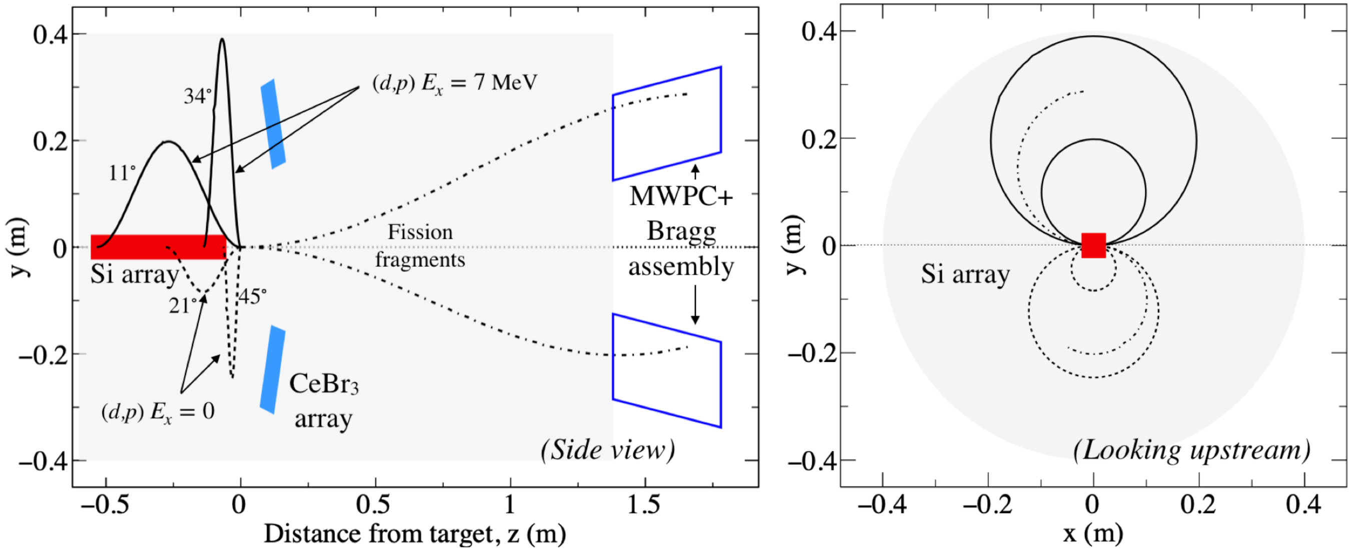
Experimental setup: d,pf

^{235}U planned as first measurement

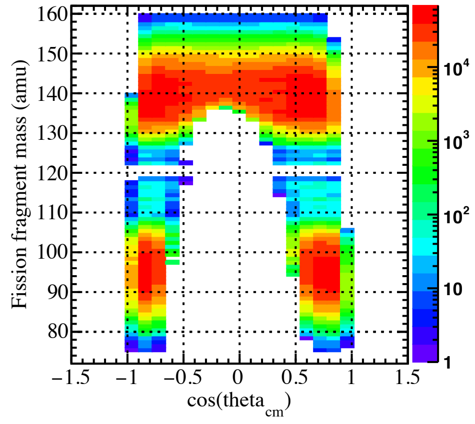
- First measurement via (d,pf) in inverse kinematics
- Fissile and high fission probability
- Feasible beam rates



Spatial distribution of fission fragments exiting the ISS



Schematic of the experimental setup with example particle trajectories, for states populated above and below the fission barrier, for ^{235}U(d,p) at 7 MeV/nucleon. The inside of the ISS vessel is represented by the grey shaded regions.



