Surrogate reaction in inverse kinematics at the ESR of the GSI/FAIR facility

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LP2i Bordeaux

European Research Council
Established by the European Commission

NECTAR
Nuclear rEaCTions At storage Rings

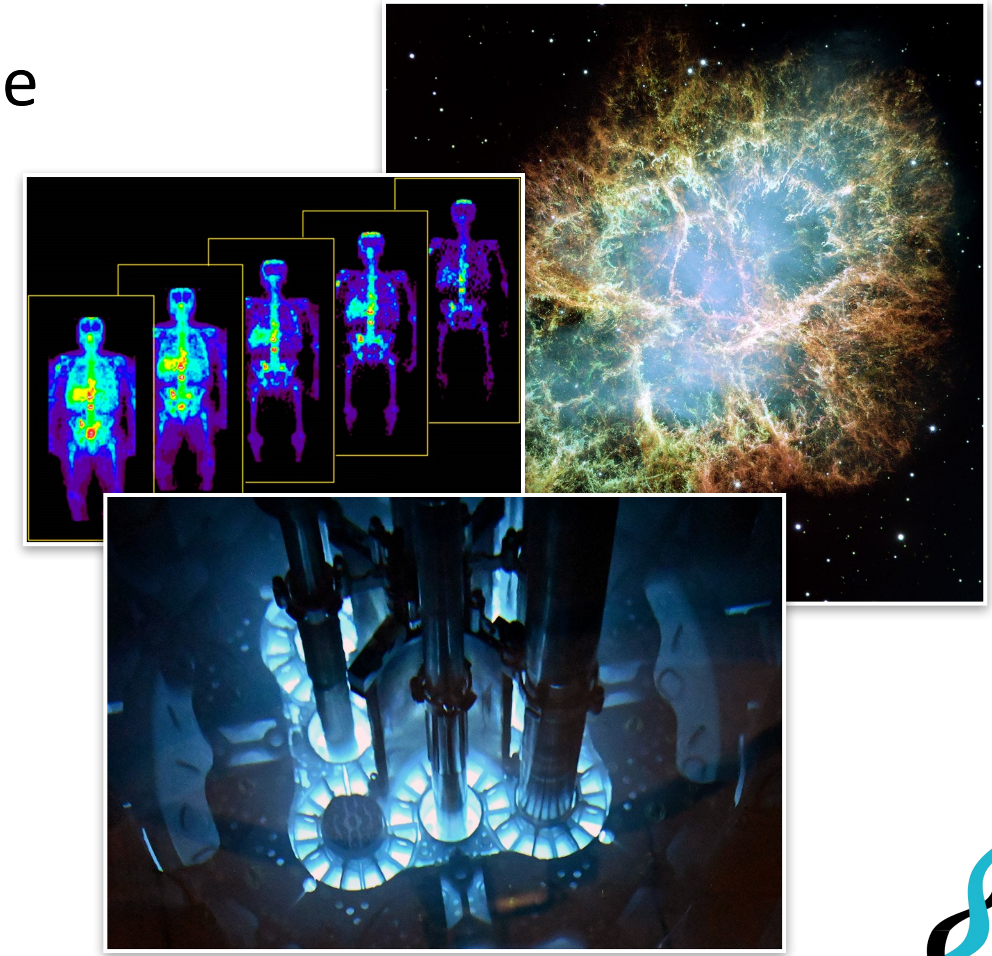
cnrs

université de BORDEAUX

FAIR
Phase 0
Research Program

Neutron capture cross sections

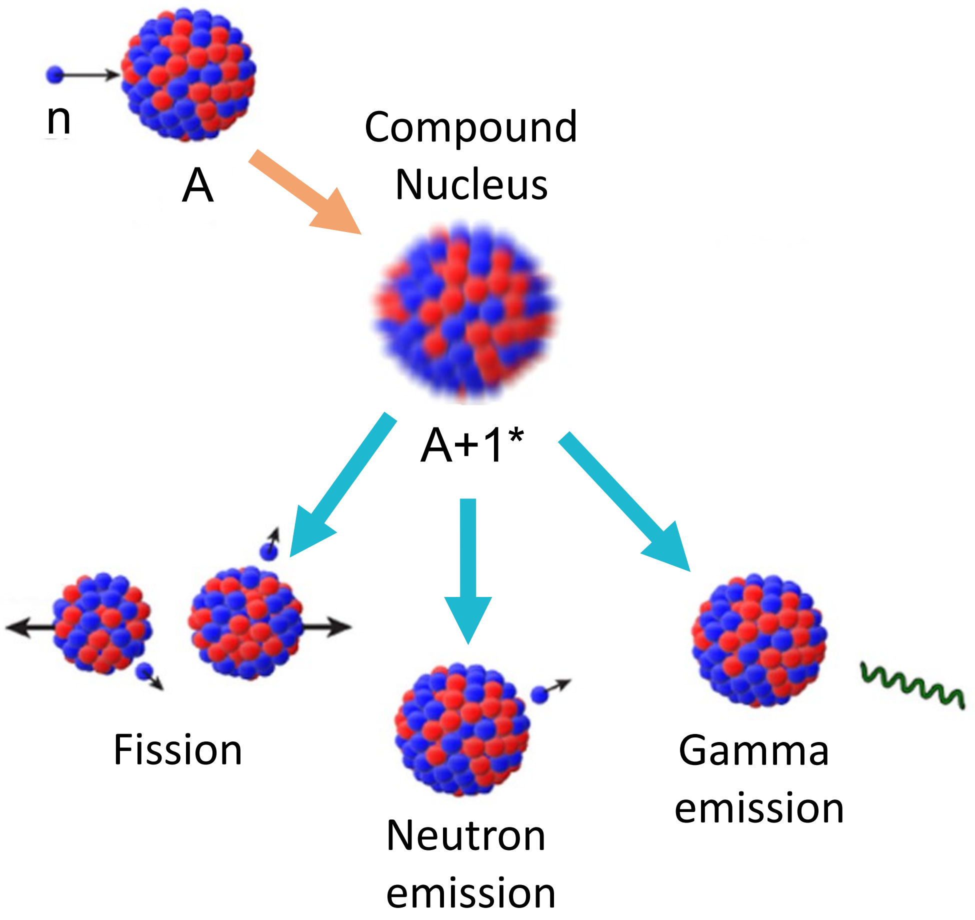
- Neutron-induced reactions are some of the most interesting nuclear reactions:
- *s*, *i* and *r* process nucleosynthesis
- Medical isotope production
- Reactor cycles and waste management



How to measure neutron cross sections?

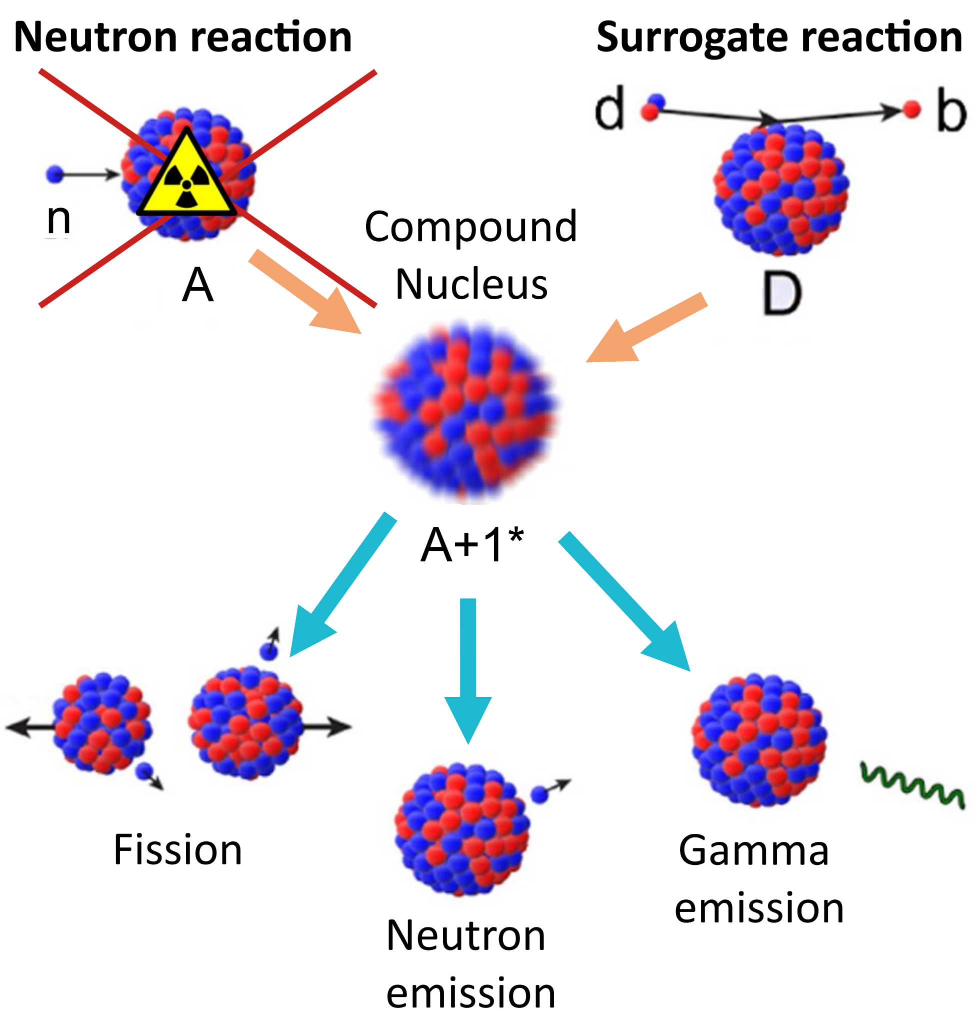
- We shoot neutrons at the nuclei
  - Heavy nuclei and E_n < few MeV
- 2 step process:
  - Formation of compound nucleus (CN) A+1
  - CN decays via competing channels
- σ_X by measuring of decay modes:
  - Fission products (easy)
  - Gamma rays (hard)
  - Neutrons (extremely difficult)

Neutron reaction



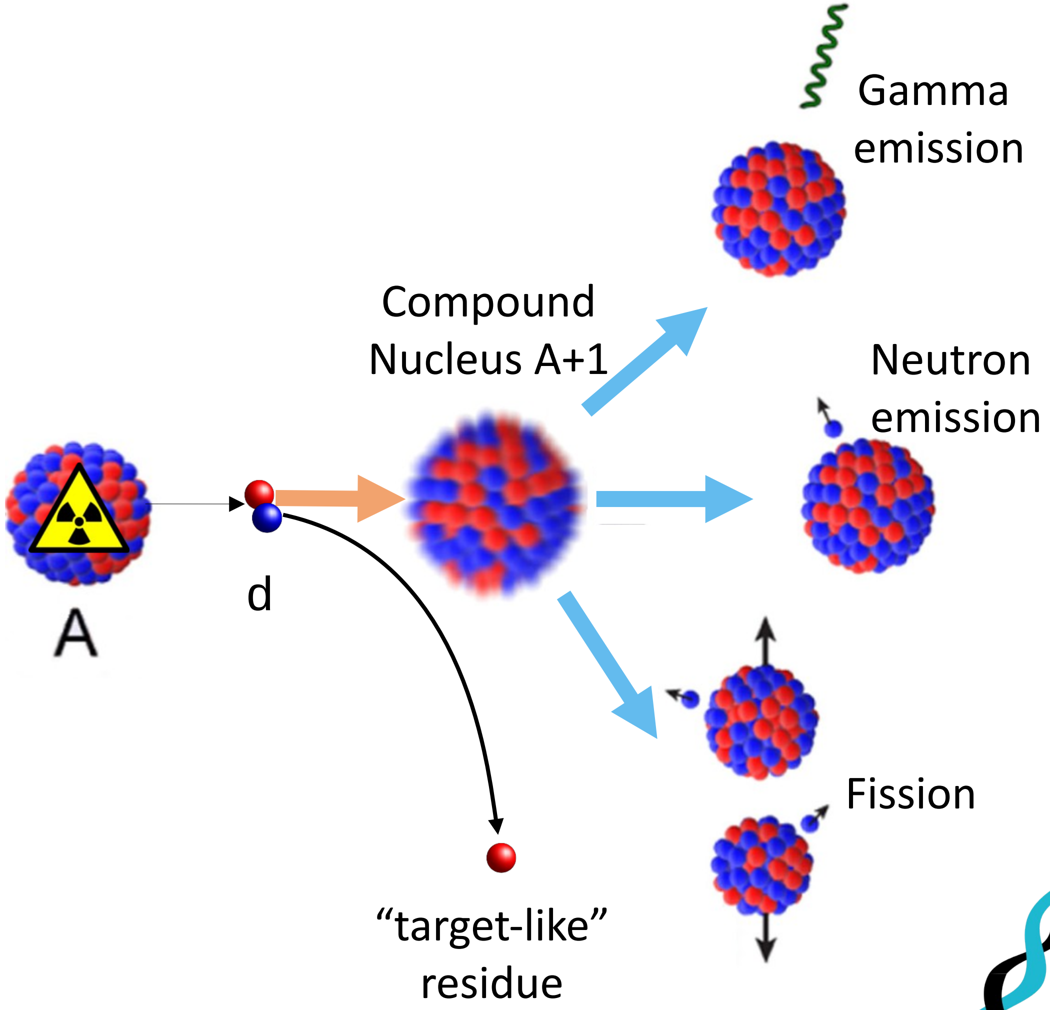
How to measure neutron cross sections?

- 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.



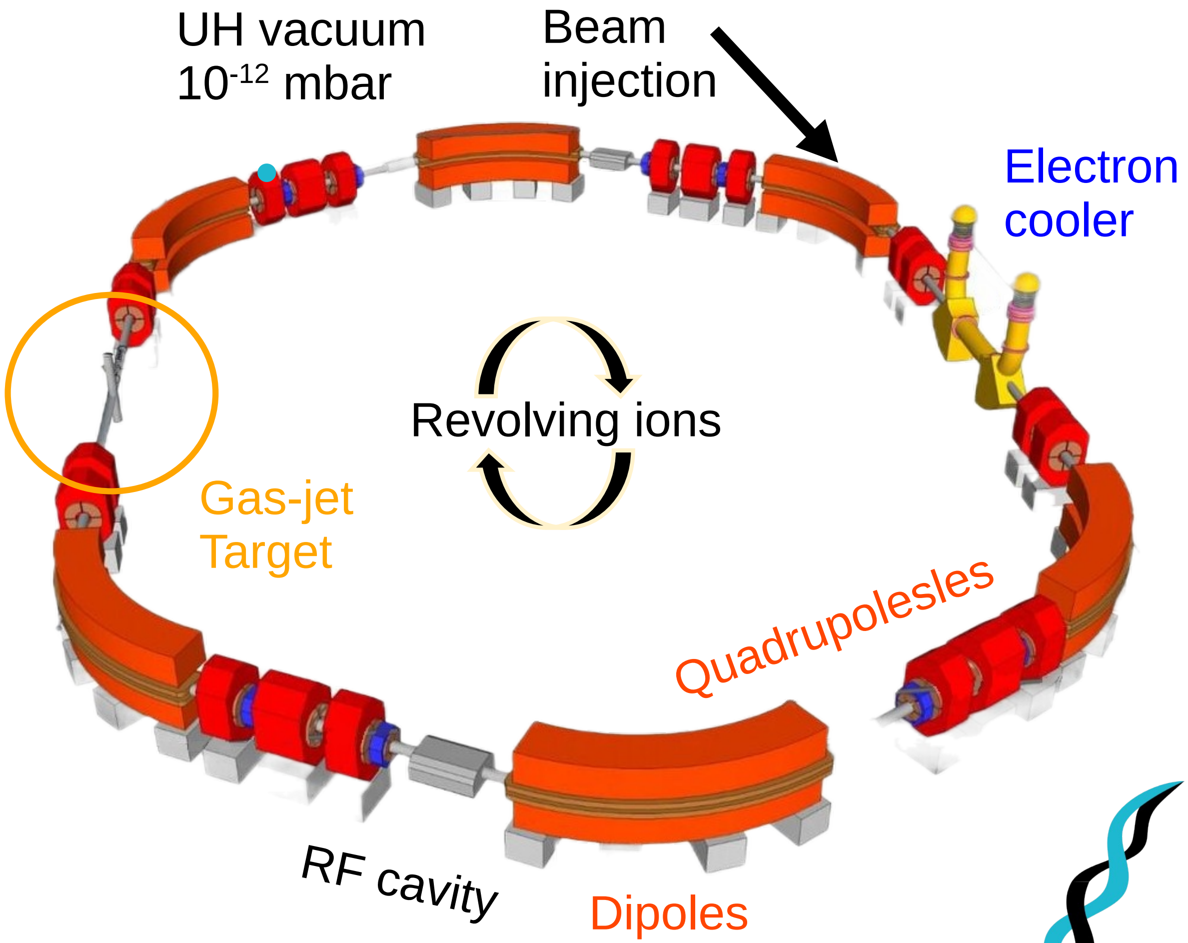
Surrogate reactions in inverse kinematics

- 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**



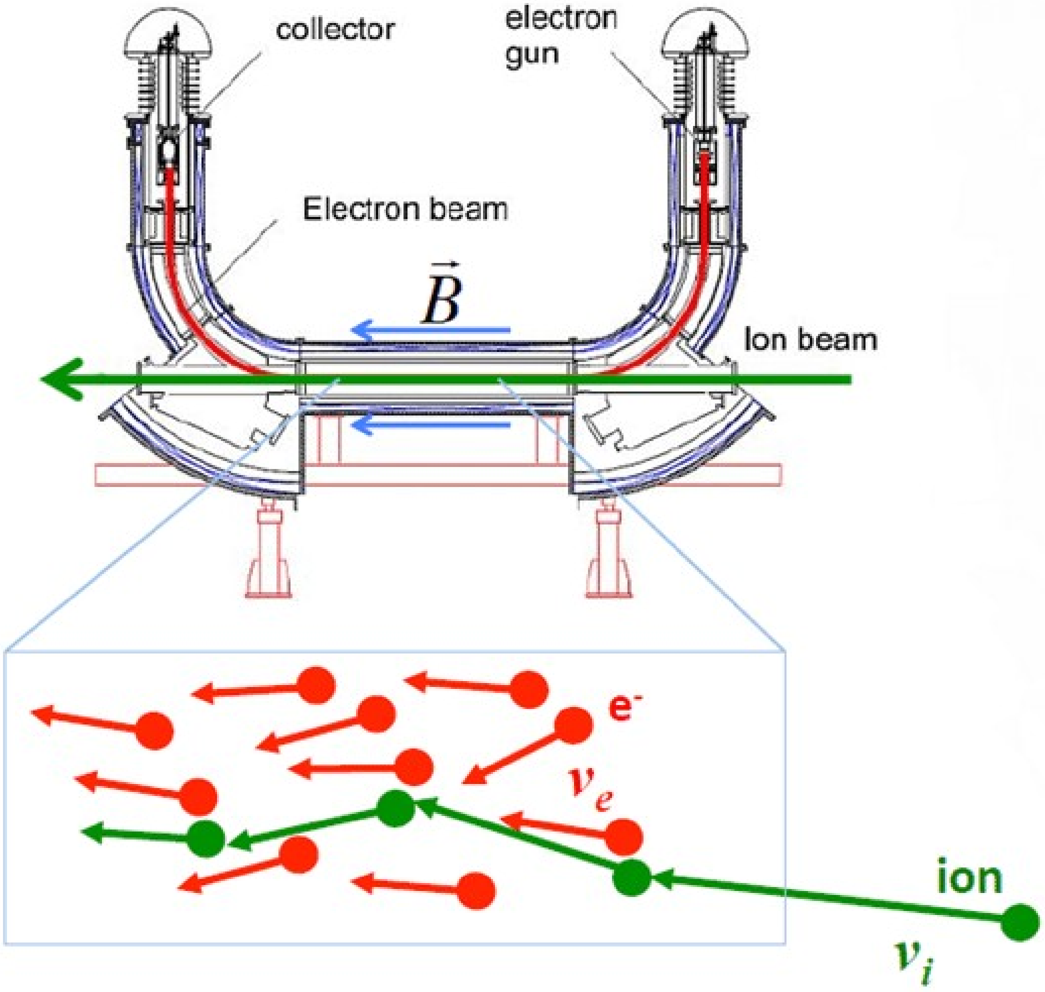
Why Surrogate reaction in Storage Rings?

- 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 and straggling
- Electron cooling restores beam quality after each passing
- Effective thickness multiplied by ~MHz ring frequency



What is electron-cooling?

