Simultaneous measurement of fission, gamma, and multi-neutron emission in surrogate reactions at heavy-ion storage ring

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GSI/FAIR Darmstadt

7th Workshop on Nuclear Fission
and Spectroscopy of Neutron Rich Nuclei

LP2i Bordeaux

European Research Council
Established by the European Commission

NECTAR
Nuclear rEaCTions At storage Rings

cnrs

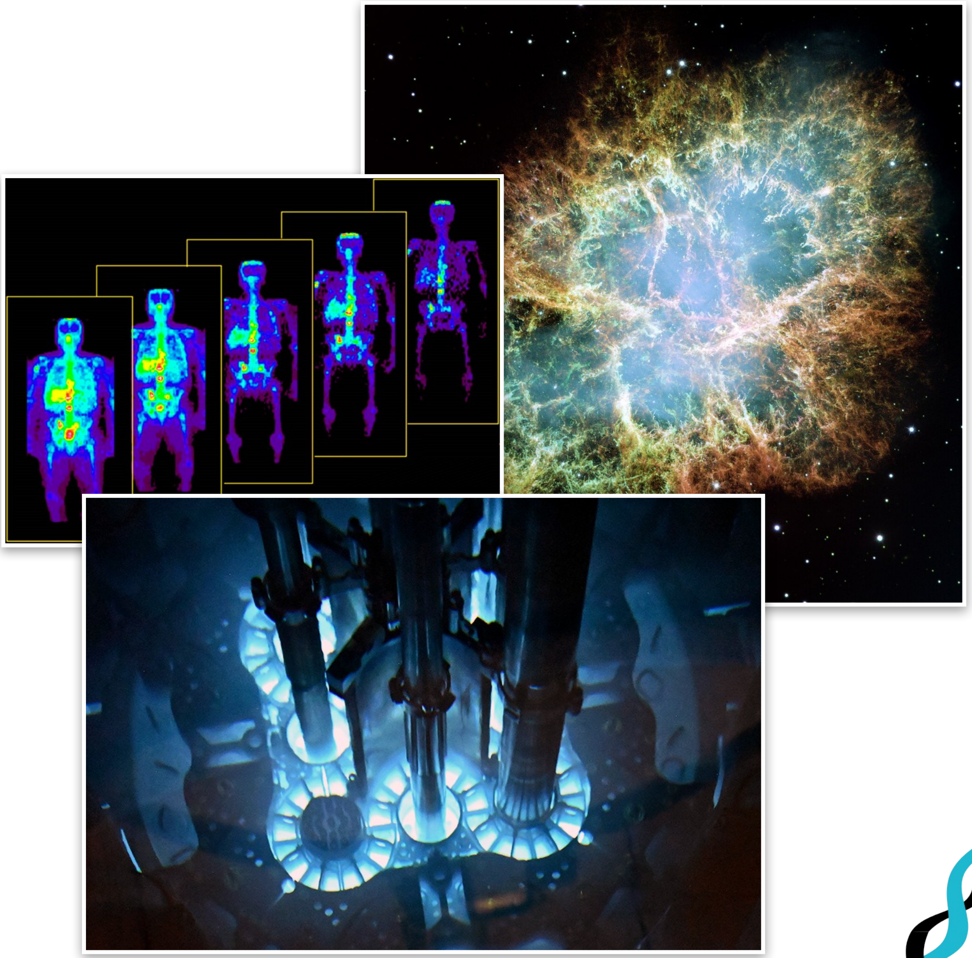
université de BORDEAUX

FAIR Phase 0 Research Program

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

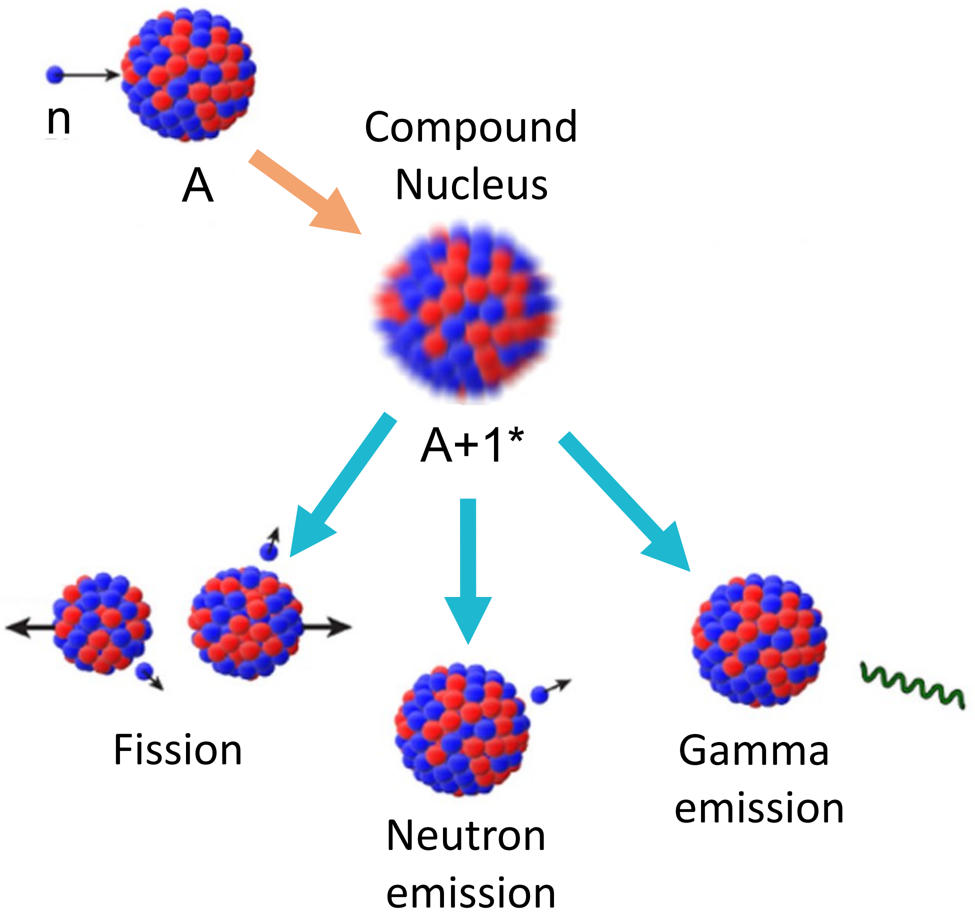
- Neutron-induced reactions are some of the most interesting nuclear reactions
    - *s*, *i* and *r* process nucleosynthesis
    - Study of Fission and nuclear structure
    - Medical isotope production
    - Reactor cycles and waste management



How to measure neutron cross sections?

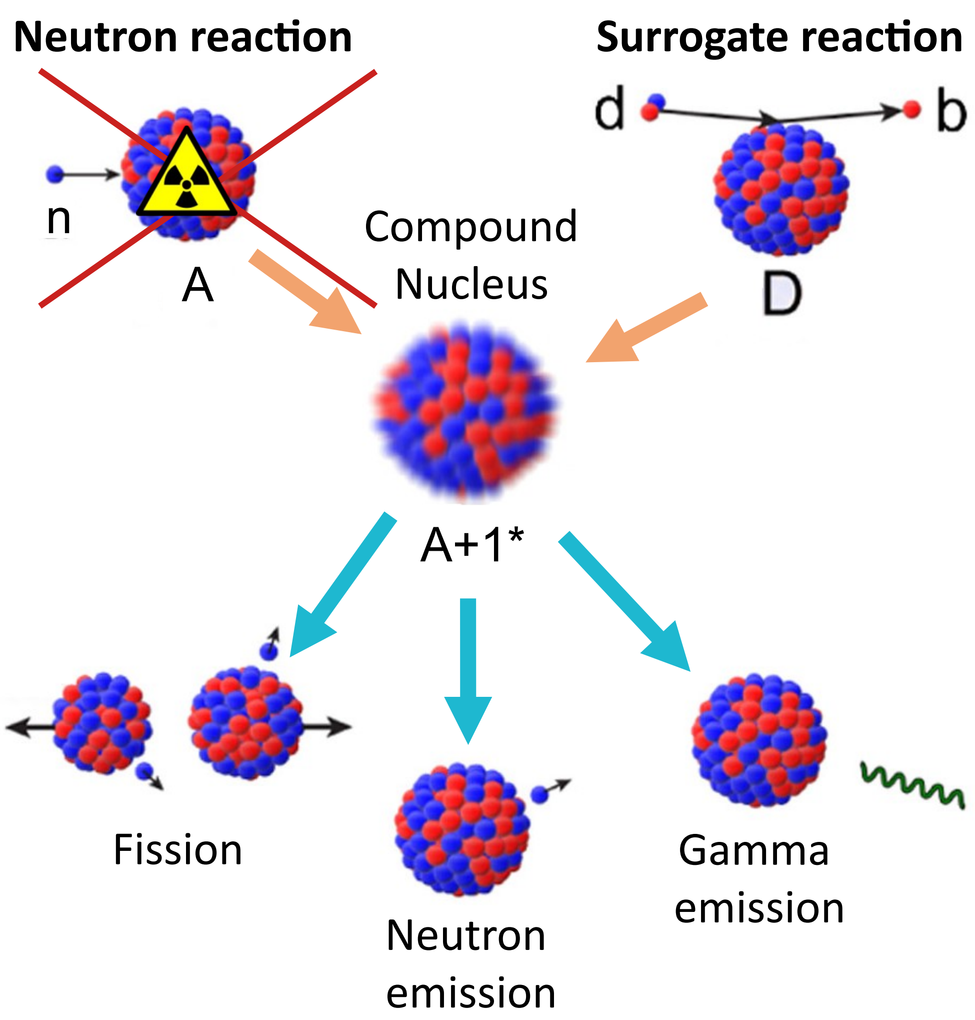
- We shoot neutrons at the nuclei
  - Heavy nuclei and E_n < few MeV
- 2 step process:
  - Formation of compound nucleus (CN) A+1
  - CN decays via competing channels
- σ_X by measuring of decay modes:
  - Fission products (easy)
  - Gamma rays (hard)
  - Neutrons (extremely difficult)

Neutron reaction



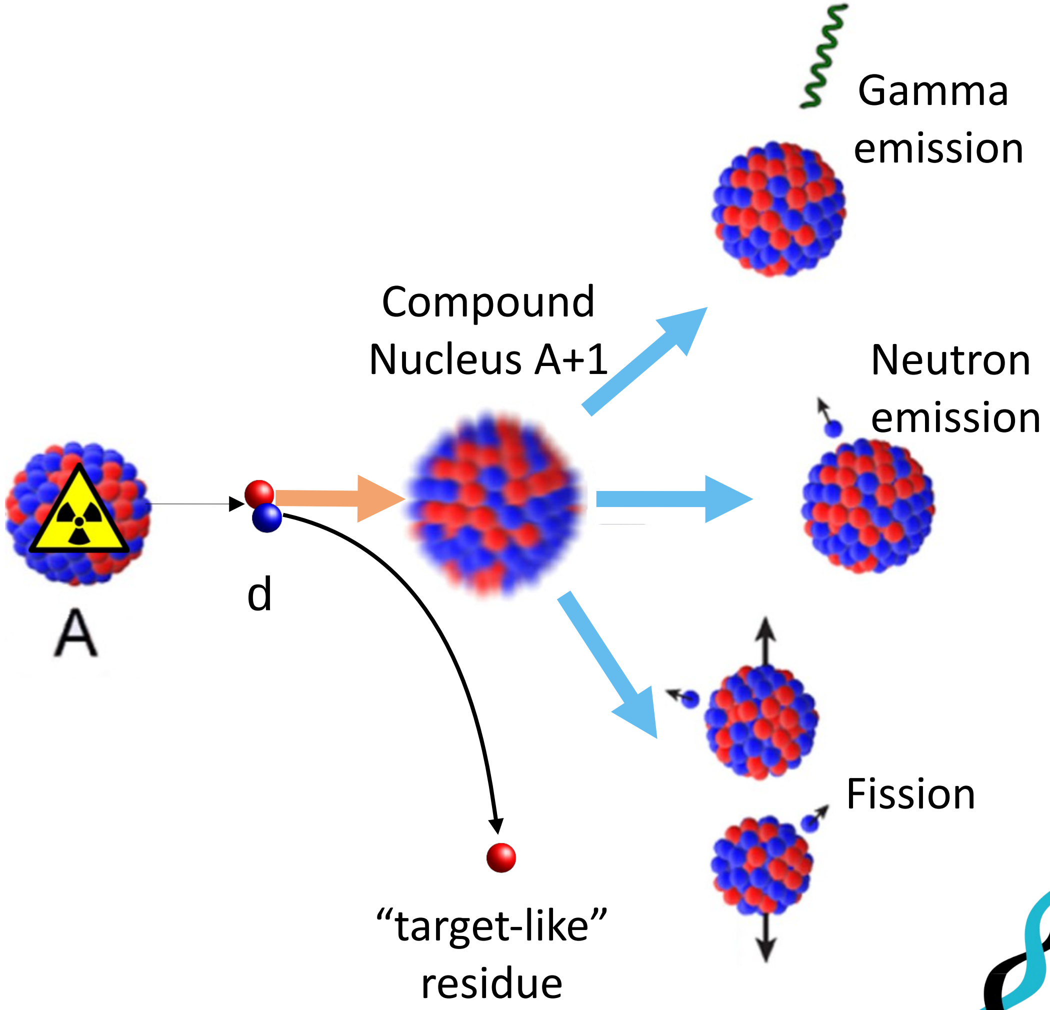
How to measure neutron cross sections?

- 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.