Coverage of fission array for fission fragment mass and c.m fission angle

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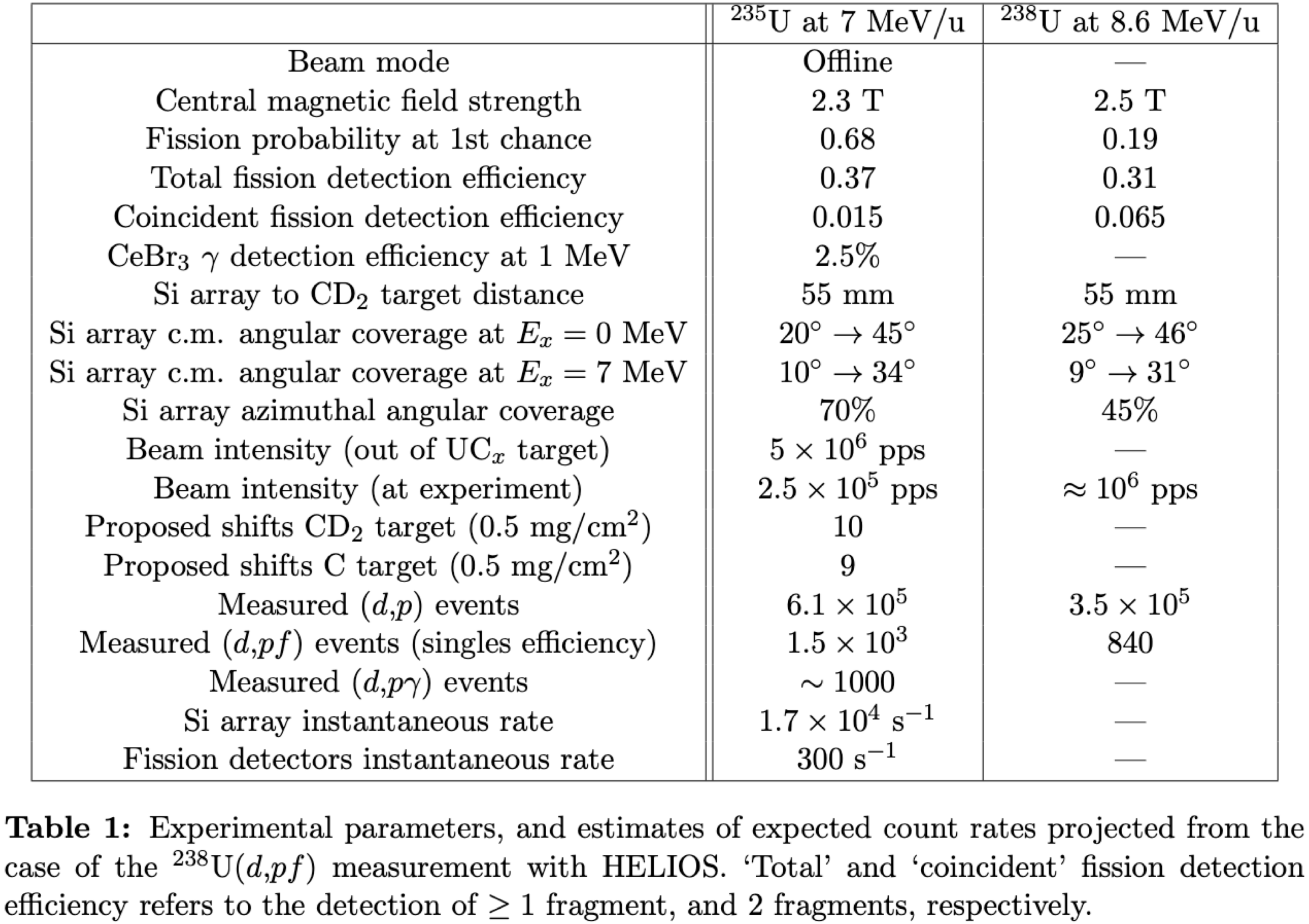
Beam and shift request

