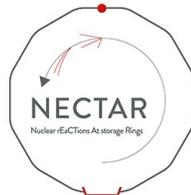
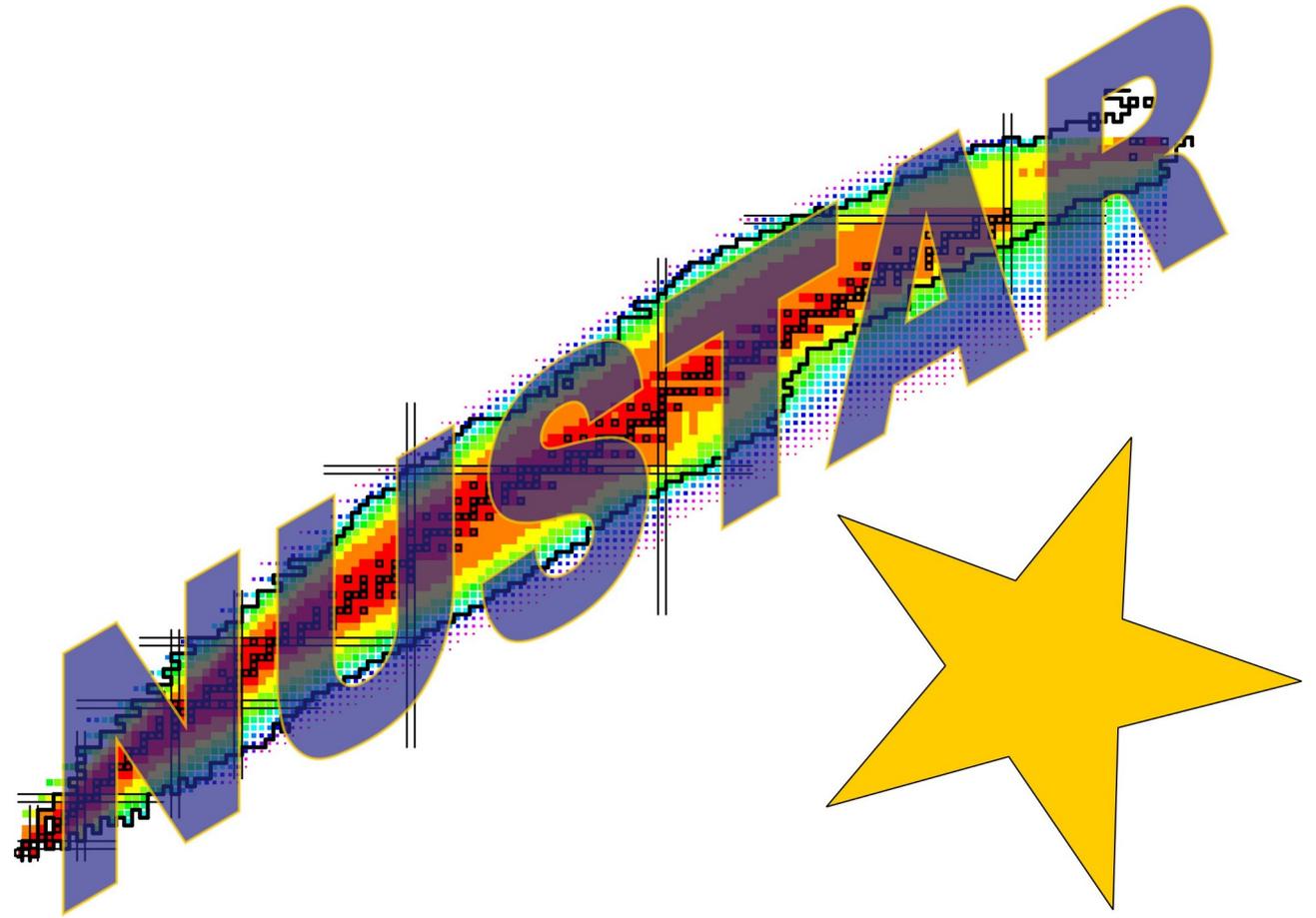


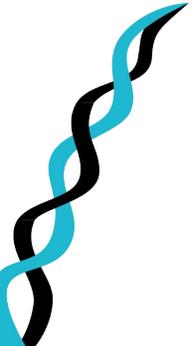
Surrogate Reactions in Inverse Kinematics at the ESR Storage Ring

Bogusław Włoch

NUSTAR annual meeting 2026



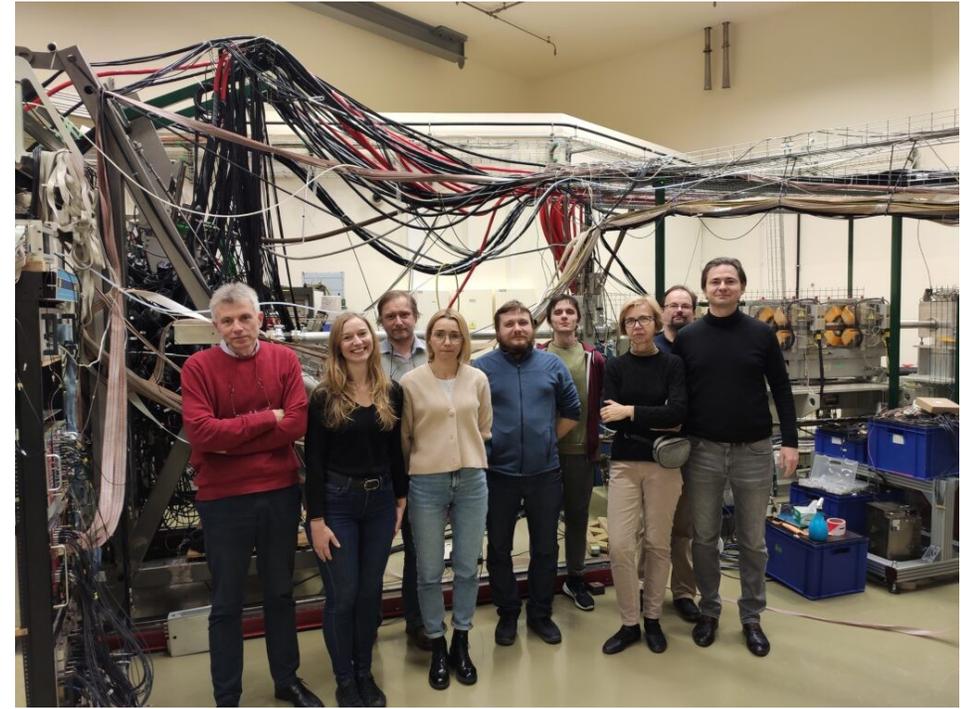
université
de BORDEAUX





My journey so far...

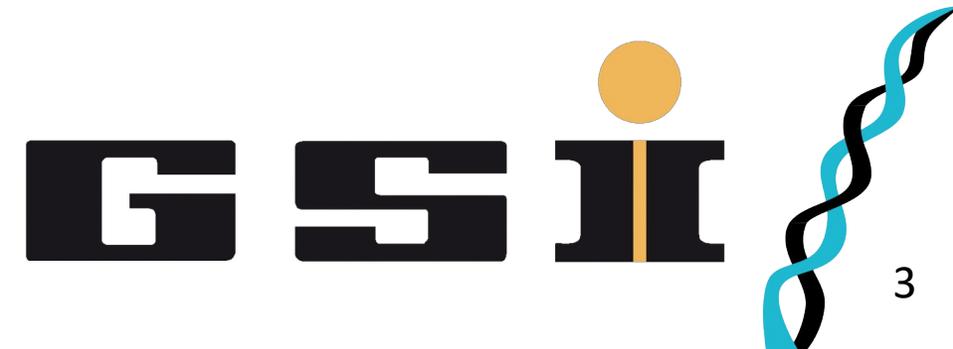
- 2021 Finished PhD at Institute of Nuclear Physics in Krakow, Poland
 - *Studies of three-nucleon force effects in the breakup reaction*
- 2021-2023 PI of project from Polish National Science Center
 - *Relativistic effects in deuteron breakup reaction*





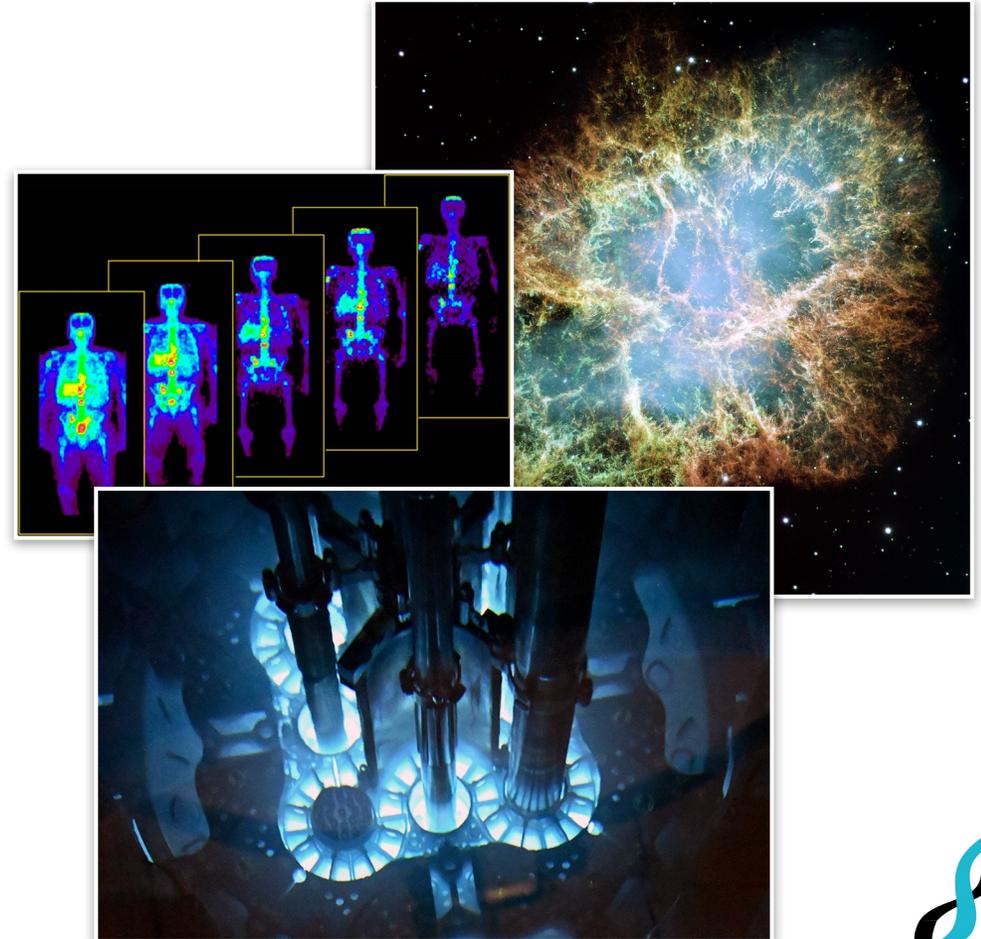
My journey so far...

- 2023-2026 Post Doc in Bordeaux, France
 - *NECTAR NuclEAr reaCtion aT StorAge Rings*
- 2026- Fair Fellow at GSI/FAIR Darmstadt
 - *Continuing working on NECTAR project and surrogate reactions*



Why we do surrogate reactions?

- Indirect way of determining cross sections for reactions that otherwise cannot be measured
 - Neutron capture cross sections of radioactive nuclei
- Neutron-induced reactions are some of the most interesting nuclear reactions
 - s , i and r process nucleosynthesis
 - Medical isotope production
 - Reactor cycles and waste management

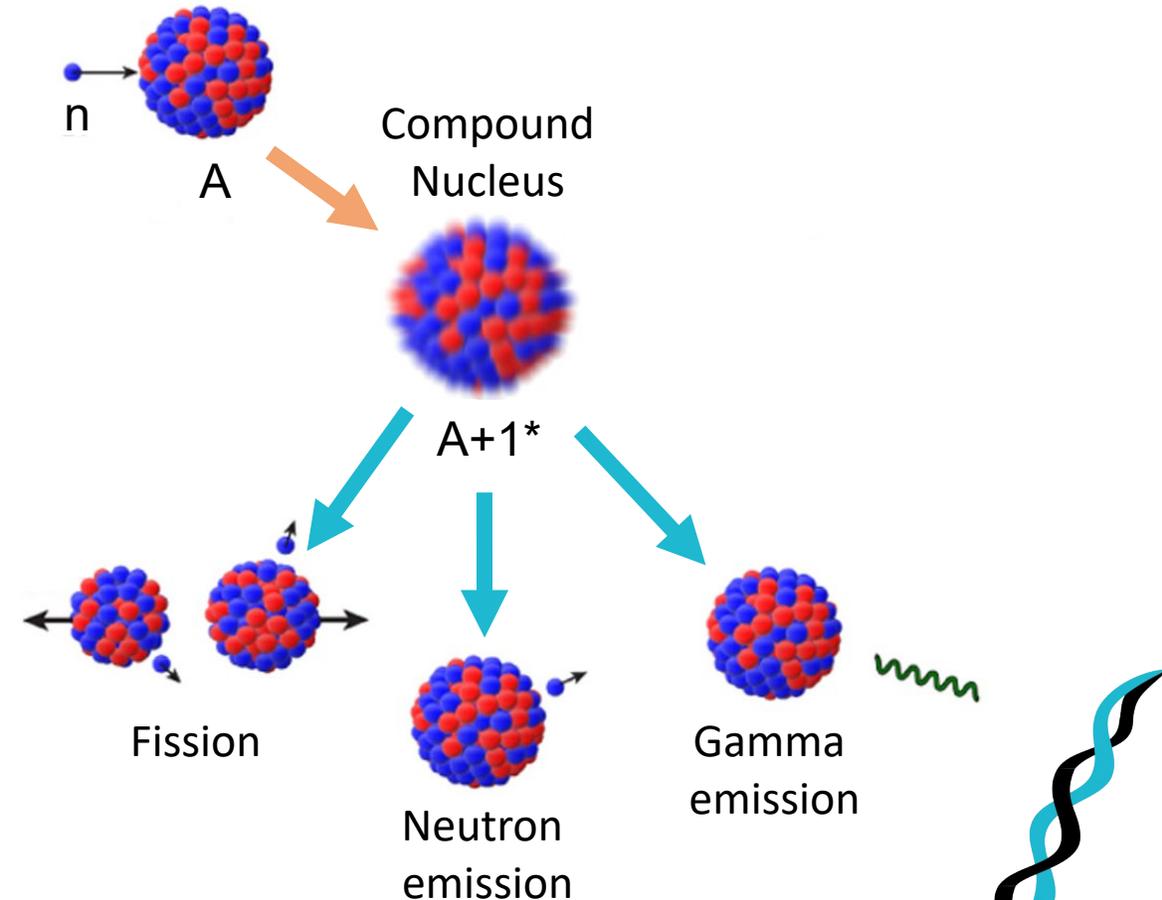




How to measure neutron cross sections?