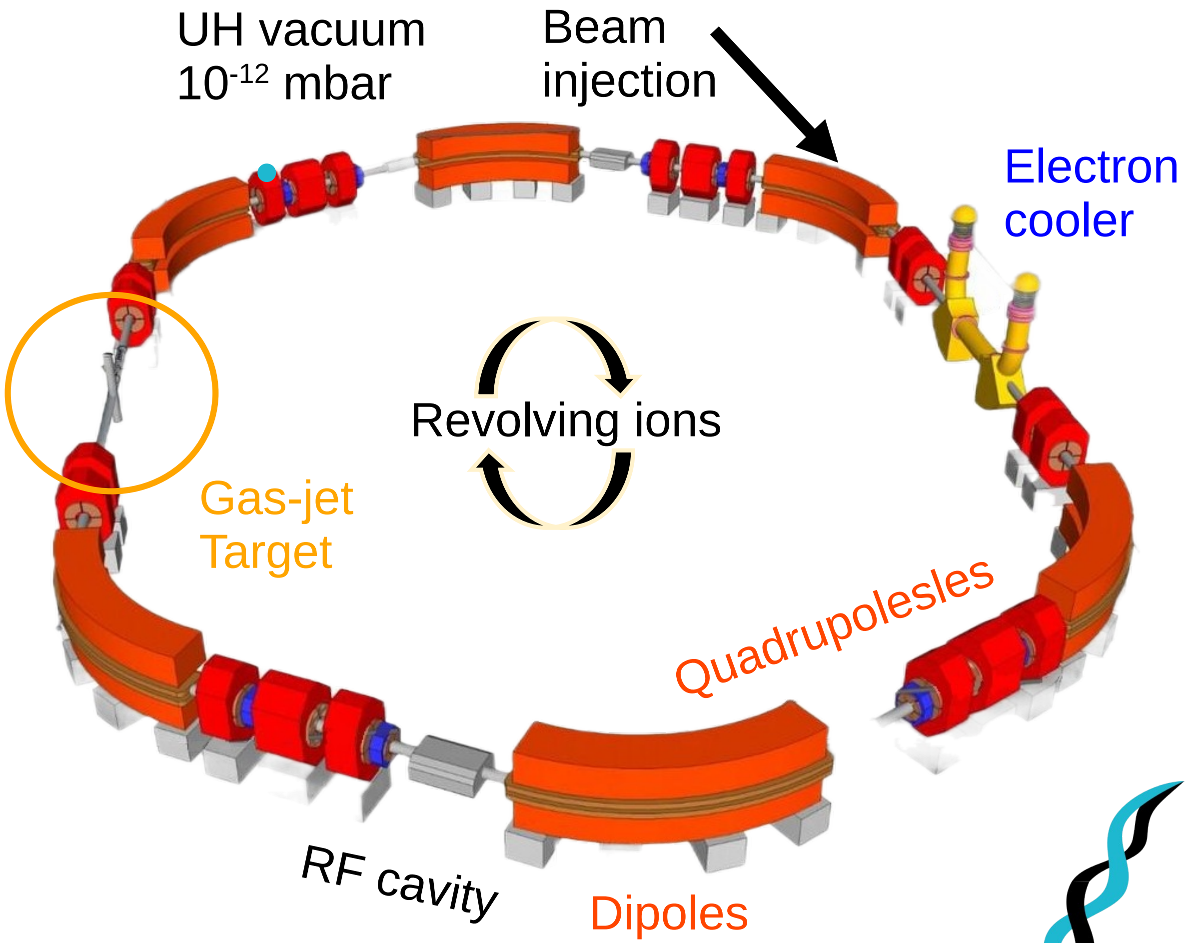
Surrogate reactions in inverse kinematics

- 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**



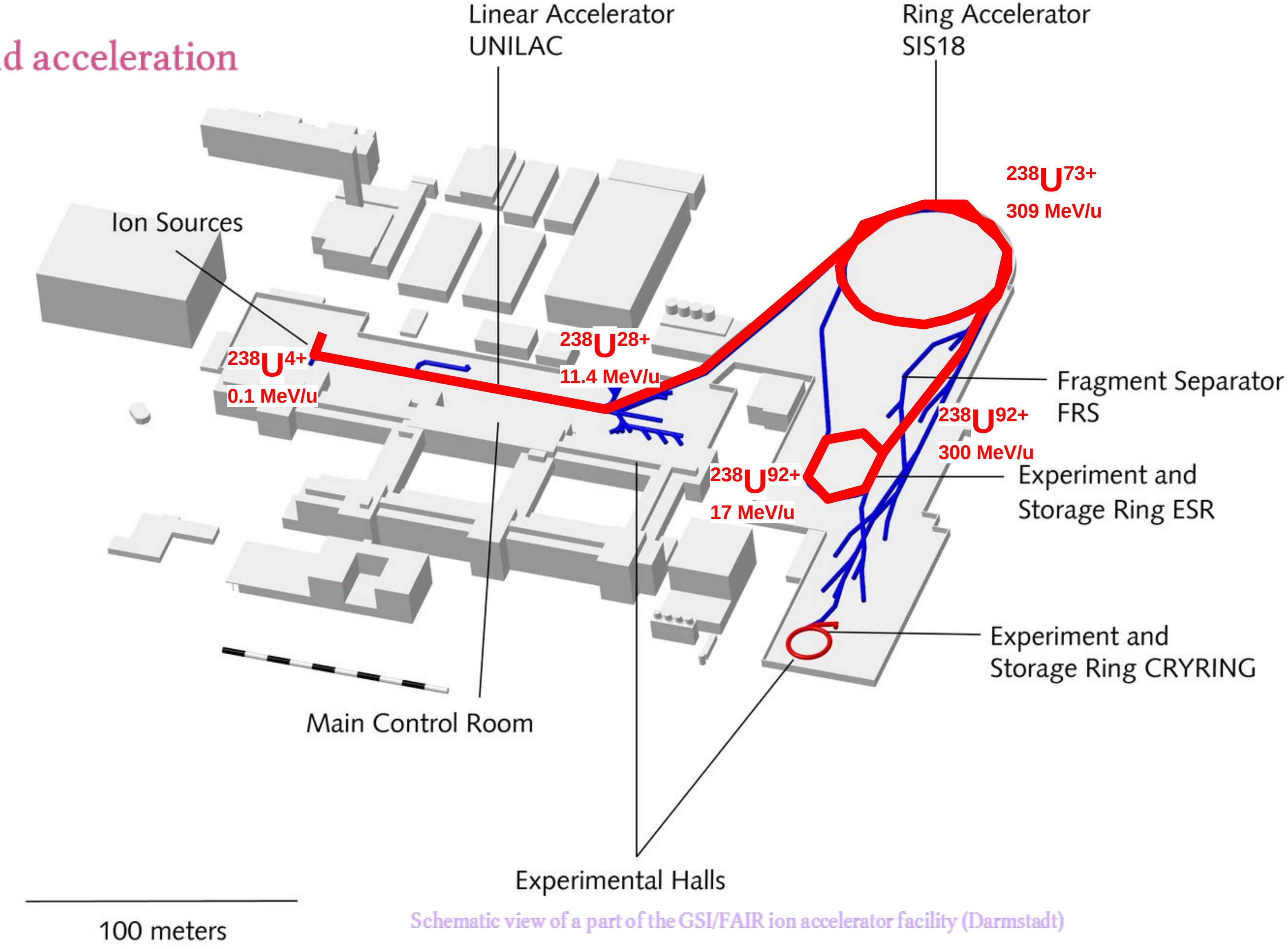
Why Surrogate reaction in Storage Rings?

- 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



ESR ring at the GSI/FAIR in Darmstadt

Beam production and acceleration



Schematic view of a part of the GSI/FAIR ion accelerator facility (Darmstadt)

NECTAR experiment at the ESR

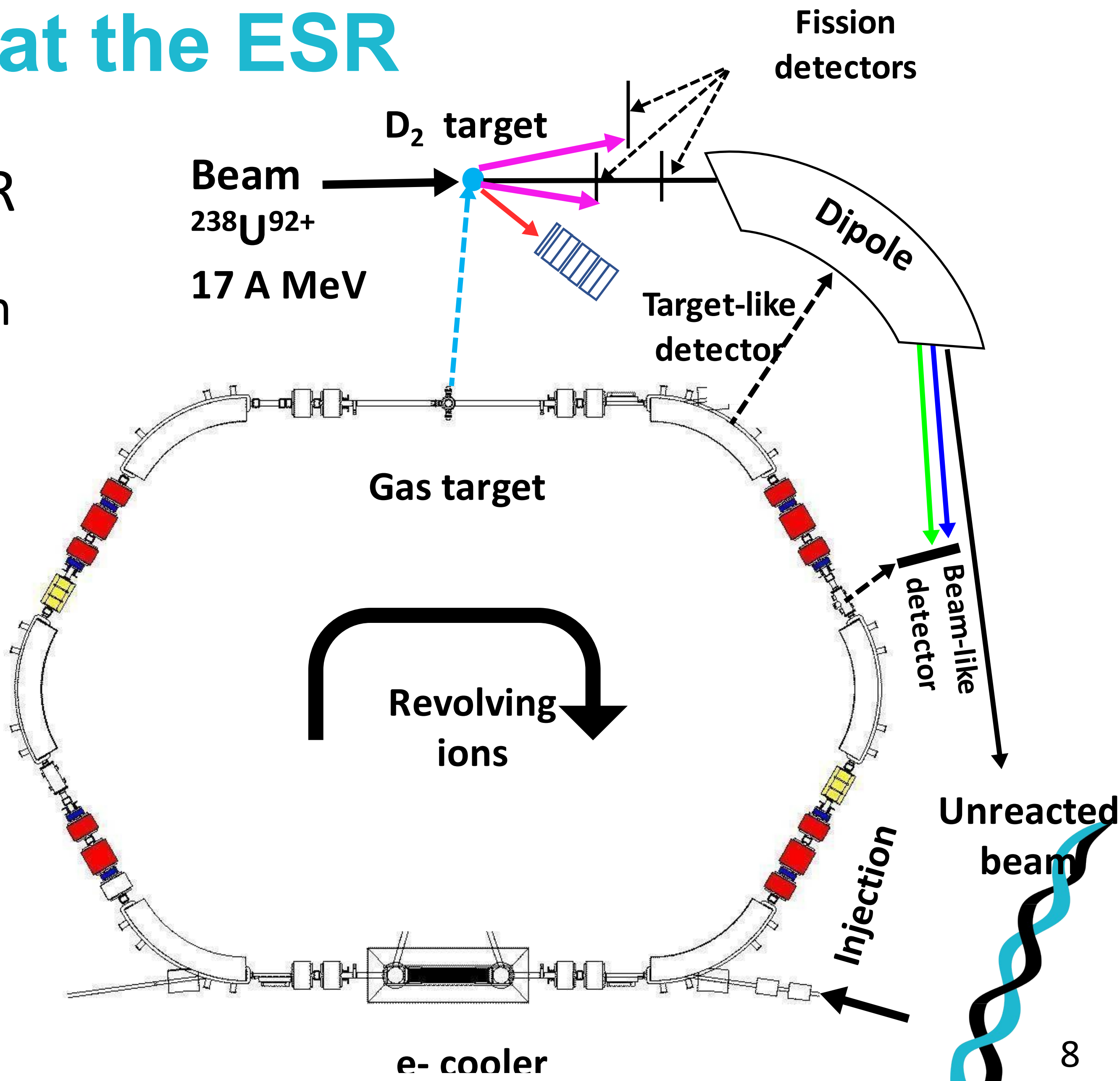
- Two experiments performed at ESR

- First proof-of-principle in 2022 $^{208}Pb^{82+}$ 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

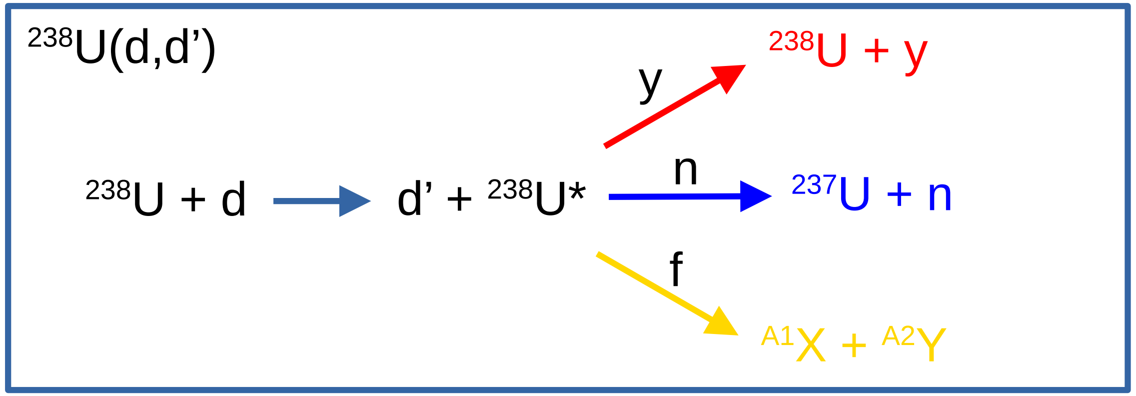
- Second proof-of-principle In 2024 $^{238}U^{92+}$ on D_2 at 17 MeV/u