- Beam after incjection is “hot” large momentum-position spread
- “Cool” electron beam is merged in the same direction as the ions
- Velocity of the electrons and ions is made the same
- Heat transfer to lighter and cooler electrons
- Electrons are removed leaving cooler ion beam



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- “Cool” electron beam is merged in the same direction as the ions
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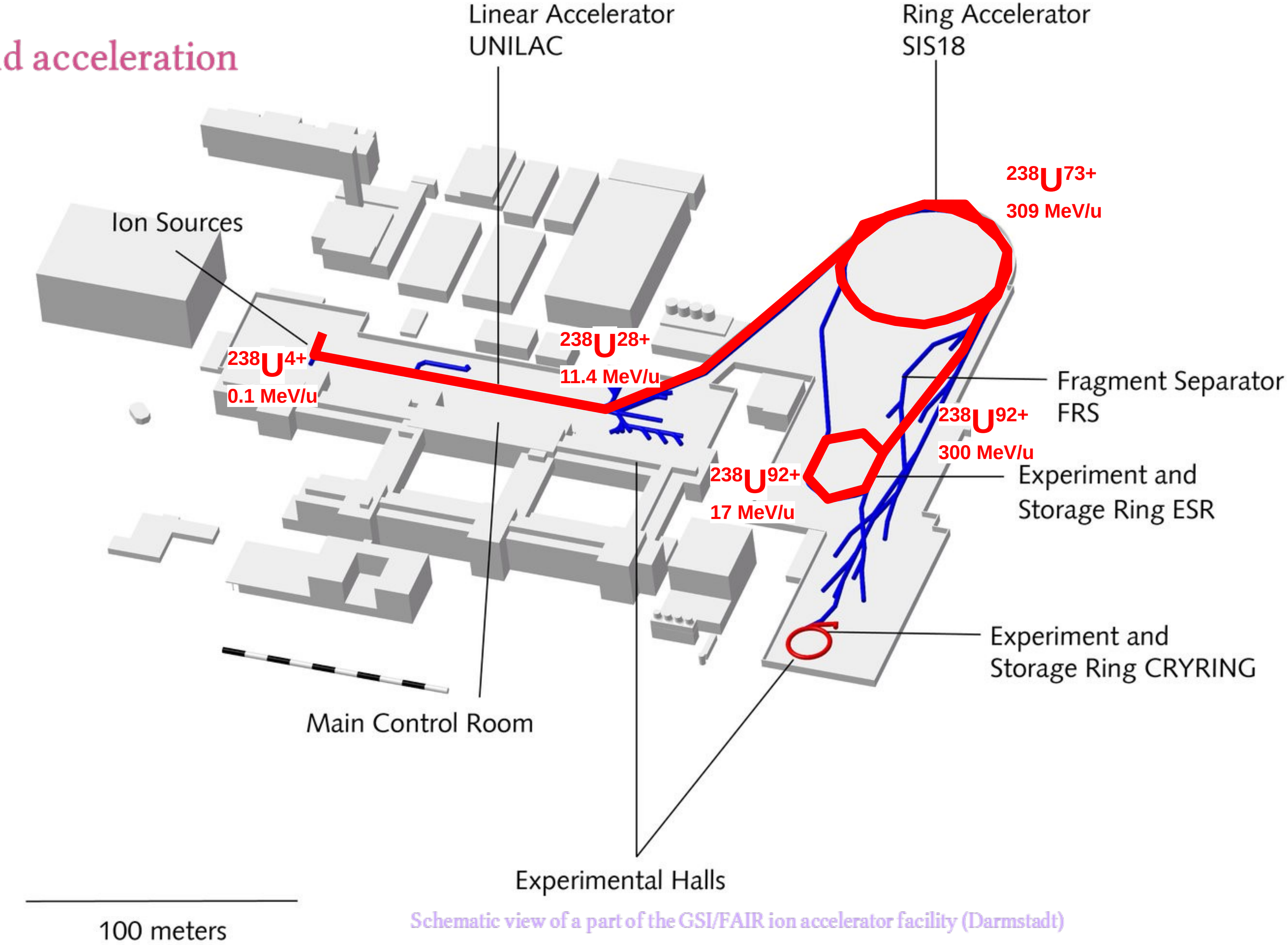
- Heat transfer to lighter and cooler electrons
- Electrons are removed leaving original beam cooler

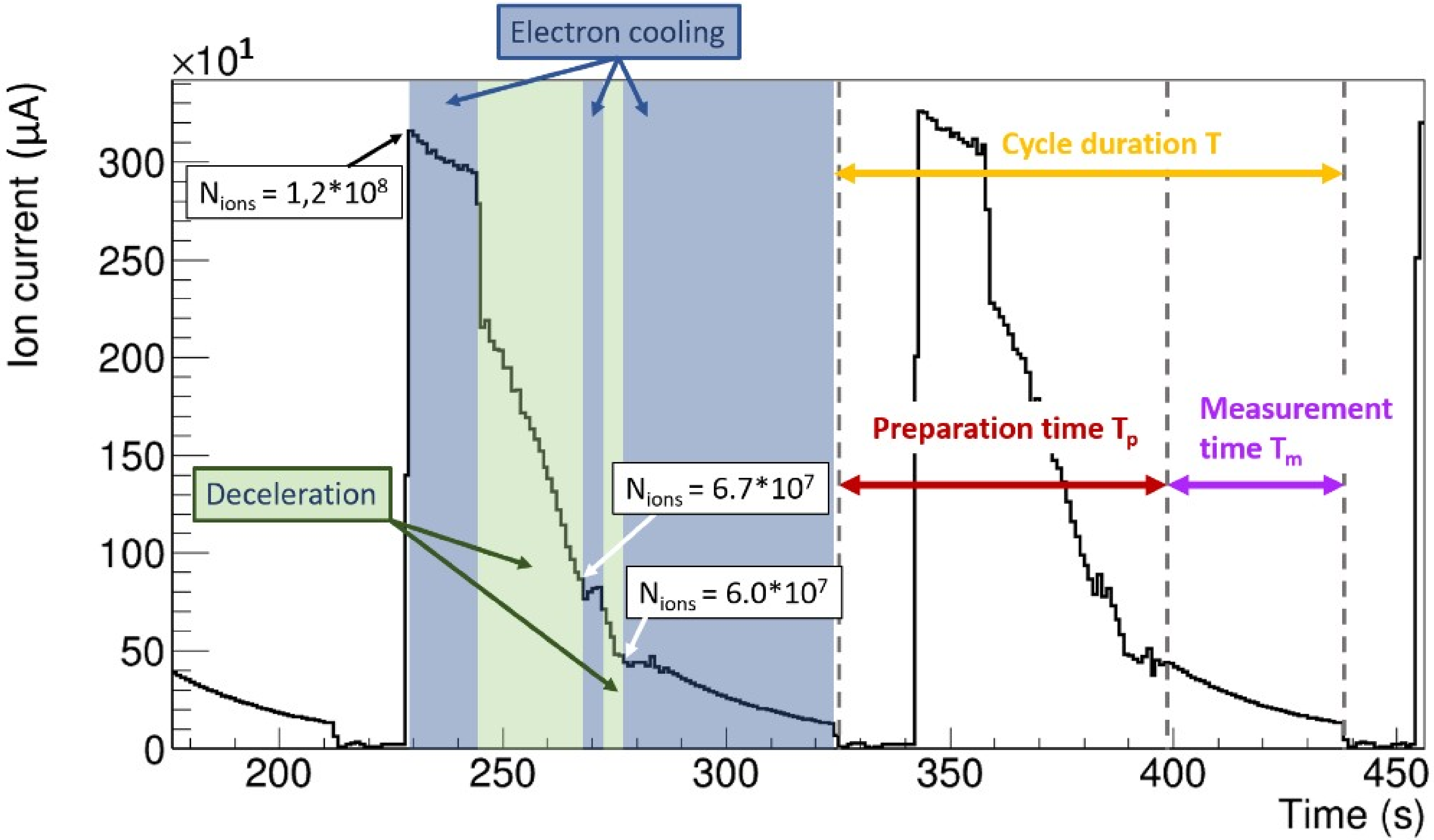
ESR ring at the GSI/FAIR in Darmstadt

Beam production and acceleration



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

ESR ring pattern



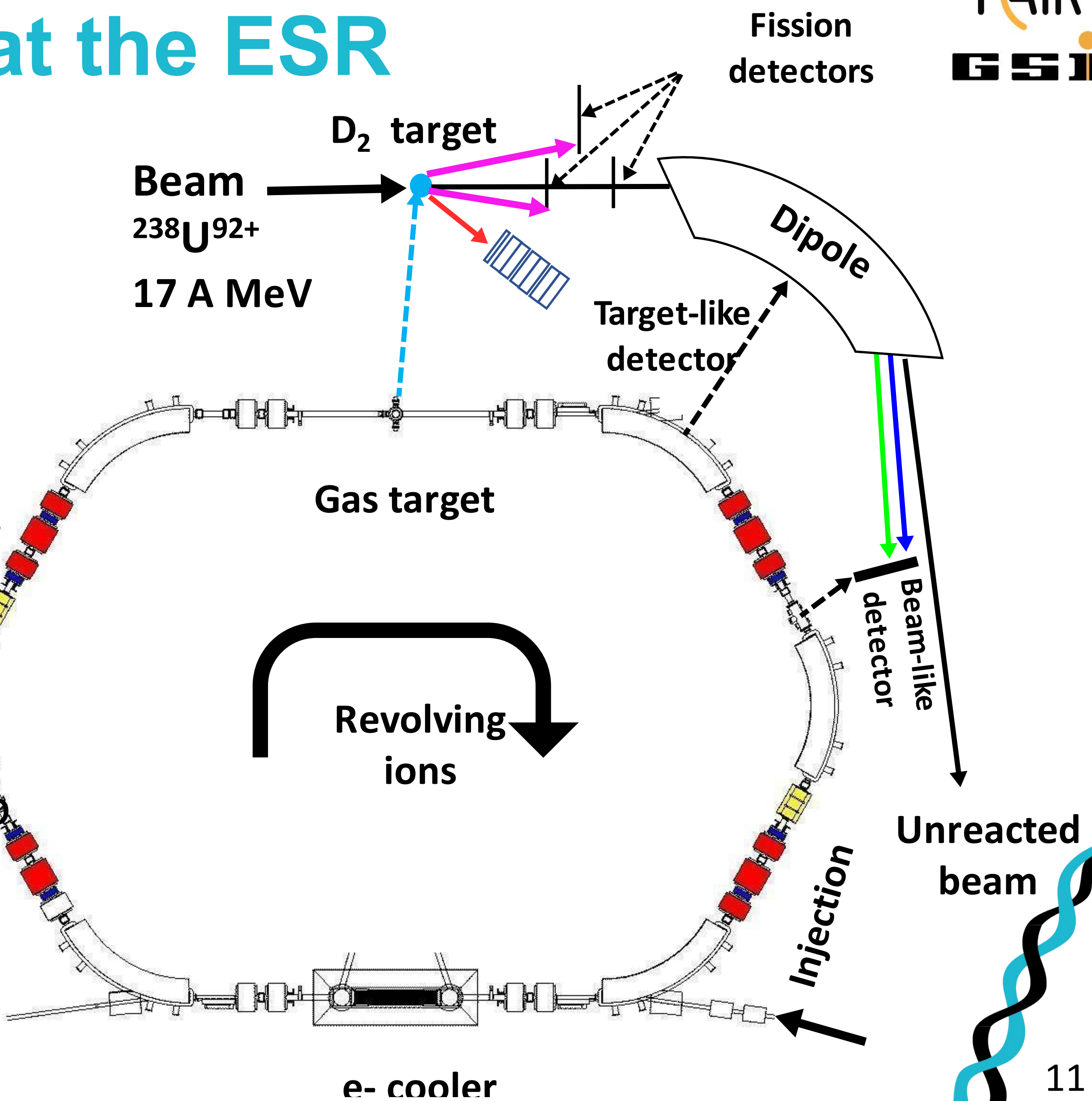
NECTAR experiment at the ESR

- Two experiments performed at ESR in Darmstadt
- 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

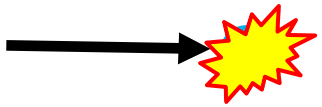
  M.Sguazzin et al., Phys. Rev. C 111 (2025) 024614

- Second proof-of-principle In 2024 $^{238}U^{92+}$ on D_2 at 17 MeV/u
  - ^{238}U(d,p) transfer as a surrogate to ^{238}U+n
  - ^{238}U(d,d') inelastic as a surrogate to ^{237}U+n



NECTAR experiment at the ESR

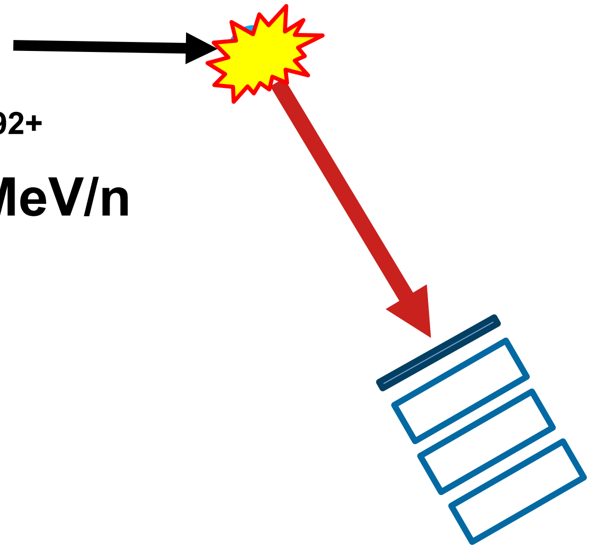
Formation and decay of compound nucleus (~10^{-20} s)



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

17 MeV/n

NECTAR experiment at the ESR



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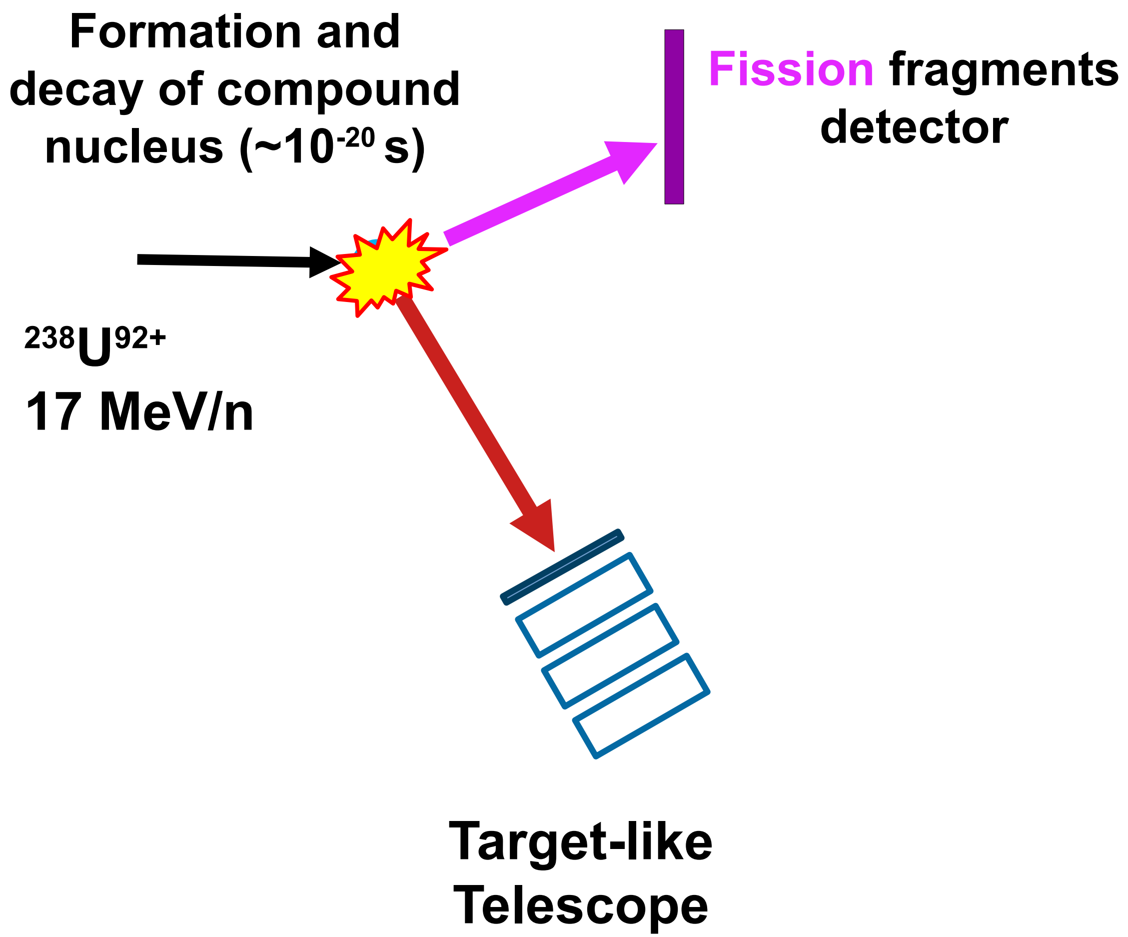

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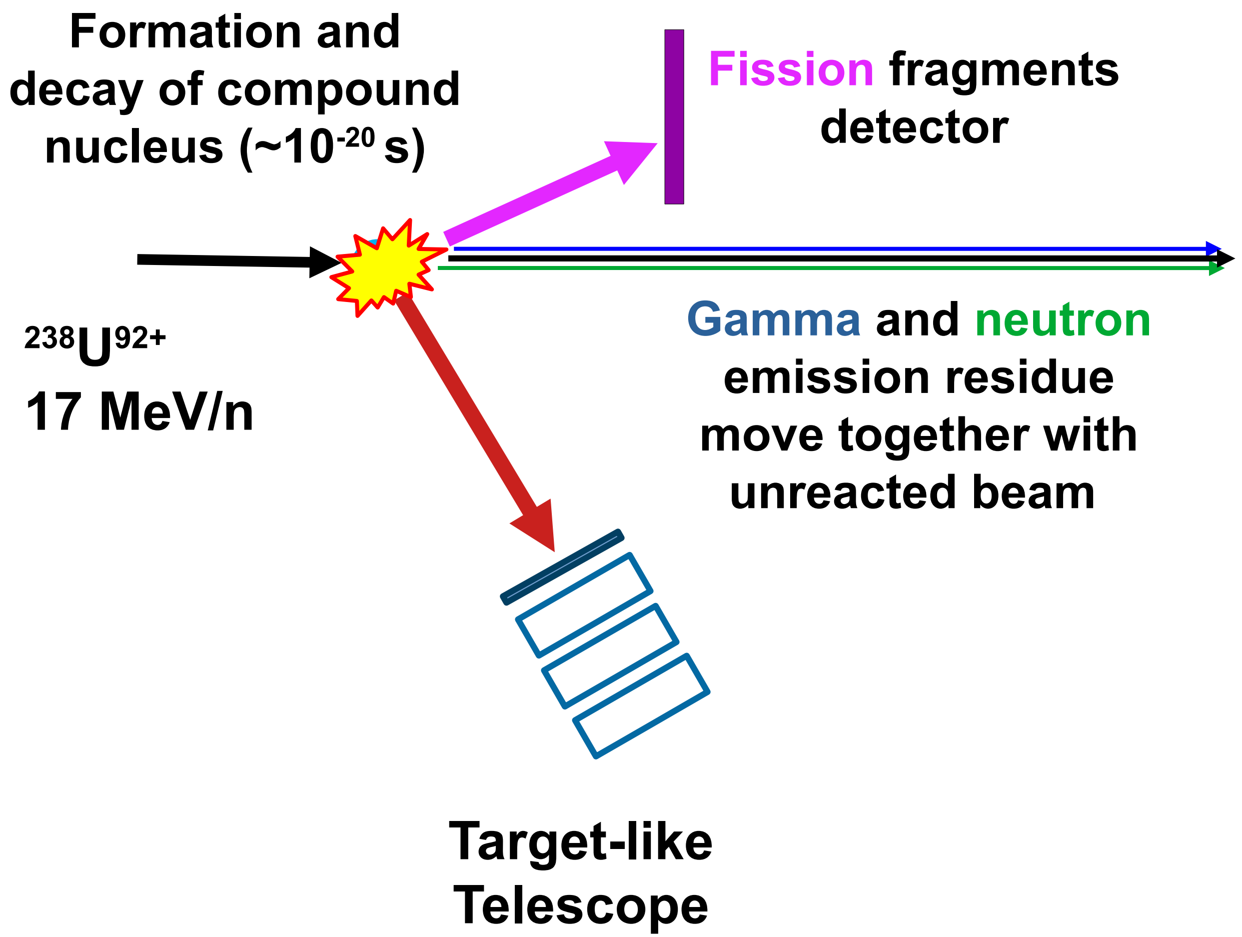

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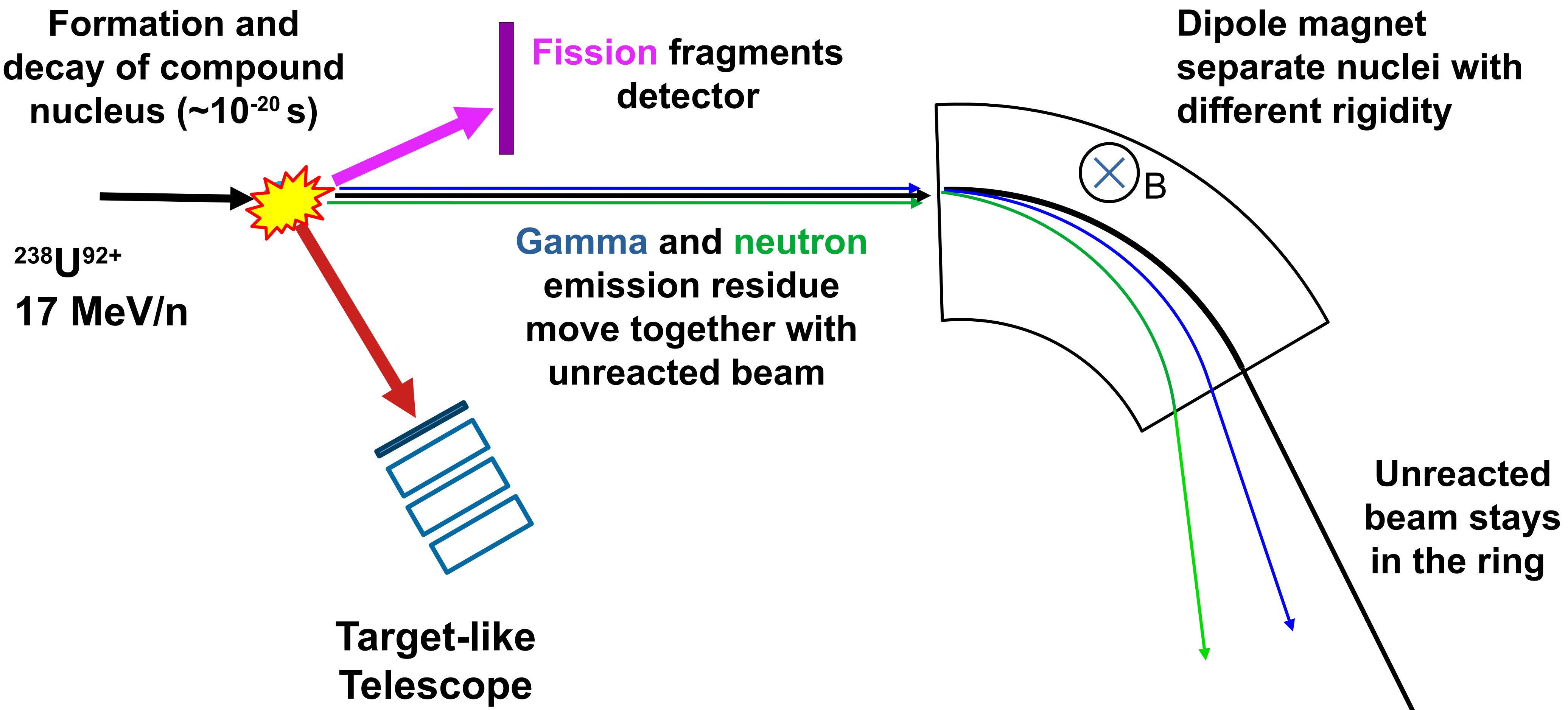