ISOLDE Solenoidal Spectrometer

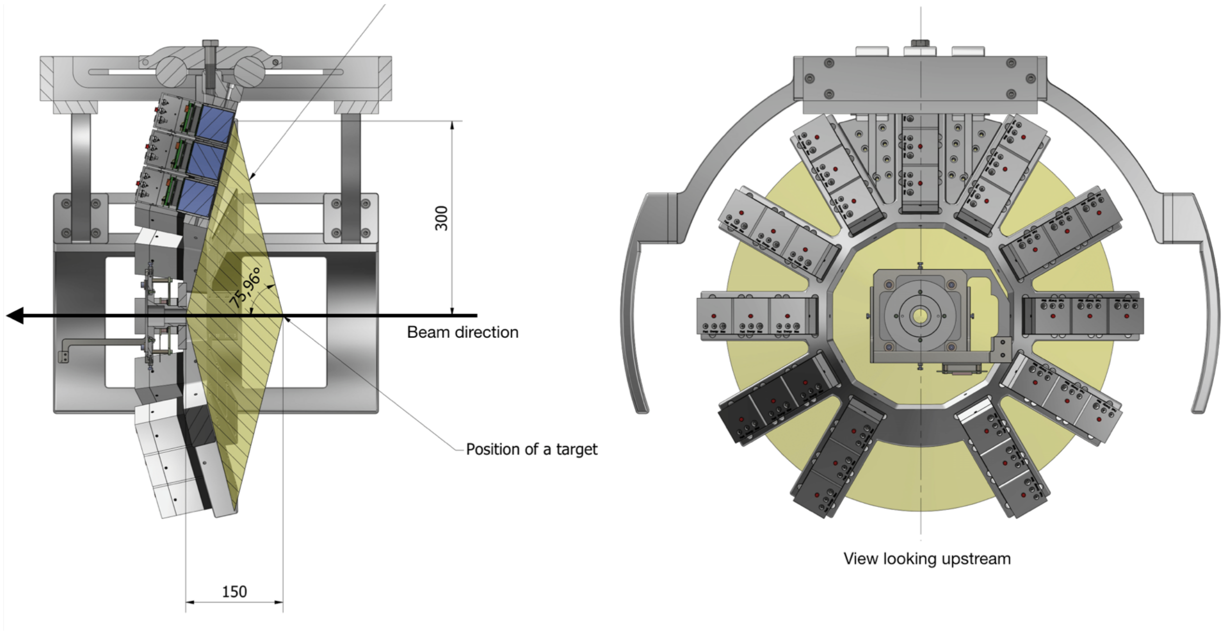
- Winter physics
- Favourable experimental conditions when beam energy is as high as possible
- Array of 64 CD_2 targets, can use 1 mg/cm^2 if beam rate is up to 50% lower than expected
- 20 shifts requested to acquire 1500 fission events and $4x10^3$ background (carbon-induced) fission events



	^{235}U at 7 MeV/u	^{238}U at 8.6 MeV/u
Beam mode	Offline	—
Central magnetic field strength	2.3 T	2.5 T
Fission probability at 1st chance	0.68	0.19
Total fission detection efficiency	0.37	0.31
Coincident fission detection efficiency	0.015	0.065
$CeBr_3$ γ detection efficiency at 1 MeV	2.5%	—
Si array to CD_2 target distance	55 mm	55 mm
Si array c.m. angular coverage at $E_x = 0$ MeV	$20° \rightarrow 45°$	$25° \rightarrow 46°$
Si array c.m. angular coverage at $E_x = 7$ MeV	$10° \rightarrow 34°$	$9° \rightarrow 31°$
Si array azimuthal angular coverage	70%	45%
Beam intensity (out of UC_x target)	5×10^6 pps	—
Beam intensity (at experiment)	2.5×10^5 pps	$\approx 10^6$ pps
Proposed shifts CD_2 target (0.5 mg/cm^2)	10	—
Proposed shifts C target (0.5 mg/cm^2)	9	—
Measured (d,p) events	6.1×10^5	3.5×10^5
Measured (d,pf) events (singles efficiency)	1.5×10^3	840
Measured $(d,p\gamma)$ events	~ 1000	—
Si array instantaneous rate	1.7×10^4 s^{-1}	—
Fission detectors instantaneous rate	300 s^{-1}	—

Table 1: Experimental parameters, and estimates of expected count rates projected from the case of the $^{238}U(d,pf)$ measurement with HELIOS. 'Total' and 'coincident' fission detection efficiency refers to the detection of ≥ 1 fragment, and 2 fragments, respectively.

Experimental setup: γ detection



Drawings showing the $CeBr_3$ array situated inside the ISS bore, with 3 concentric rings of 11 individual crystals, read out by silicon photomultipliers. The detectors are situated approximately 150 mm downstream of the CD_2 target. Dimensions in mm.

- γ-rays in coincidence with proton and fission – prompt fission γ-rays
- γ-rays in coincidence with proton – d,pγ rays

Considerations:

- Many sources of background in each case – use differences in spectra shape at different excitation energies/gating conditions
- For d,pγ rays, detection efficiency must be insensitive to the decay path -> Pulse Height Weighting Technique
- Decay probability sensitive to spin of compound nucleus -> use proton angular distribution measurement

Measurement is parasitic thus ideal for commissioning and to understand capabilities

Thank you for your attention

Beam-energy dependence

- Beam energy impacts in multiple ways.
    - Transfer cross section
    - Minimum energy of ejectiles – maximum excitation energy

- Drop in energy of 1 MeV/u from proposed 7MeV/u results in a factor of 2 reduction in rate.

- Higher energies result in significant gains.