2024 Uranium experiment

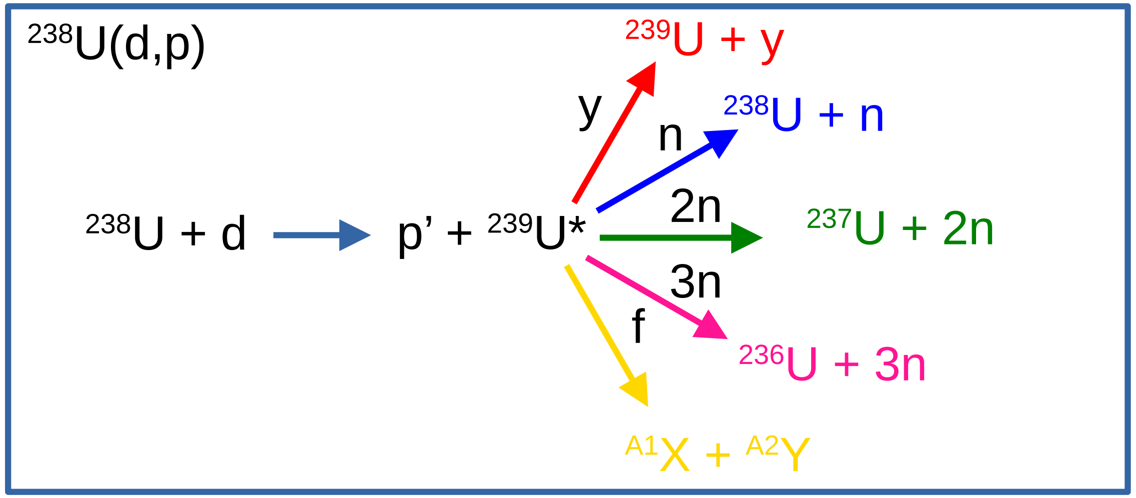
- Deuteron inelastic scattering

  Surrogate for n + ^{237}U



- Neutron transfer reaction

  Surrogate for n + ^{238}U



2024 Uranium experiment

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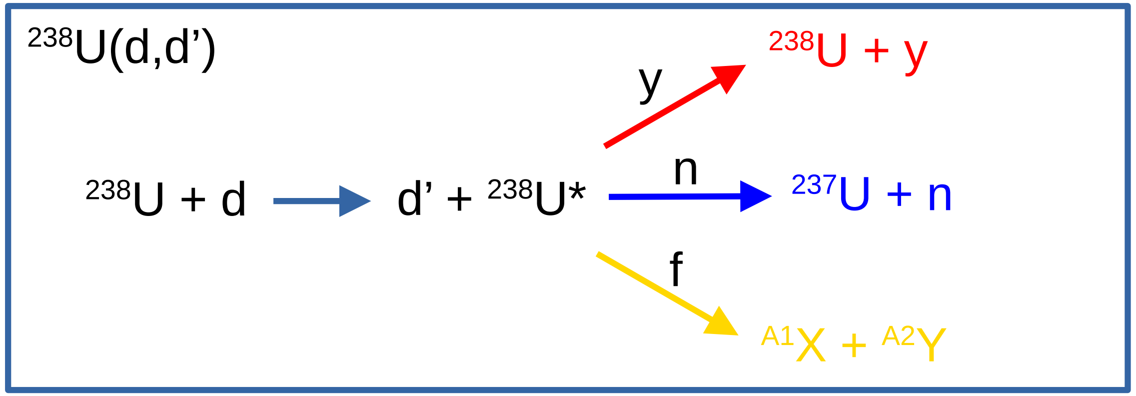
Surrogate for n + ^{237}U



- Neutron transfer reaction

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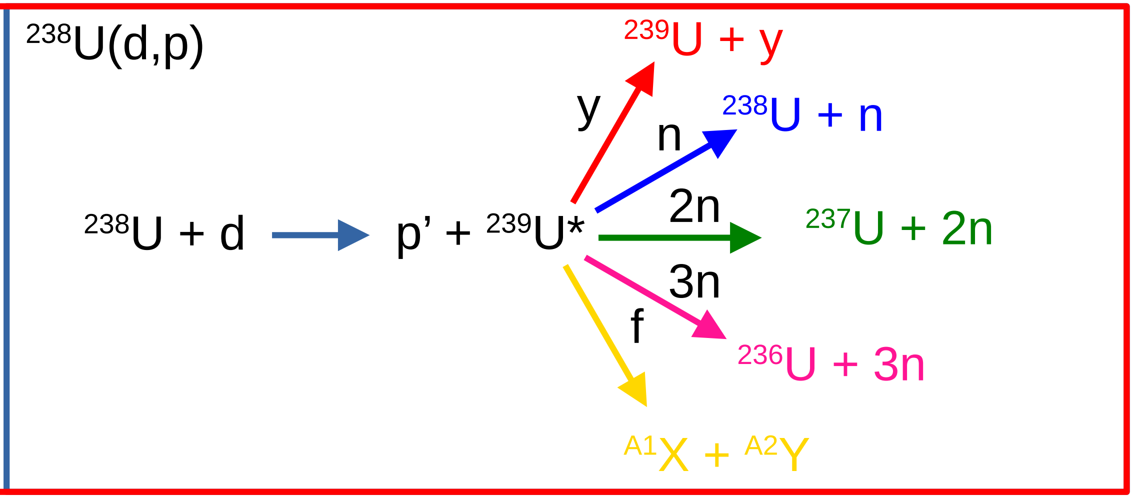
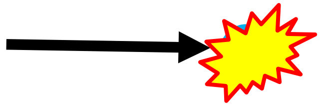


NECTAR experiment at the ESR

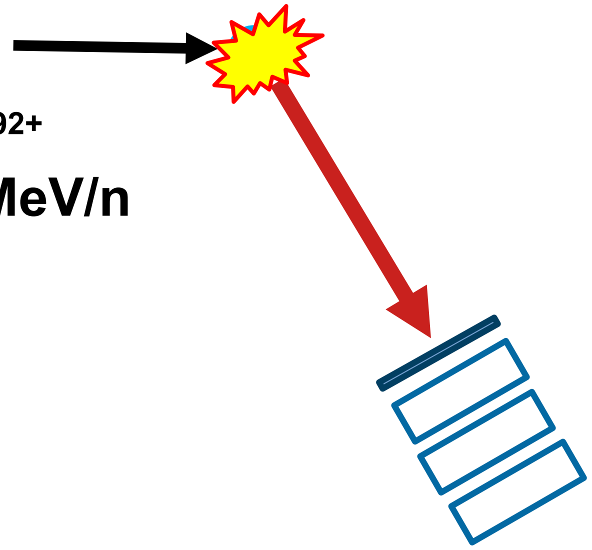
Formation and decay of compound nucleus (~10^{-20} s)