- We shoot neutrons at the nuclei
 - Heavy nuclei and $E_n < \text{few MeV}$
- 2 step process:
 - Formation of compound nucleus (CN) $A+1$
 - CN decays via competing channels
- σ_x by measuring of decay modes:
 - Fission products (easy)
 - Gamma rays (hard)
 - Neutrons (extremely difficult)

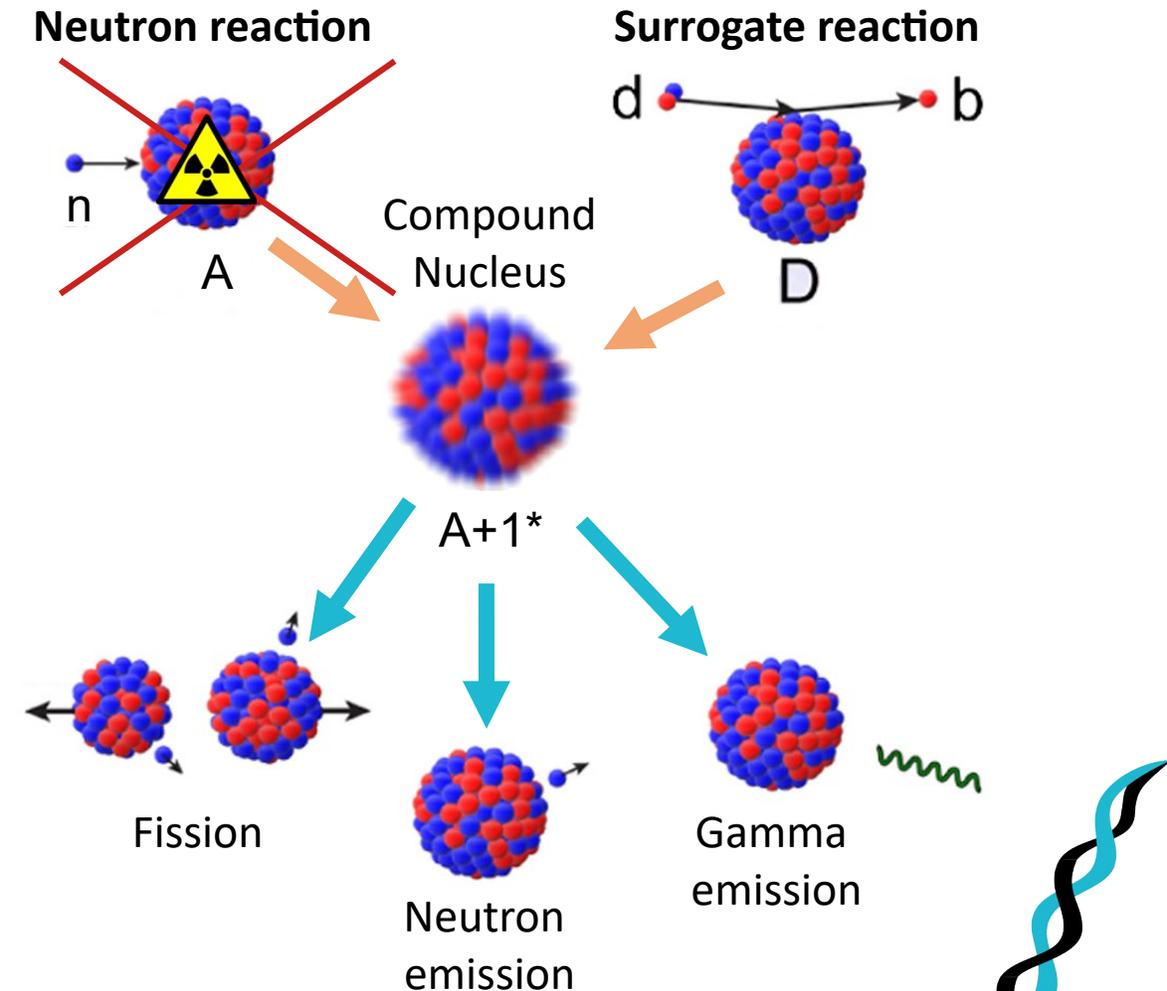
Neutron reaction





How to measure neutron cross sections?

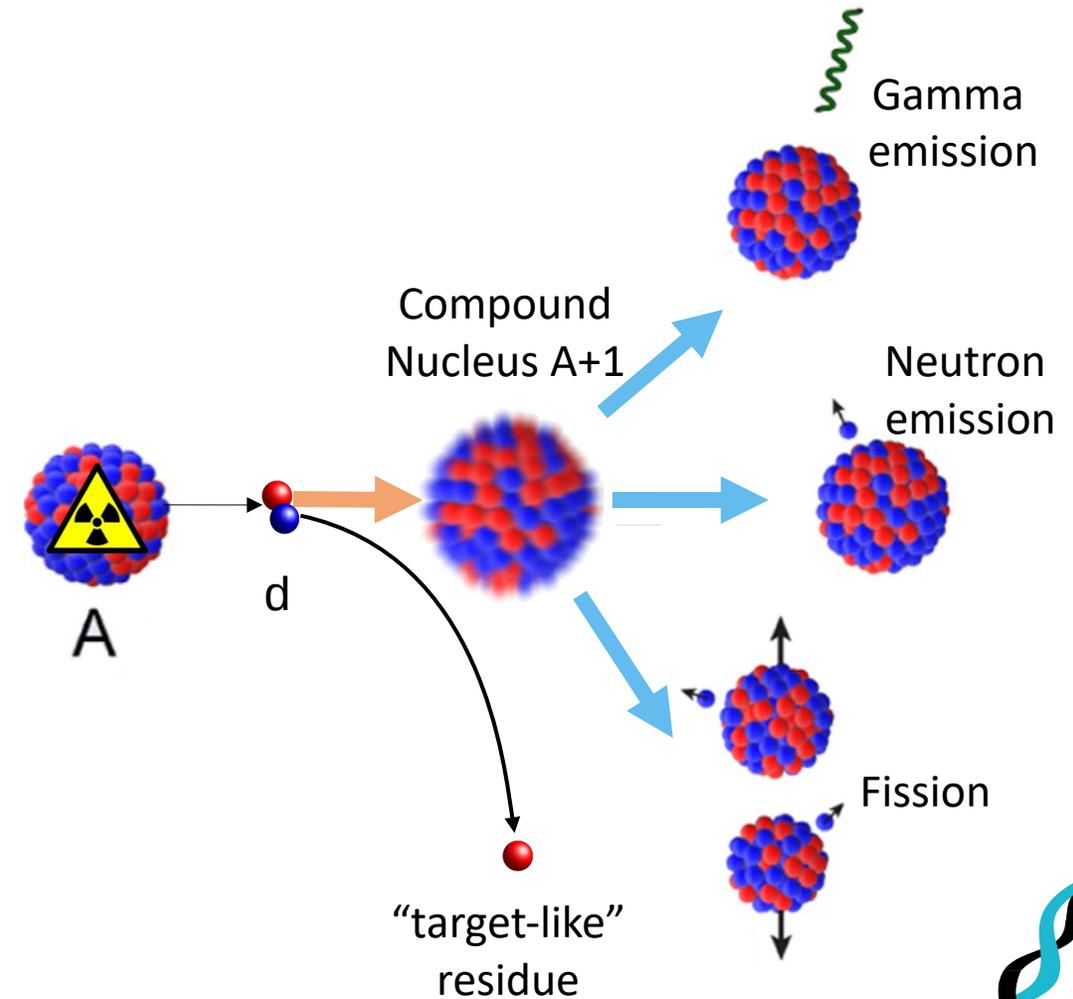
- What if nuclei are radioactive?
 - Making or handling can be impossible
- Surrogate method
 - Different 2-body reaction that forms the same CN
 - Light residue used to calculate excitation energy
- We can measure probabilities:
 - Can be used as an input for theory to constrain gSF, NLD etc.





Surrogate reactions in inverse kinematics

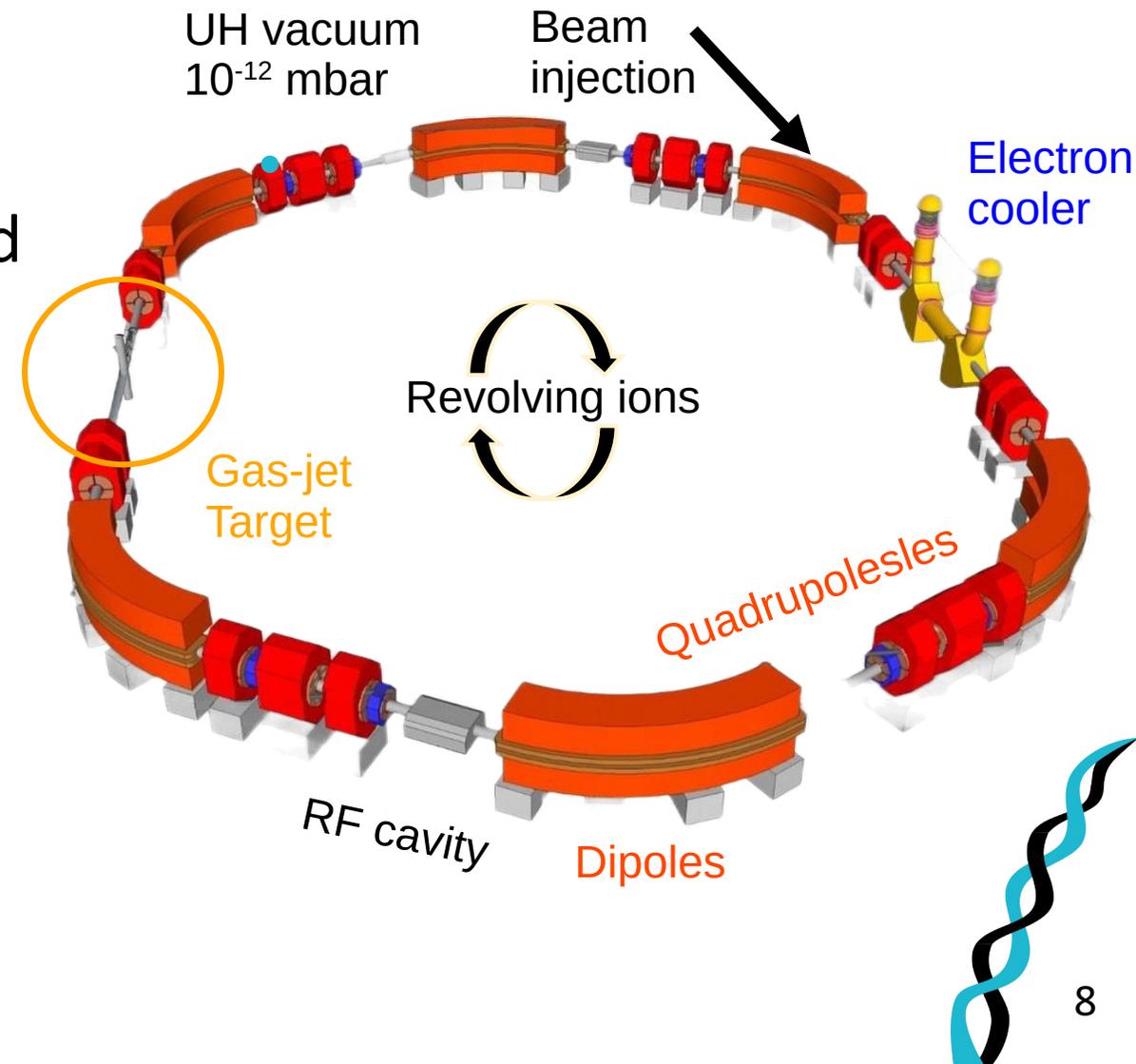
- Serious limitations in direct kin.
 - Target availability, gamma/neutron measurement, background
- Inverse kinematics:
 - Access to RIB
 - Heavy products escape target, boost in efficiency
 - Can measure P_n
- lower E^* resolution, Low beam intensity, straggling in the target.
 - Our solution: **Heavy Ion Storage Rings**





Why Surrogate reaction in Storage Rings?