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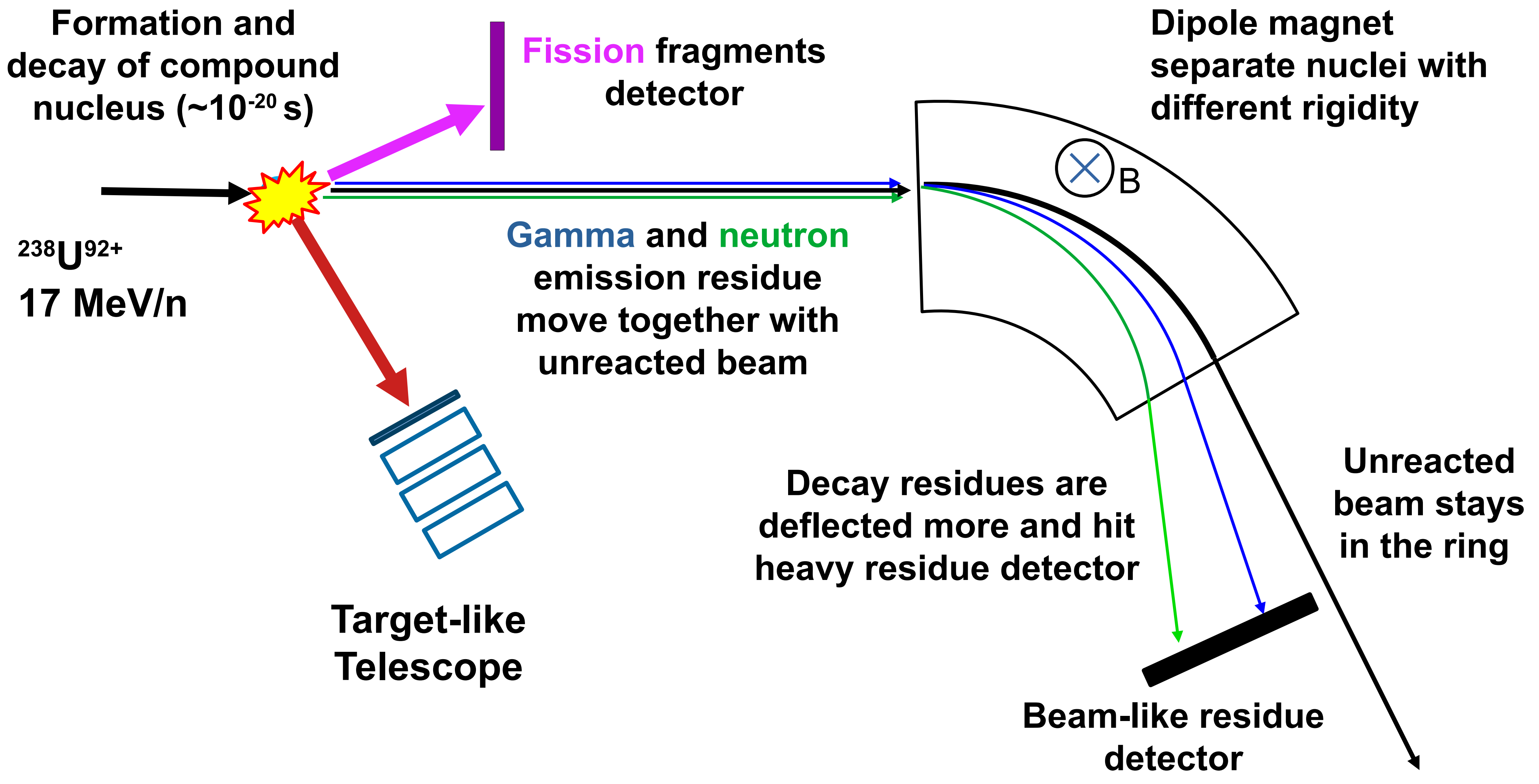

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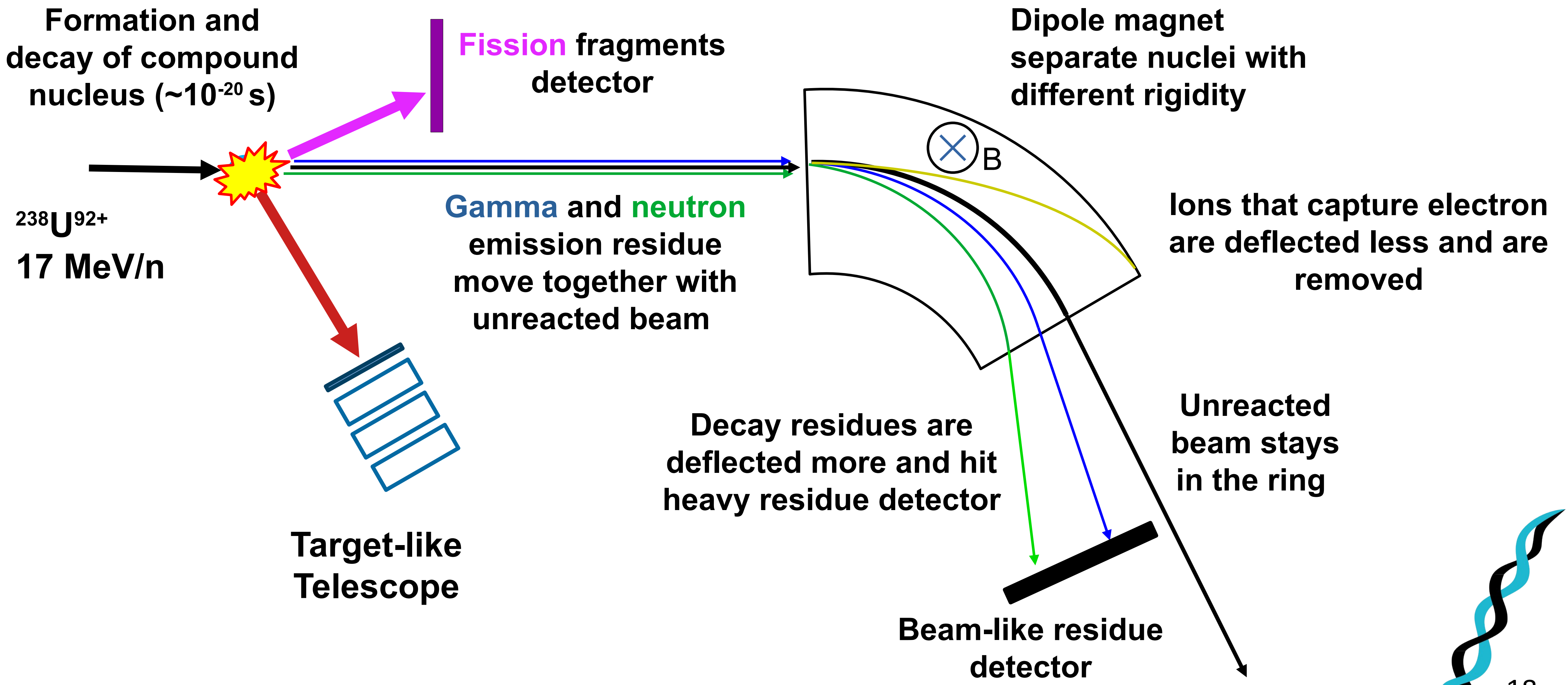

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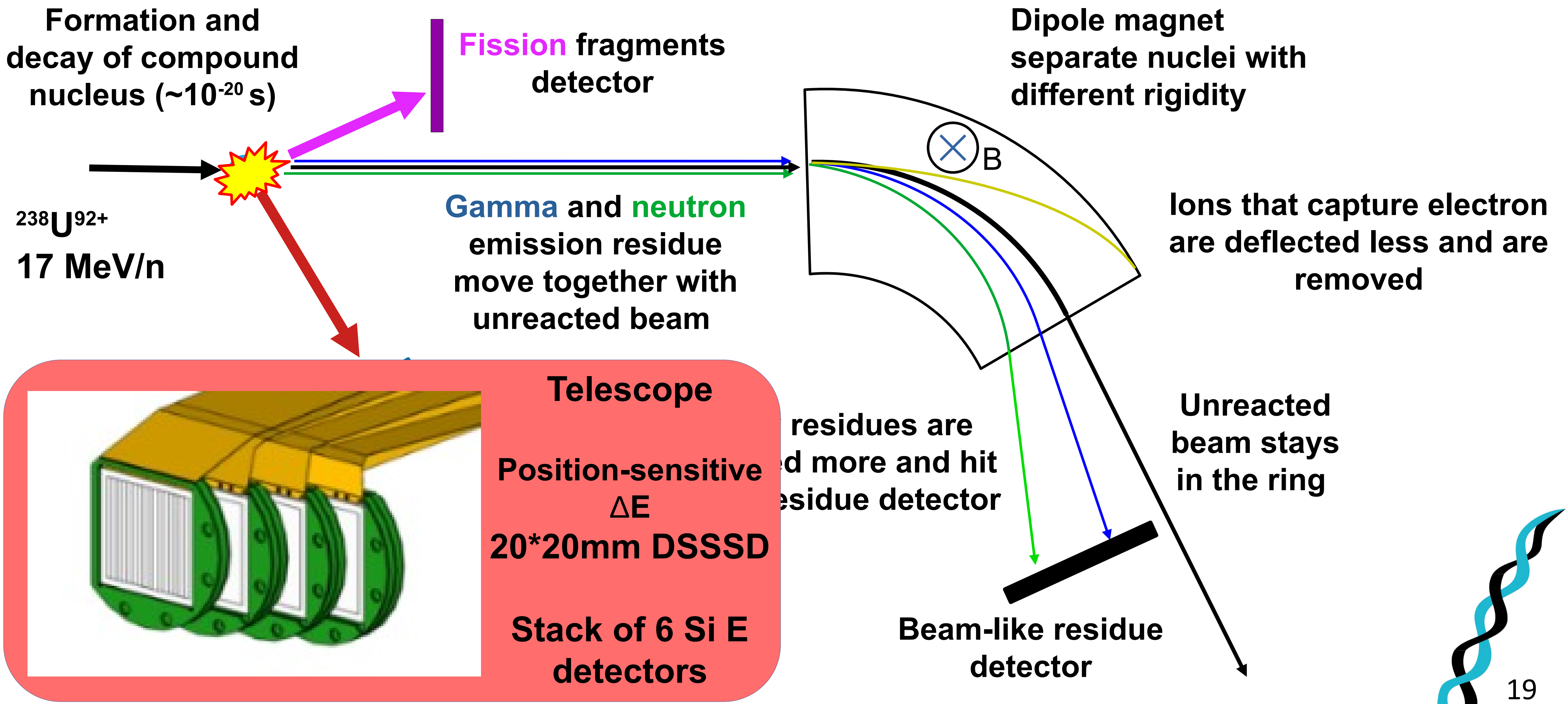

NECTAR ex

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

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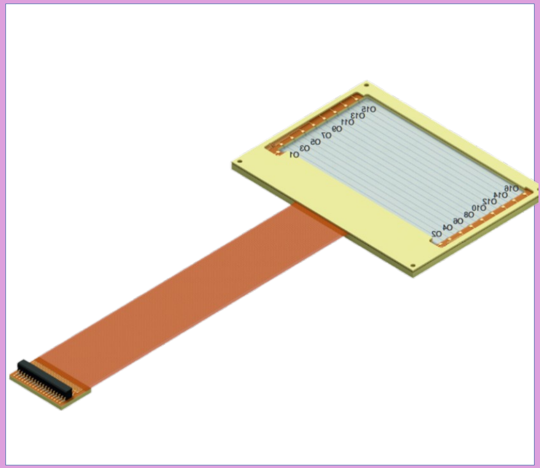
17 MeV/n



Fission detectors

Top and bottom 80*40mm DSSSD

Side 122*44mm DSSSD

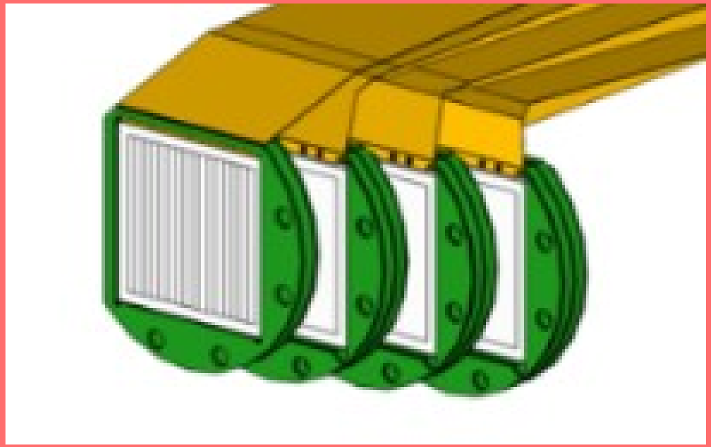
magnet

e nuclei with

t rigidity

Gamma and neutron emission residue move together with unreacted beam

Ions that capture electron are deflected less and are removed



Telescope

Position-sensitive ΔE 20*20mm DSSSD

Stack of 6 Si E detectors

residues are

d more and hit

esidue detector

Unreacted beam stays in the ring

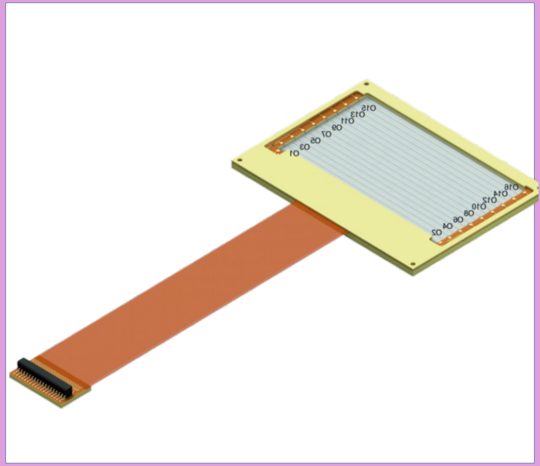
Beam-like residue detector

NECTAR ex

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

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

17 MeV/n



Fission detectors

Top and bottom
80*40mm DSSSD

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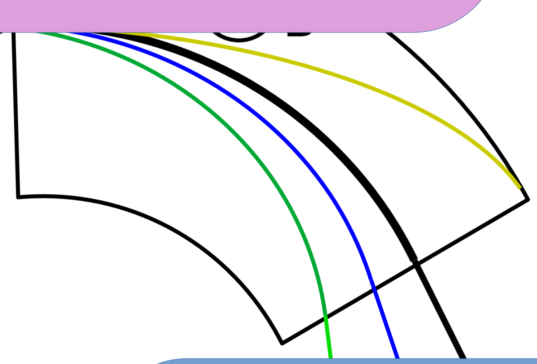
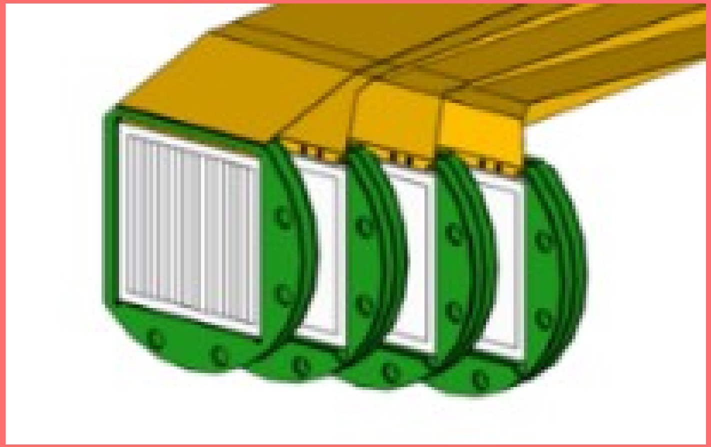


Gamma and neutron emission residue move together with unreacted beam

Ions that capture electron are deflected less and are removed



Telescope

Position-sensitive
ΔE
20*20mm DSSSD

Stack of 6 Si E detectors

resid
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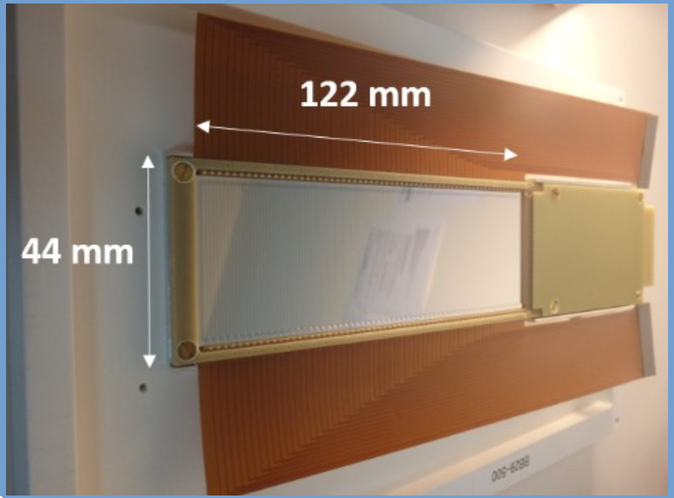
esidue



Beam-like Detector

122*44mm DSSSD

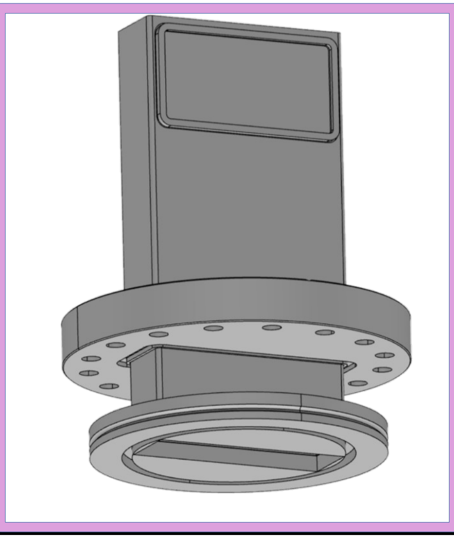
NECTAR ex

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

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

17 MeV/n

Fission detectors



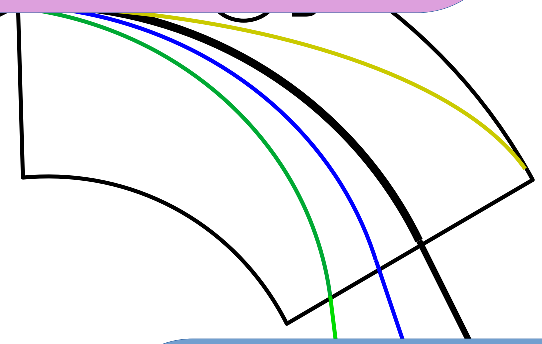
Rectangular pocket (MPIK Heidelberg)

magnet

e nuclei with

t rigidity

Gamma and neutron emission residue move together with unreacted beam



Ions that capture electron are deflected less and are removed

Telescope

Cylindrical pocket

(MPIK Heidelberg)

resid

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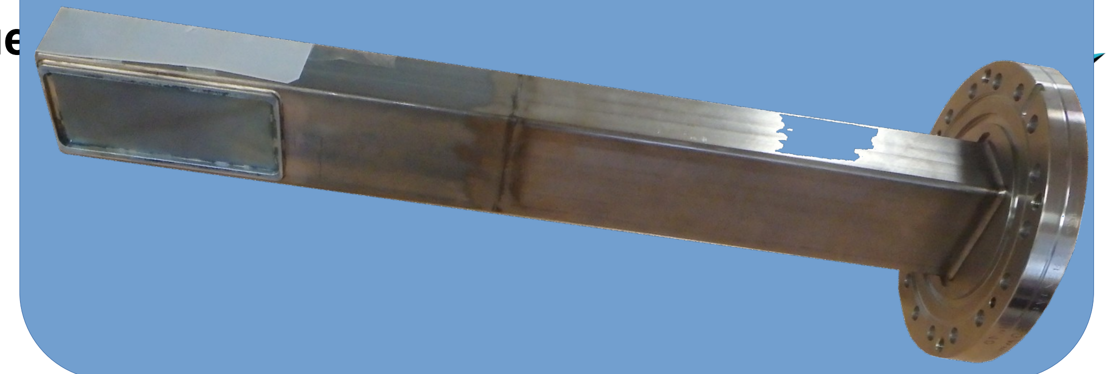
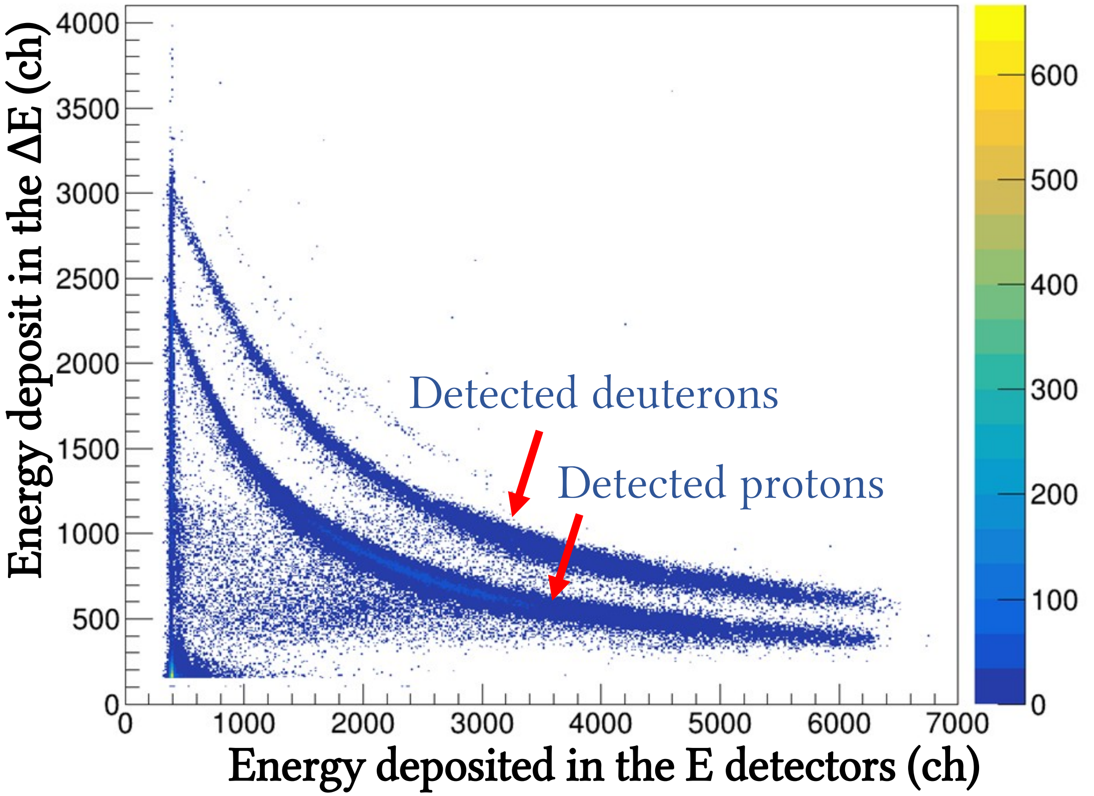
esidue