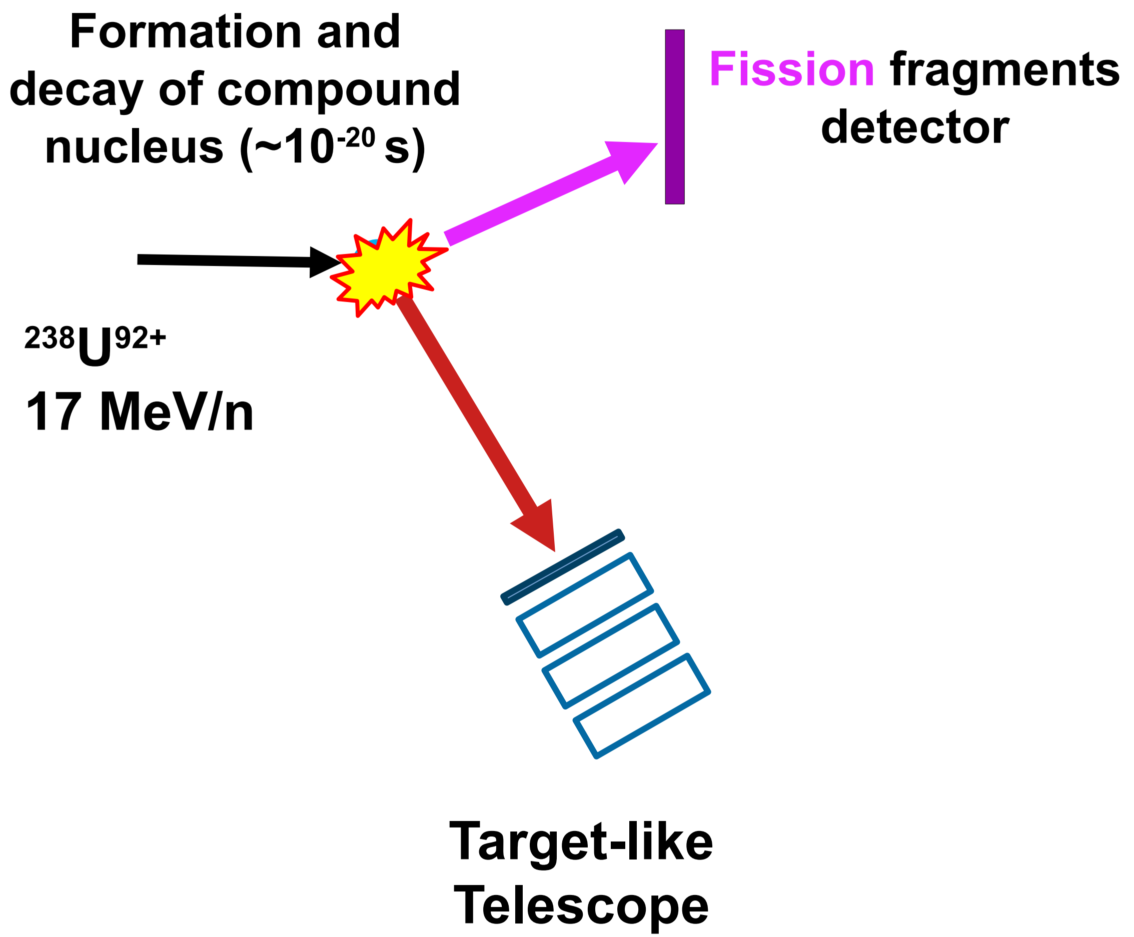
$^{238}U^{92+}$

17 MeV/n

NECTAR experiment at the ESR



NECTAR experiment at the ESR



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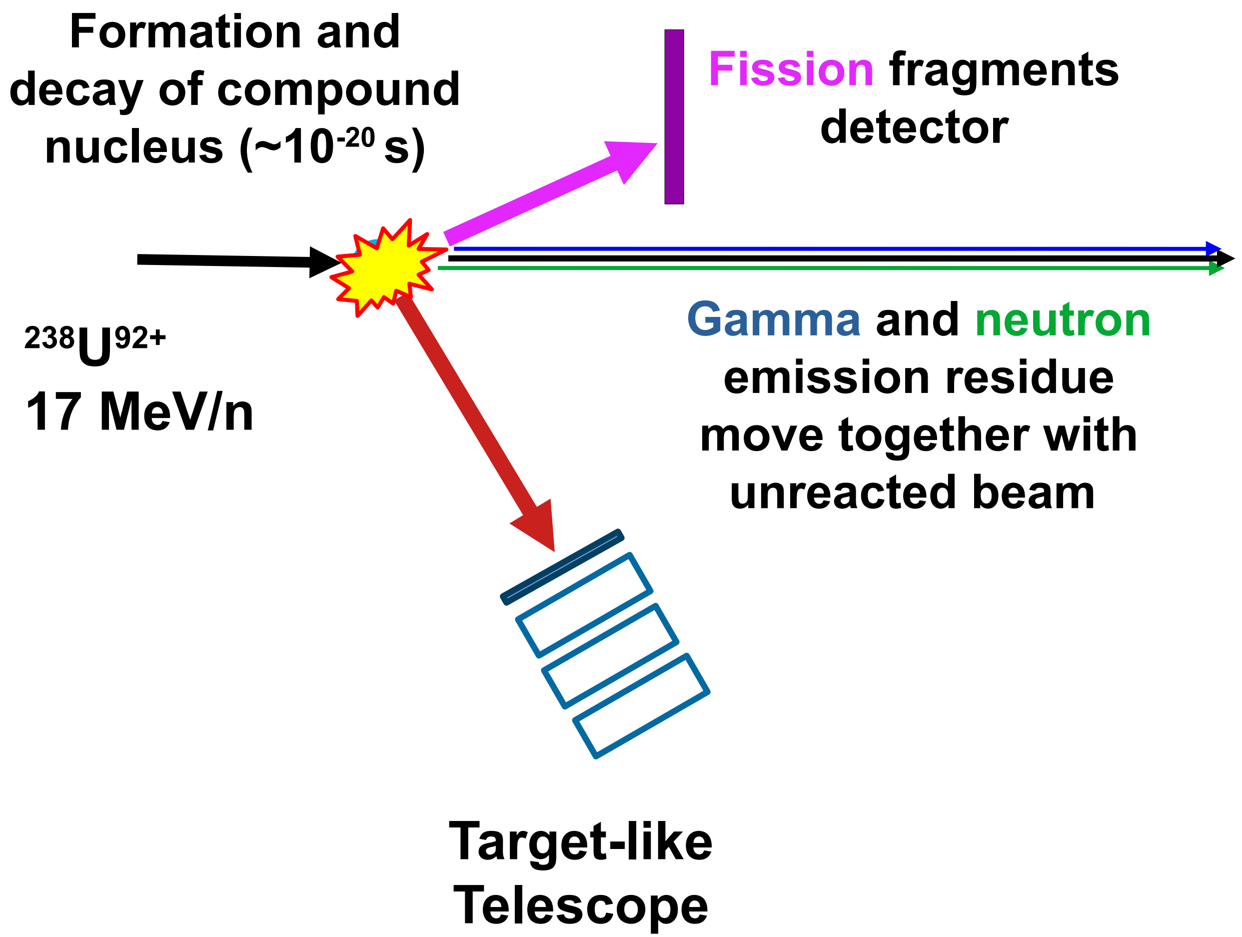
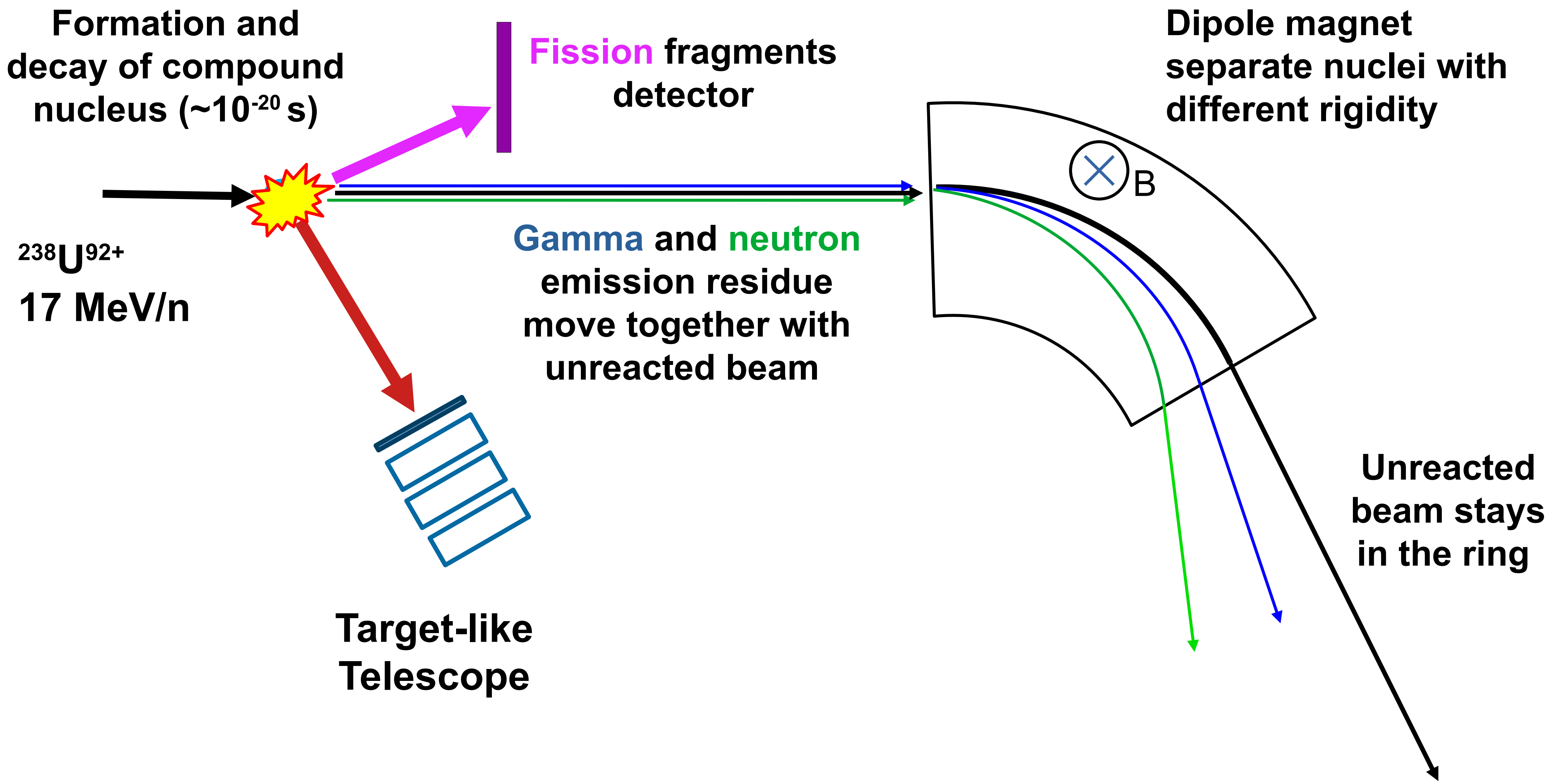
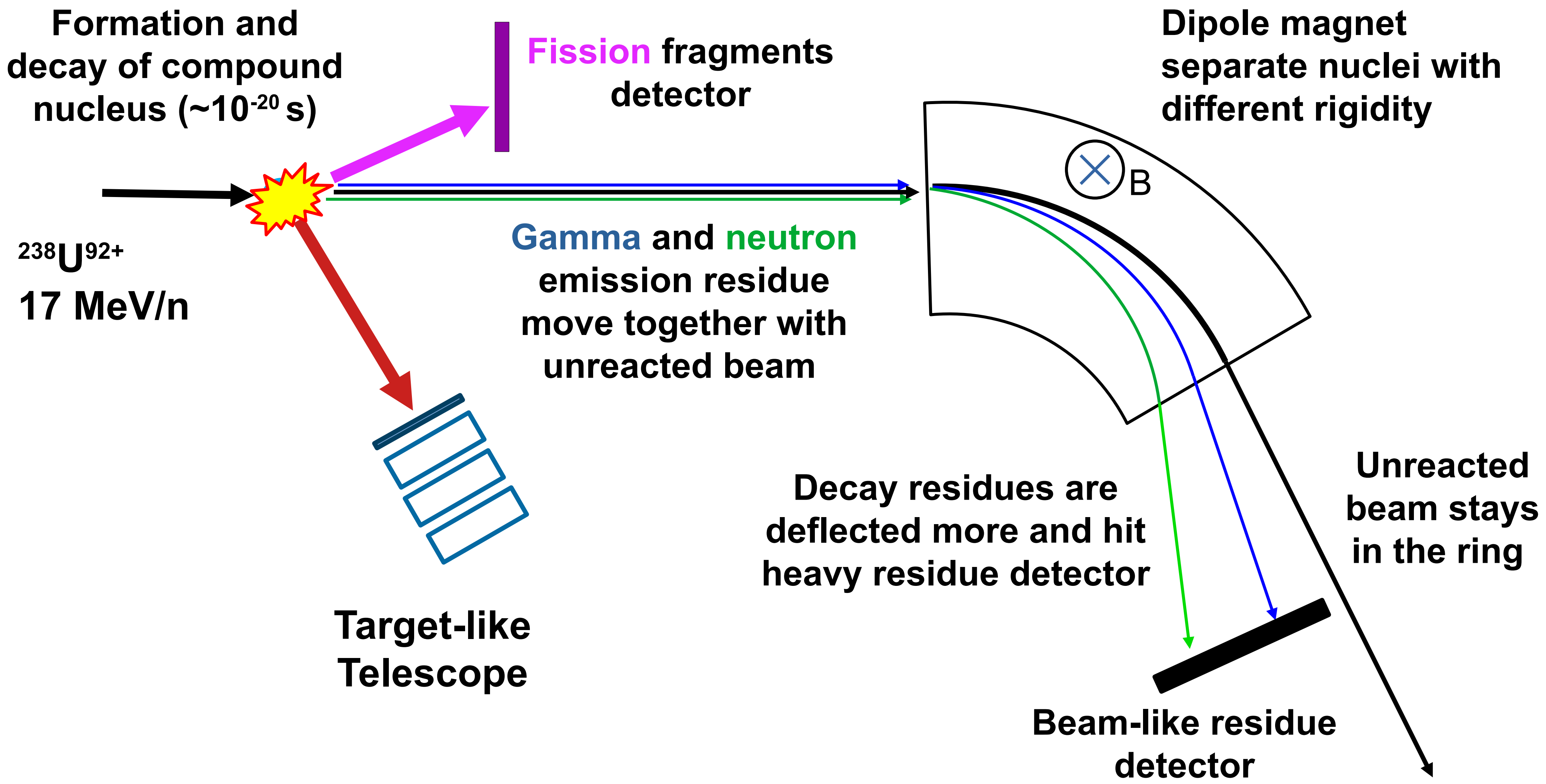