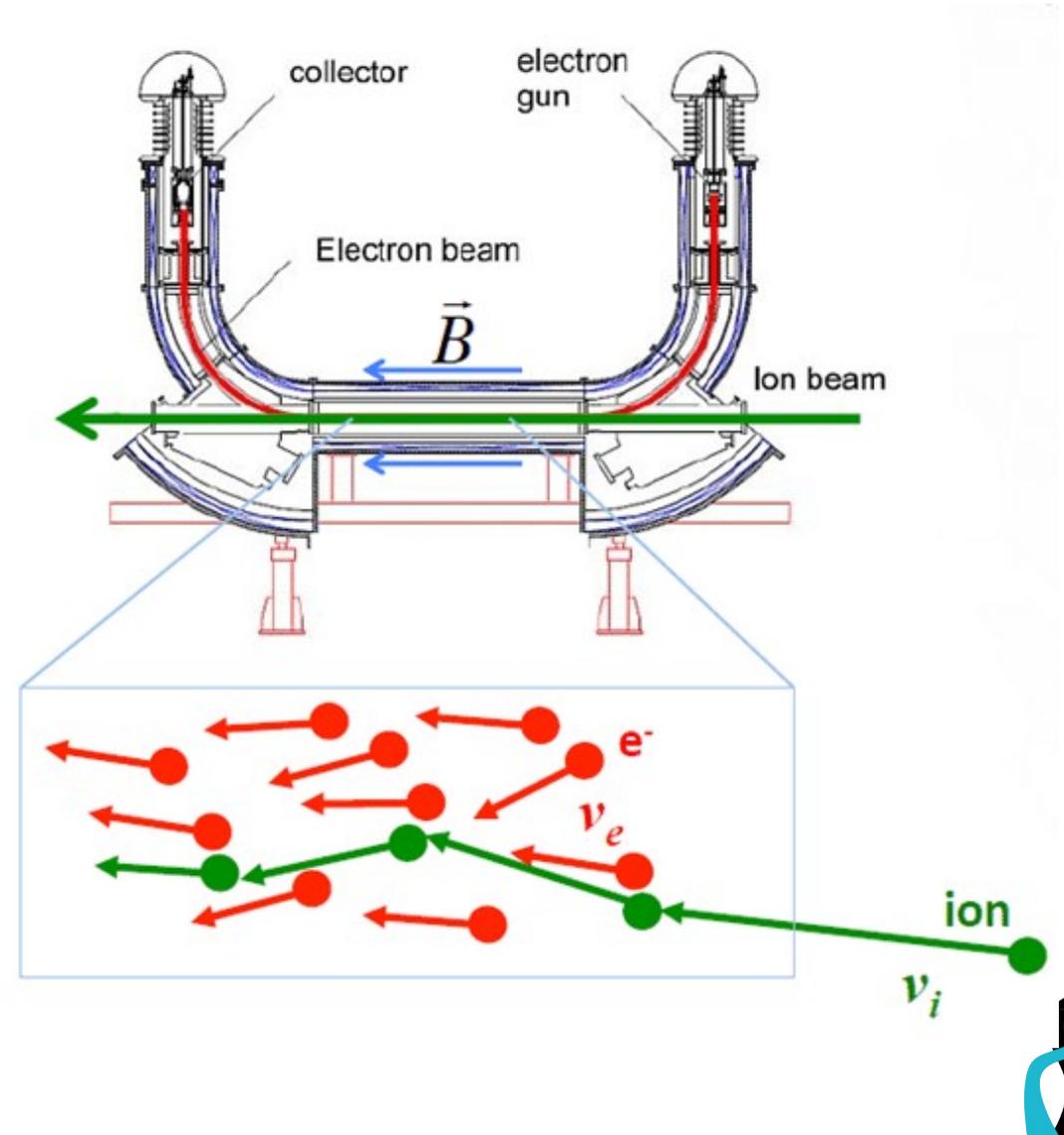
- Access to high quality, fully stripped radioactive beams
- Beam can be decelerated, cooled and fine tuned to desired energy
- Ultra-thin gas jet target (10^{14} cm⁻²) negligible energy loss restored by electron cooler
- Effective thickness multiplied by ~MHz ring frequency
- But the system must be compatible with UHV





What is electron-cooling?

- Beam after injection has large momentum-position spread
- Electron beam is merged in the same direction as the ions
- Velocity of the electrons and ions is the same
- Heat transfer to lighter and cooler electrons
- Electrons are removed leaving cooler ion beam





What is electron-cooling?

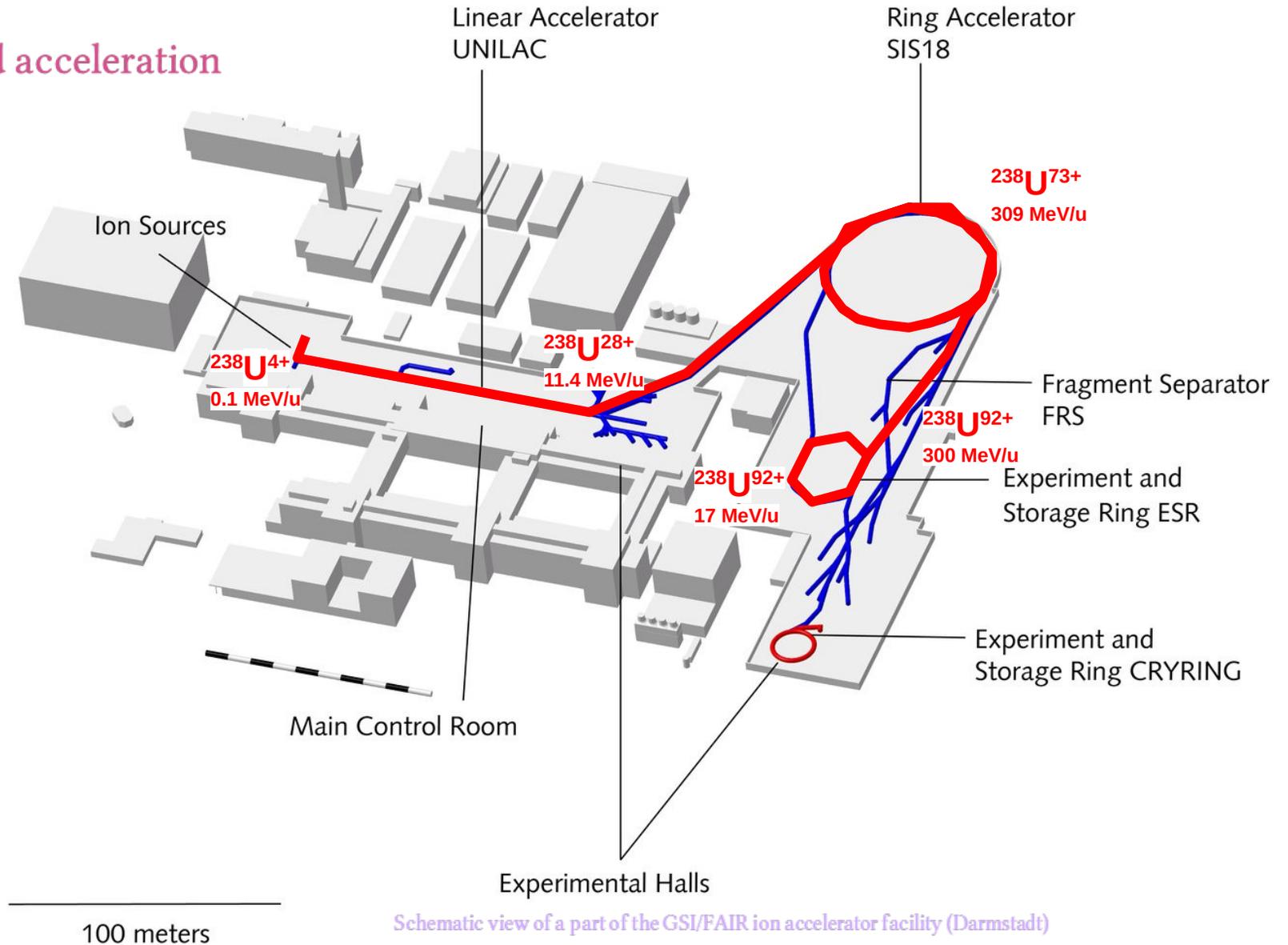
- Beam after injection has large momentum-position spread
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ESR ring at the GSI/FAIR in Darmstadt

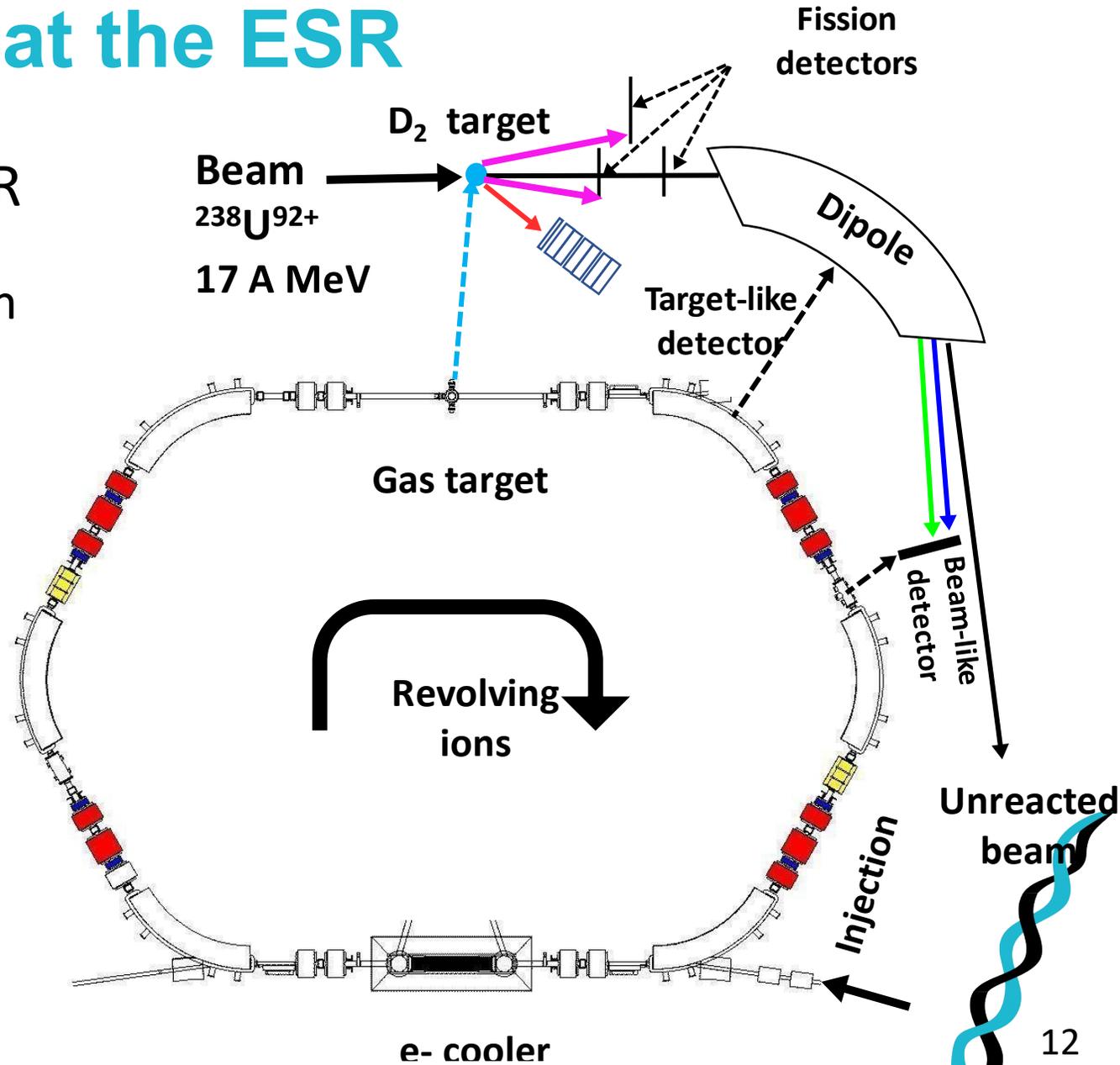
Beam production and acceleration





NECTAR experiment at the ESR

- Two experiments performed at ESR
- First proof-of-principle in 2022 $^{208}\text{Pb}^{82+}$ on H_2 at 30 MeV/u
 - M. Squazzin et al., Phys. Rev. Lett. 134 (2025) 072501
 - M. Sguazzin et al., Phys. Rev. C 111 (2025) 024614
- Second proof-of-principle In 2024 $^{238}\text{U}^{92+}$ on D_2 at 17 MeV/u

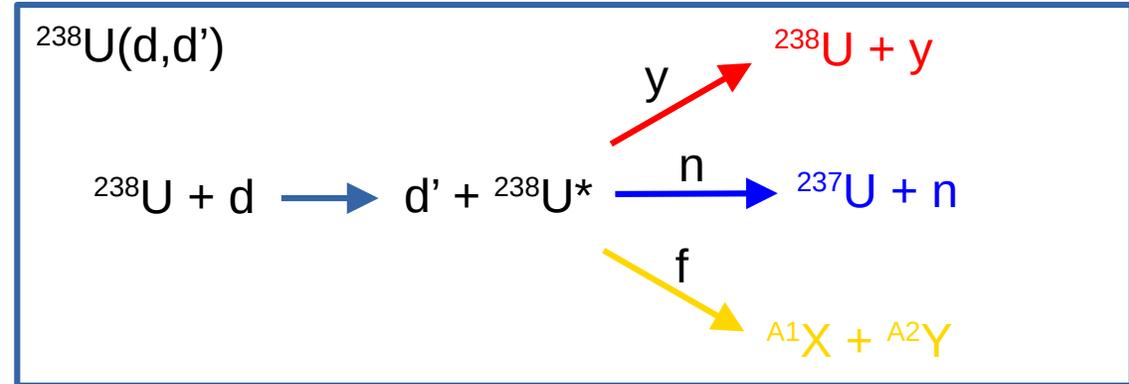




2024 Uranium experiment

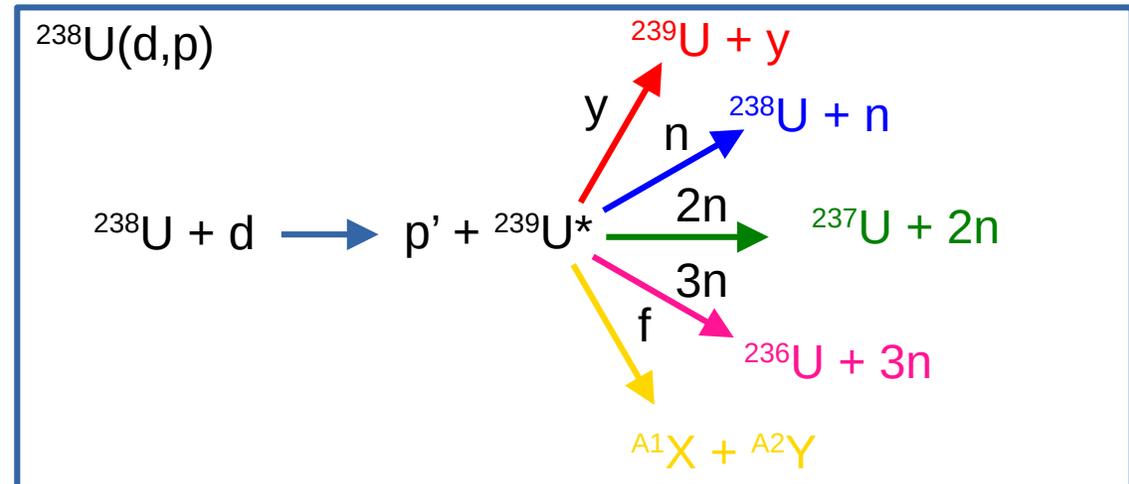
- Deuteron inelastic scattering

Surrogate for $n + {}^{237}\text{U}$



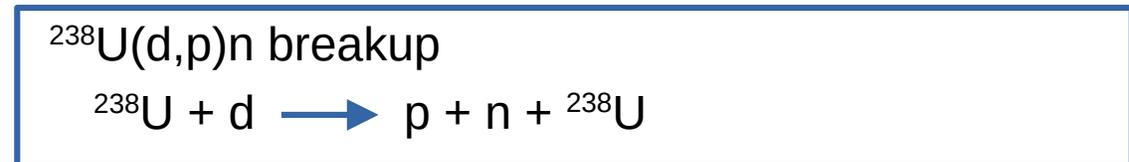
- Neutron transfer reaction

Surrogate for $n + {}^{238}\text{U}$



- Deuteron breakup reaction

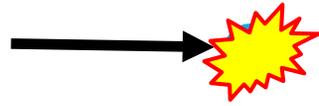
main source of a background





NECTAR experiment at the ESR

Formation and
decay of compound
nucleus ($\sim 10^{-20}$ s)