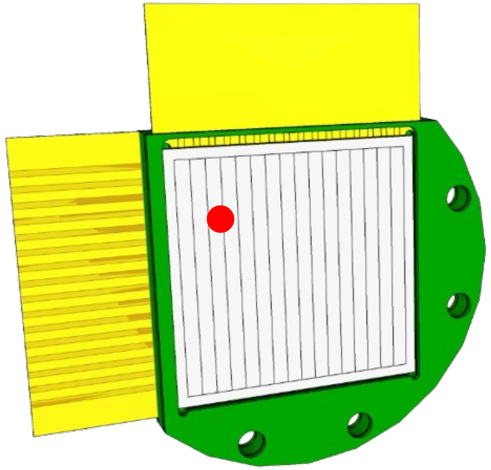
Beam-like Detector Rectangular Pocket (GSI)



Target-like residue detector (Telescope)

- Signles detected in the Telescope
- Excitation energy $E^* = f(E_B, E_s, \theta_s)$

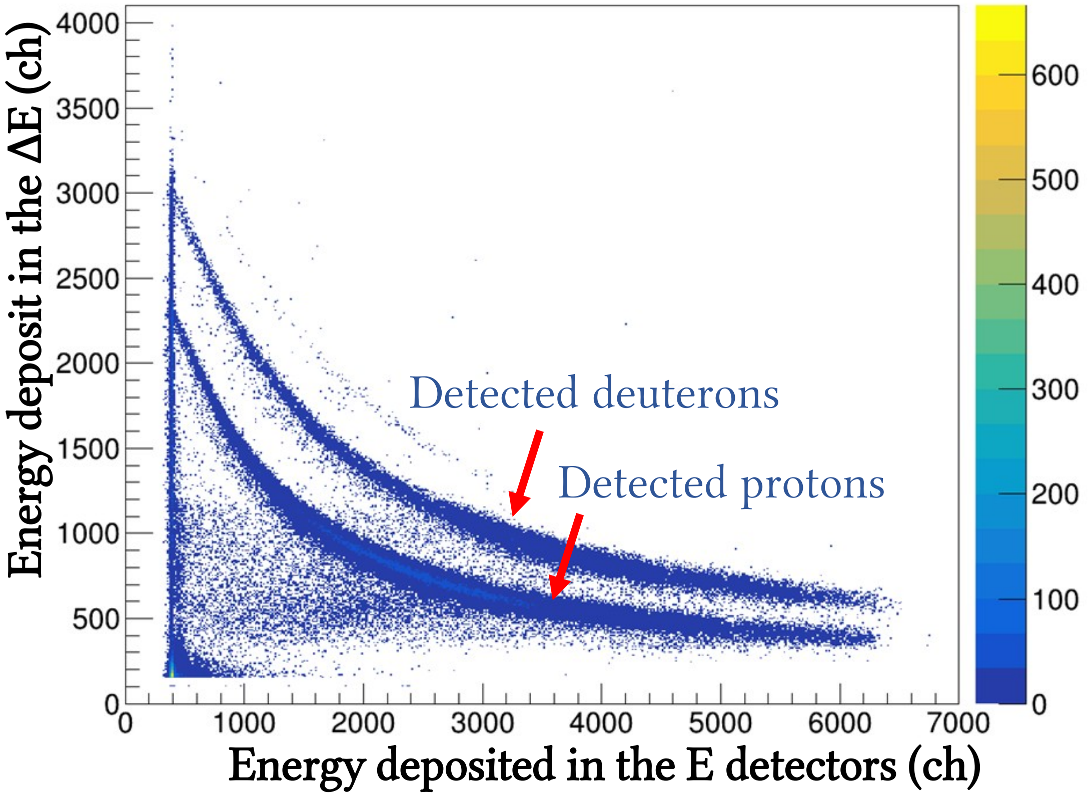


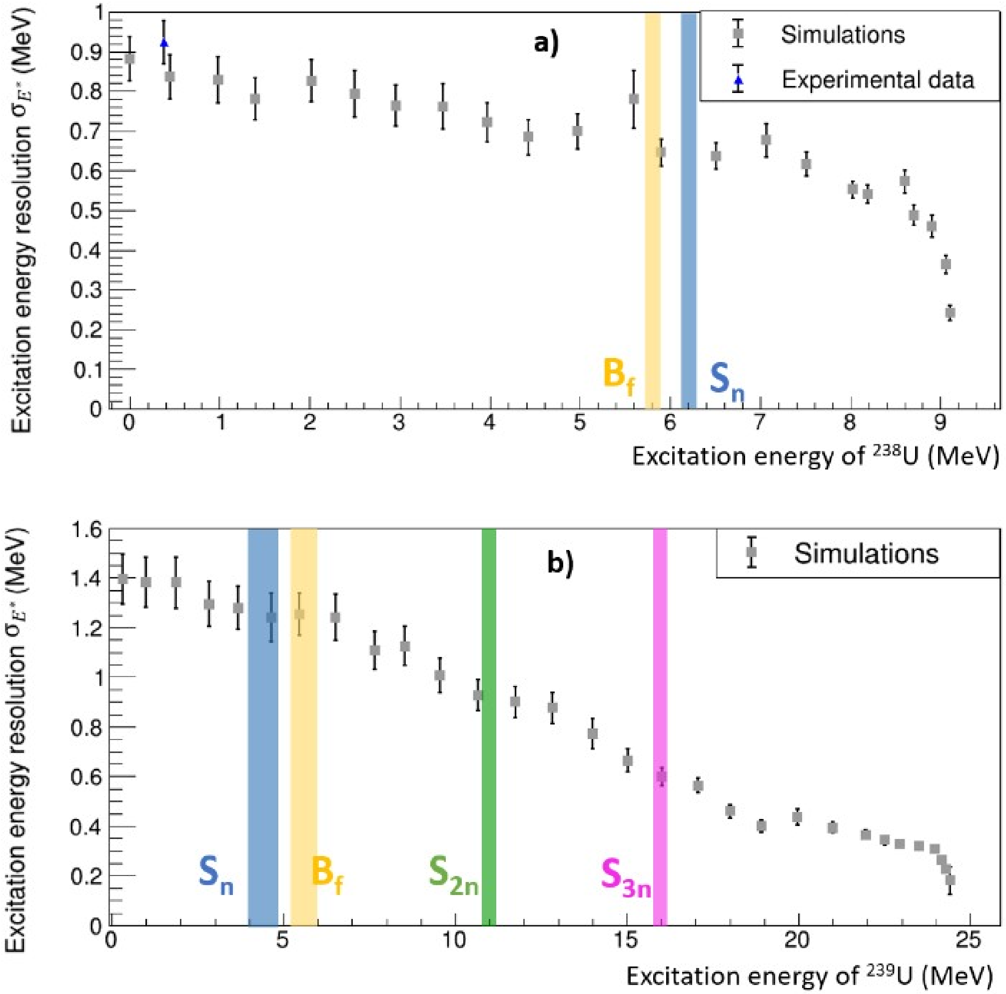


Scattering angle θ_s
ΔE pixel (0.2º resolution)

Target-like residue detector (Telescope)

- Signles detected in the Telescope
- Excitation energy $E^* = f(E_B, E_s, \theta_s)$

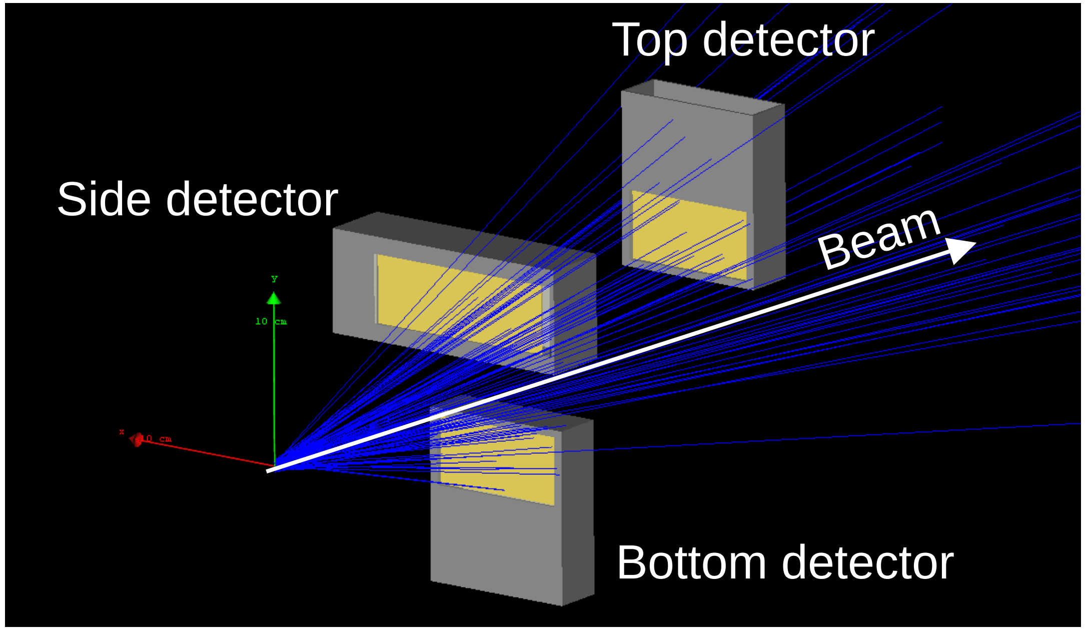




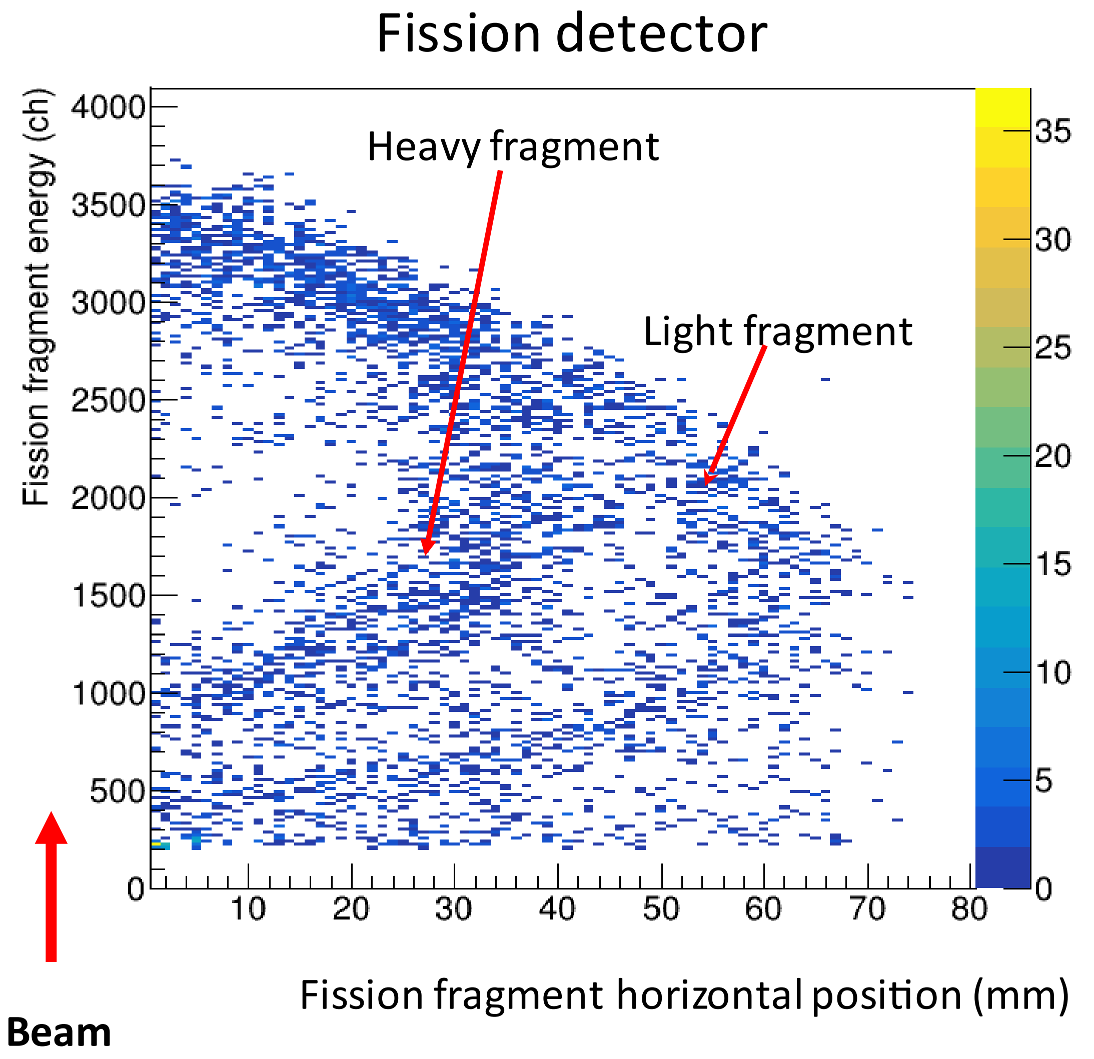
ion)

Fission fragments detector

- Fission coincidences

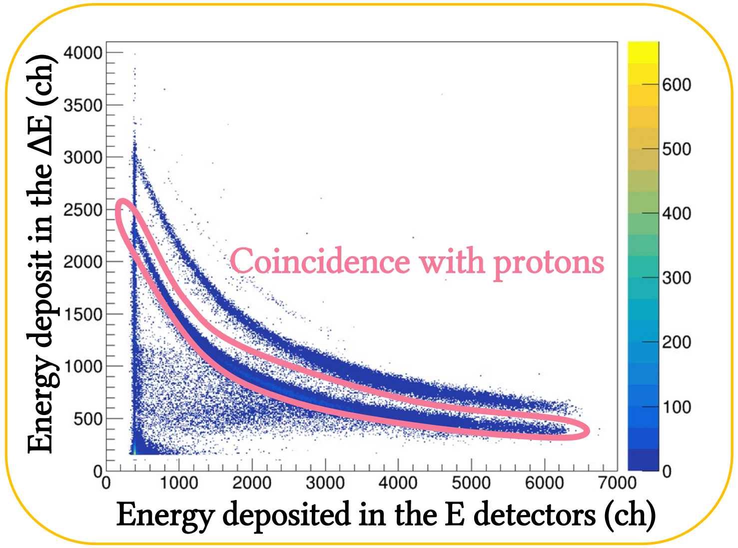


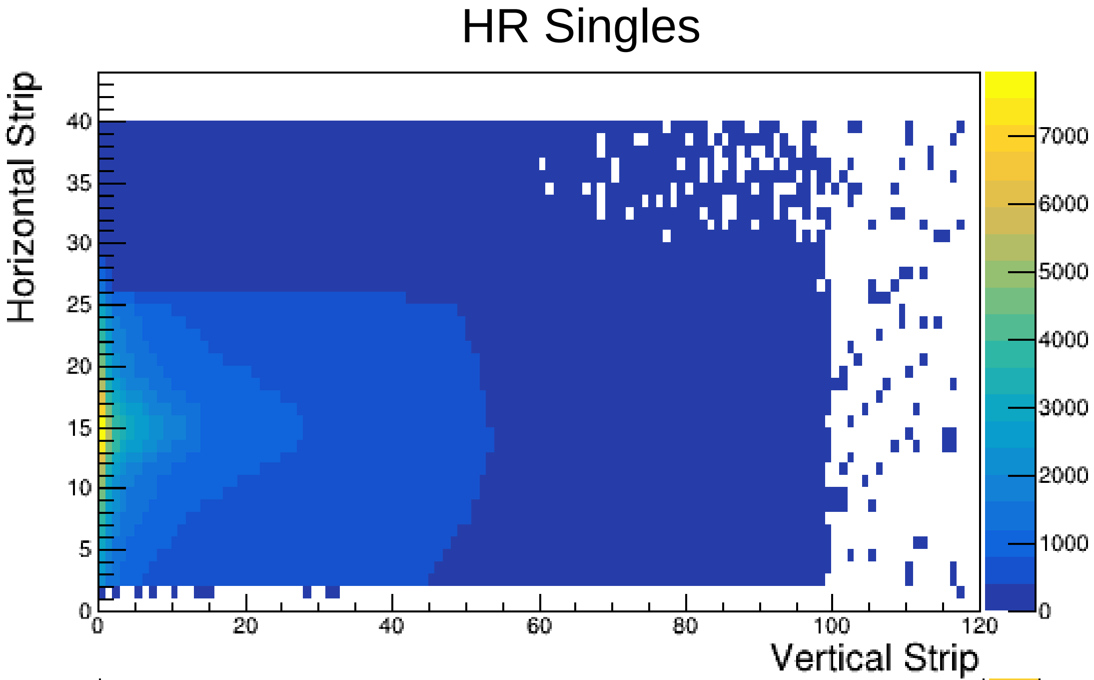
Fission detection efficiency:
Intrinsic (100%)
Geometric ε_f = 41+/-3% (Geant4 sim)

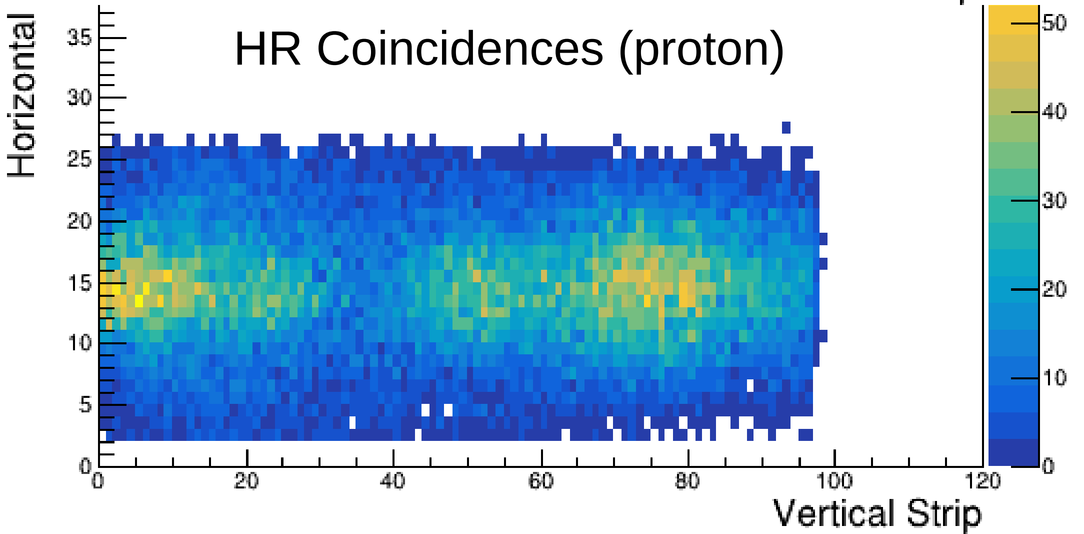


Beam-like residue detector, $^{238}U(d,p)$

- No Coincidences
  - Mostly elastic scattering etc.
- With coincidences (protons)
  - $^{238}U(d,p)$ channel