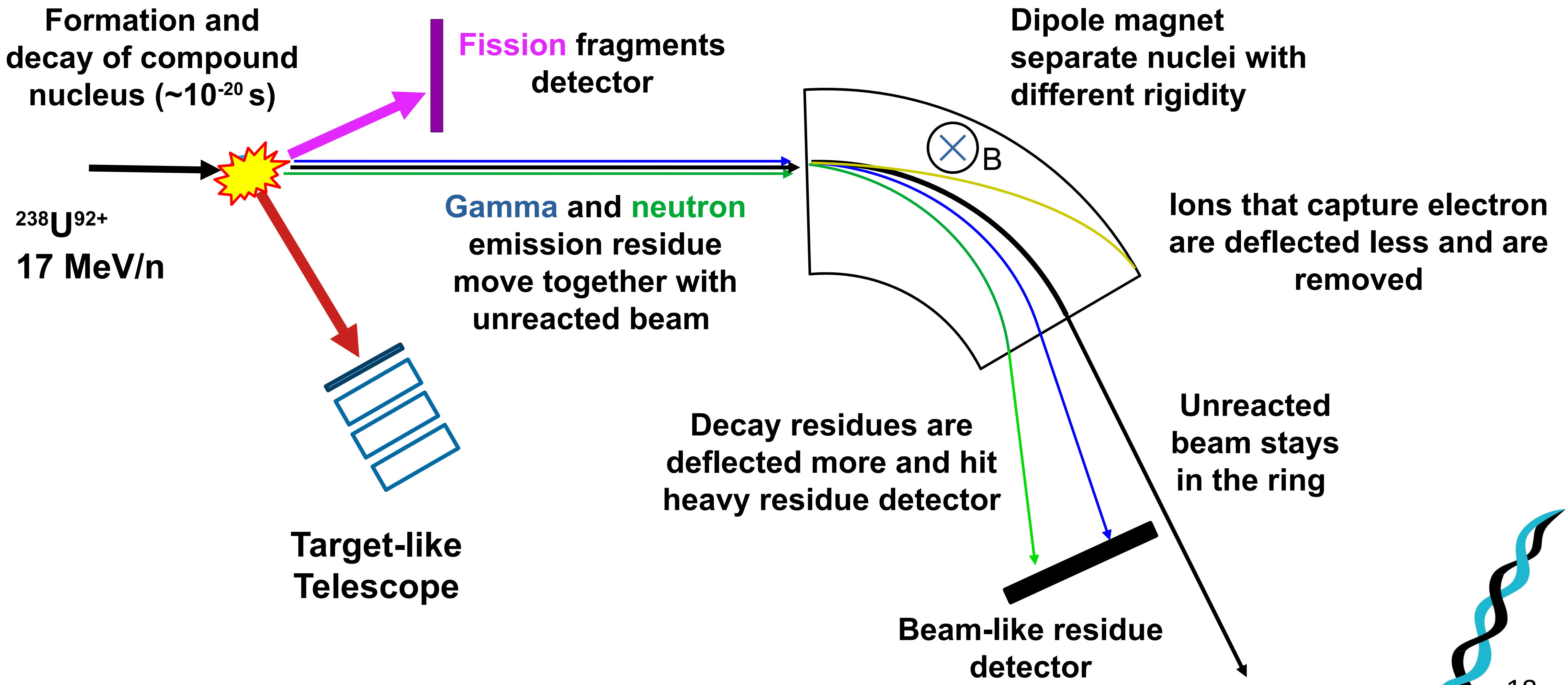
NECTAR experiment at the ESR



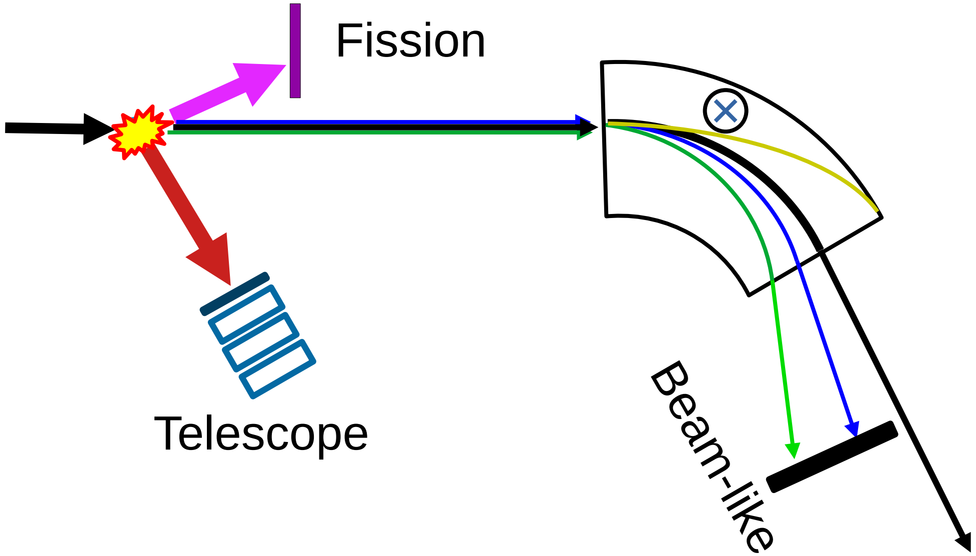
NECTAR experiment at the ESR



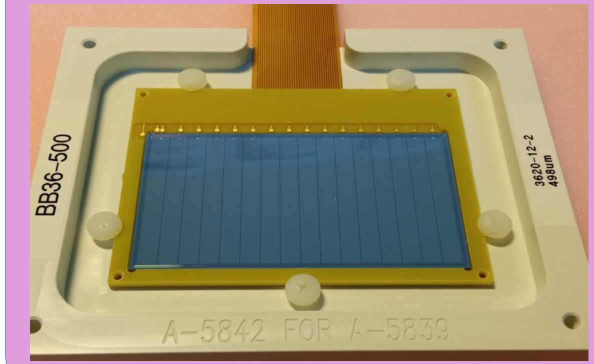
NECTAR experiment at the ESR



Detectors design

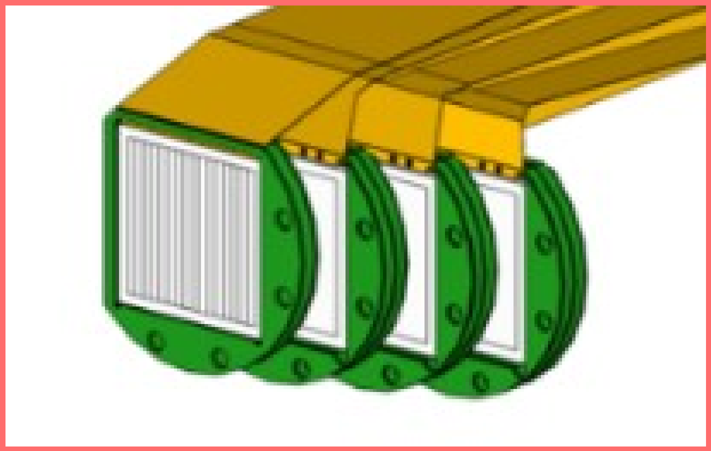


Fission detectors



Top and bottom
80*40mm DSSSD

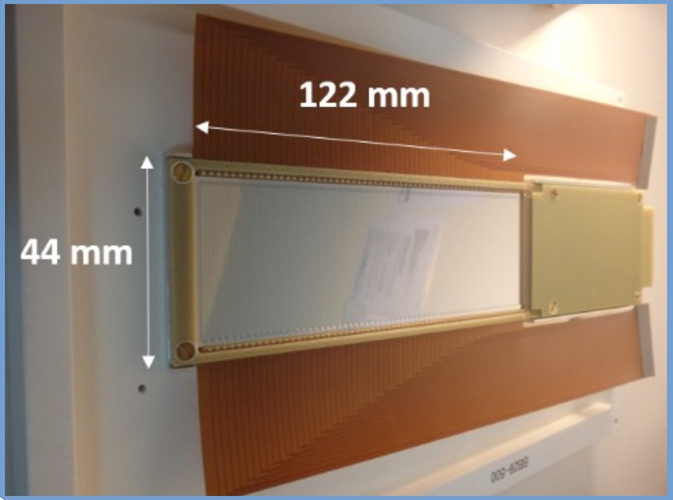
Side
122*44mm DSSSD



Telescope

Position-sensitive
ΔE
20*20mm DSSSD

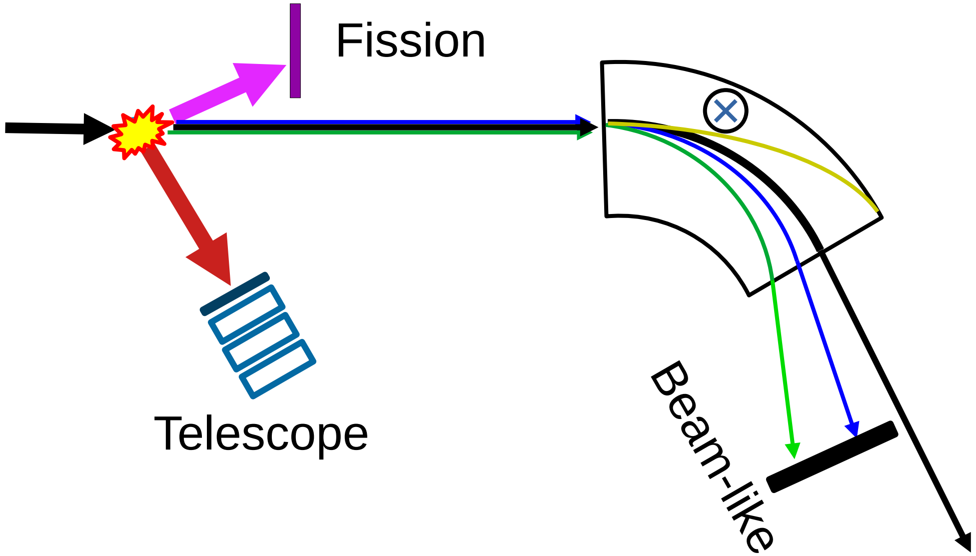
Stack of 6 Si E detectors

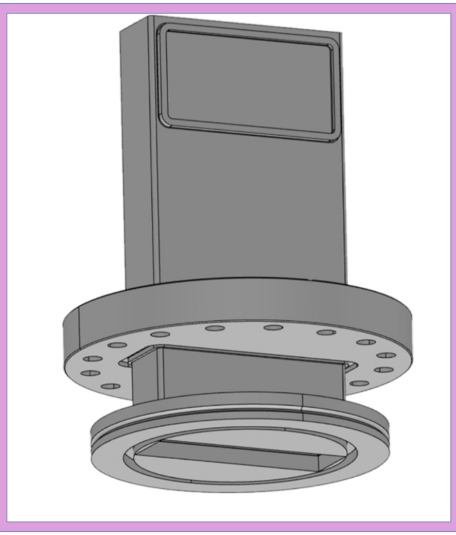


Beam-like Detector

122*44mm DSSSD

Ultra-high vacuum compatible pockets





Fission detectors

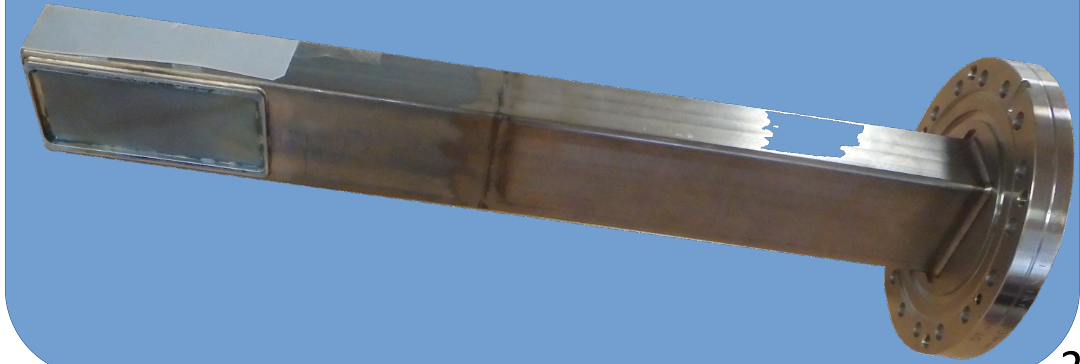
Rectangular pocket (MPIK Heidelberg)

Telescope

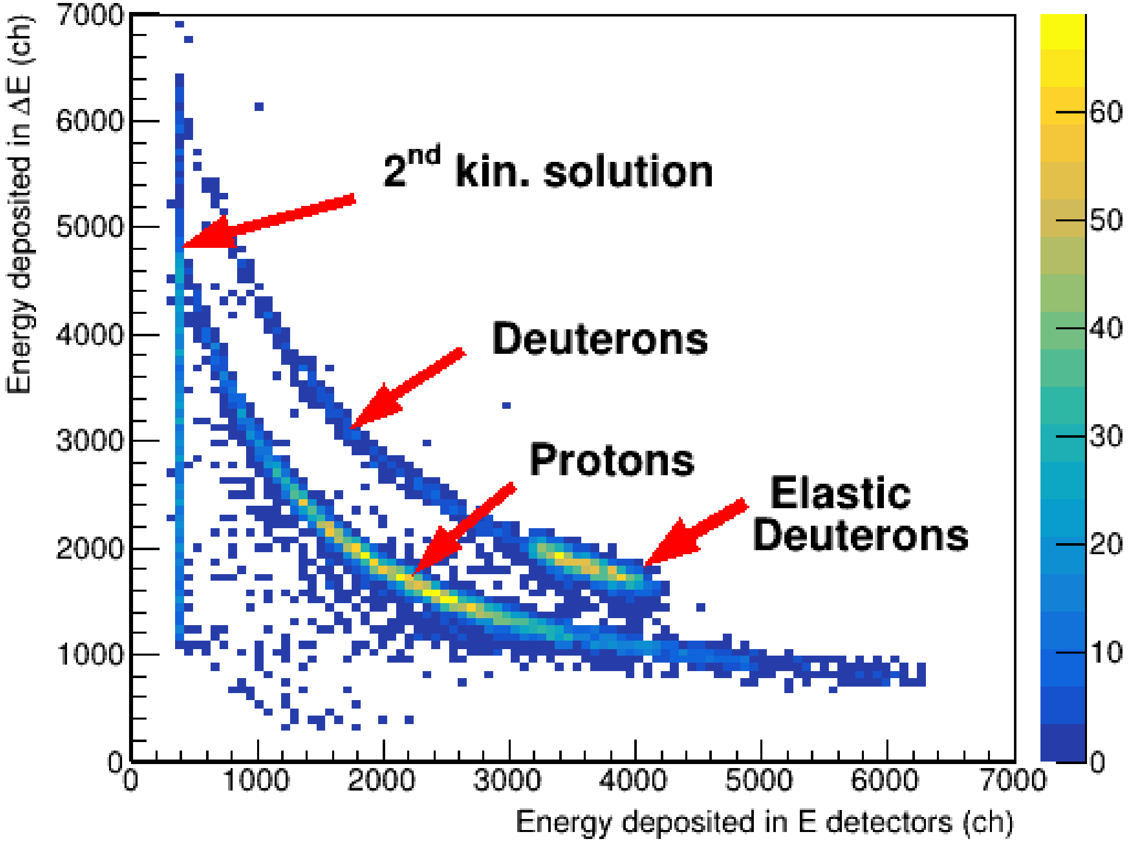
Cylindrical pocket

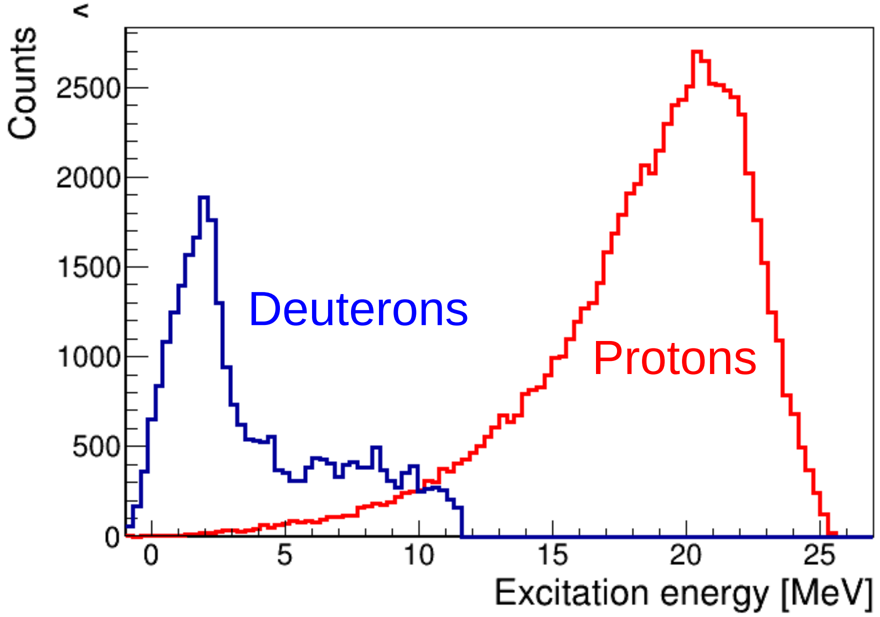
(MPIK Heidelberg)

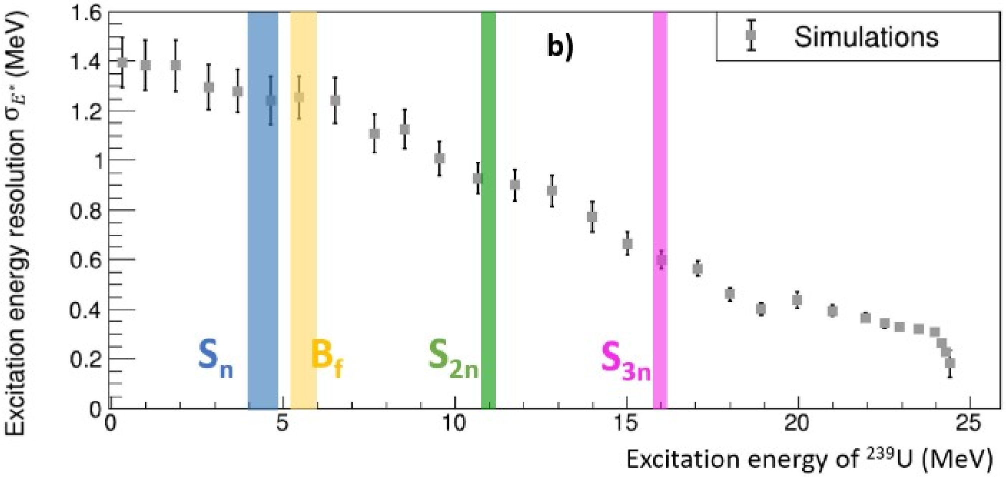
Beam-like Detector
Rectangular Pocket (GSI)



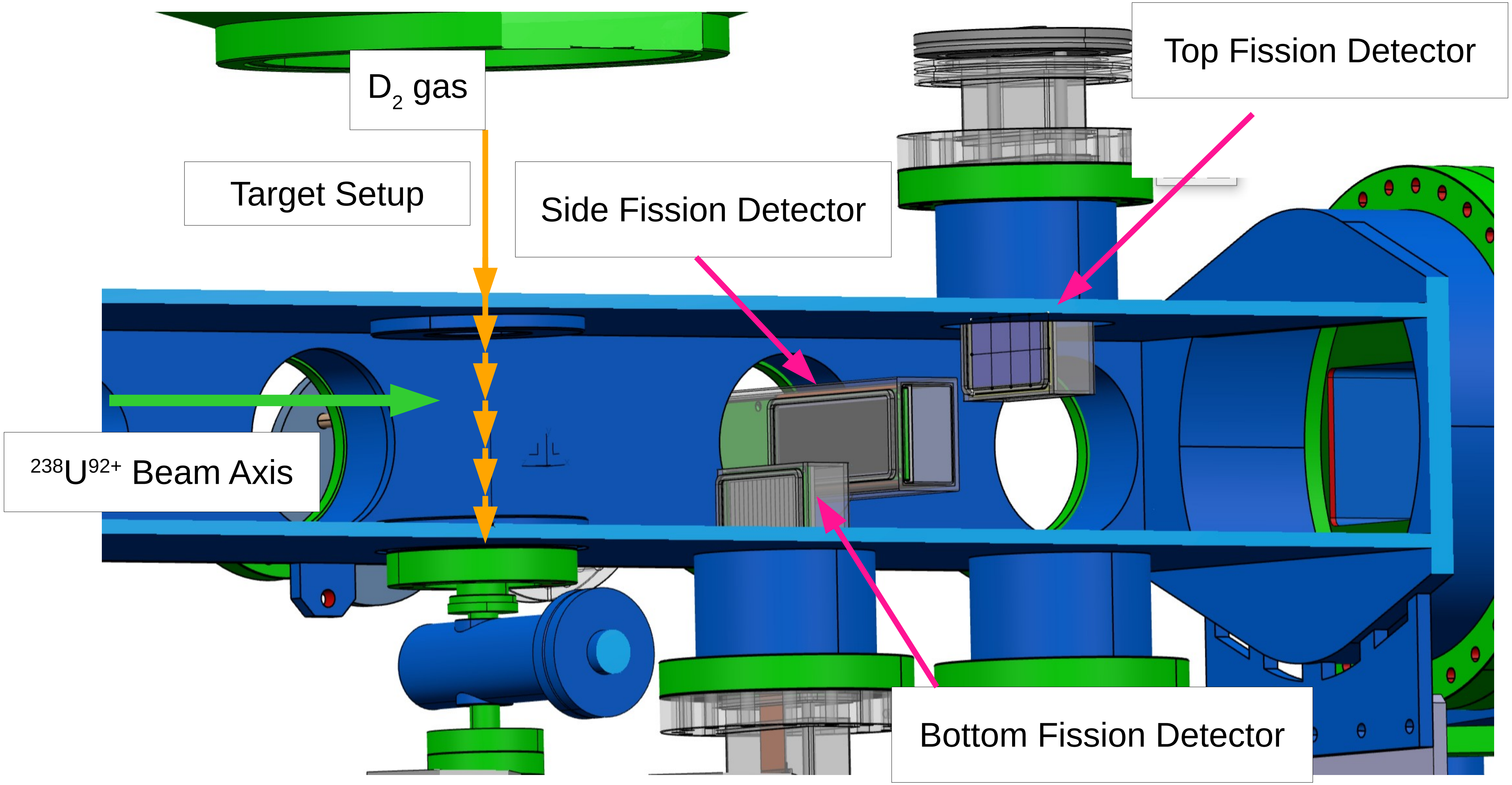
Target-like residue detector (Telescope)





