# Surrogate Reactions at Heavy-Ion Storage Rings

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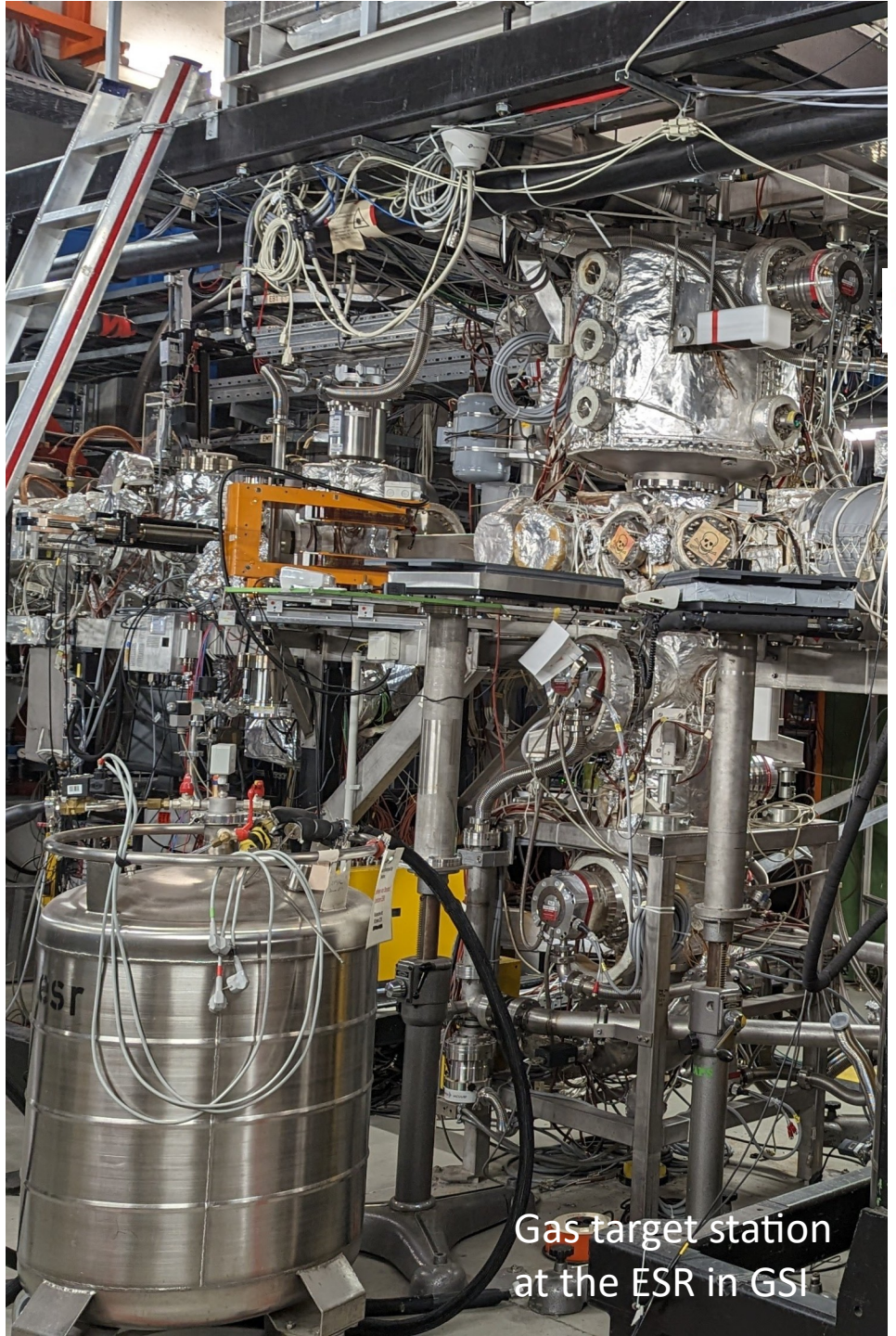
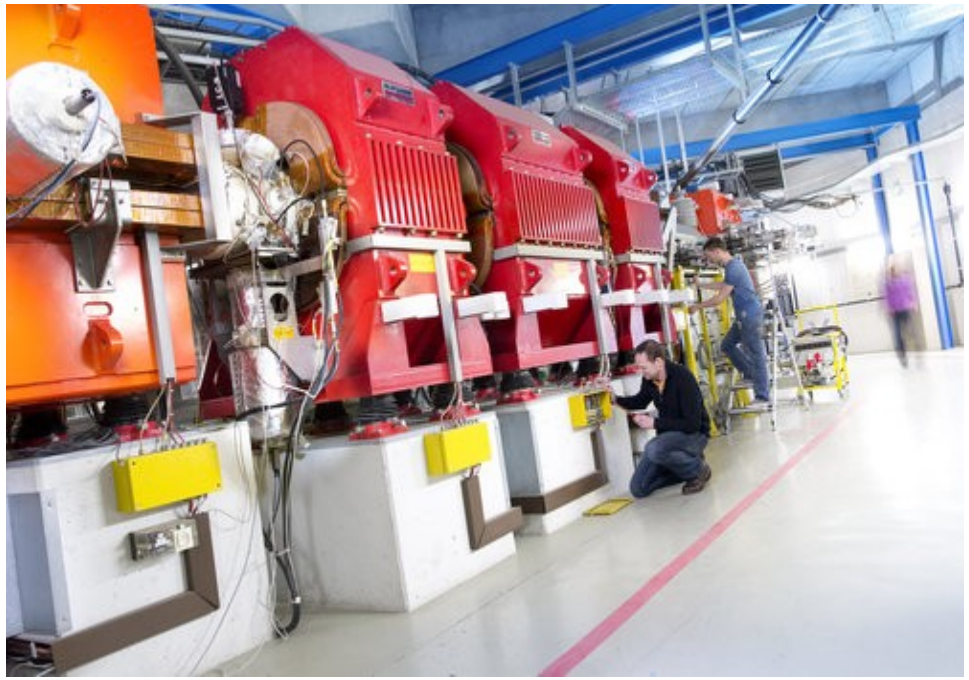
NECTAR
Nuclear rEaCTions At storage Rings