$^{238}\text{U}^{92+}$

17 MeV/n

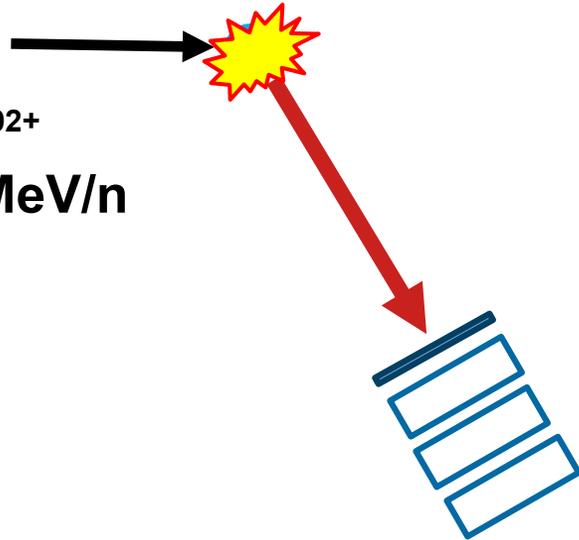




NECTAR experiment at the ESR

Formation and
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$^{238}\text{U}^{92+}$
17 MeV/n

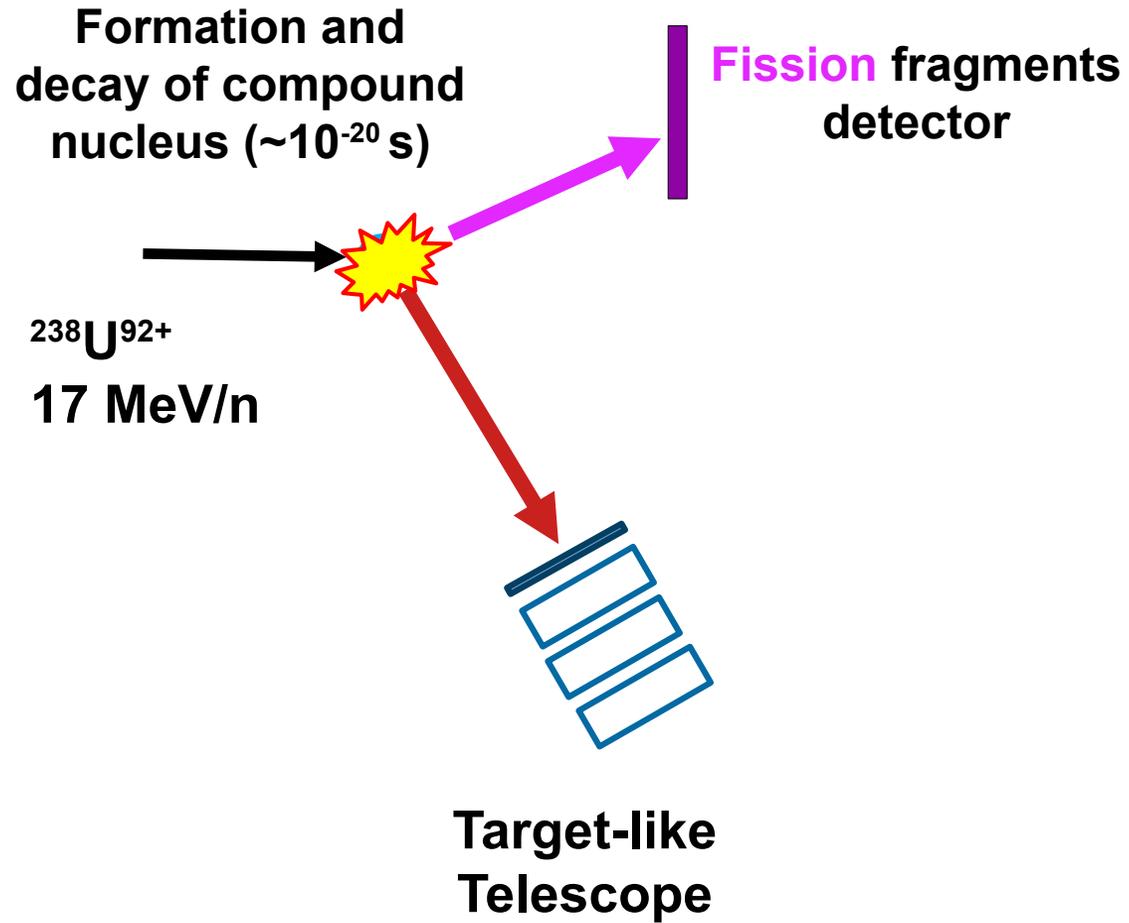


Target-like
Telescope



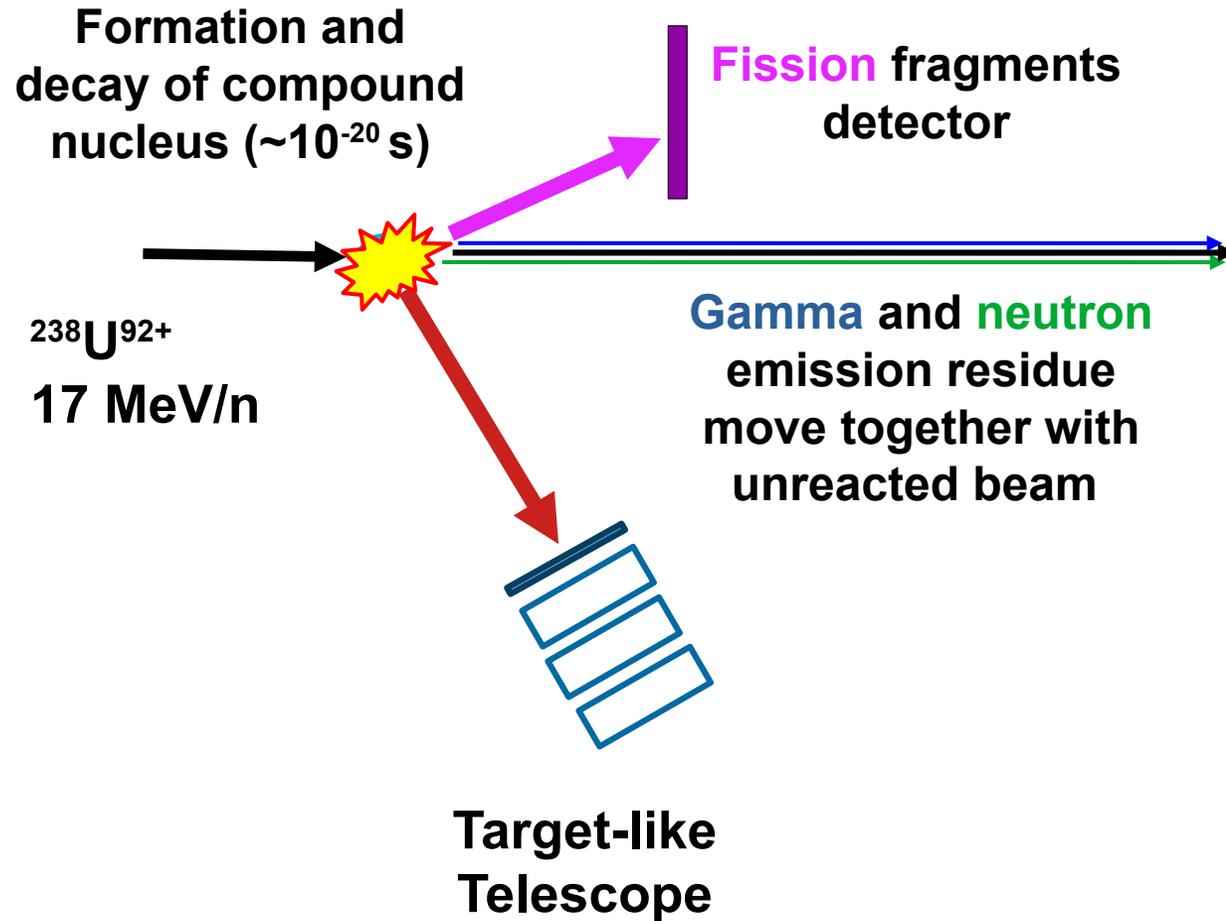


NECTAR experiment at the ESR



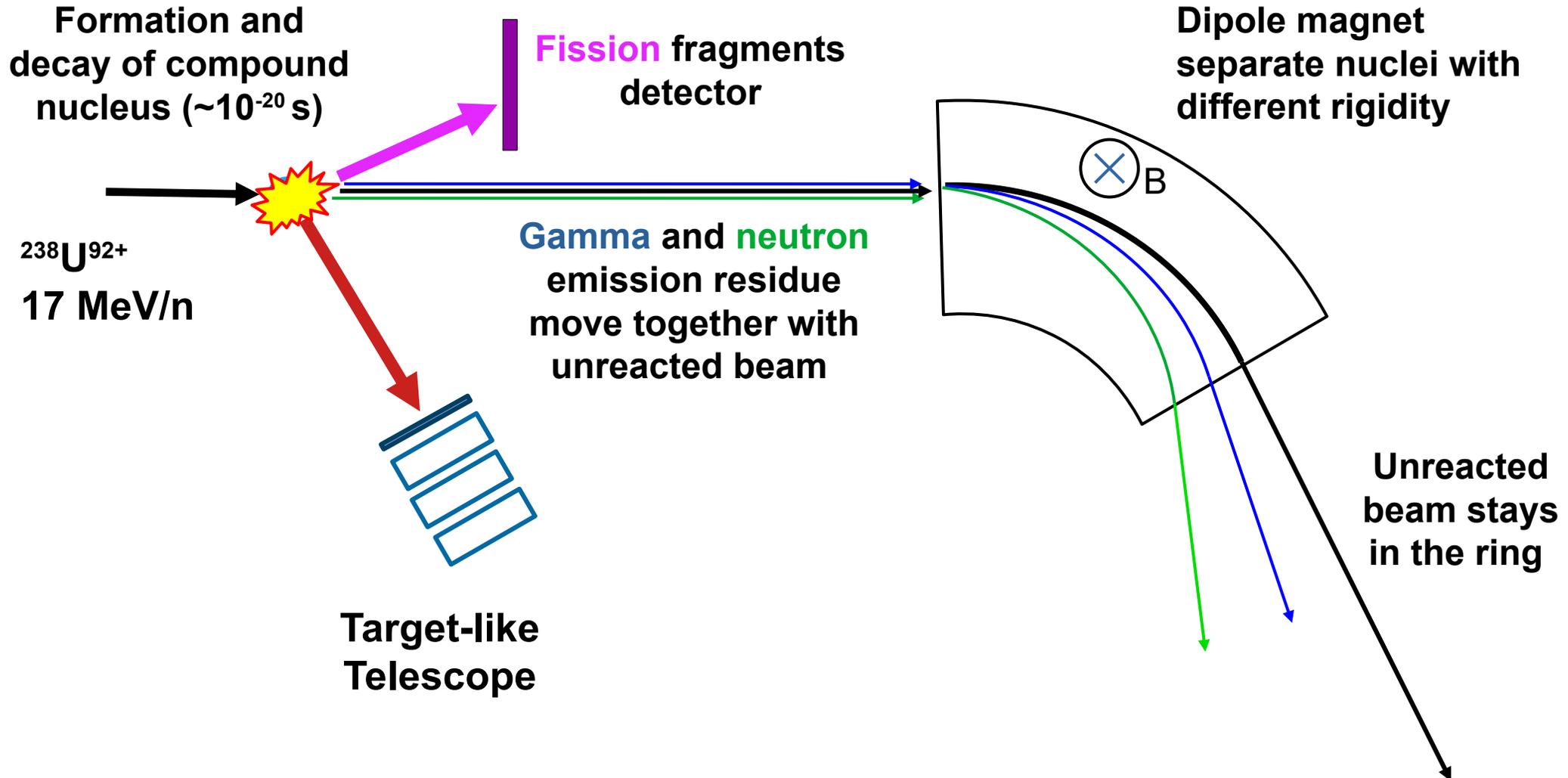


NECTAR experiment at the ESR



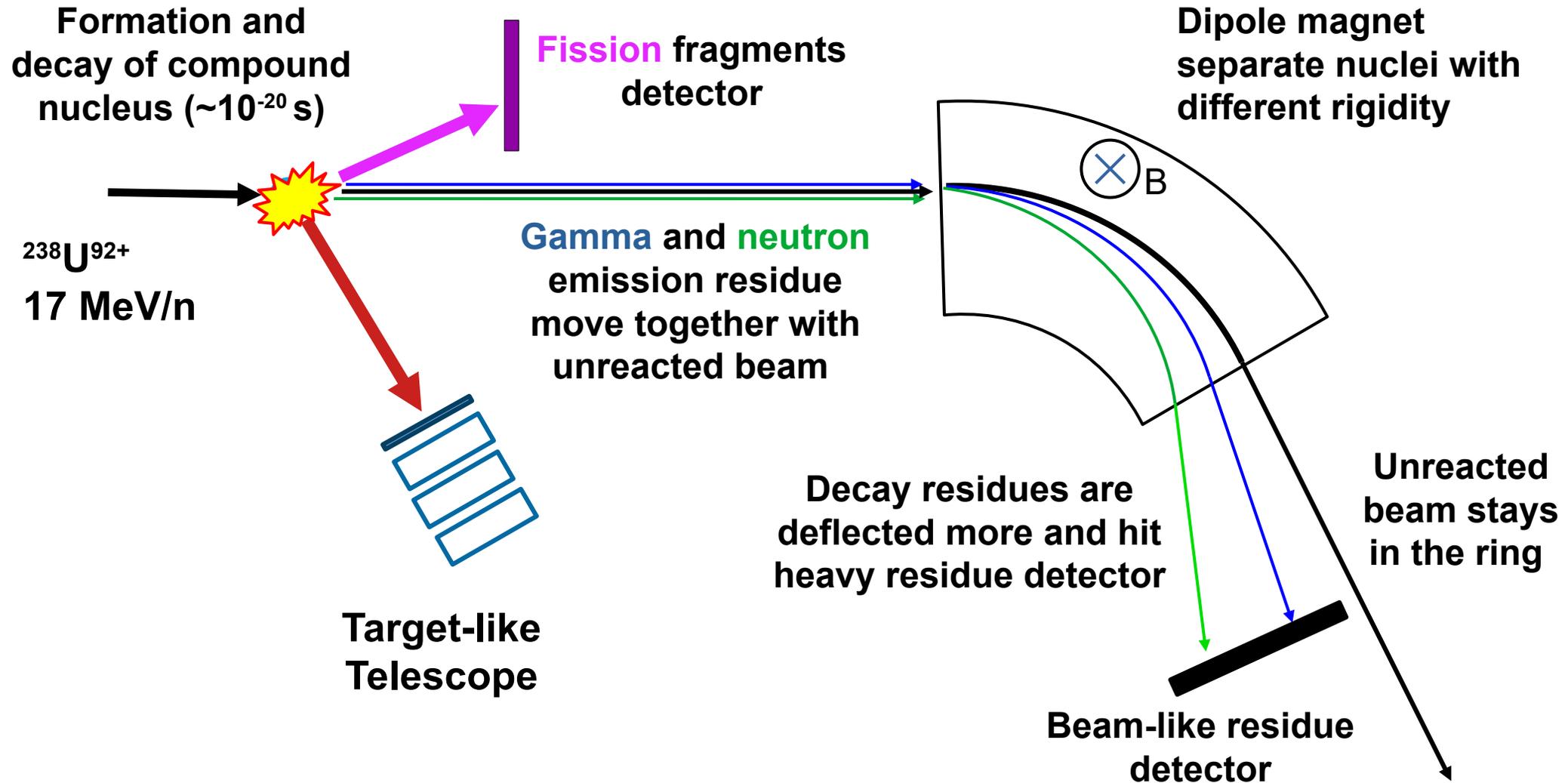