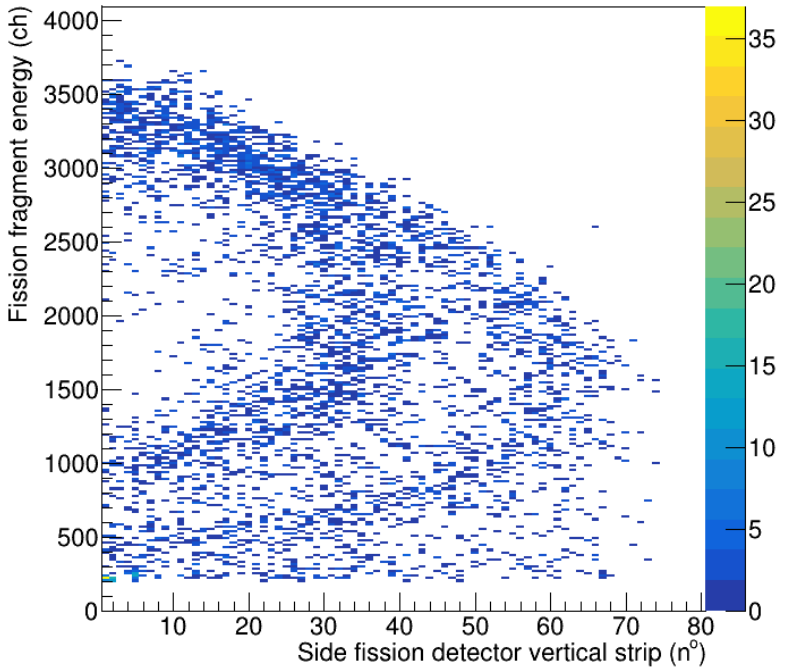


Fission fragments detectors

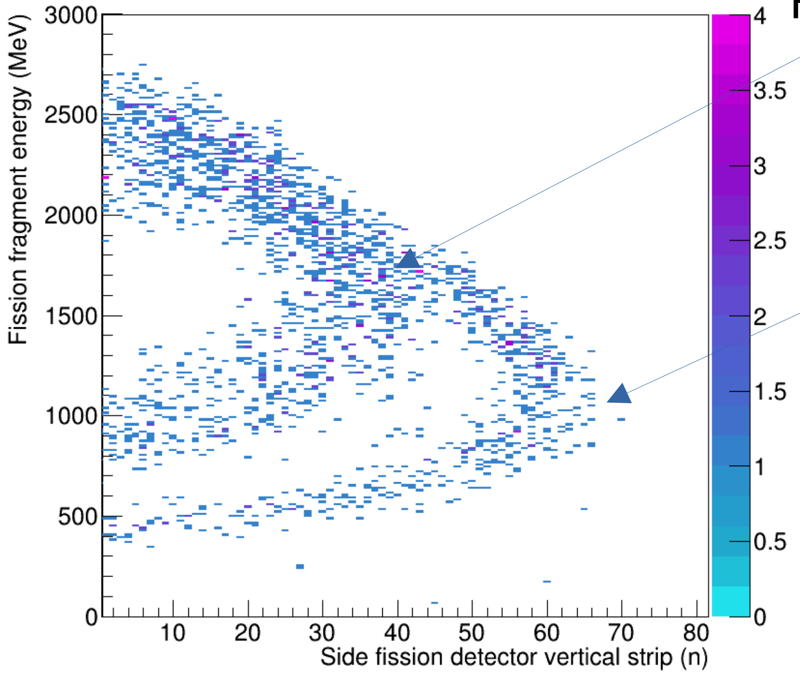


Fission fragments detector

Experimental results

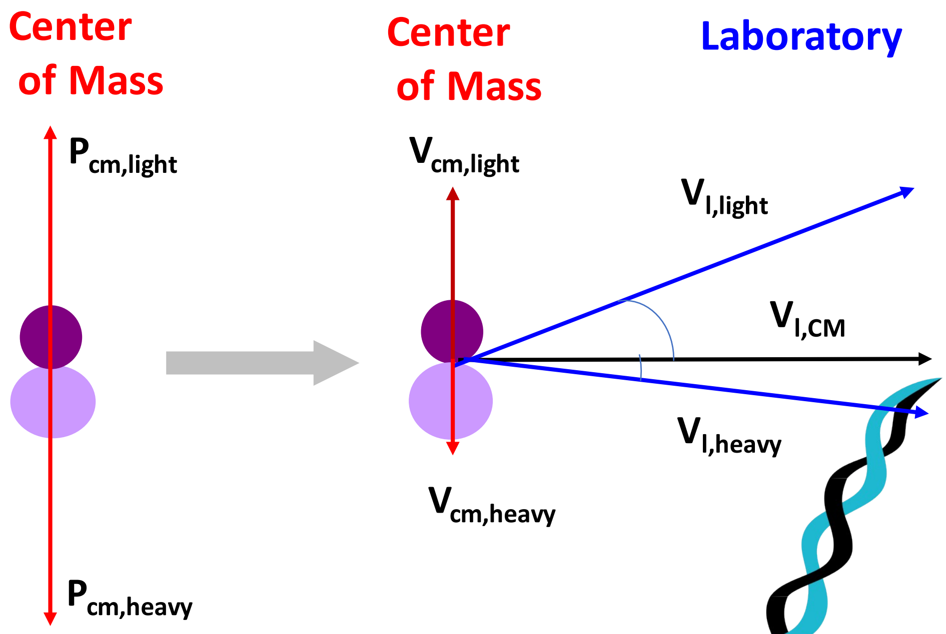


Simulated distribution



Heavy fission fragments

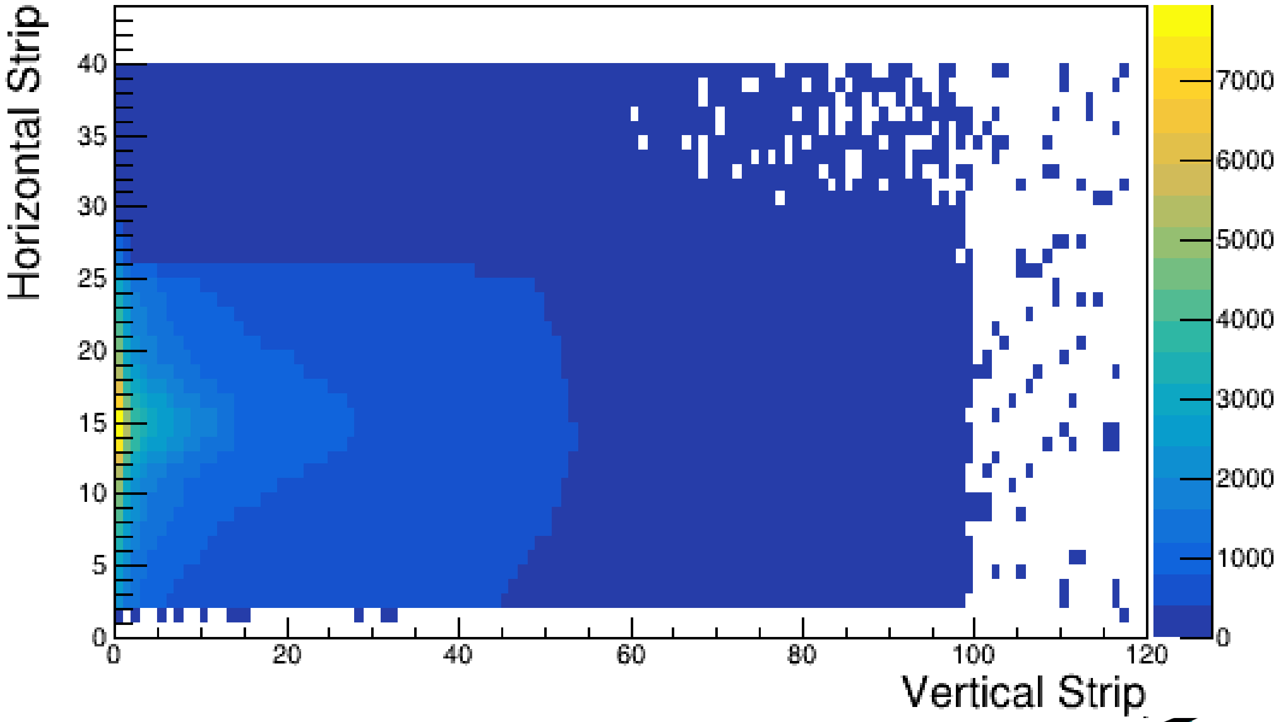
Light fission fragments



First ever Fission measurement in heavy-ion storage rings!

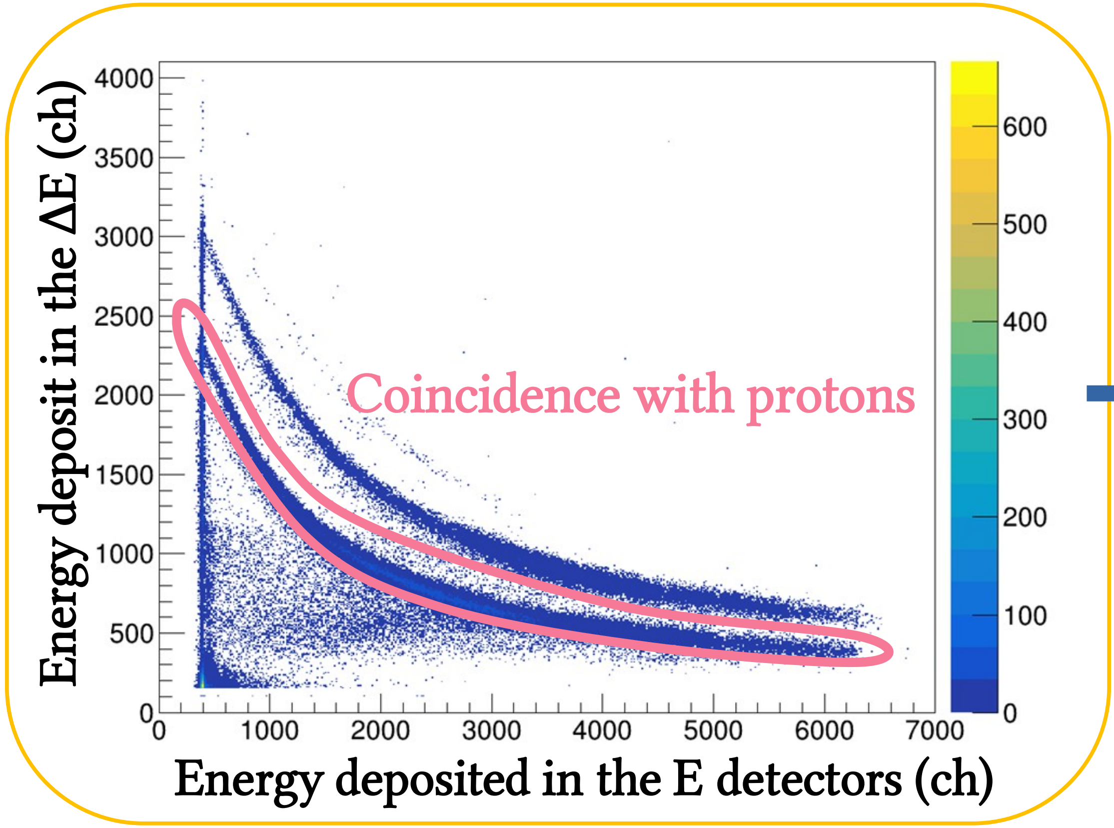
Beam-like residue detector, $^{238}U(d,p)$

- Without coincindeces (singles)