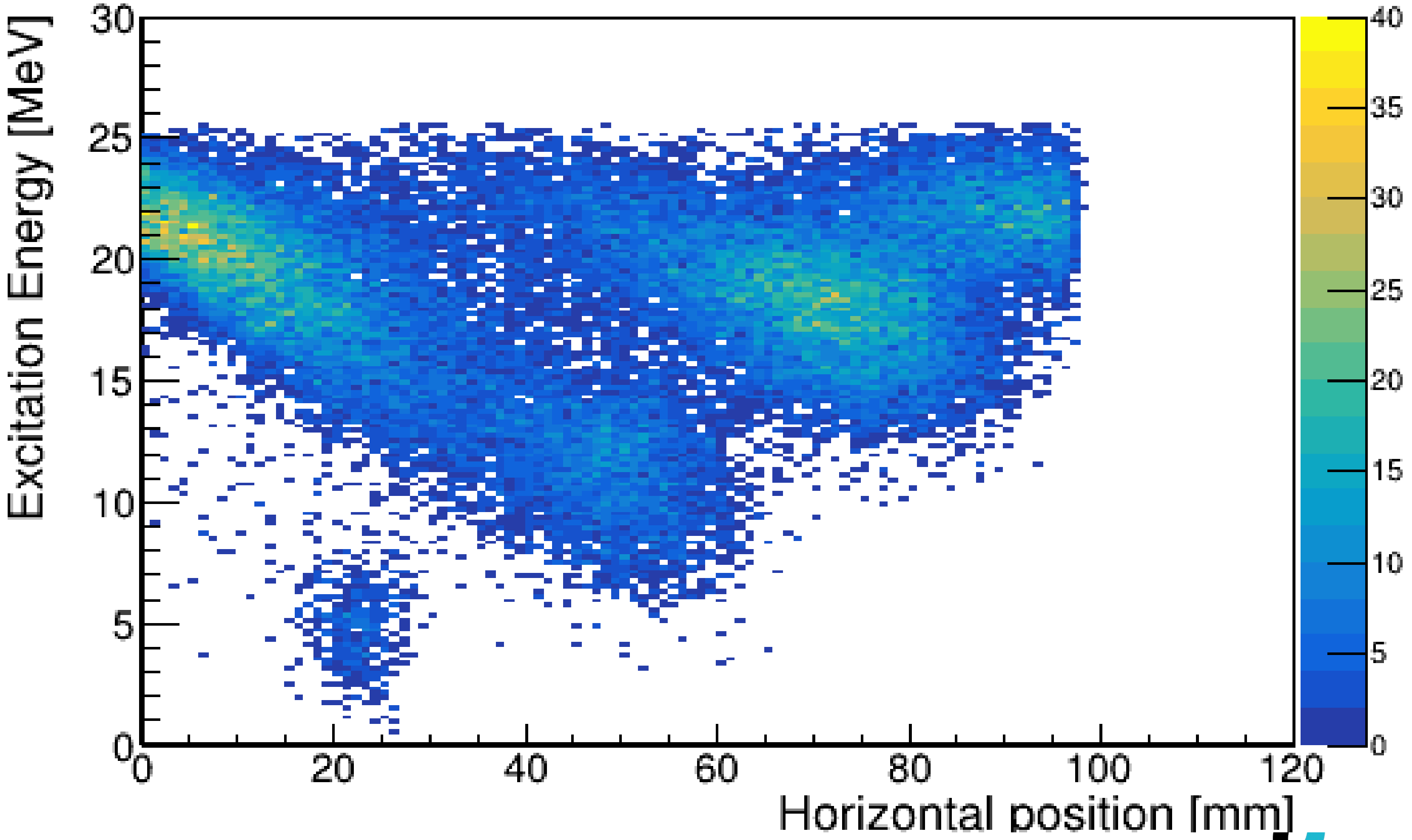






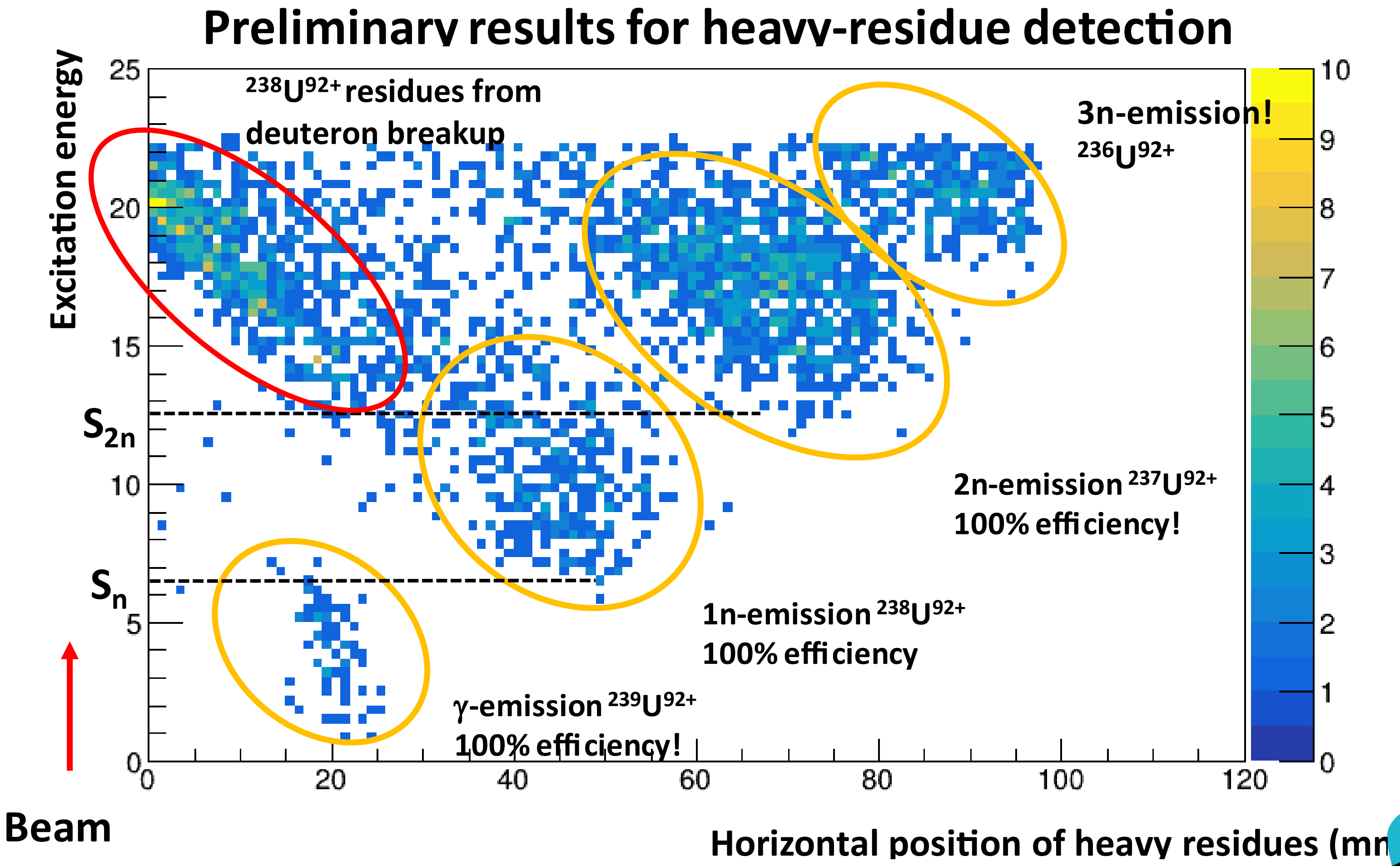
Beam-like residue detector, $^{238}U(d,p)$

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



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

- We can identify γ-emission and n,2n,3n emission!
- 100% detection efficiency!
- All possible decay channels measured simultaneously!



De-excitation probabilities

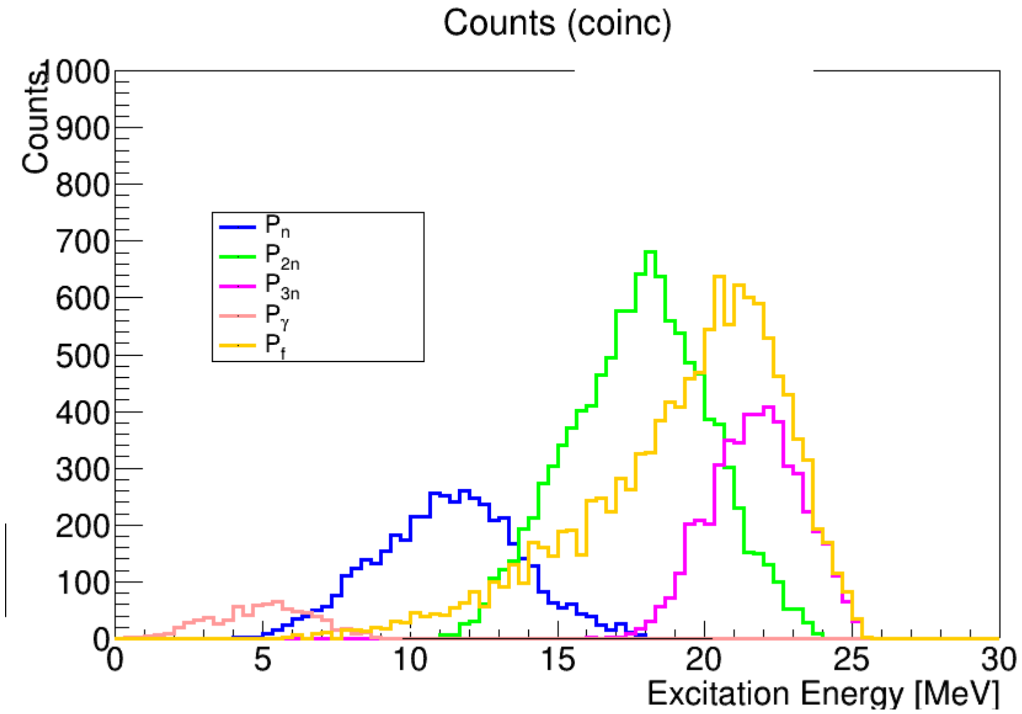
- Expression of the probability for a given decay mode χ:

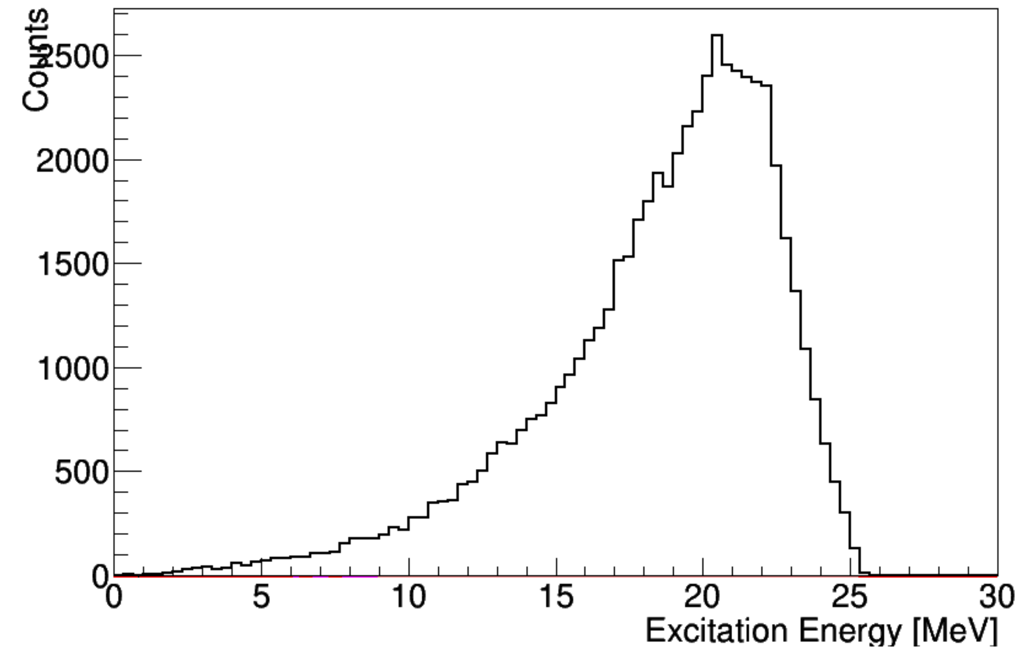
Number of coincidence events

$$P_\chi(E^*) = \frac{N_{c,\chi}(E^*)}{N_s(E^*) \cdot \varepsilon_\chi(E^*)}$$

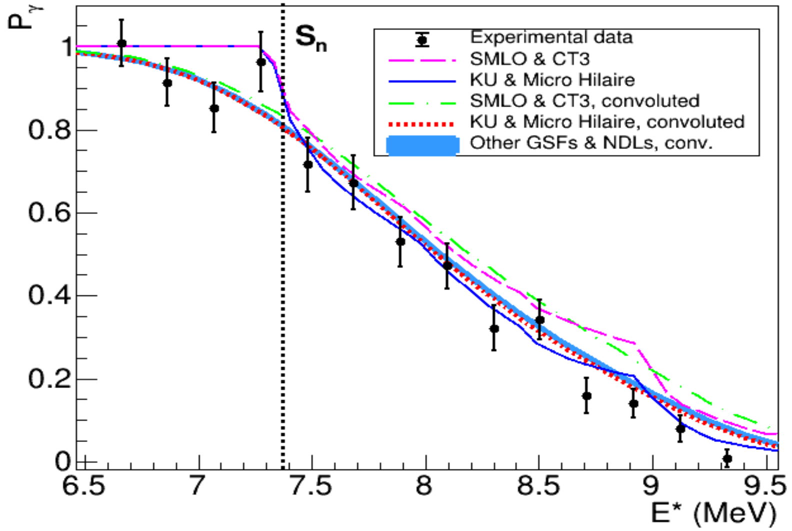
Number of singles in Telescope

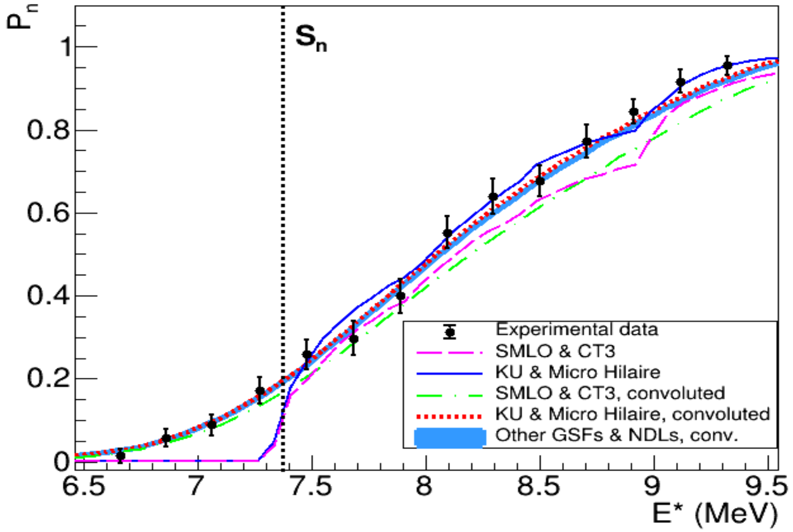
Detection Efficiency

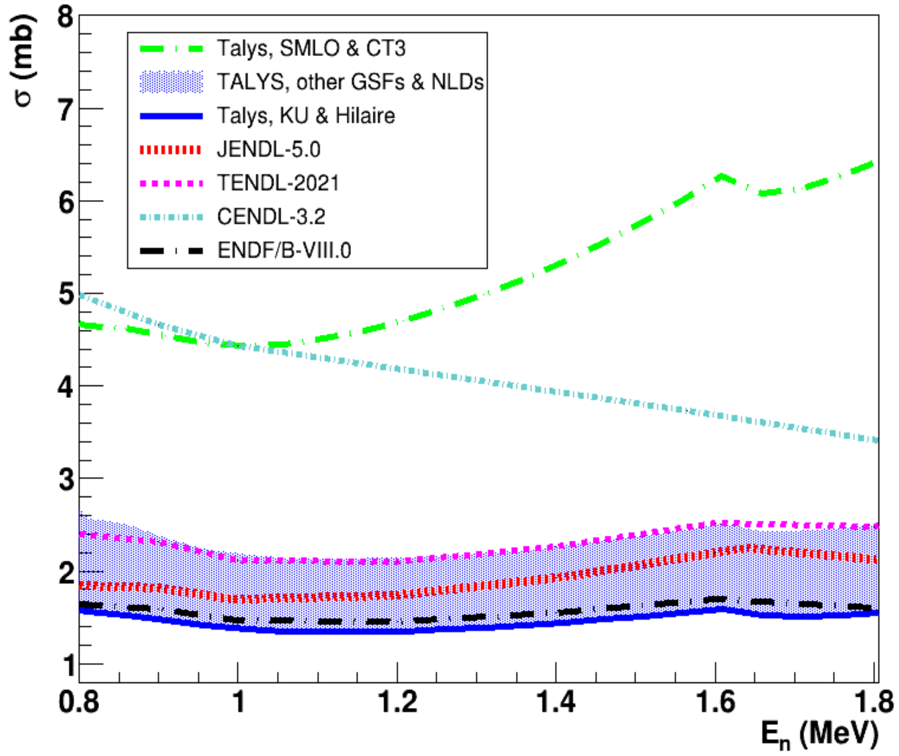




Results of ^{208}Pb(p,p') experiment



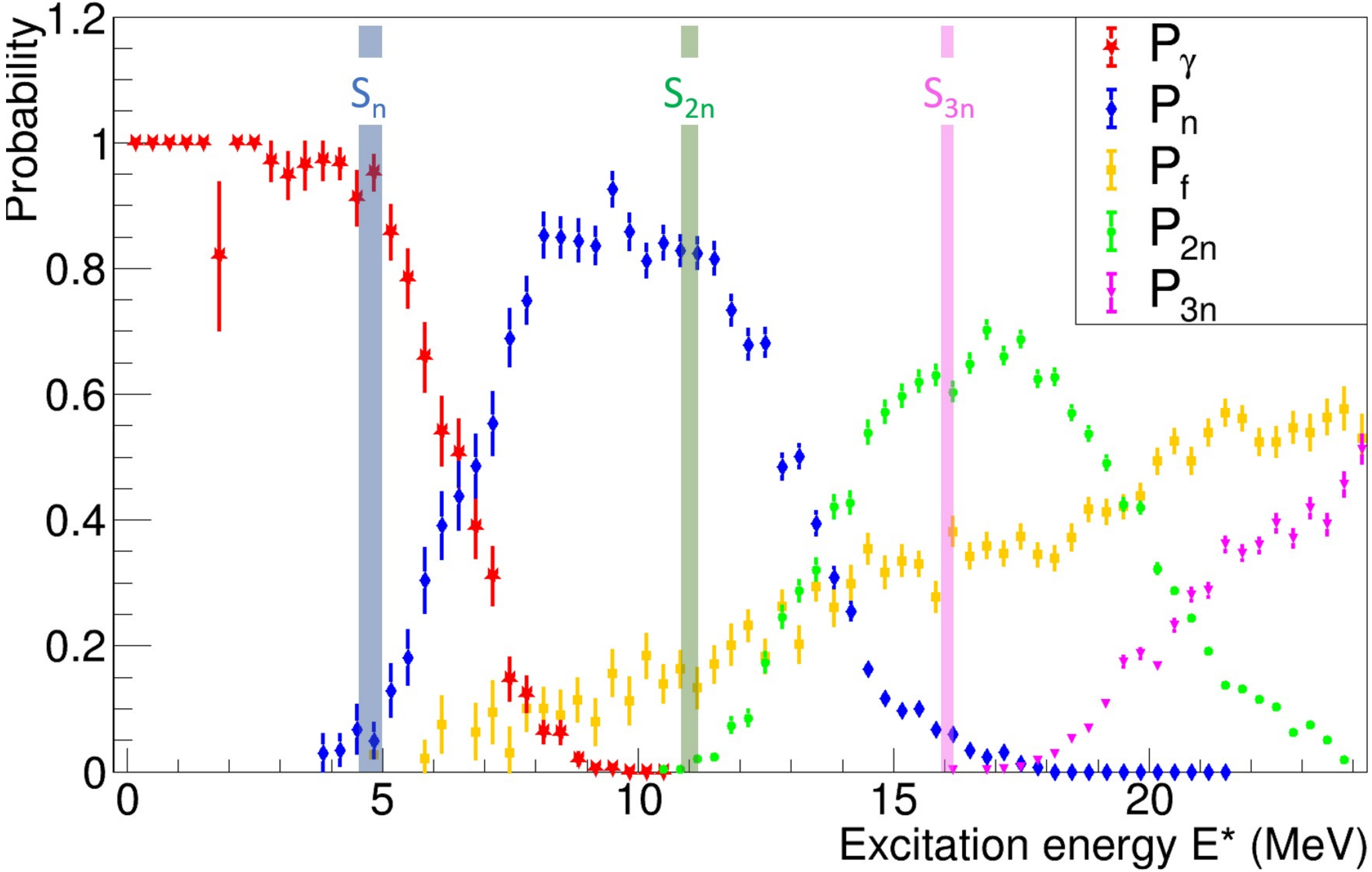




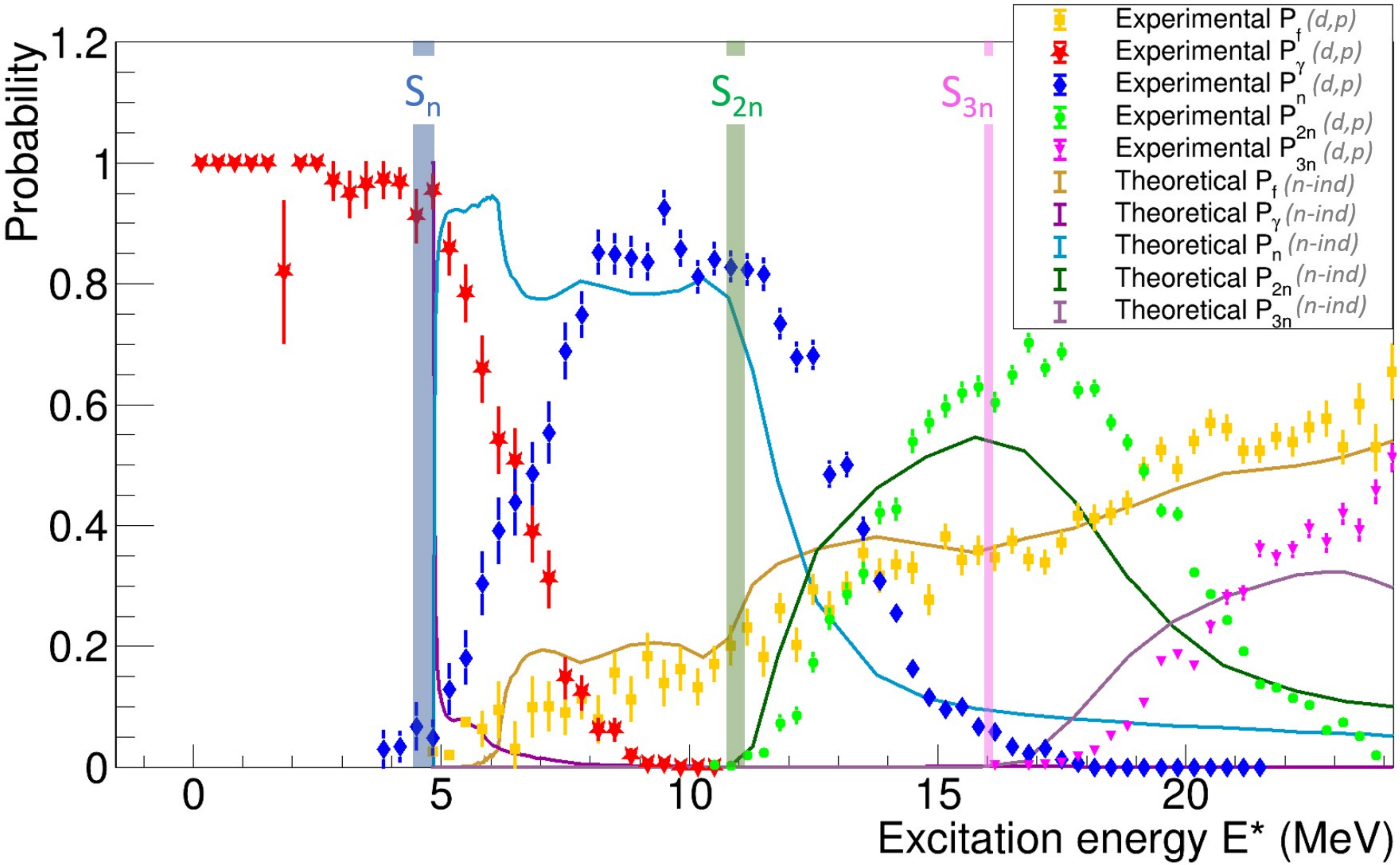
M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501