NECTAR experiment at the ESR



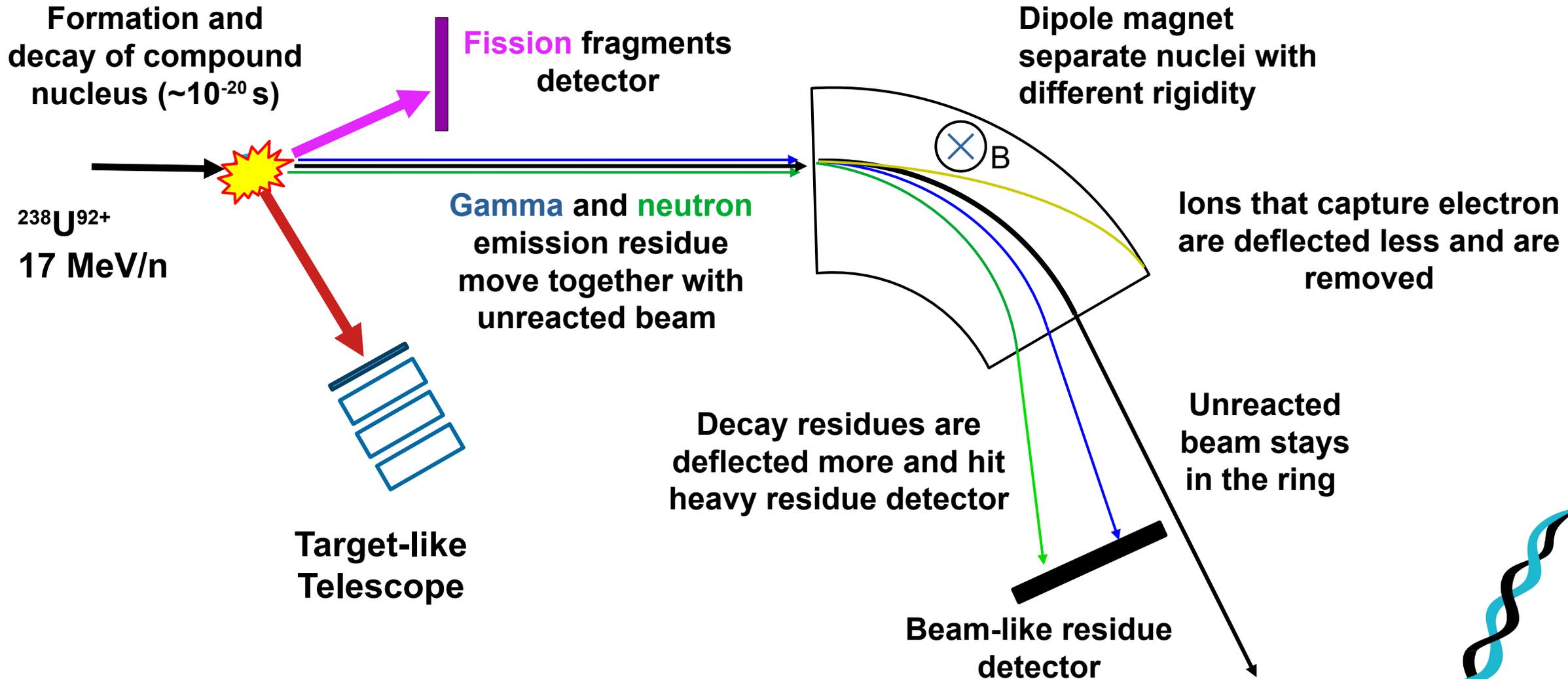


NECTAR experiment at the ESR



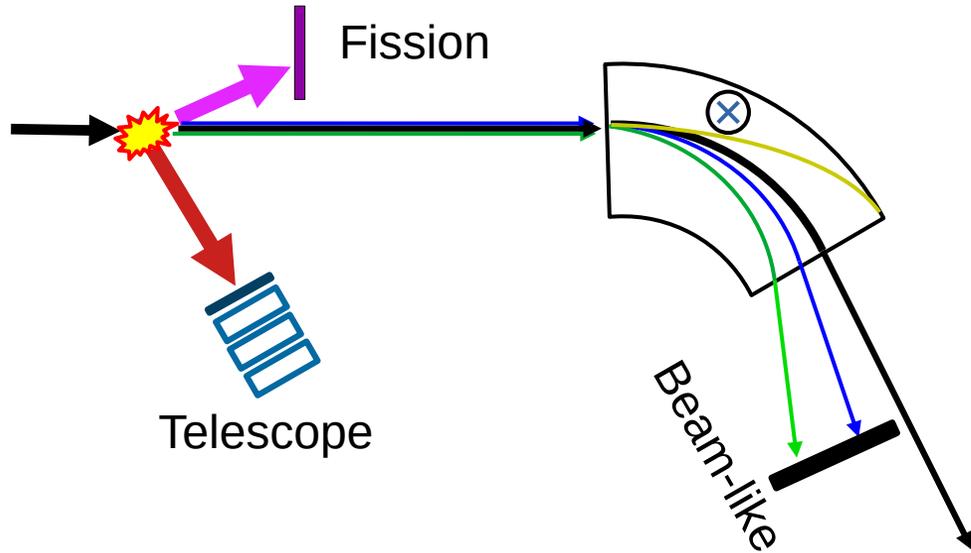


NECTAR experiment at the ESR





Detectors design



Fission detectors

Top and bottom
80*40mm DSSSD

Side
122*44mm DSSSD

Telescope

Position-sensitive
 ΔE
20*20mm DSSSD

Stack of 6 Si E
detectors

**Beam-like
Detector**

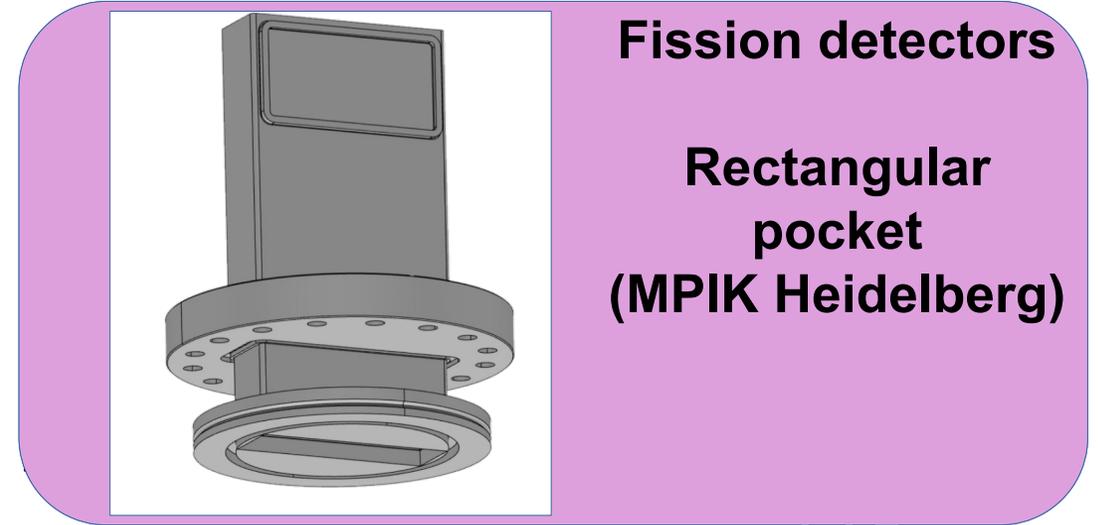
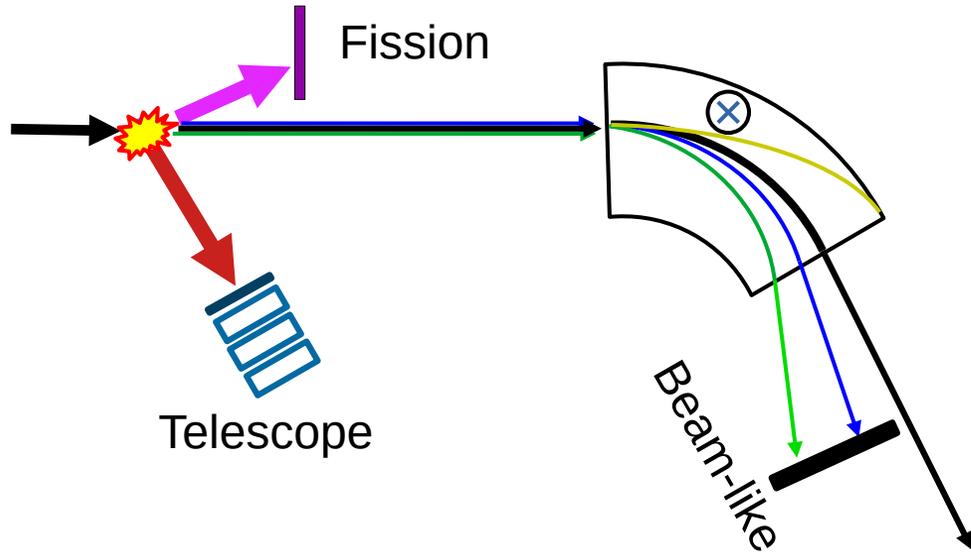
122 mm