Gas target station at the ESR in GSI

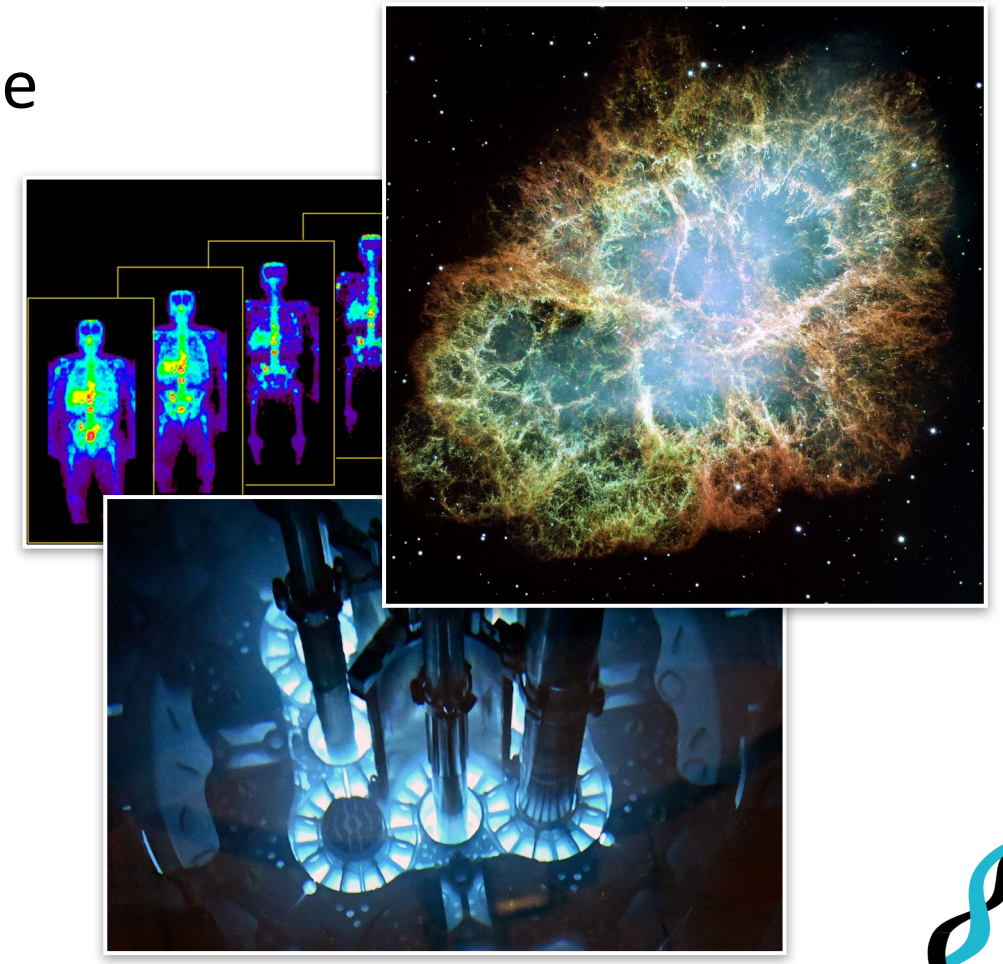
# What will I be talking about?

1. Motivation
   - Neutron induced reactions
2. The surrogate method
3. Why Storage rings? – NECTAR project
   - ESR storage ring in GSI/FAIR
   - Experimental setup
   - Results of $^{208}$Pb and $^{238}$U experiments
4. Conclusions and future outcome



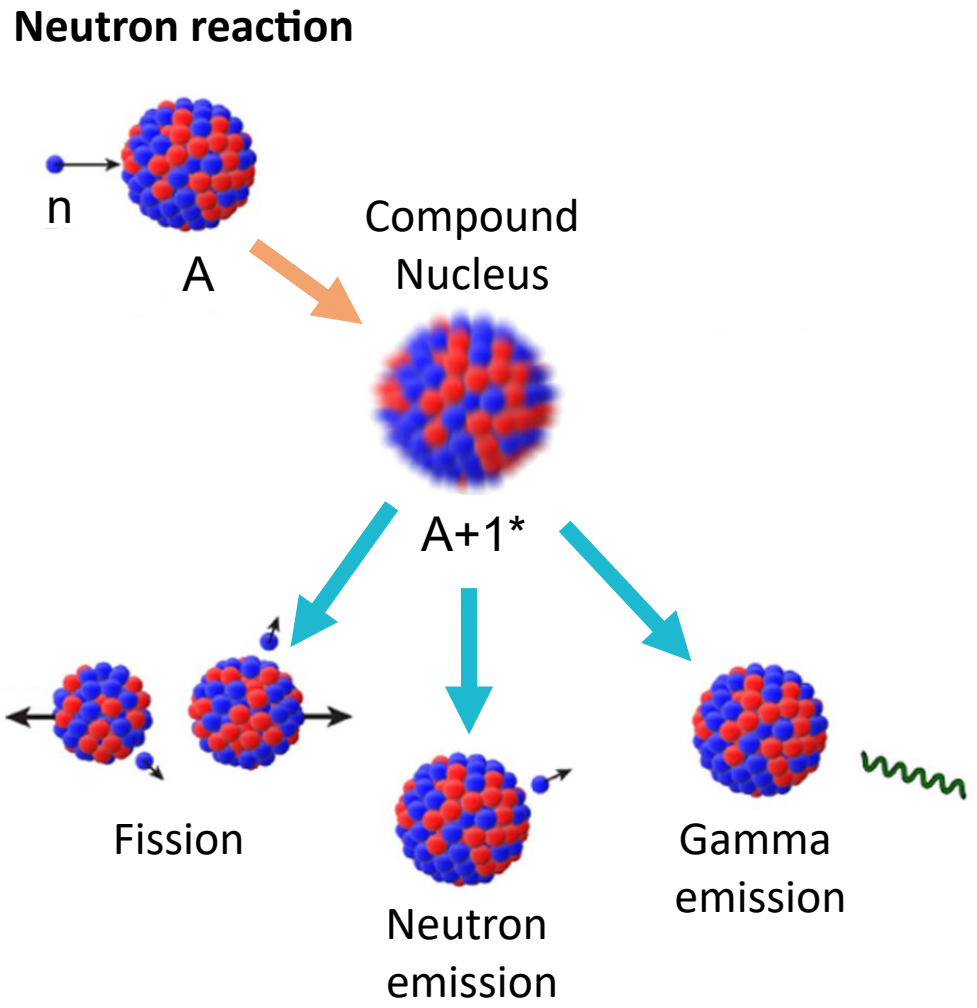
# Neutron capture cross sections are hard