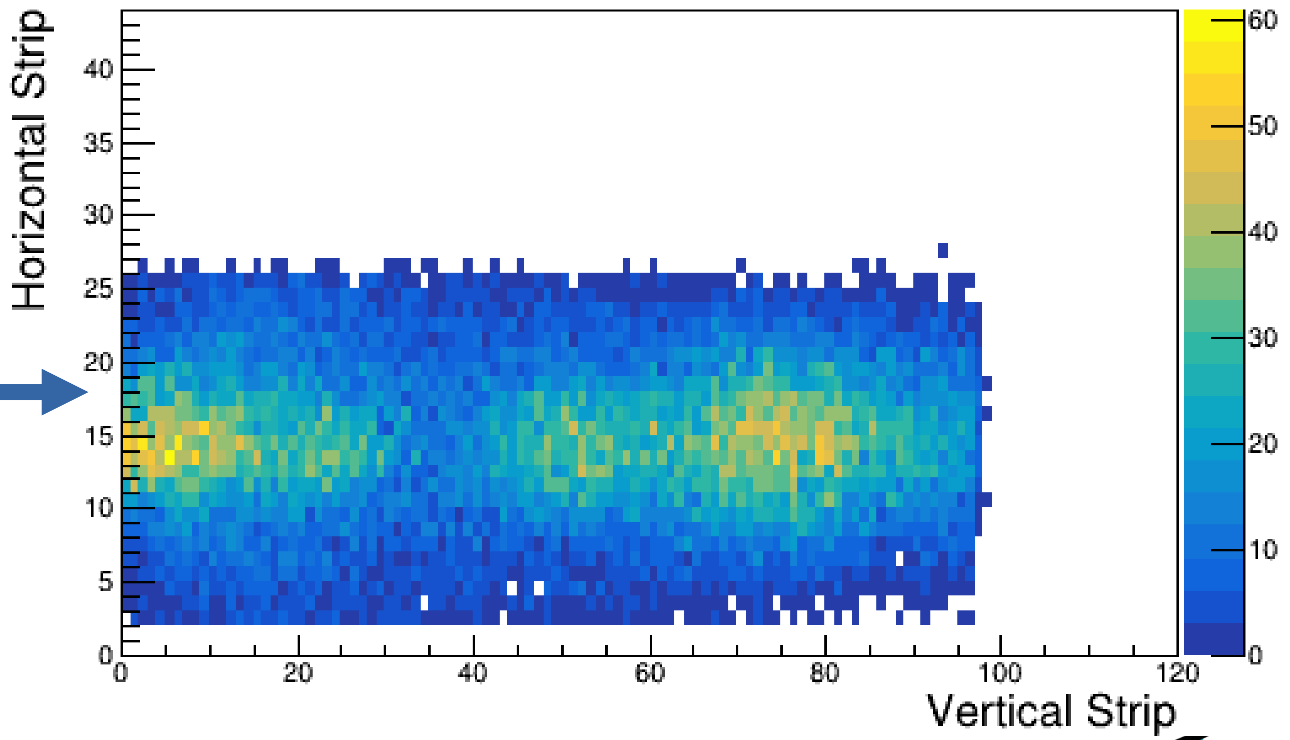


Beam-like residue detector, $^{238}U(d,p)$

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

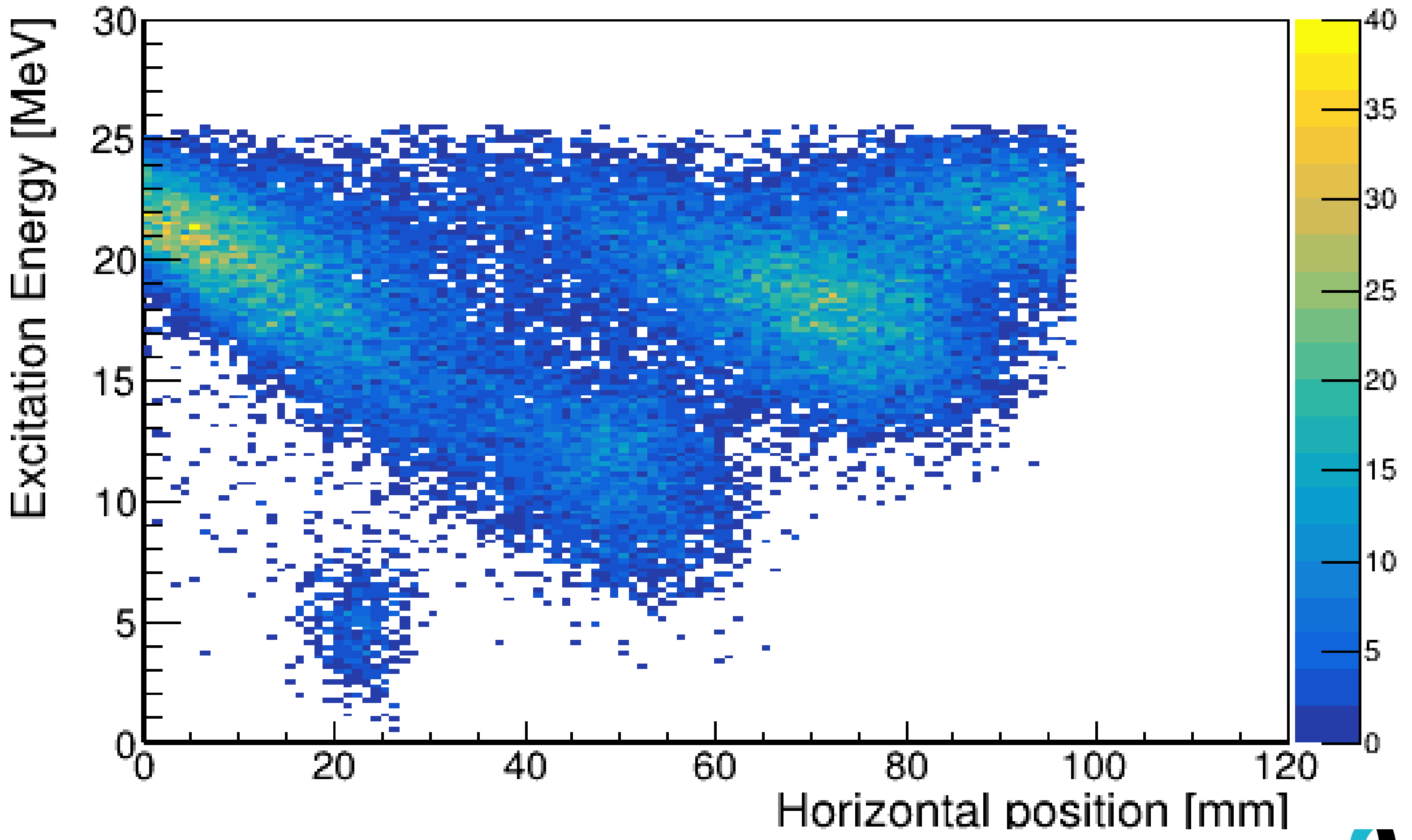


HR Coincidences (proton)



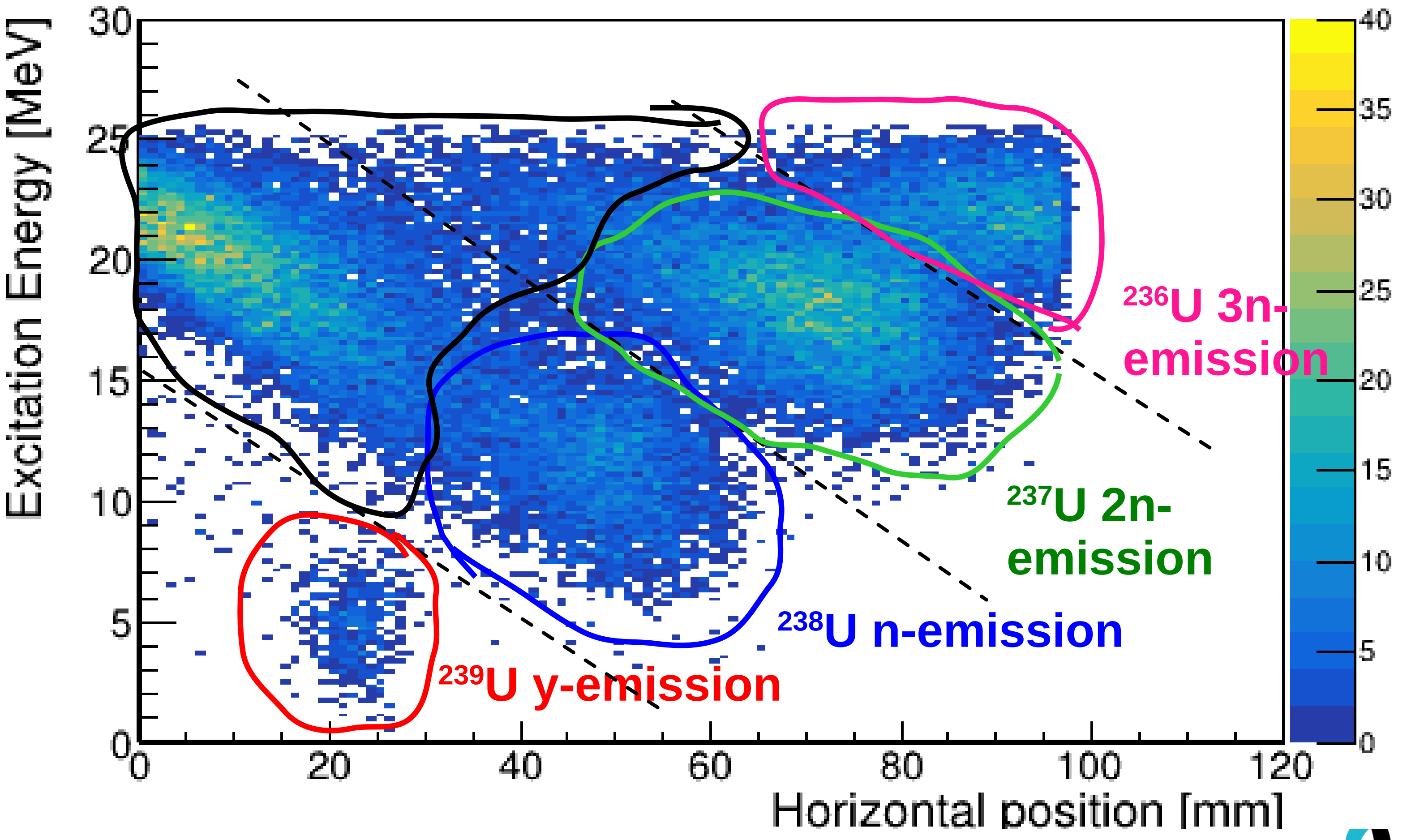
Beam-like residue detector, $^{238}U(d,p)$

- Beam-like residue position as a function of Excitation energy



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

- Beam-like residue position as a function of Excitation energy
- We can identify y-emission and n,2n,3n emission!
- Very high detection efficiency!
- All possible decay channels measured simultaneously!



De-excitation probabilities

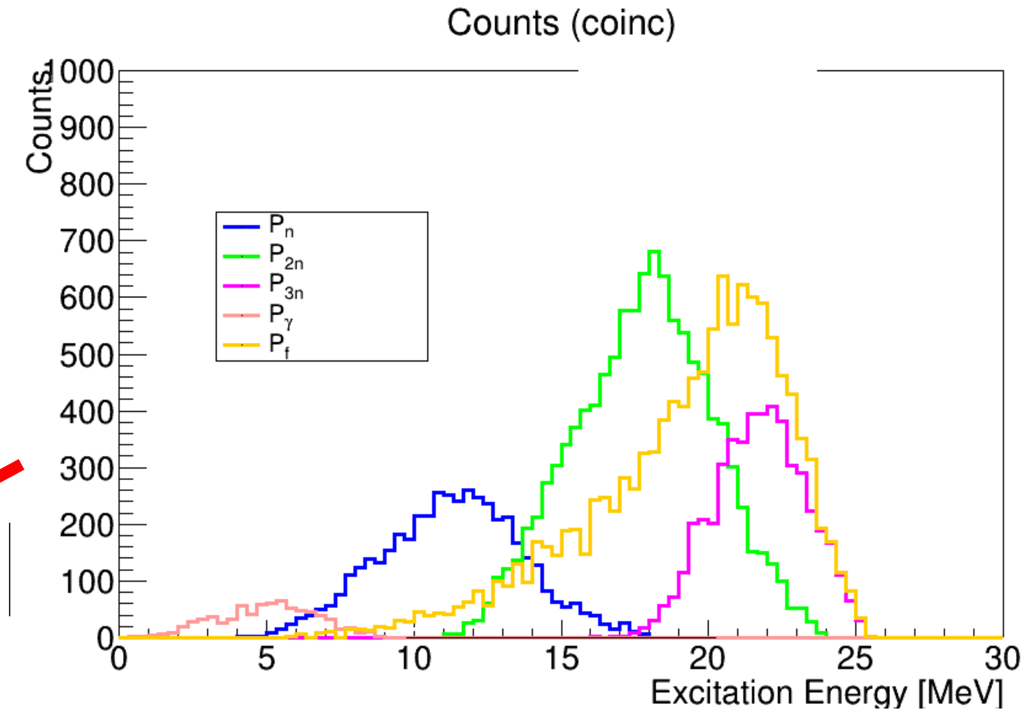
- Probability for a given excitation E* and decay mode χ:

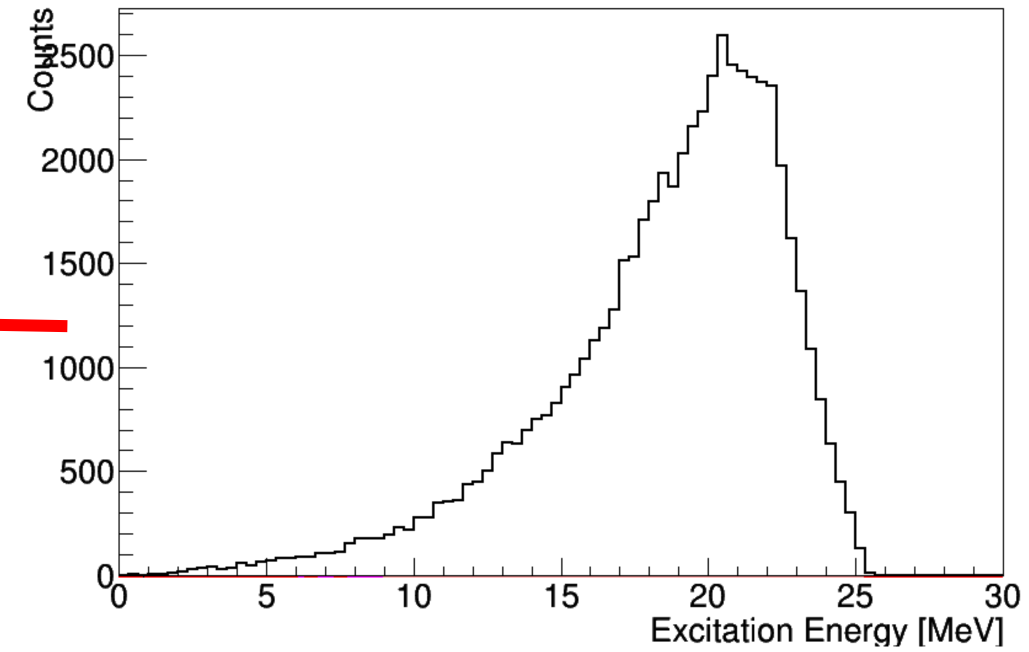
Number of coincidence events

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

Detection Efficiency

Number of singles in Telescope



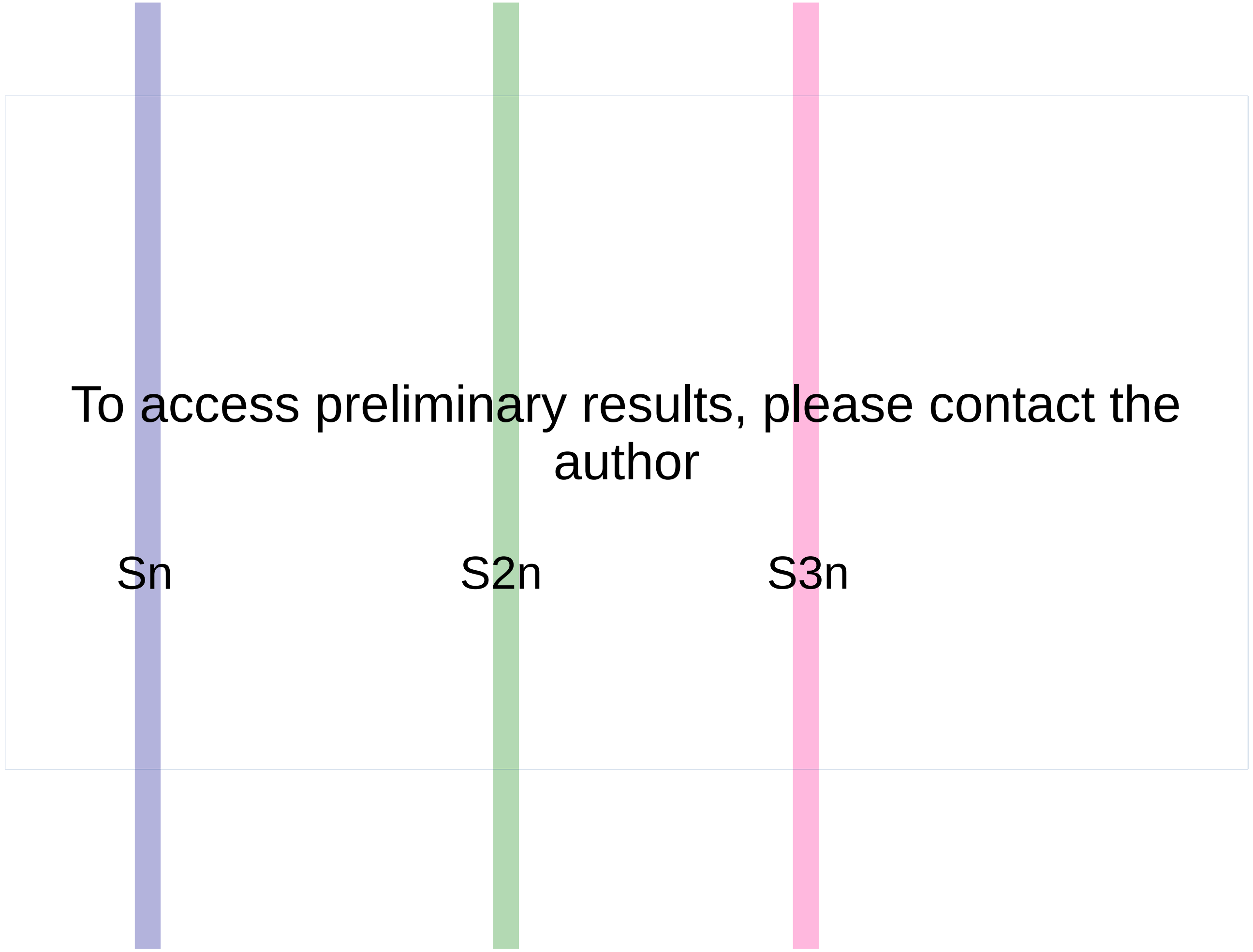


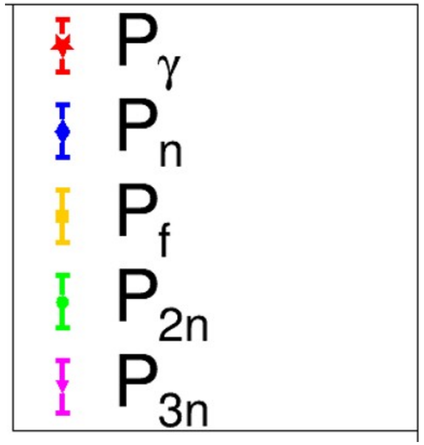
Comparison with the n-induced calculations

To access preliminary results, please contact the author

Done by Pascal Romain

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

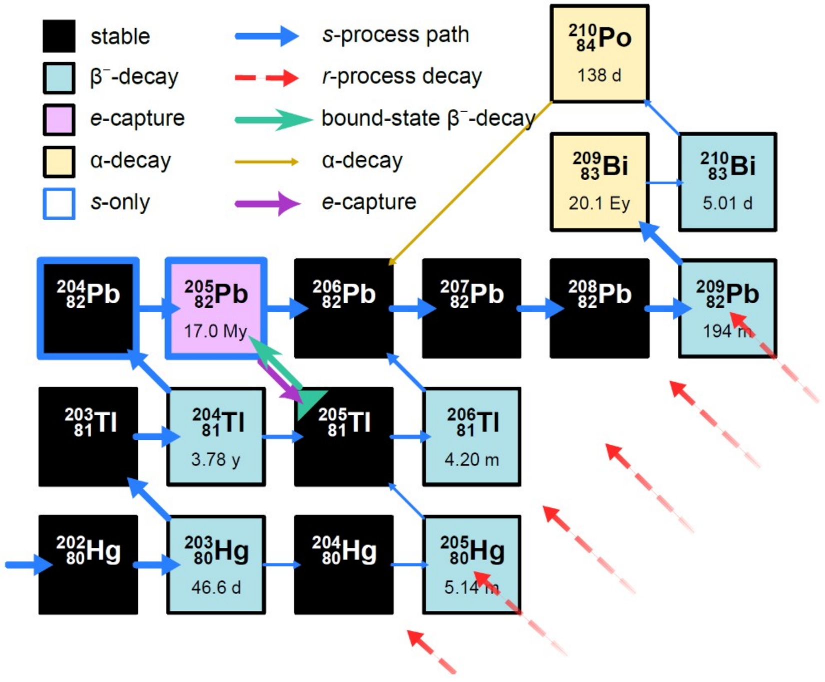




Calculation by Gregory Potel, Experimental resolution included

Plans for the future – radioactive beams!

- 2027 NECTAR experiment will study ^{206}Pb* with two reactions
  - ^{206}Pb(p,p’) and ^{205}Pb(d,p)
- ^{205}Pb radioactive beam produced by 1n removal on Au target
- Motivated by astrophysics and nuclear technology
  - ^{205}Pb as a cosmochronometer for early Solar System
  - Accelerator driven reactors



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High-temperature ^{205}Tl decay clarifies ^{205}Pb dating in early Solar System

Guy Leckenby, Ragandeep Singh Sidhu, Rui Jiu Chen, Riccardo Mancino, Balázs Szányi, Mei Bai, Umberto Battino, Klaus Blaum, Carsten Brandau, Sergio Cristallo, Timo Dickel, Iris Dillmann, Dmytro Dmytriiev, Thomas Faestermann, Oliver Forstner, Bernhard Franczak, Hans Geissel, Roman Gernhäuser, Jan Glorius, Chris Griffin, Alexandre Gumberidze, Emma Haettner, Pierre-Michel Hillenbrand, Amanda Karakas, ... Jianwei Zhao + Show authors

Nature 635, 321–326 (2024) | Cite this article

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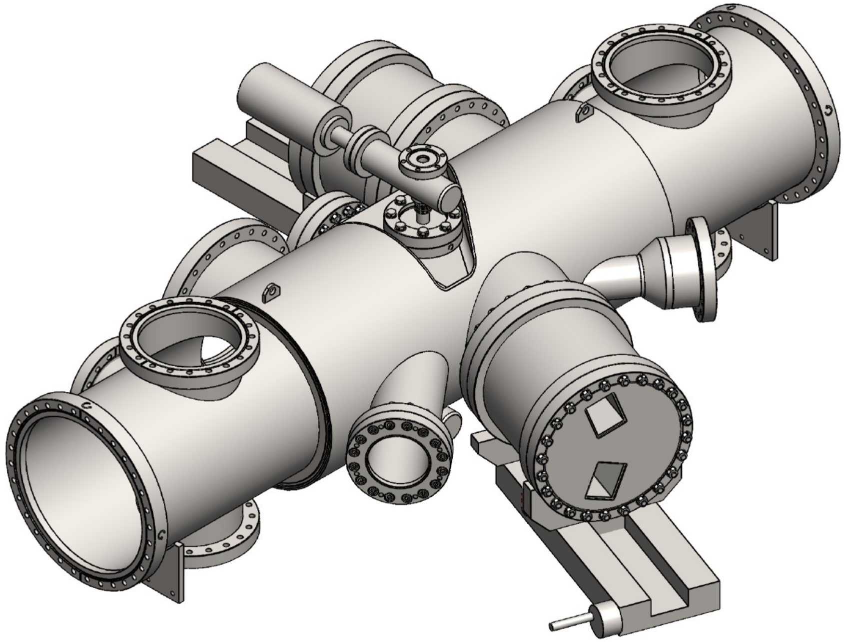
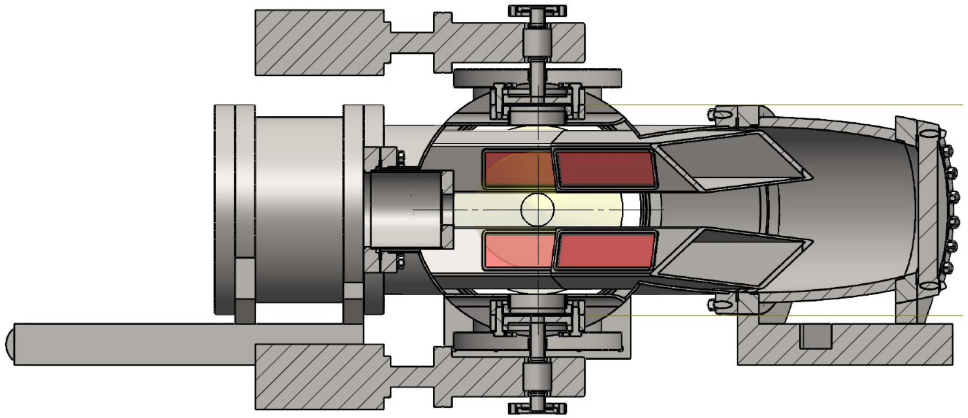
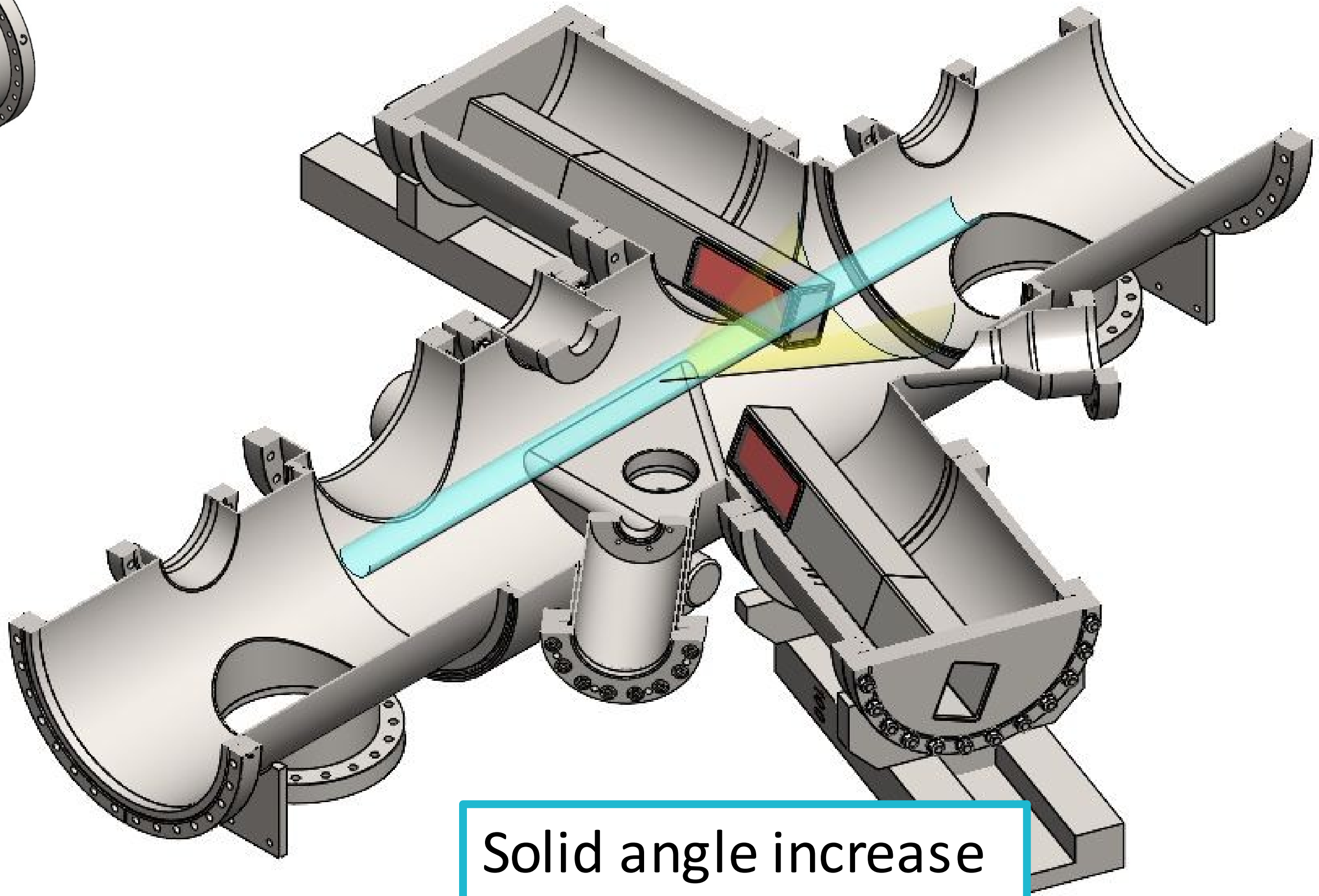
New reaction chamber at the ESR

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG







Solid angle increase by a factor of 230!!!

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}Pb(d,p) and ^{206}Pb(p,p') , our first experiment with radioactive beams,
- New reaction chamber and gas target, better resolution and more solid angle

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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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