M. Sguazzin *et al.*, Phys. Rev. C 111 (2025) 024614

Preliminary probabilities of $^{238}U(d,p)$

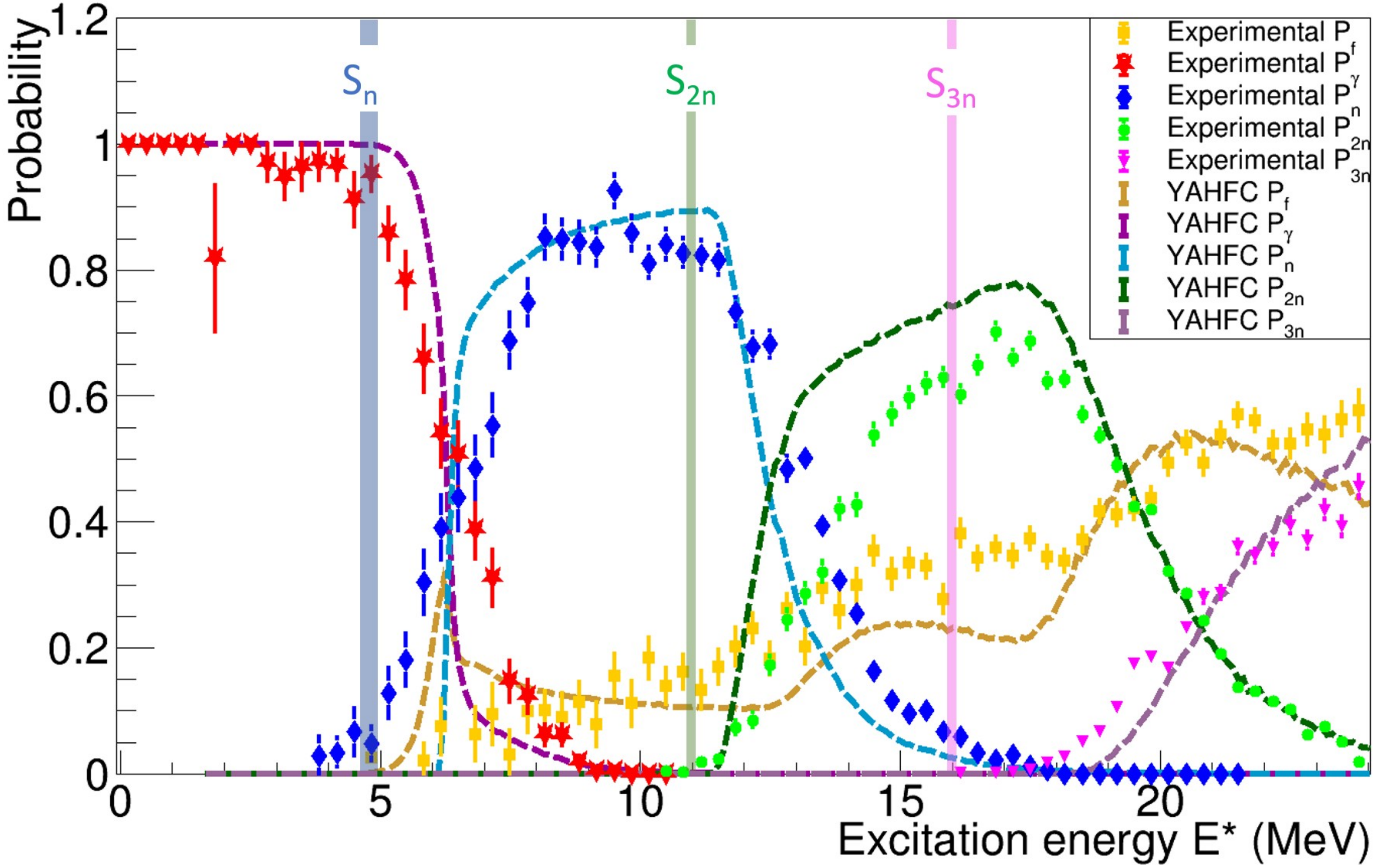


Comparison with the n-induced calculations



Done by Pascal Romain

Comparison with the (d,p)-induced calculations



Done by Gregory Potel

Conclusions and perspectives

New post-doc
Position at LP2I
Bordeaux,
starting January

- 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 (2x) resolution and more (100x) solid angle

NECTAR team

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C. Berthelot PhD student, Bordeaux

G. Leckenby Post-doc, Bordeaux

B. Jurado Nectar PI, Bordeaux

J. Pibernat, Engineer, Bordeaux

M. Grieser MPIK Heidelberg

J. Glorius GSI Darmstadt

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5-IJCLAB, Orsay, France *6-Triumf, Vancouver, Canada*
7-IFIC, Valencia, Spain *8-CEA-DAM & CEA-IRFU, France*
9-University of Chalmers, Sweden *10-University of Edinburgh, UK*
11-GANIL, France *12-University of Osaka, Japan*
13-FRIB, USA

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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

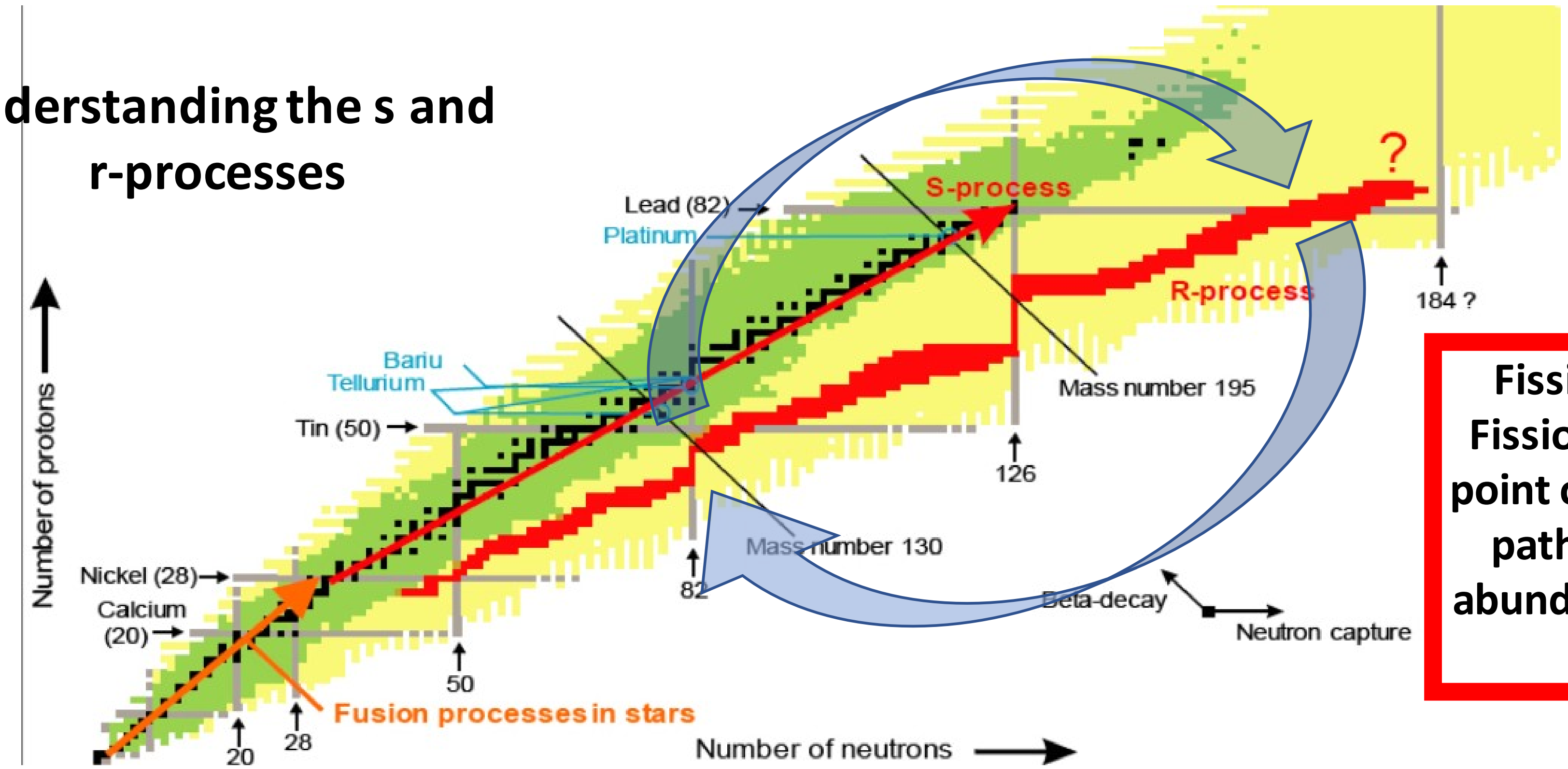
The results presented here are based on the experiment E146, which was performed at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-(

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

BACKUP SLIDES

Need for neutron-induced cross sections for short-lived nuclei

Understanding the s and r-processes



Fission recycling! Fission sets the end point of the r-process path and impacts abundances and light curves.

→Very difficult or even impossible to measure with standard techniques because of the radioactivity of the targets.

→Complicated to calculate due to the difficulty to describe the de-excitation process. Calculations can be wrong by several orders of magnitude!

De-excitation probabilities

- Expression of the probability for a given decay mode χ:

$$P_{\chi}(E^{*}) = \frac{N_{c,\chi}(E^{*})}{N_{s}(E^{*}) \cdot \varepsilon_{\chi}(E^{*})}$$

Number of coincidence events

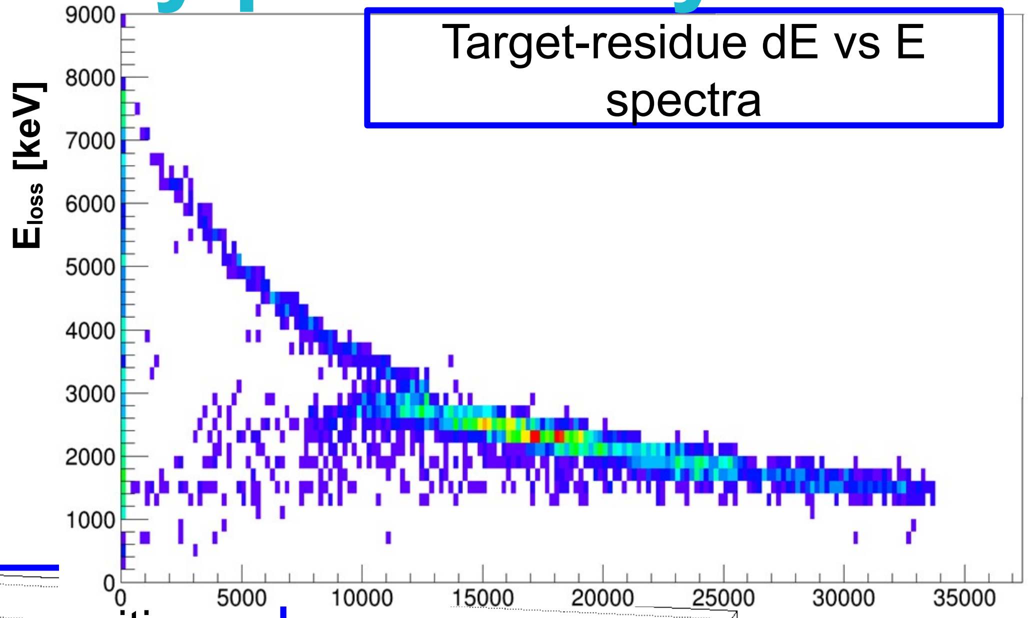
Number of singles in Telescope

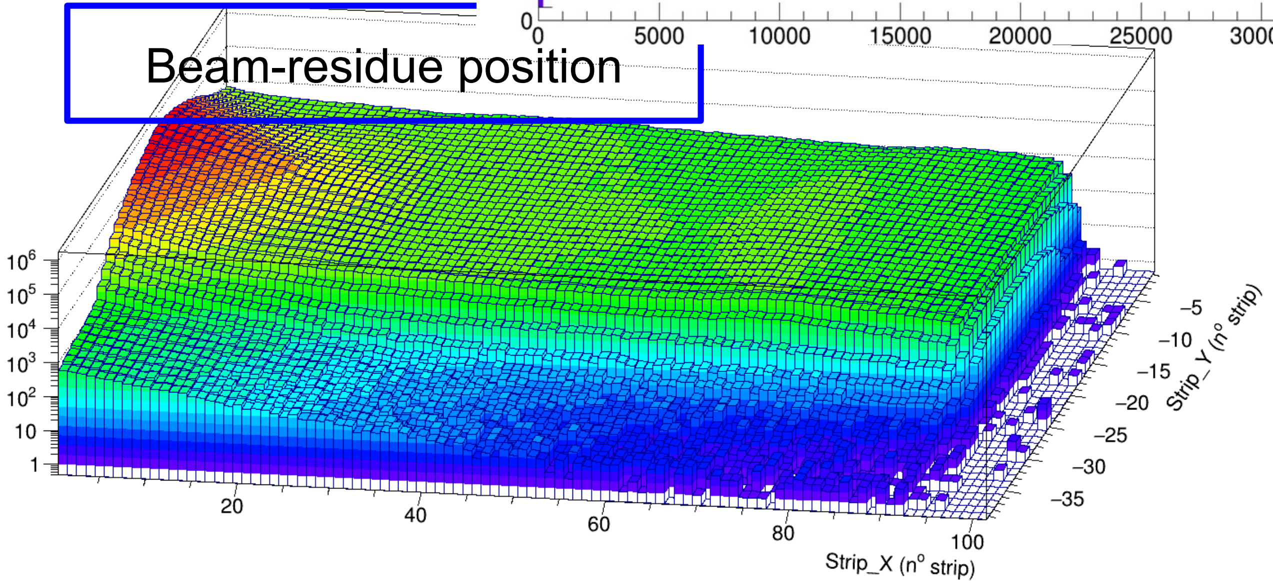
Detection efficiency

- Fission
- Neutron emission
- Gamma emission

How to get the ^{208}Pb(p,p') decay probability?

- We select the reaction based on the signals from telescope
  - We calculate excitation energy E*

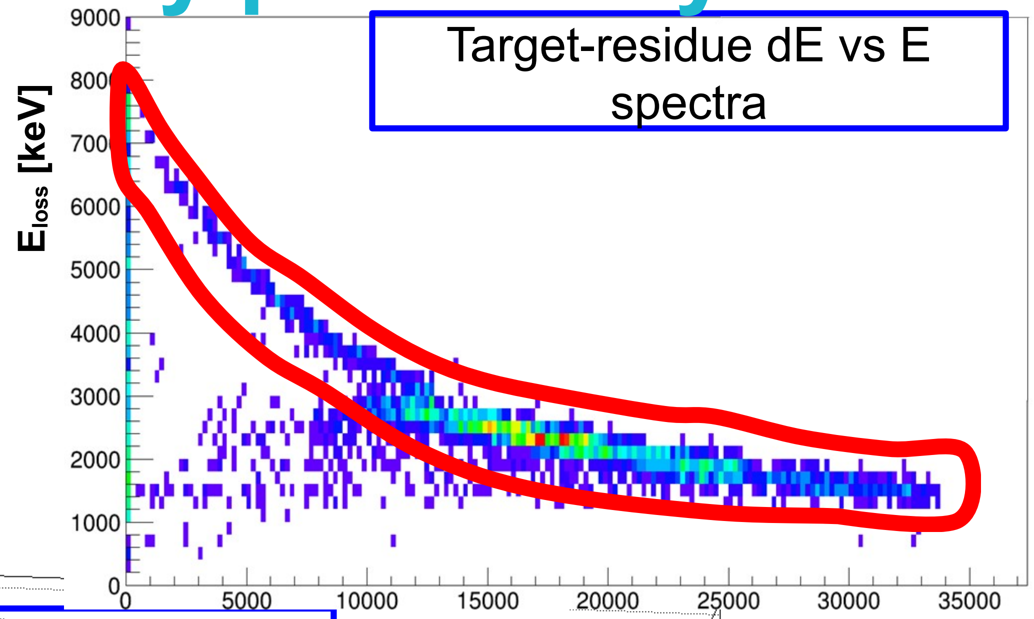


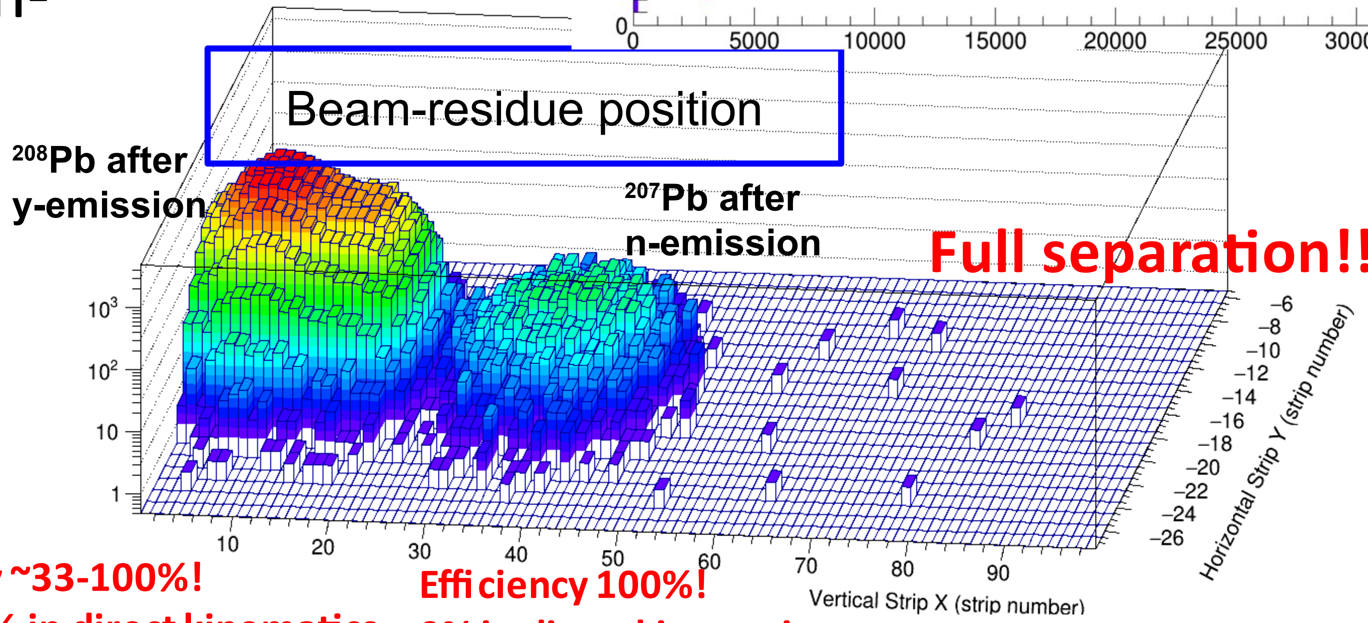


How to get the ^{208}Pb(p,p’) decay probability?

- We select the reaction based on the signals from telescope
  - We calculate excitation energy E*
- We look for coincidences in fission detectors or beam-residue detector

$$P_{\chi}(E^{*}) = \frac{N_{c,\chi}(E^{*})}{N_{s}(E^{*}) \cdot \varepsilon_{\chi}(E^{*})}$$





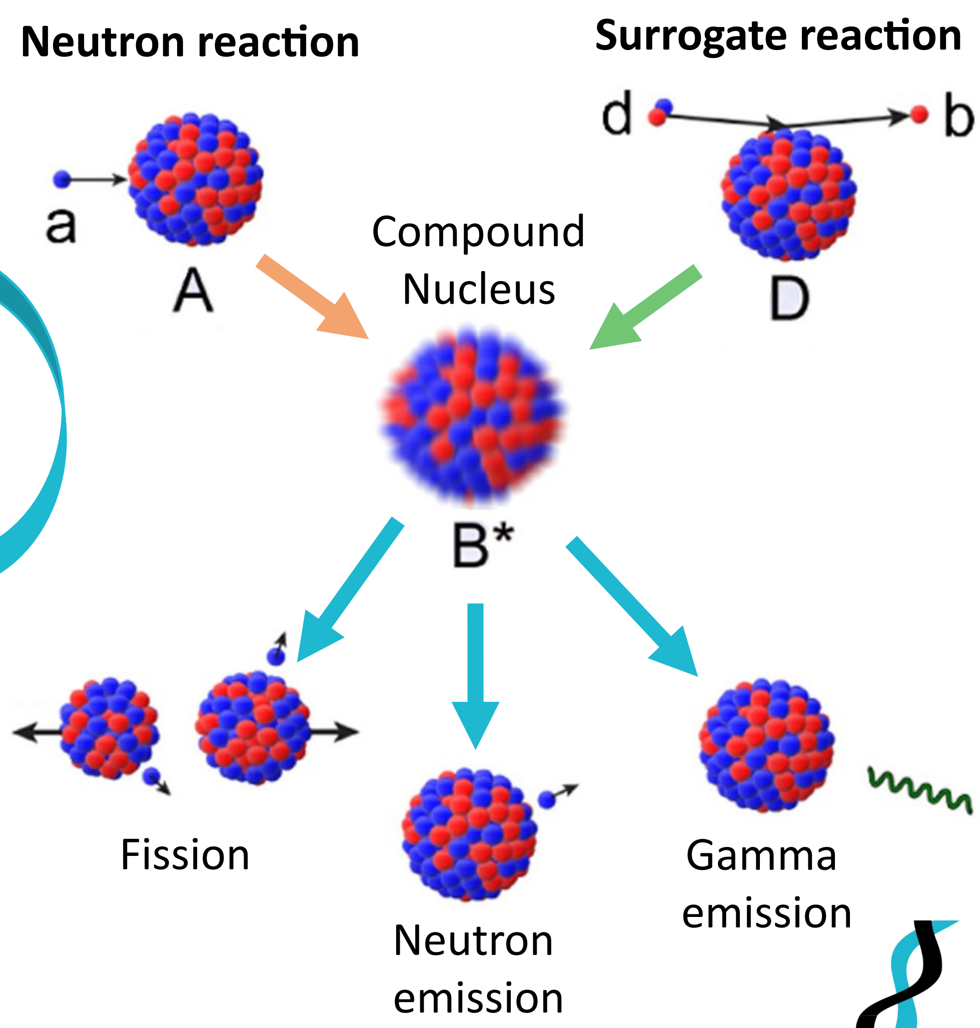
Full separation!!