- Neutron-induced reactions are some of the most interesting nuclear reactions:
  - *s* and *r* process nucleosynthesis
  - Reactor cycles and waste management
  - Medical isotope production
- Currently neutron induced reactions are impossible in inverse kinematics
- Theoretical predictions vary by orders of magnitude



# 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



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- 2 step process:
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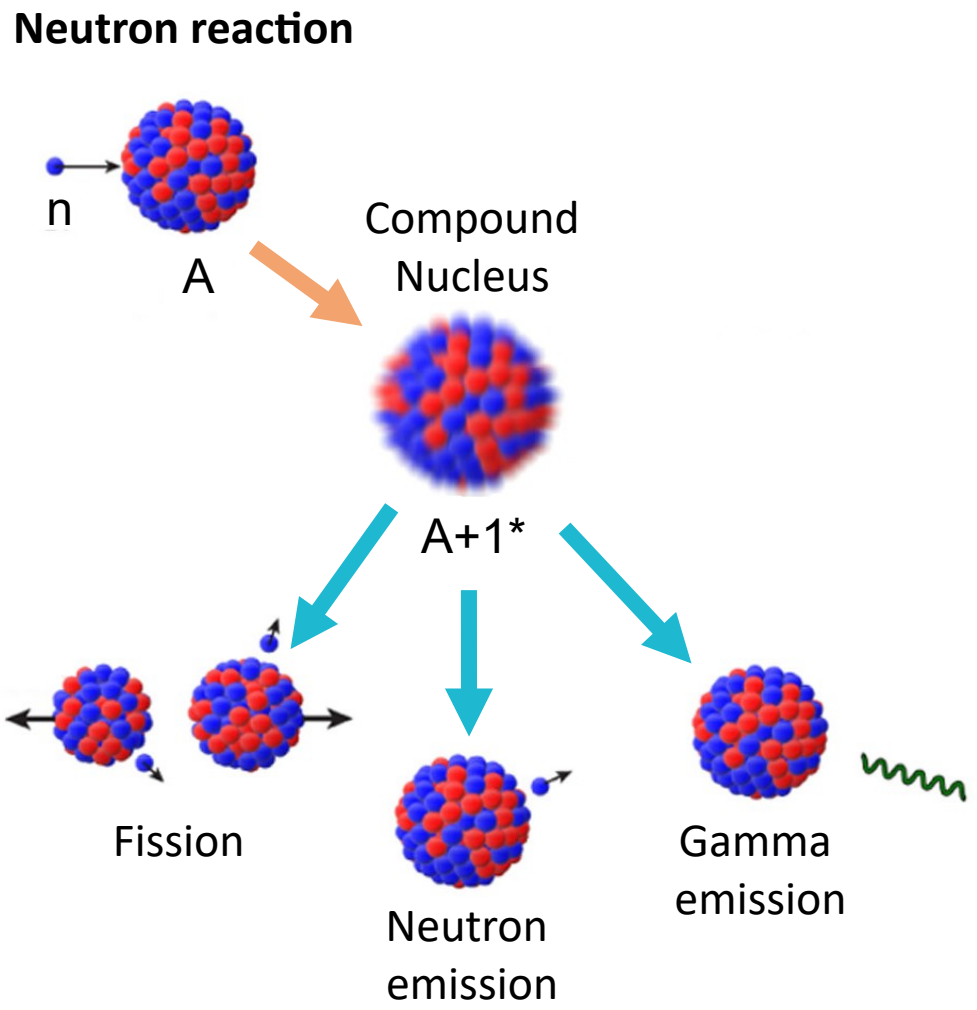
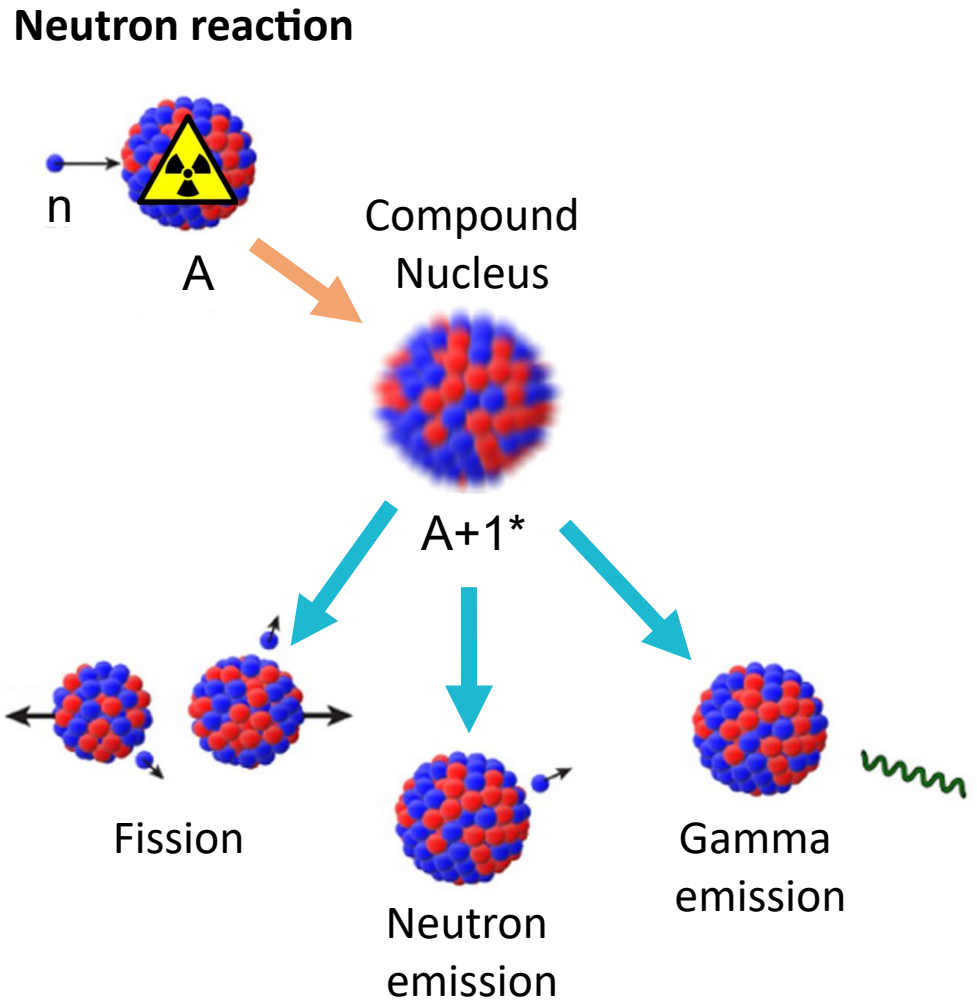
- $\sigma_X$ by measuring of decay modes:
  - Fission products (easy)
  - Gamma rays (hard)
  - Neutrons (extremely difficult)