44 mm

122*44mm
DSSSD



Ultra-high vacuum compatible pockets

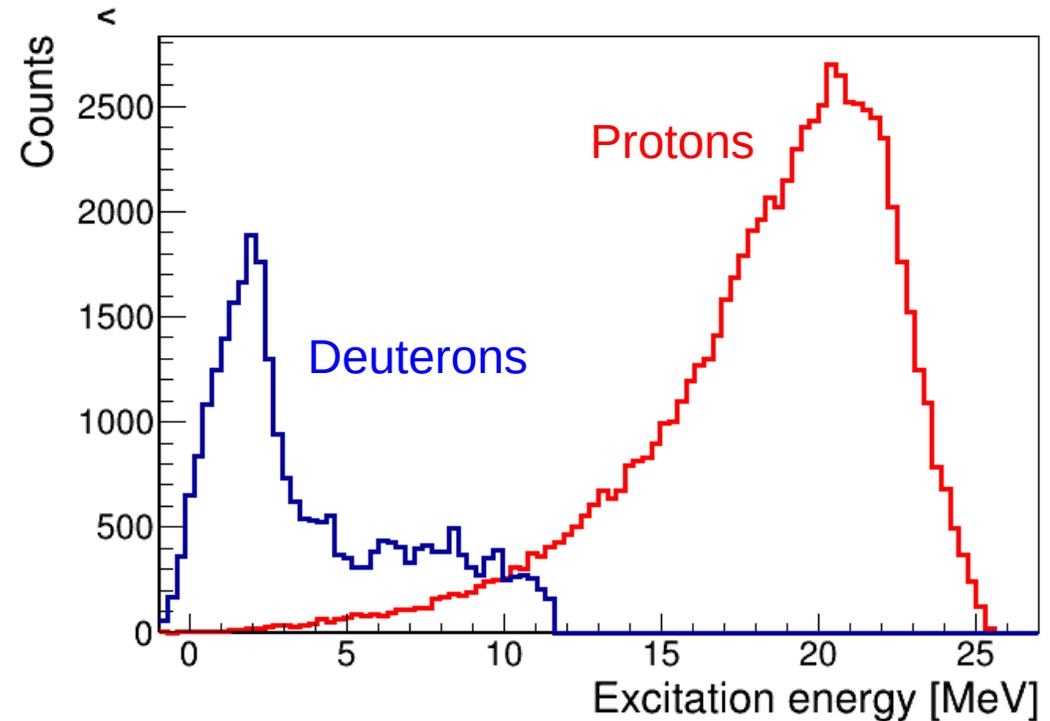
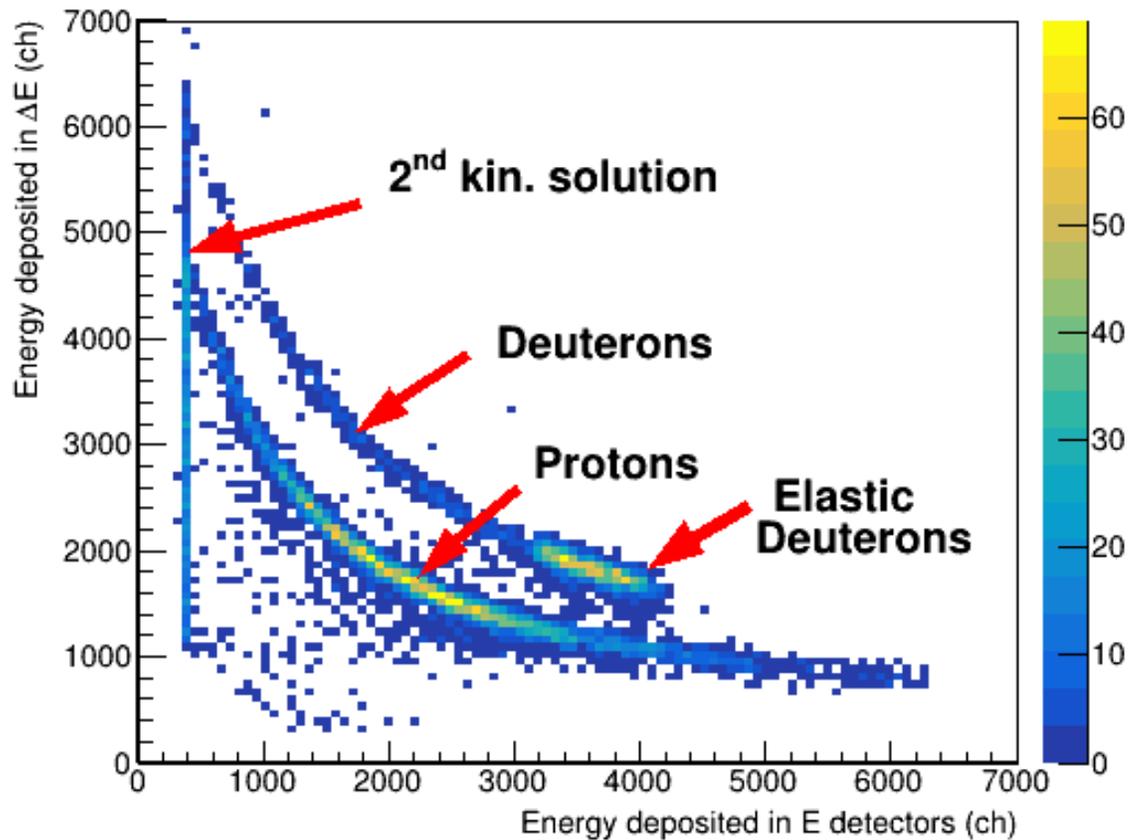




Target-like residue detector (Telescope)

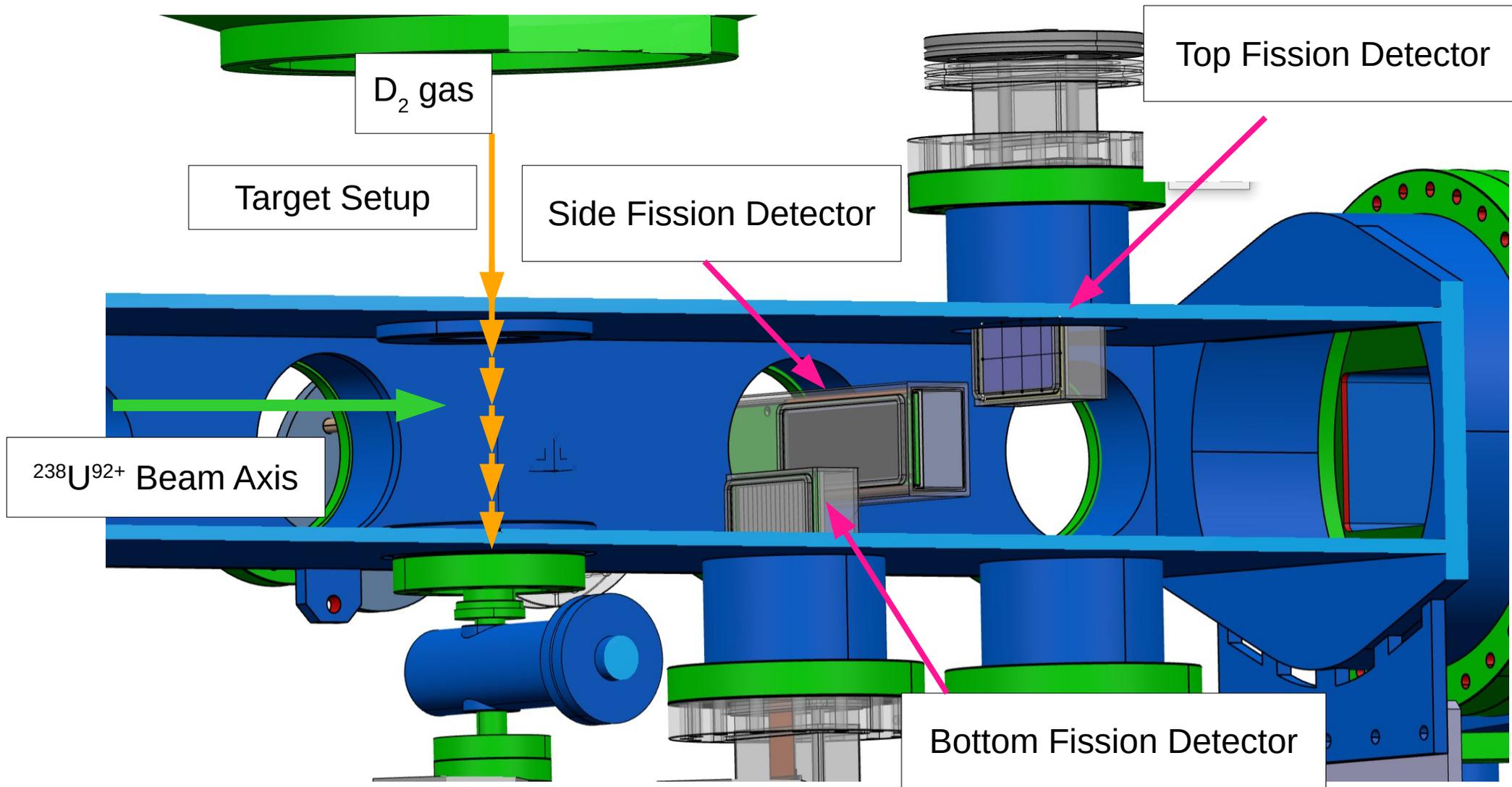
Excitation energy of CN is given by:

$$E^* = f(E_B, E_S, \theta_s)$$





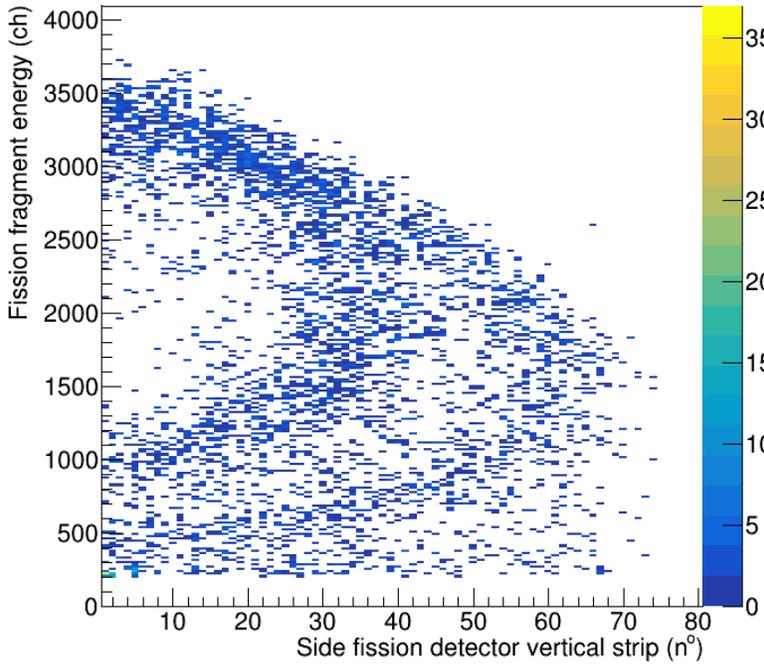
Fission fragments detectors



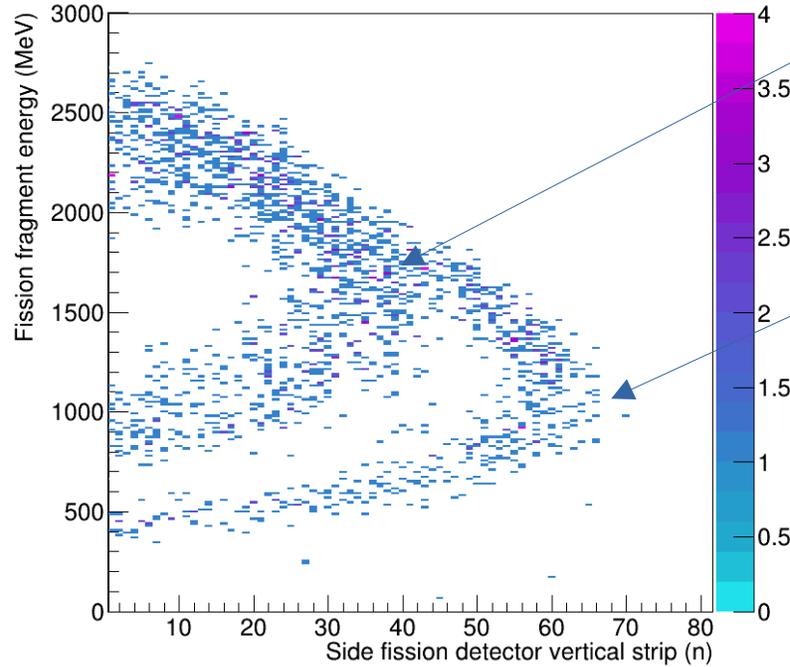


Fission fragments detector

Experimental results



Simulated distribution



First ever Fission measurement in heavy-ion storage rings!

Heavy fission fragments

Light fission fragments

Center of Mass

Center of Mass

Laboratory

$P_{cm,light}$

$V_{cm,light}$

$V_{I,light}$

$V_{I,CM}$

$P_{cm,heavy}$

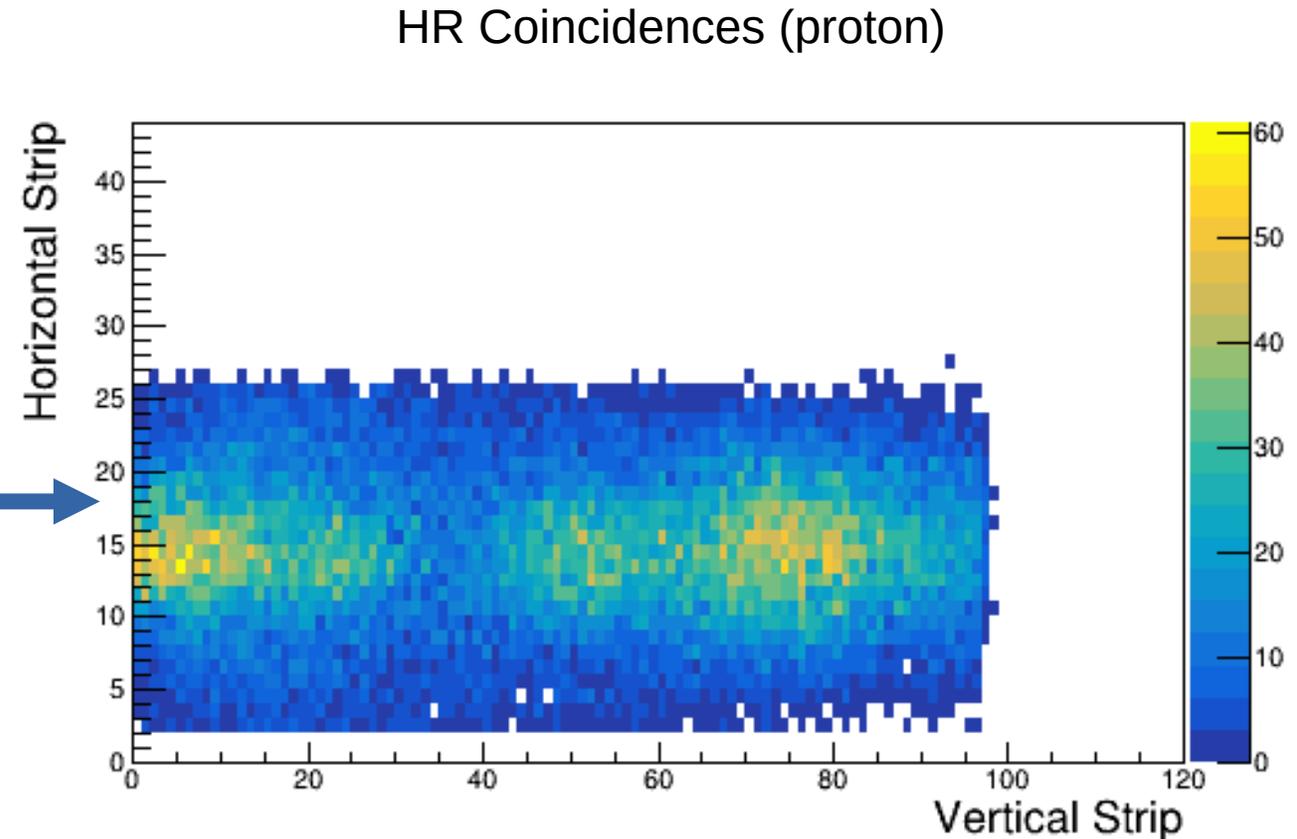
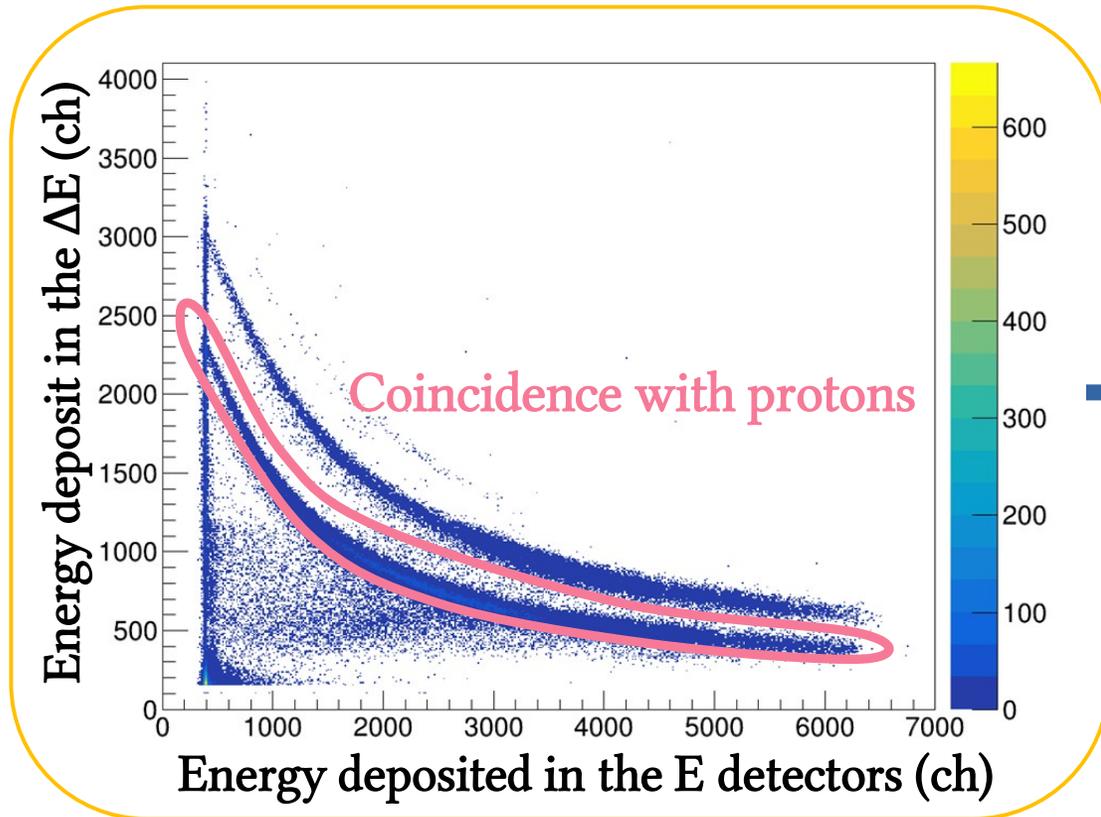
$V_{cm,heavy}$