Efficiency ~33-100%!
≈ Max 20 % in direct kinematics

Efficiency 100%!
0% in direct kinematics…

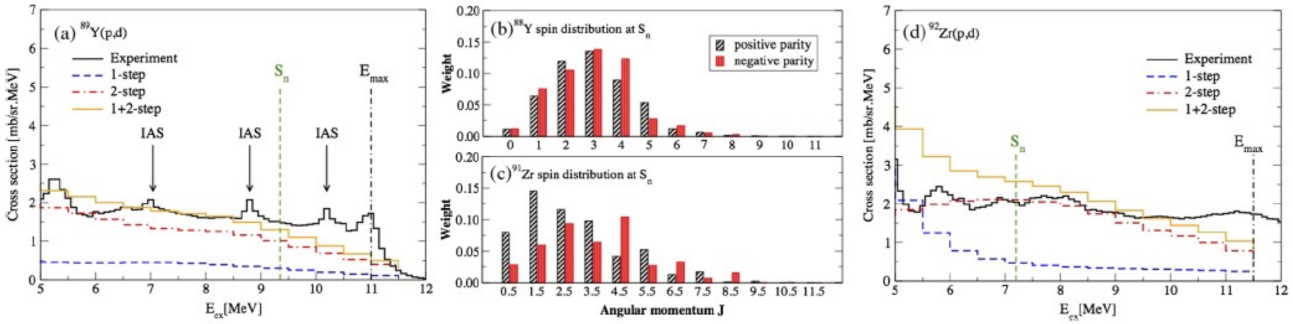
Surrogate reaction method

- Surrogate reaction forms the same CN to constrain **decay probabilities**:
  - $P_\chi(E^*) = \sum_{J,\pi} F_\delta^{CN}(E^*, J, \pi)\ G_\chi^{CN}(E^*, J, \pi)$
- Experimentally measured probabilities are then used for the cross section:
  - $\sigma_{n\chi}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E^*, J, \pi)\ G_\chi^{CN}(E^*, J, \pi)$
- Formation computed theoretically

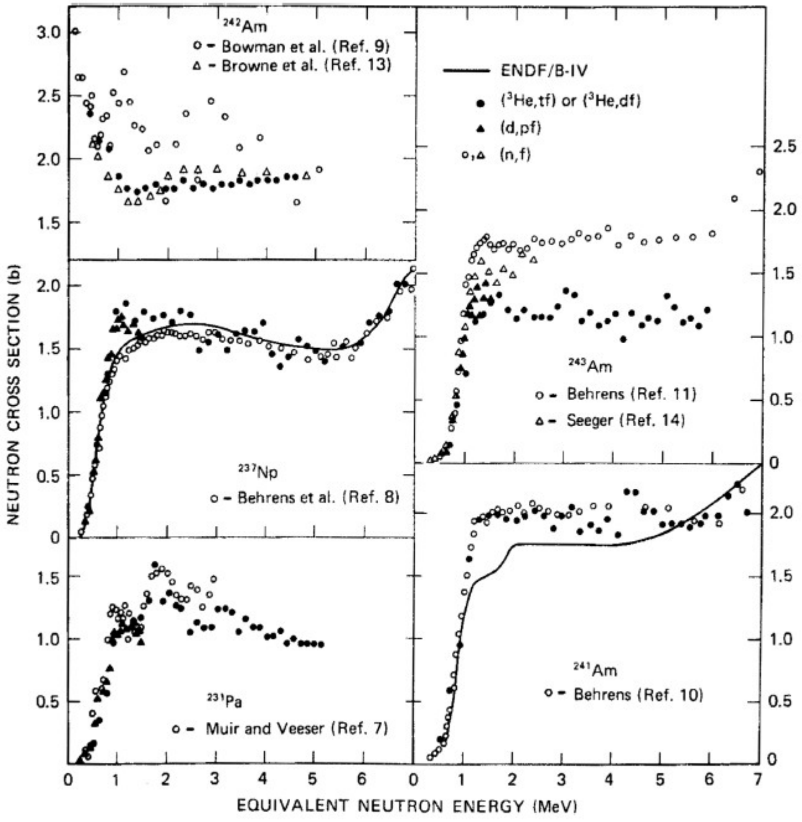


Surrogate reactions: a quick history

- Early surrogate work looked at fission
- Used Weisskopf-Ewing approx. – branching ratios independent of spin-parity
- Worked quite well for (n,f) – not for (n,γ)
- Modern fission studies use theoretical spin-parity distributions



Escher *et al*, 2018, Phys. Rev. Lett., 121:052501.

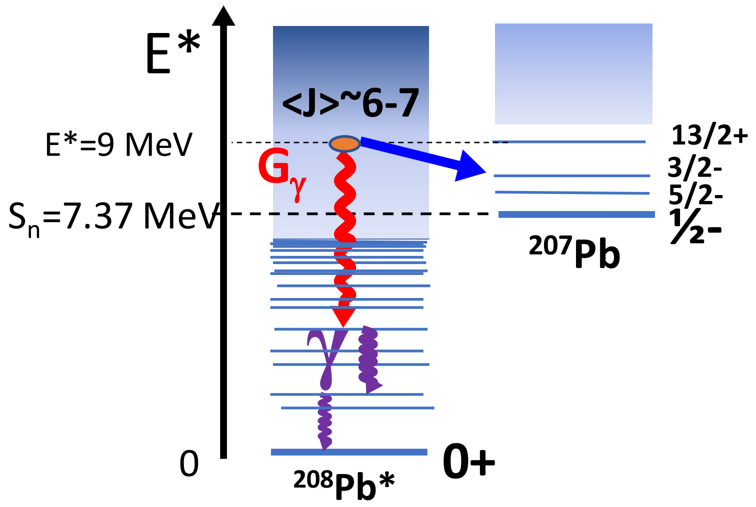


Britt & Wilhelmy, 1979, Nucl. Sci. Eng. 72, 222.

HF formalism, with i=s or i=n

$$P_{i,\chi}(E^*) = \sum_{J^\pi} F_i(E^*, J^\pi) G_\chi(E^*, J^\pi)$$

Probability — Formation — Decay probability of CN

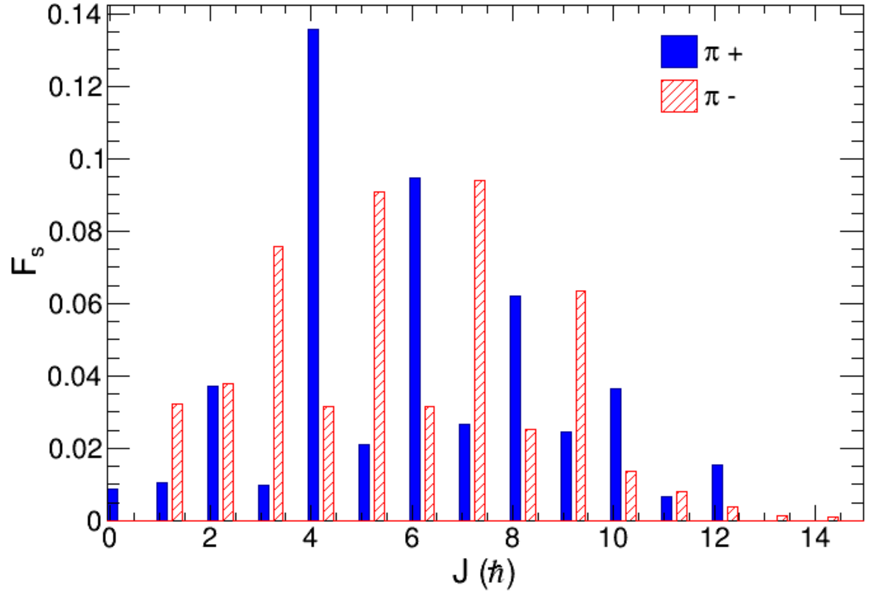


At high E*, G_χ becomes independent of J^π

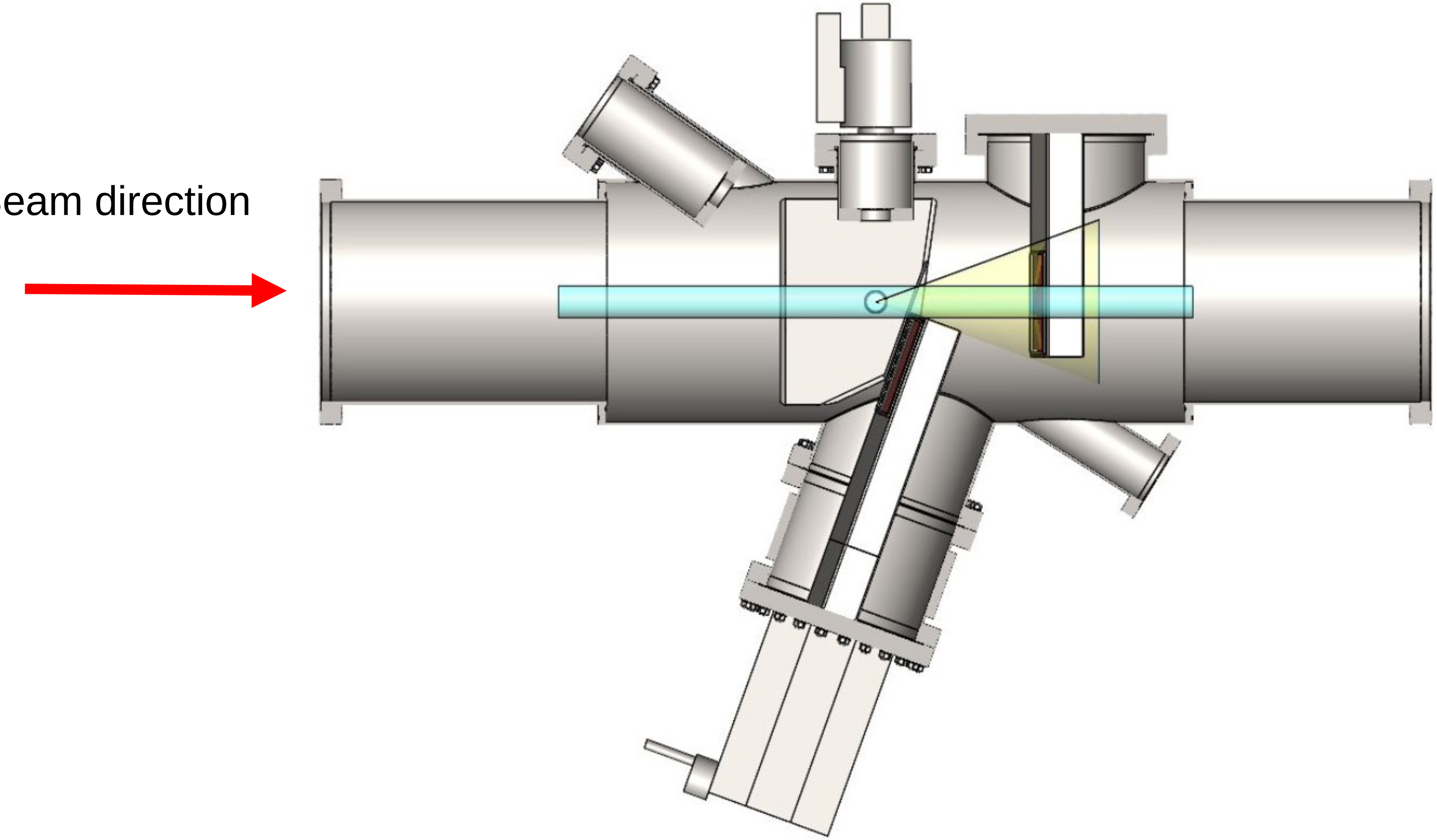
=> $P_{s,\chi} \approx P_{n,\chi}$ and

$$\sigma_{n,\chi}(E_n) \cong \sigma_{\rm CN}(E_n) P_{s,\chi}(E^*)$$

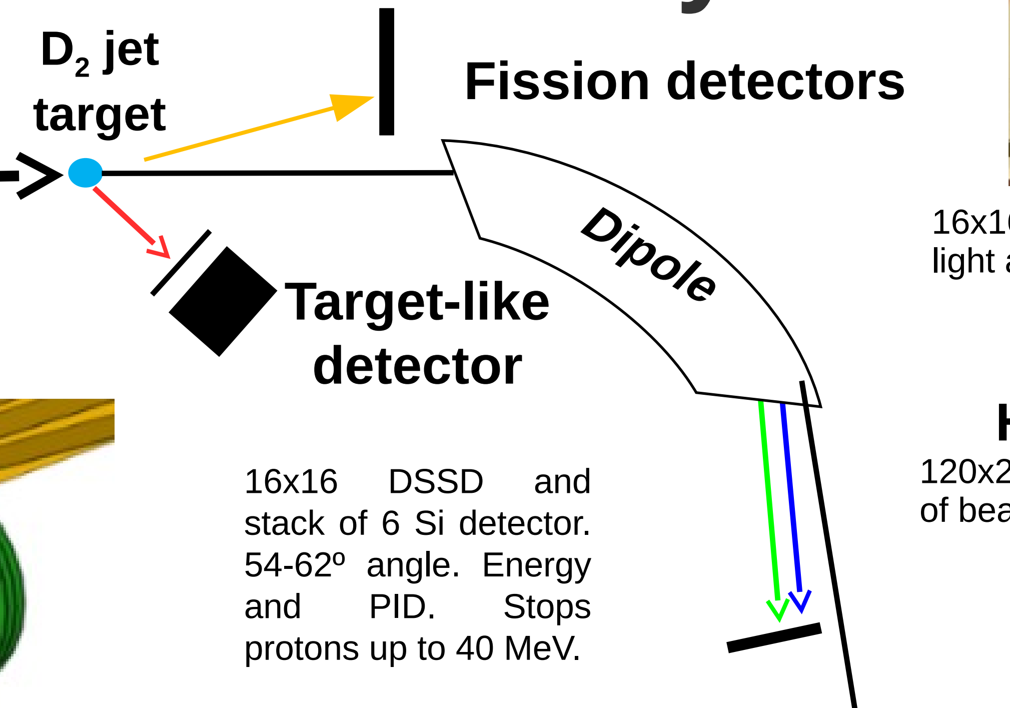
n-induced CS — CS for CN formation — Probability



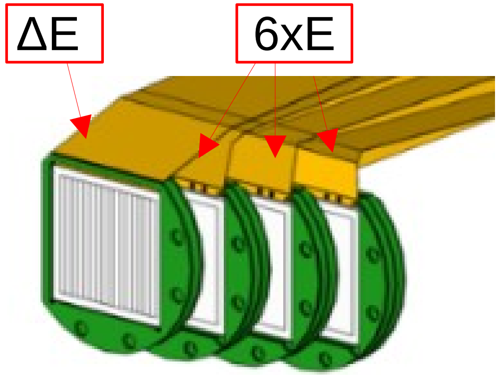
Beam direction

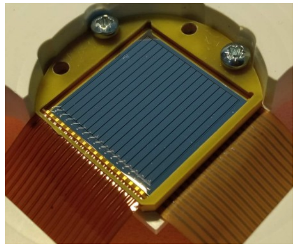


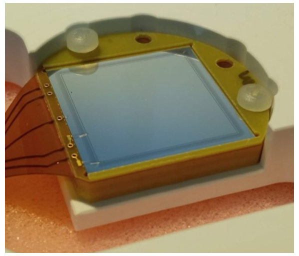
NECTAR Detection System

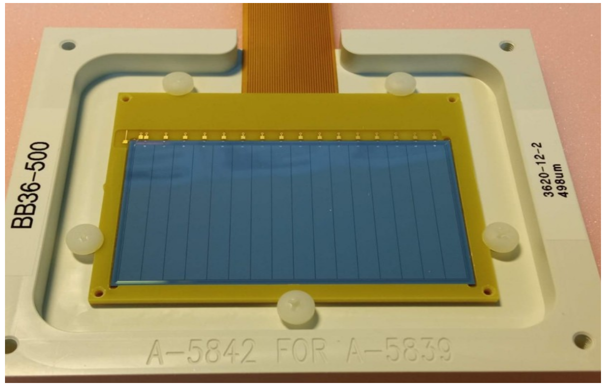


16x16 DSSD and stack of 6 Si detector. 54-62° angle. Energy and PID. Stops protons up to 40 MeV.





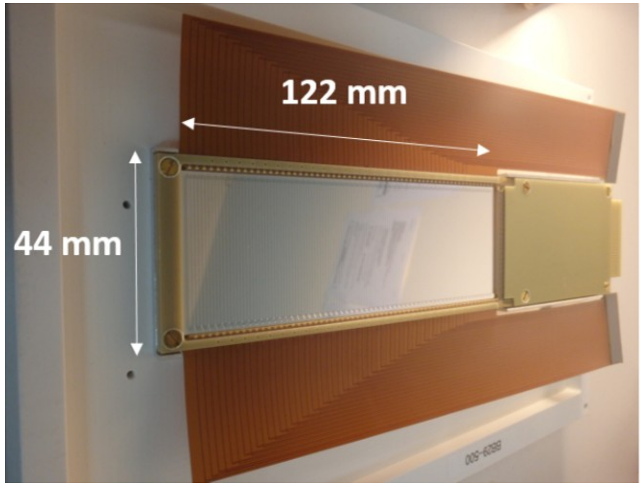




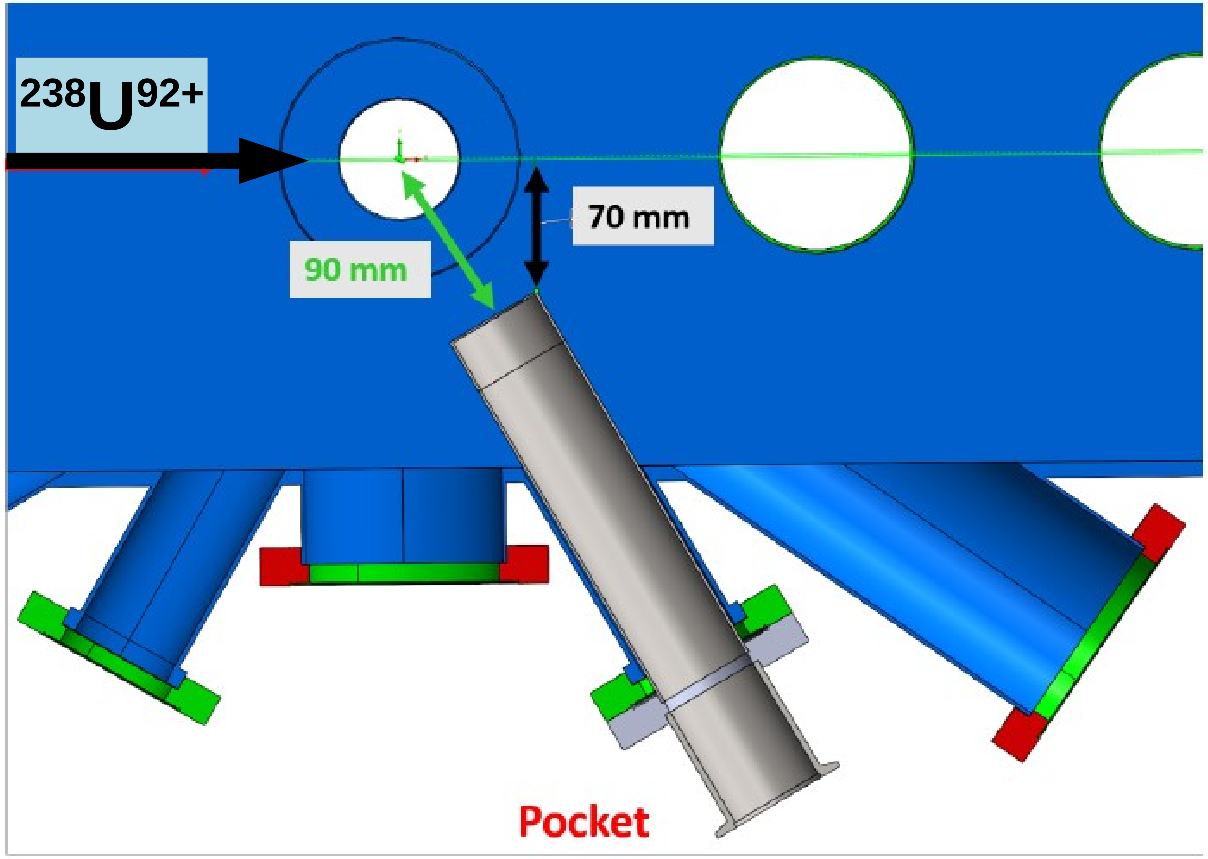
16x16 DSSD for detecting position and energy of light and heavy fragments from uranium fission

Heavy residue detector

120x20 DSSD for detecting position and energy of beam-like ($^{238,239}U^{92+}$) residues



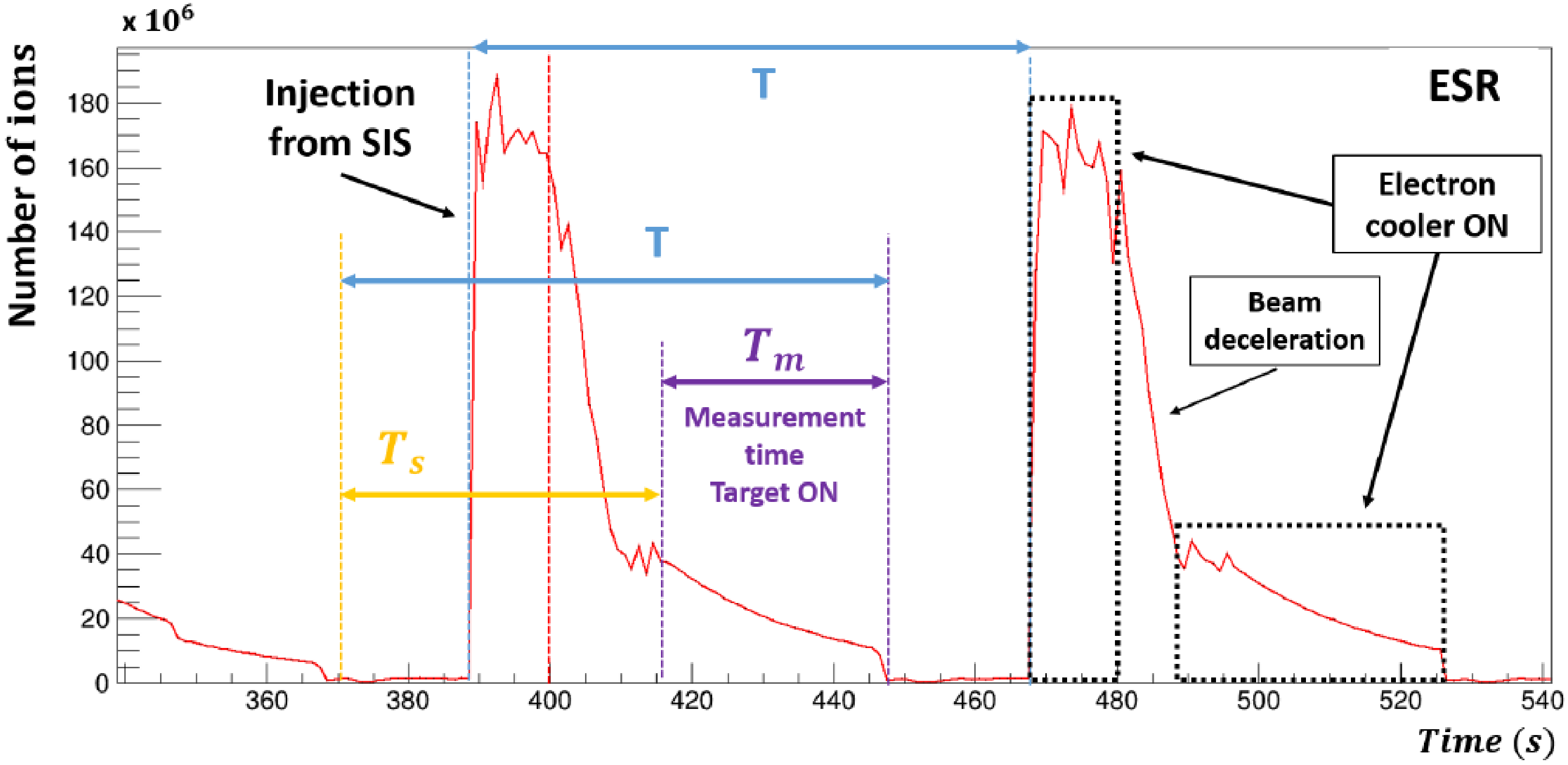
NECTAR Target-like Detector



25 µm stainless steel Window

Stainless steel pocket
(MPIK Heidelberg)