# How to measure neutron cross sections?

- What if nuclei are radioactive?
  - Making or handling can be impossible



# How to measure neutron cross sections?

- What if nuclei are radioactive?
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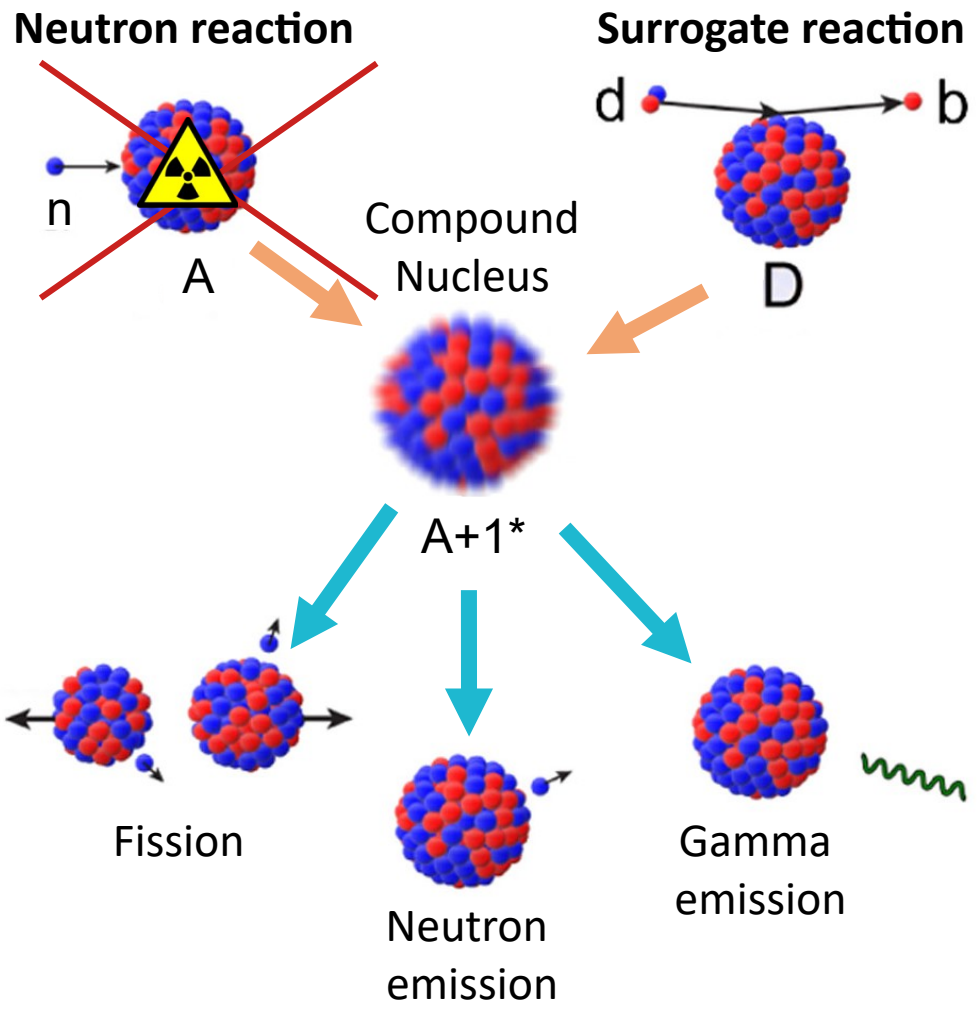