$V_{I,heavy}$



Beam-like residue detector, $^{238}\text{U}(\text{d},\text{p})$

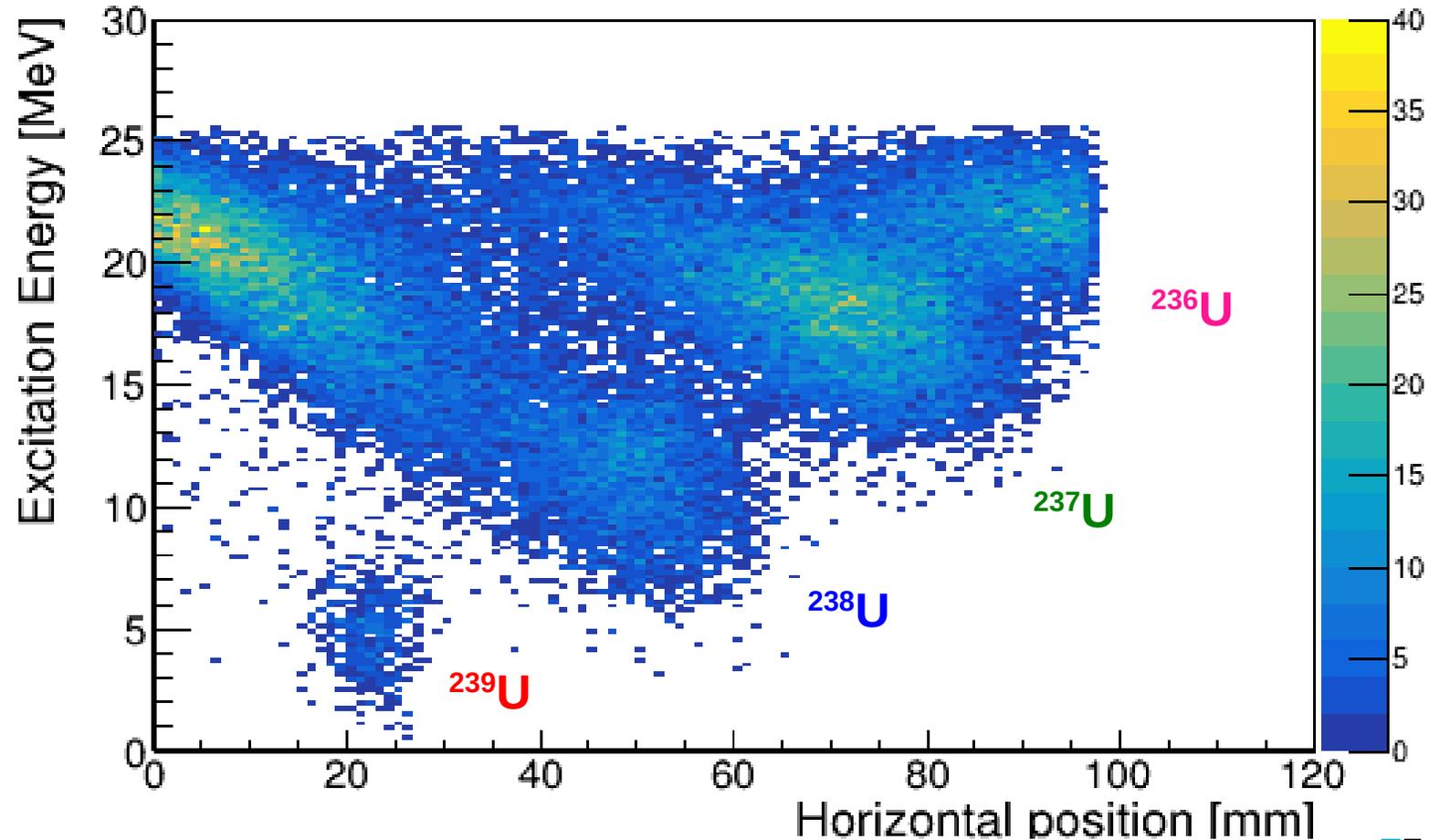
- With coincidences (protons)
 - $^{238}\text{U}(\text{d},\text{p})$ channel





Beam-like residue detector, $^{238}\text{U}(d,p)$

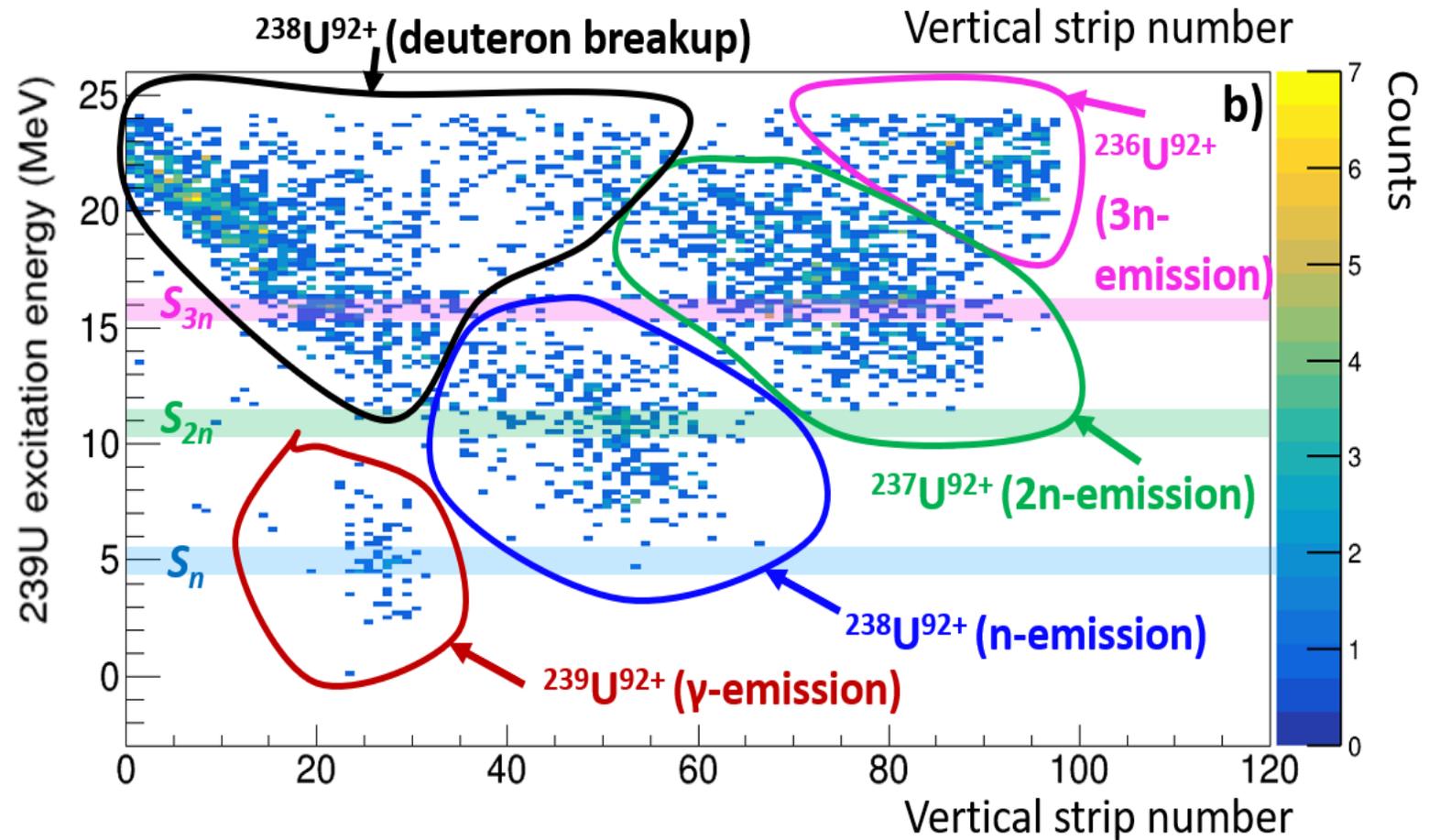
- Beam-like residue position as a function of Excitation energy
- We can identify different uranium isotopes





Beam-like residue detector, $^{238}\text{U}(d,p)$

- We can identify γ -emission and n,2n,3n emission!
- Very high detection efficiency!
- All possible decay channels measured simultaneously!





De-excitation probabilities

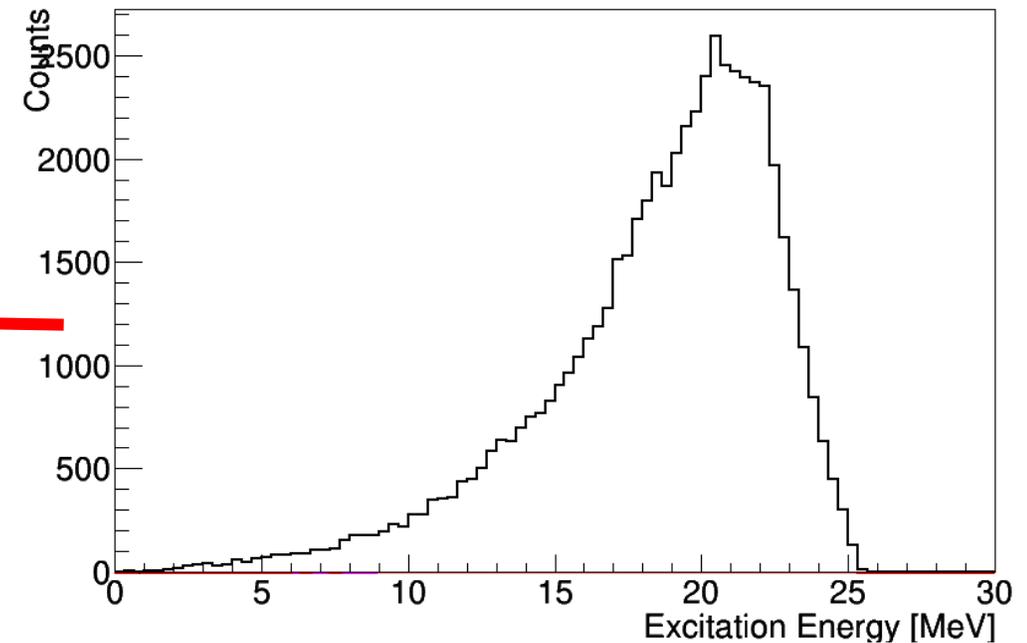
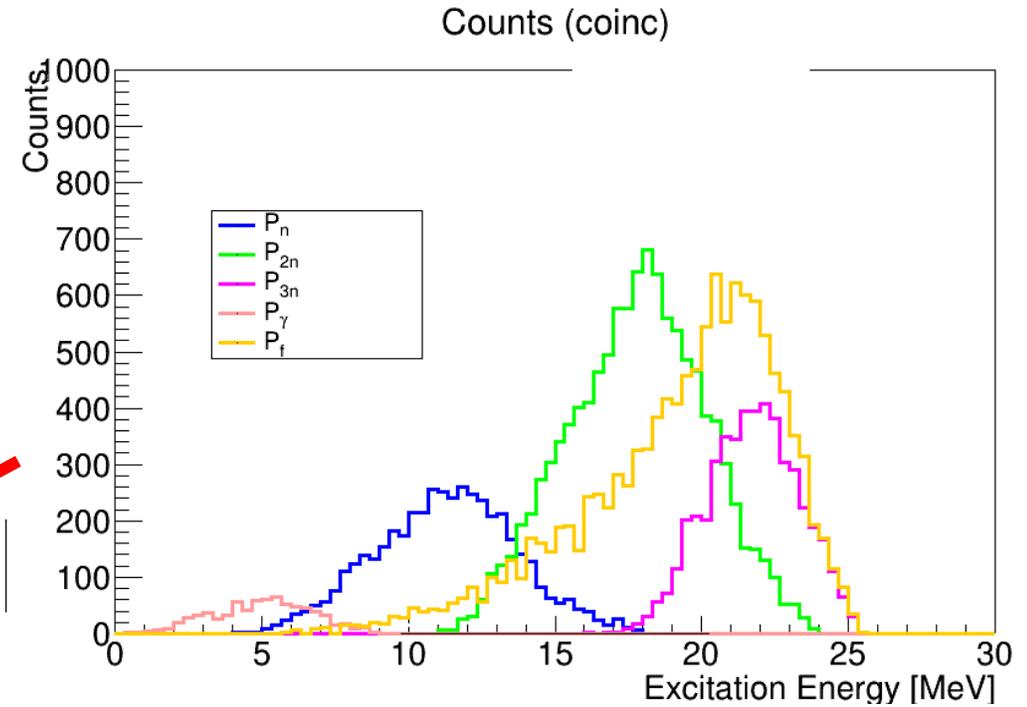
- Probability for a given excitation E^* and decay mode χ :