Beam pattern



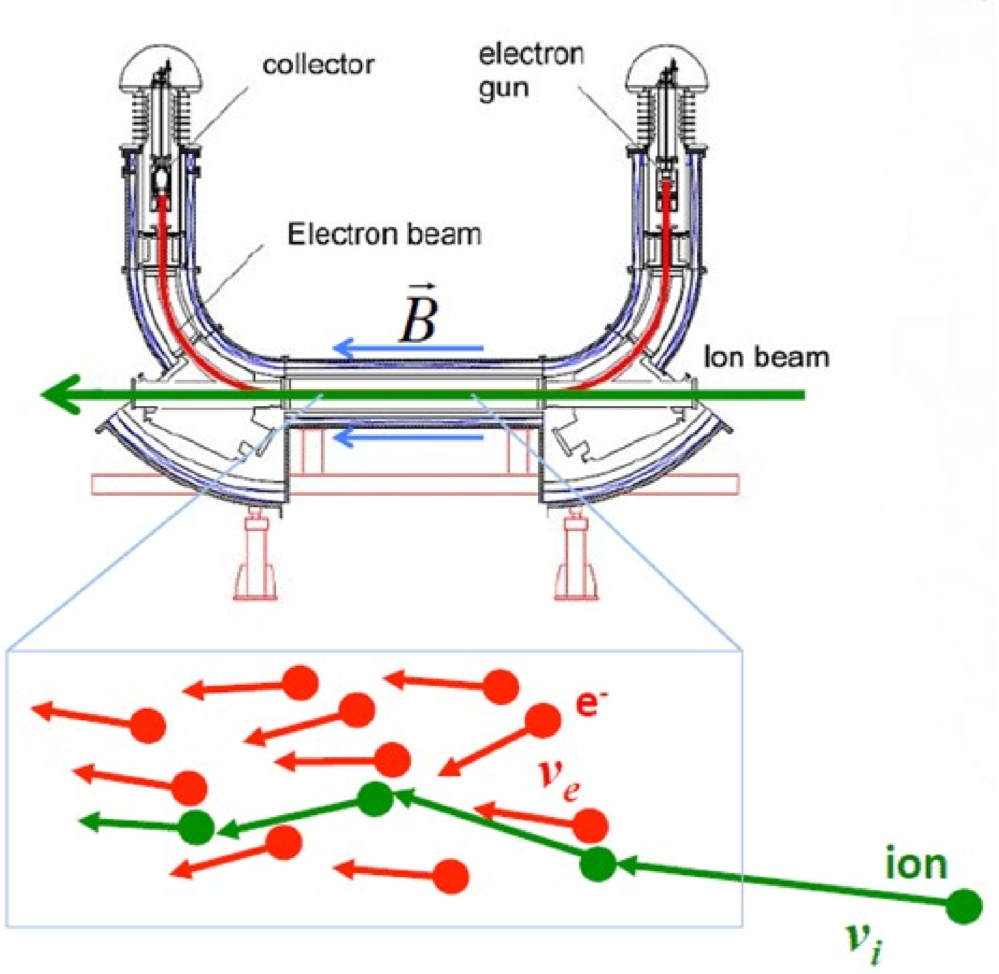
T= 80 s

Ts = 50 s Preparation time

Tm = 30 s Measurement time

What is electron cooling?

- Newly injected beam is “hot” meaning it have large spread in position and momentum space
- “Cool” electron beam is merged in the same direction as the beam
- Velocity of the electron is made equal to the velocity of the beam
- Net heat transfer to lighter electrons
- Electrons are removed leaving original beam with lower momentum spread



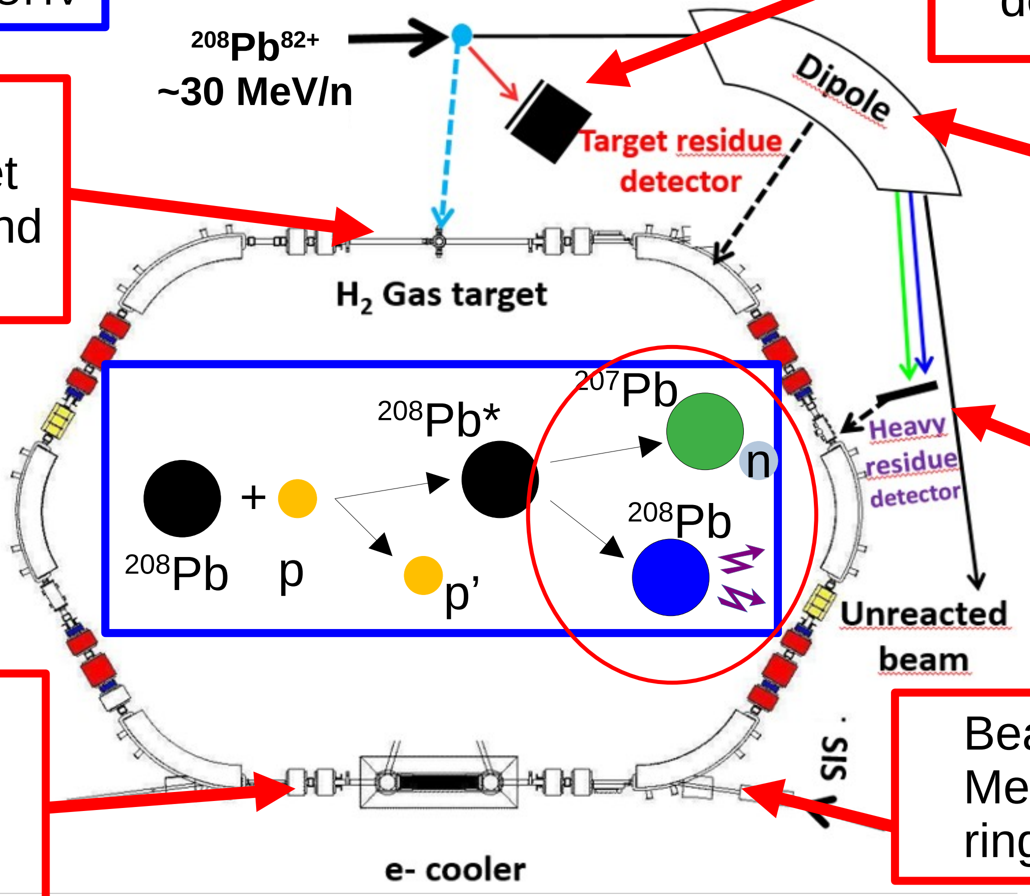
NECTAR Proof-of-principle I (June 2022)

Camille Berthelot poster about detectors and UHV

When beam was ready, gas jet target was switched on and reactions started

Target off, beam off, cycle repeat

Then beam was decelerated to 30 MeV/A and cooled by e-cooler



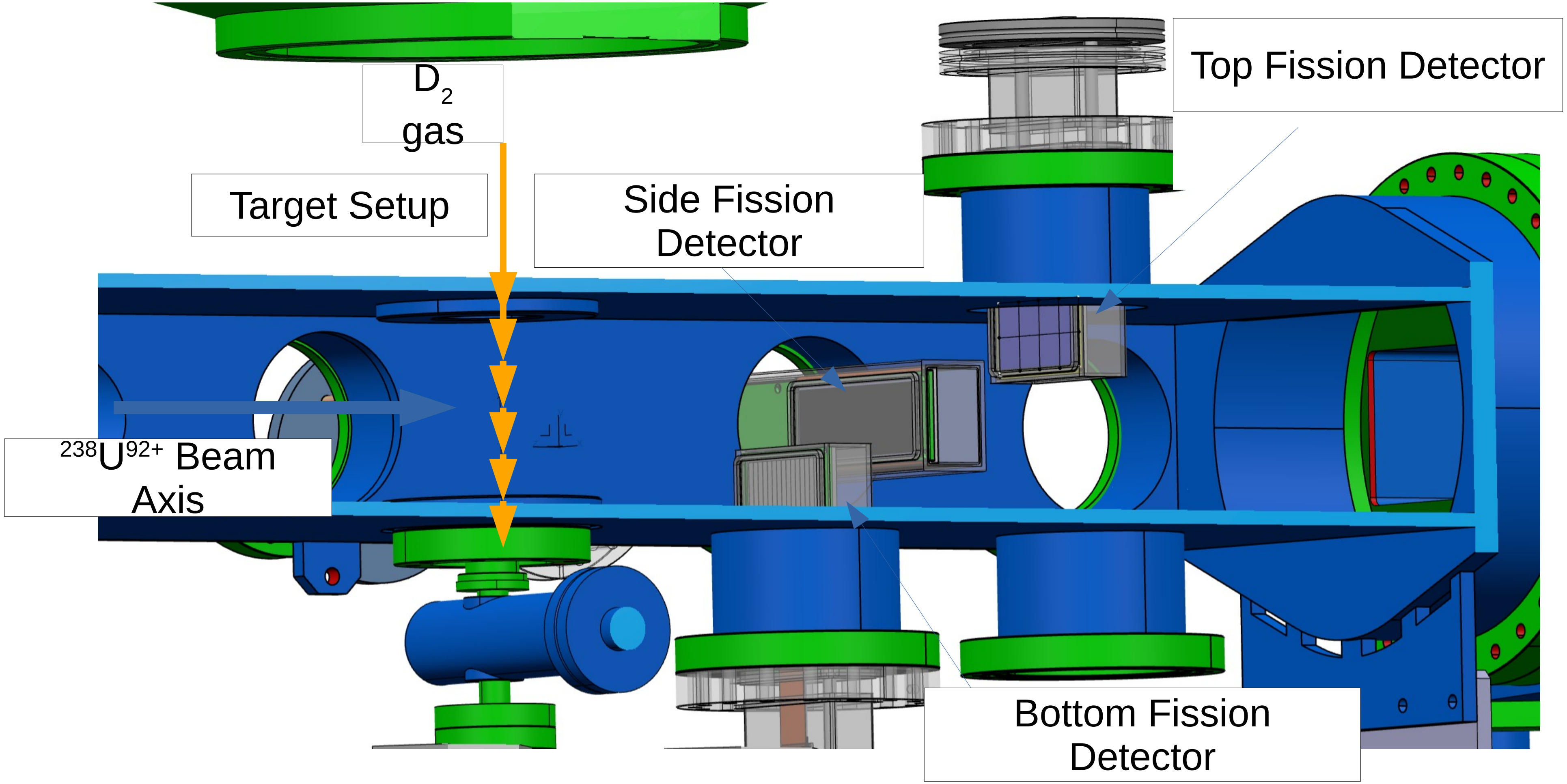
Telescope detects protons

Dipole separate unreacted beam and products. Bare ions! No e^- removal

Heavy products were detected after the magnet

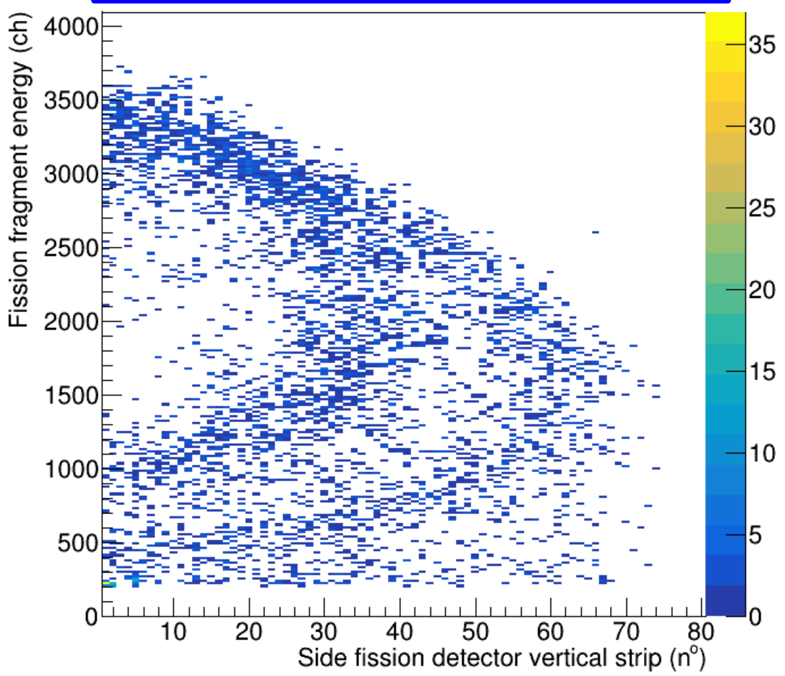
Beam of ^{208}Pb at 350 MeV/n was injected into ring

NECTAR Fission Detectors

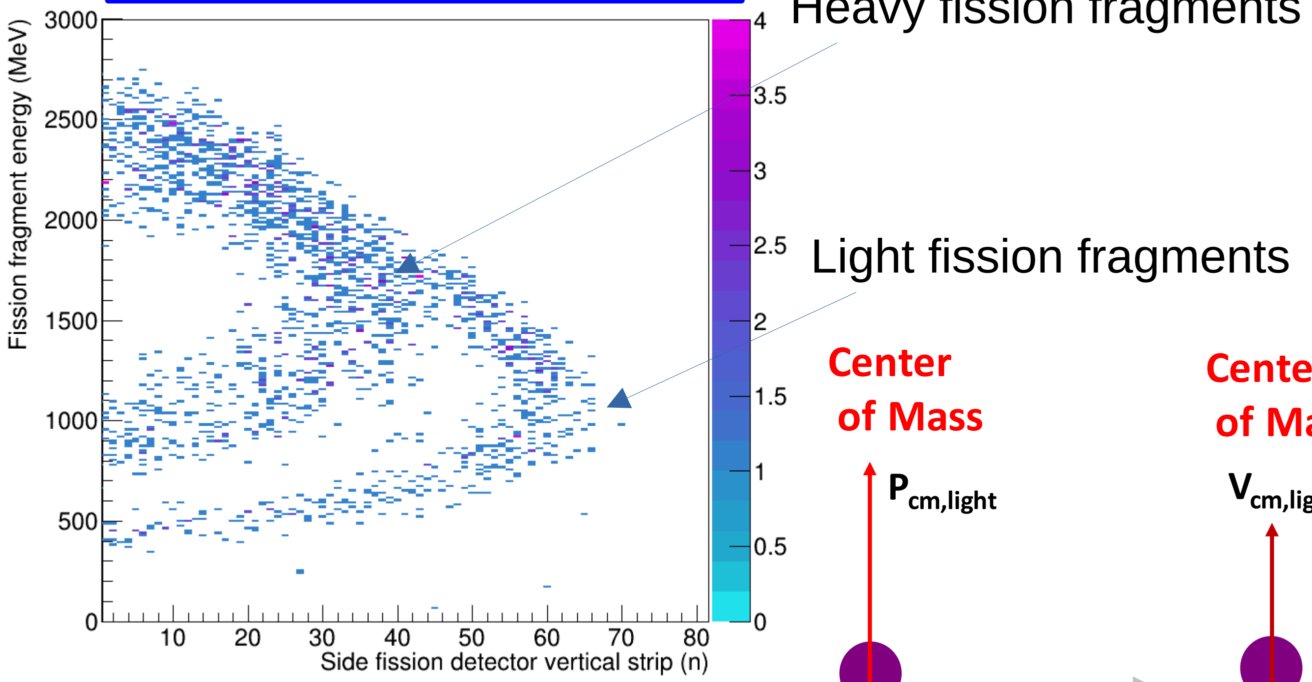


Preliminary Results (Fission detectors)

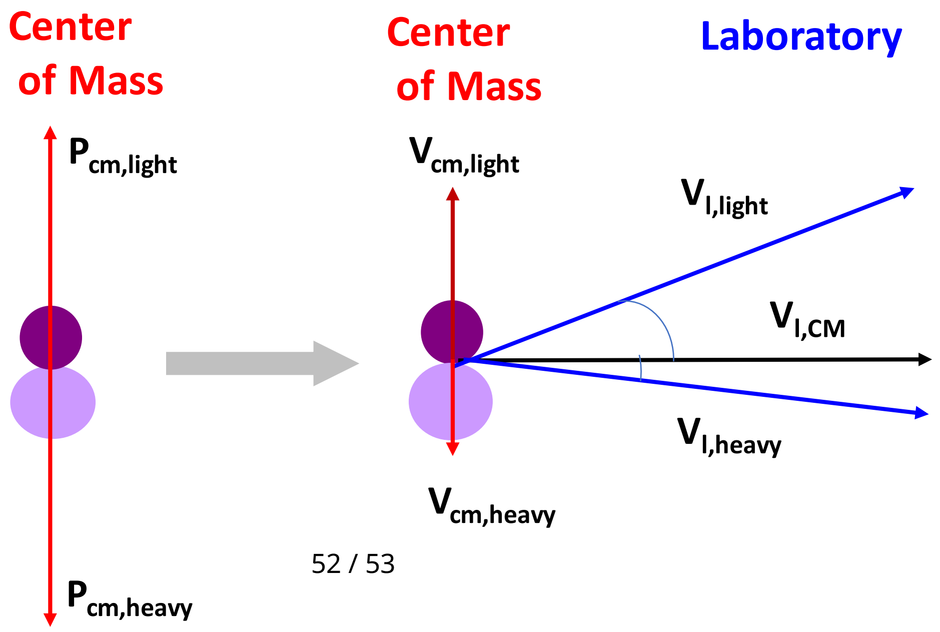
Experimental results

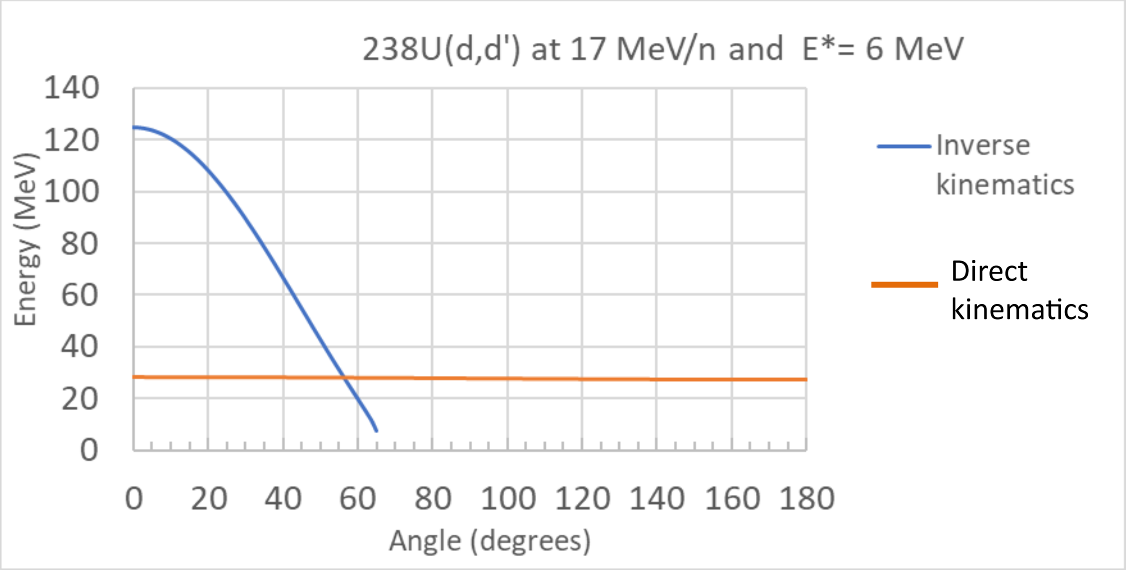


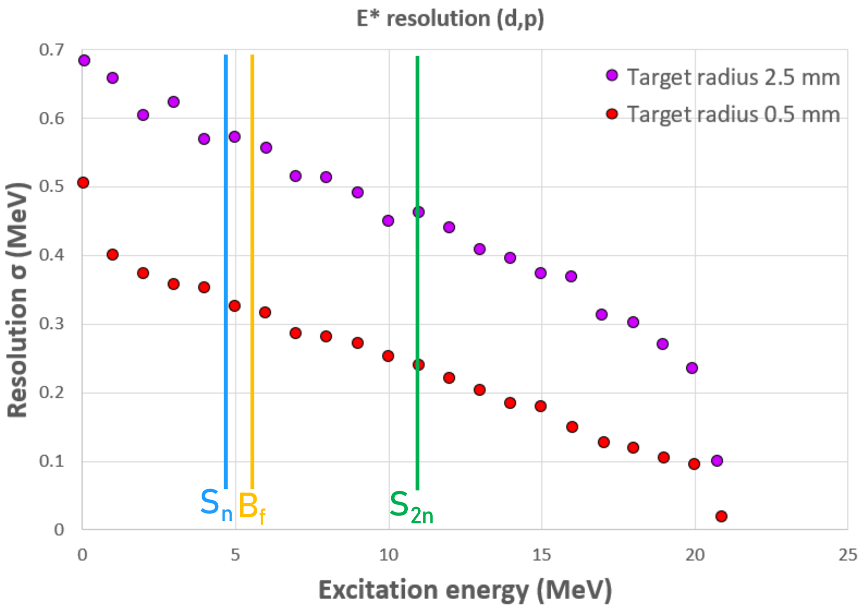
Simulated distribution



First ever Fission measurement in heavy-ion storage rings!




238U(d,d') at 17 MeV/n and E*= 6 MeV
Energy (MeV)
140
120
100
80
60
40
20
0
0 20 40 60 80 100 120 140 160 180
Angle (degrees)
Inverse kinematics
Direct kinematics


E* resolution (d,p)
Resolution σ (MeV)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 5 10 15 20 25
Excitation energy (MeV)
Target radius 2.5 mm
Target radius 0.5 mm
Sn
Bf
S2n