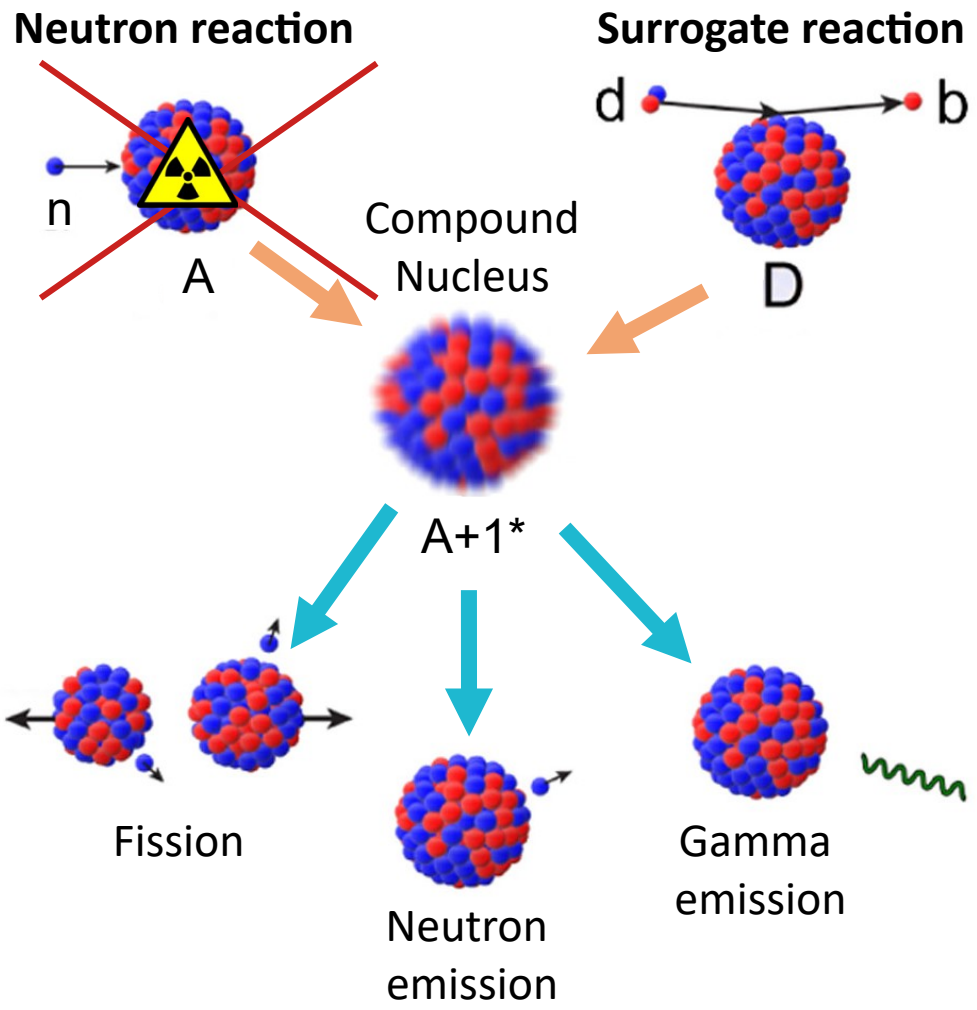
- Surrogate method
  - Different 2-body reaction that forms the same CN
  - Light residue used to calculate excitation energy



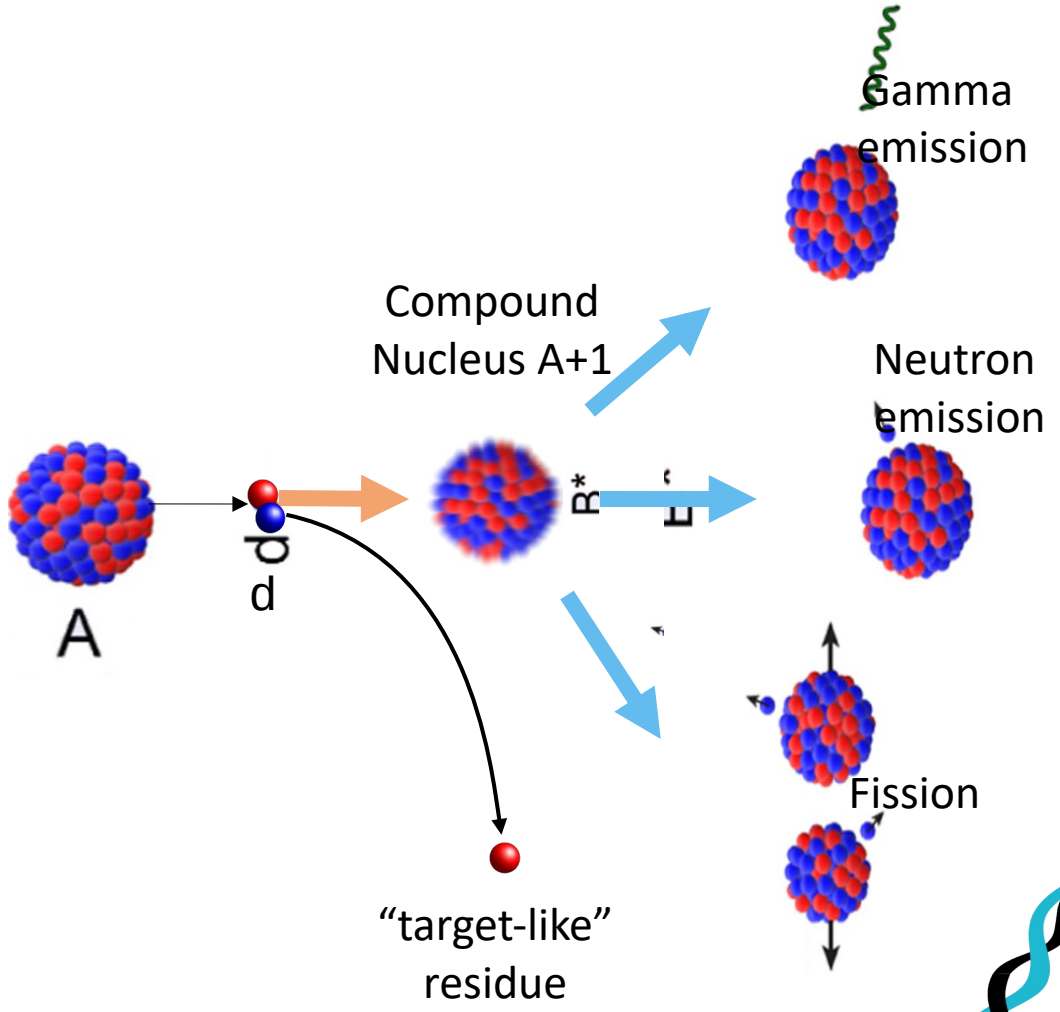
# How to measure neutron cross sections?