Number of coincidence events

$$P_X(E^*) = \frac{N_{C,X}(E^*)}{\epsilon_X(E^*) \cdot N_S(E^*)}$$

Detection Efficiency

Number of singles in Telescope





Preliminary probabilities of $^{238}\text{U}(d,p)$ Comparison with the (d,p)-induced calculations

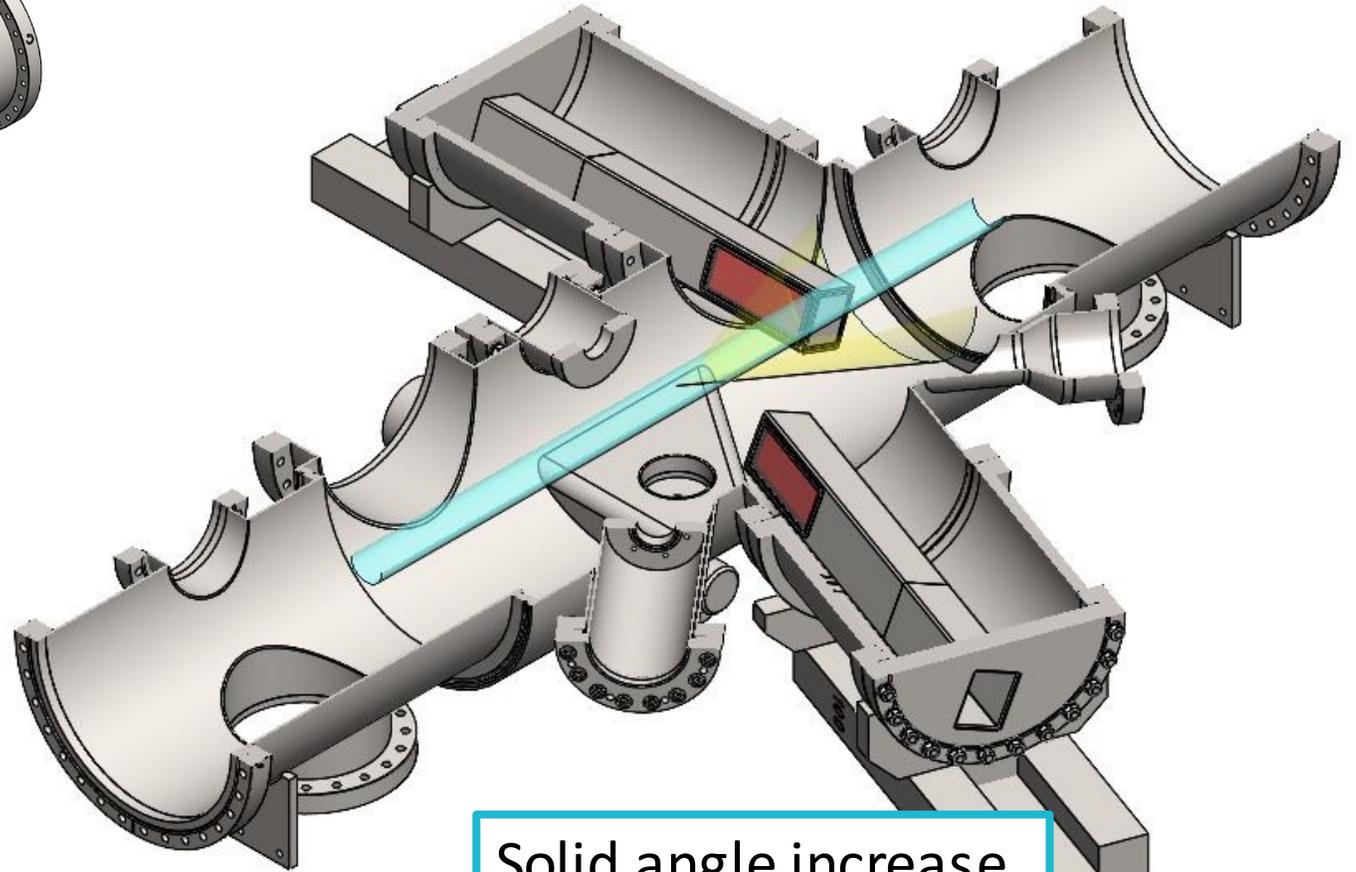
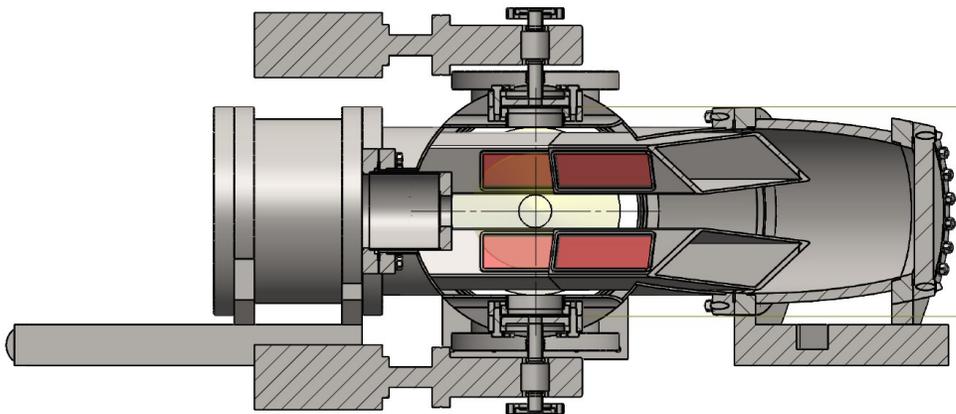
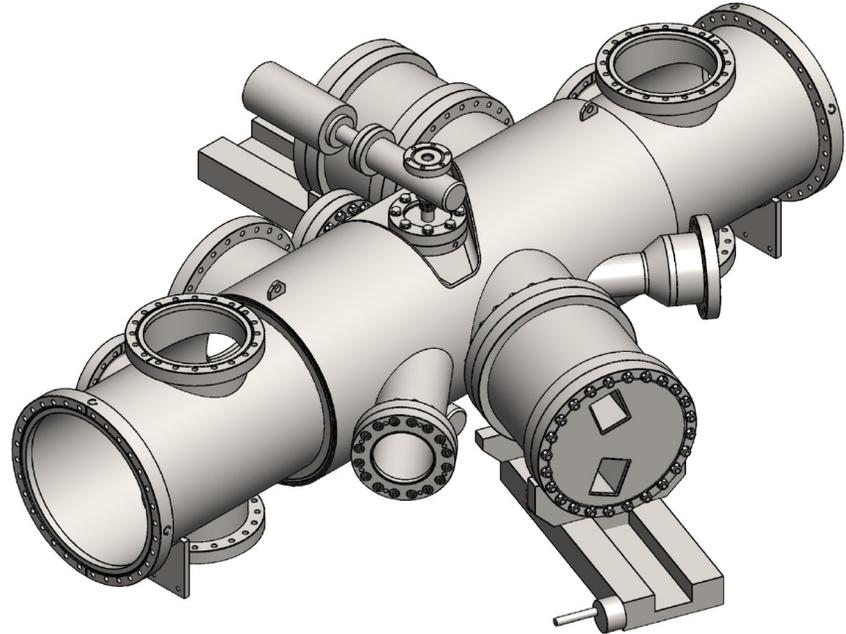
**For preliminary results
please contact the authors**

	P_γ
	P_n
	P_f
	P_{2n}
	P_{3n}

Calculation by
Gregory Potel,
Experimental
resolution
included



New reaction chamber at the ESR



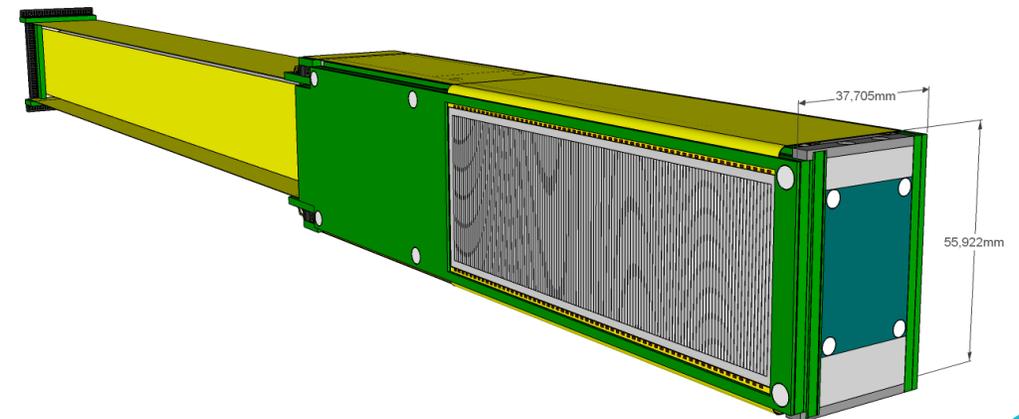
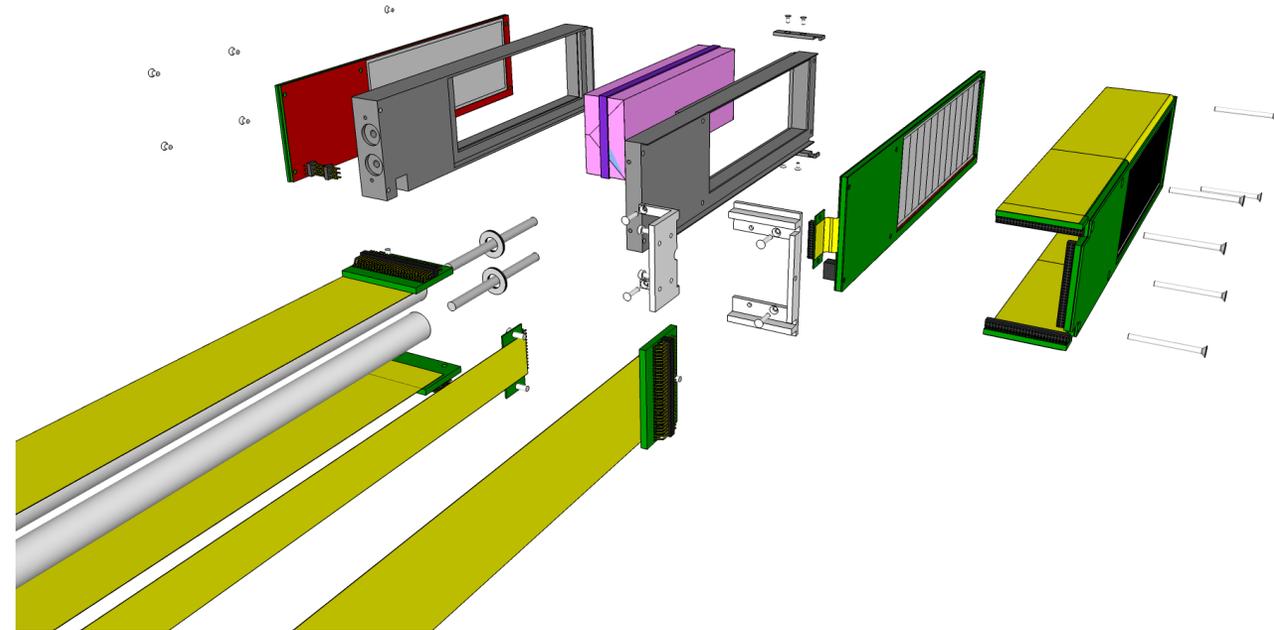
Solid angle increase
by a factor of 230!!!





New detection system

- New telescope design
 - Measure protons with energy 0-100MeV
- Sandwich of Si DSSSD, thick Si E and CsI(Tl)
 - Compact design, must fit inside the pocket!
- Test and calibrations with p,d beams
- In-vacuum detector for backward scattered protons?
 - Interesting physics case but difficult





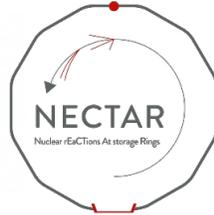
Conclusions and perspectives

- Storage rings offers unique conditions to investigate surrogate reactions, pure gas-jet target,
- For the first time fission, gamma, one two and three neutron-emission probabilities measured
- Next experiment (2027) infer n-induced cross section with $^{205}\text{Pb}(d,p)$ and $^{206}\text{Pb}(p,p')$, our first experiment with radioactive beams,
- New reaction chamber and gas target, better resolution and more solid angle





Acknowledgements



This work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC-Advanced grant NECTAR, grant agreement No 884715).
NECTAR: Nuclear rEaCTions At storage Rings



Prime 80 program from CNRS, PhD thesis of M. Sguazzin



Accord de collaboration 19-80 GSI/IN2P3



The results presented here are based on the experiment E146, which was performed at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-



This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.





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9-University of Chalmers, Sweden 10-University of Edinburgh, UK
11-GANIL, France 12-University of Osaka, Japan
13-FRIB, USA