- 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



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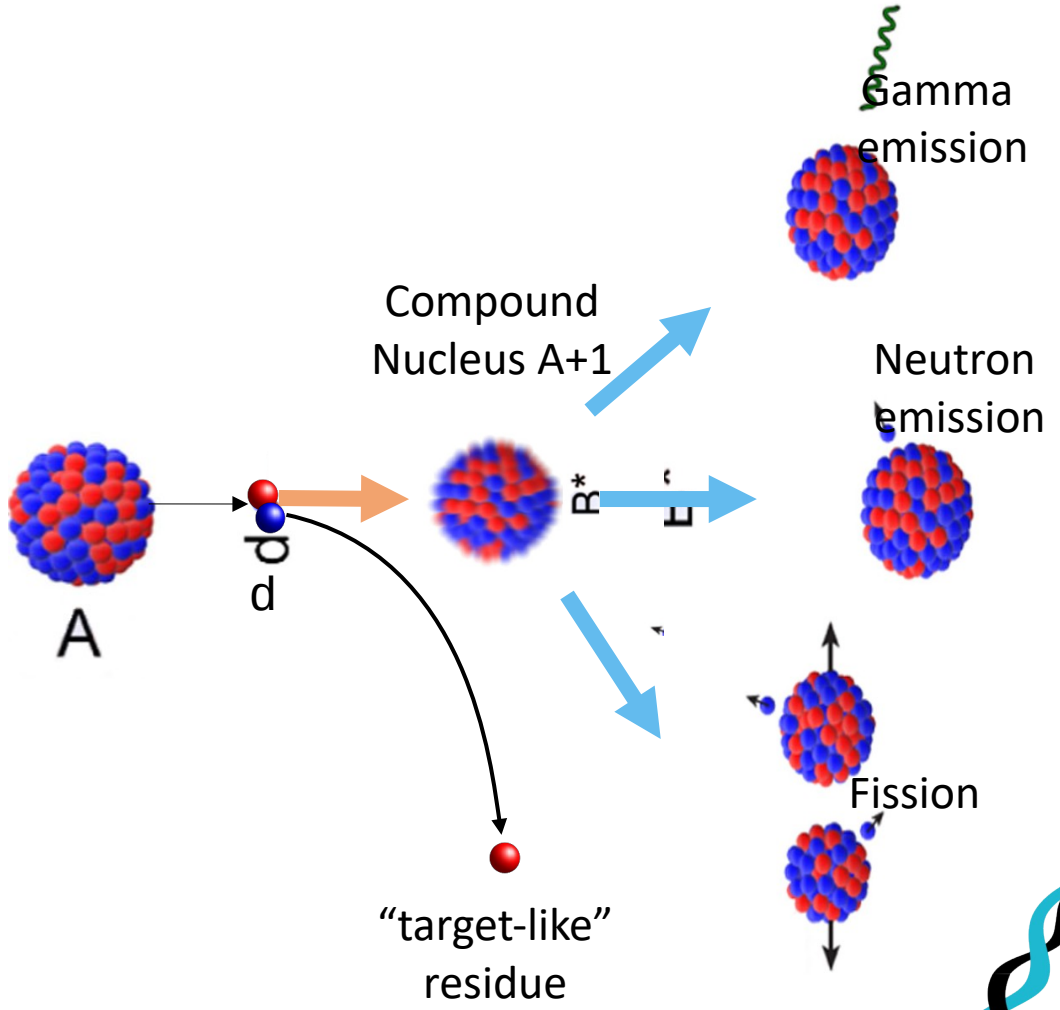
  - Heavy products escape target, boost in efficiency
  - Can measure $P_n$



# Surrogate reactions in inverse kinematics

- Serious limitations in direct kin.
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- Inverse kinematics:
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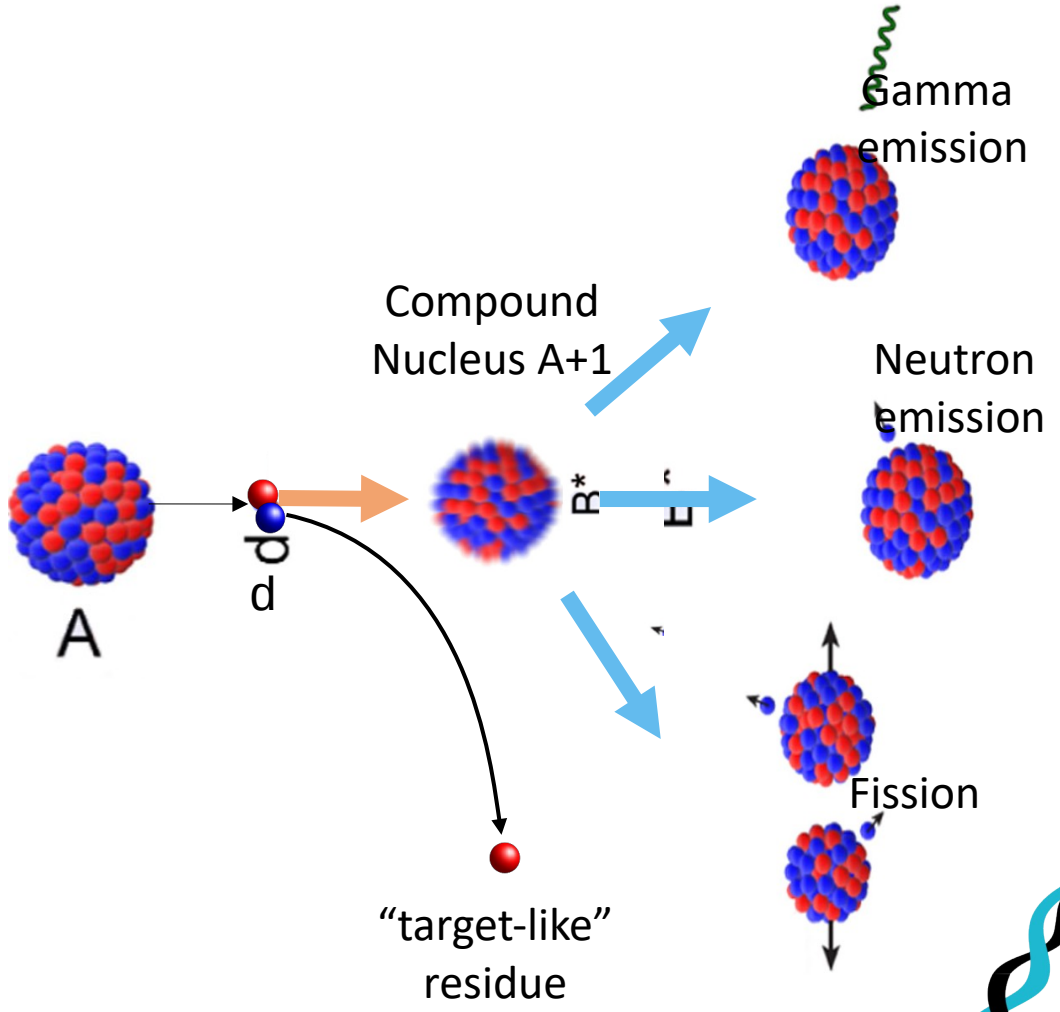
  - Heavy products escape target, boost in efficiency
  - Can measure $P_n$
- lower E* resolution, Low beam intensity, straggling in the target.
  - Our solution: **Heavy Ion Storage Rings**



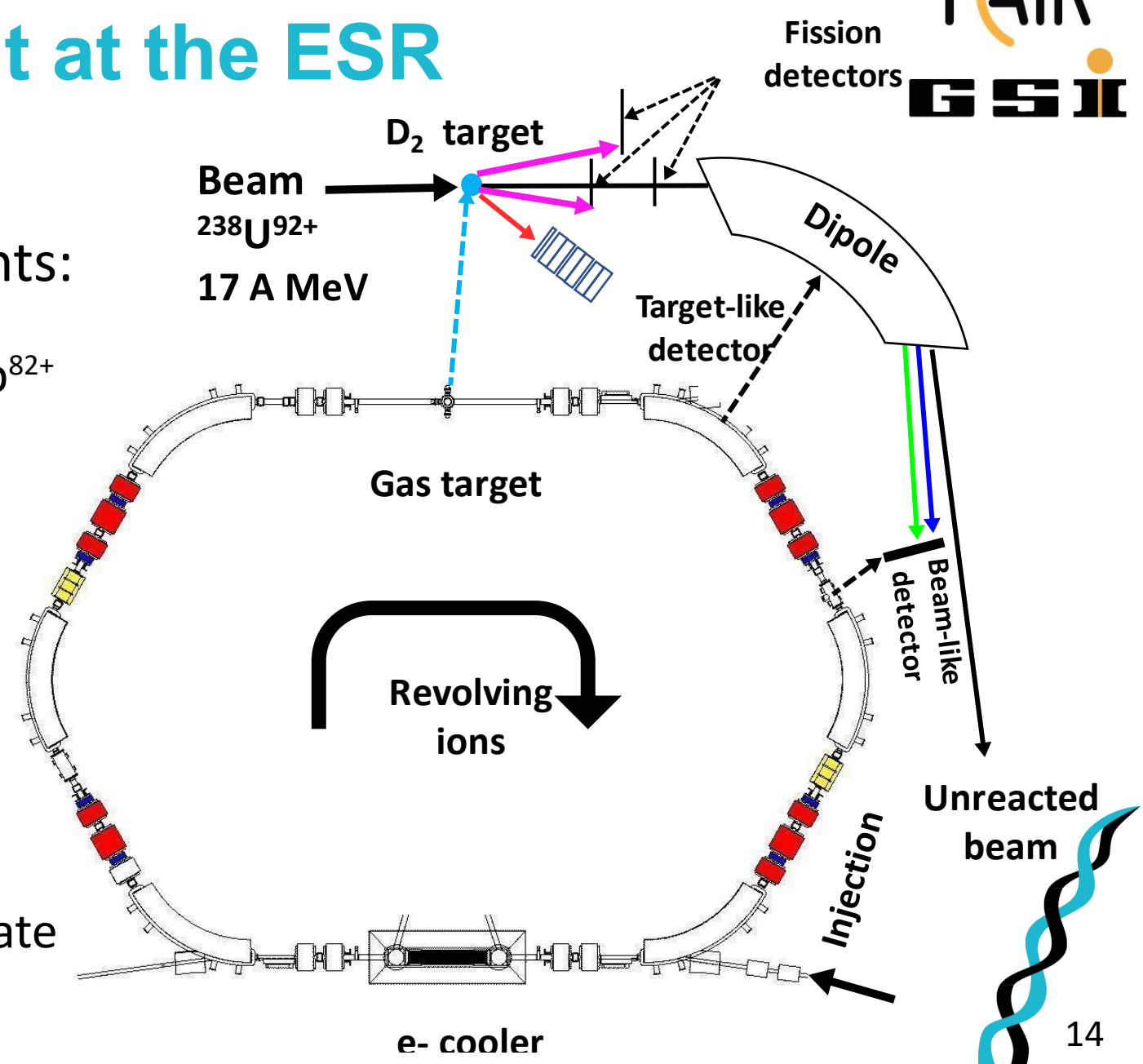
# Why Surrogate reaction in Storage Rings?

- Access to high quality, fully stripped radioactive beams
- Beam can be decelerated, cooled and fine tuned to desired energy
- Ultra-thin gas jet target ($10^{14}$ $cm^{-2}$)
  - Pure target, now windows
  - Negligible straggling
  - Energy restored by e-cooler
- Effective thickness multiplied by ~MHz ring frequency


Electron cooler at the ESR in GSI Darmstadt

# NECTAR experiment at the ESR

- At the ESR ring in GSI/FAIR in Darmstadt we did 2 experiments:
- First proof-of-principle in 2022 $^{208}Pb^{82+}$ on $H_2$ at 30 AmeV
  - **(p,p') inelastic scattering as a surrogate to $^{207}$Pb+n**
- Second proof-of-principle In 2024 $^{238}U^{92+}$ on $D_2$ at 17 AMeV
  - **Two reactions: (d,p) transfer as a surrogate to $^{238}$U+n**
  - and (d,d') inelastic as a surrogate to $^{237}$U+n



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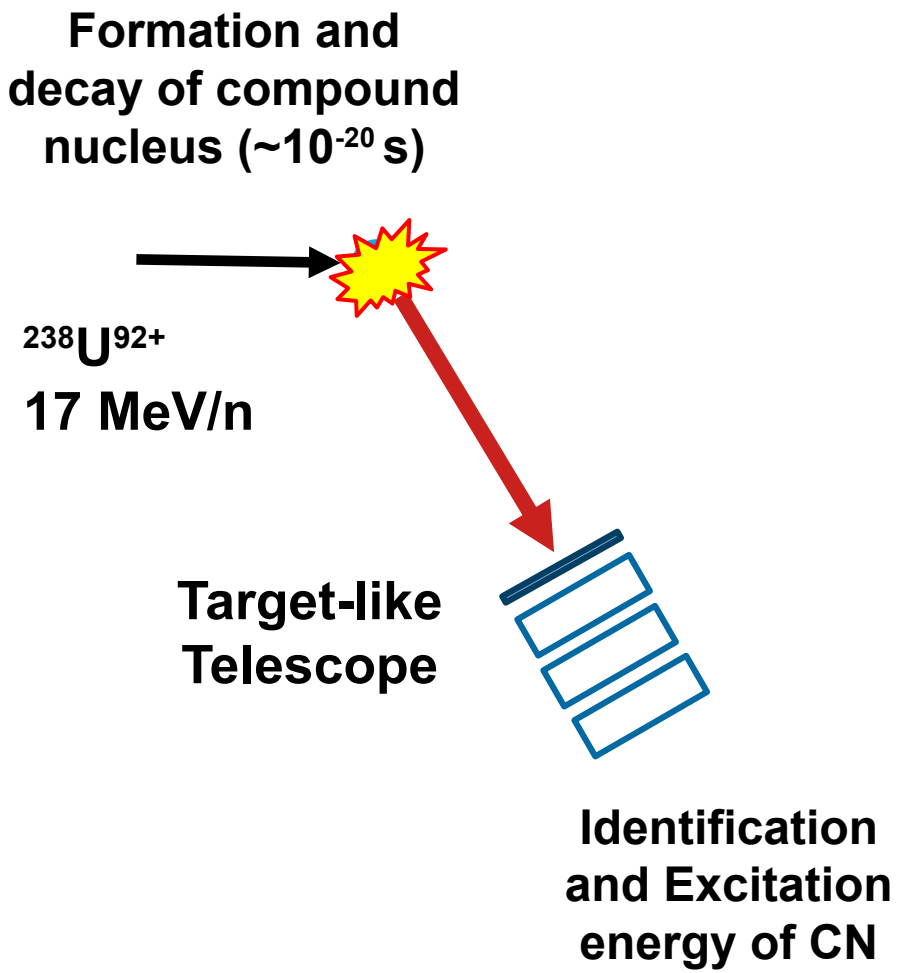

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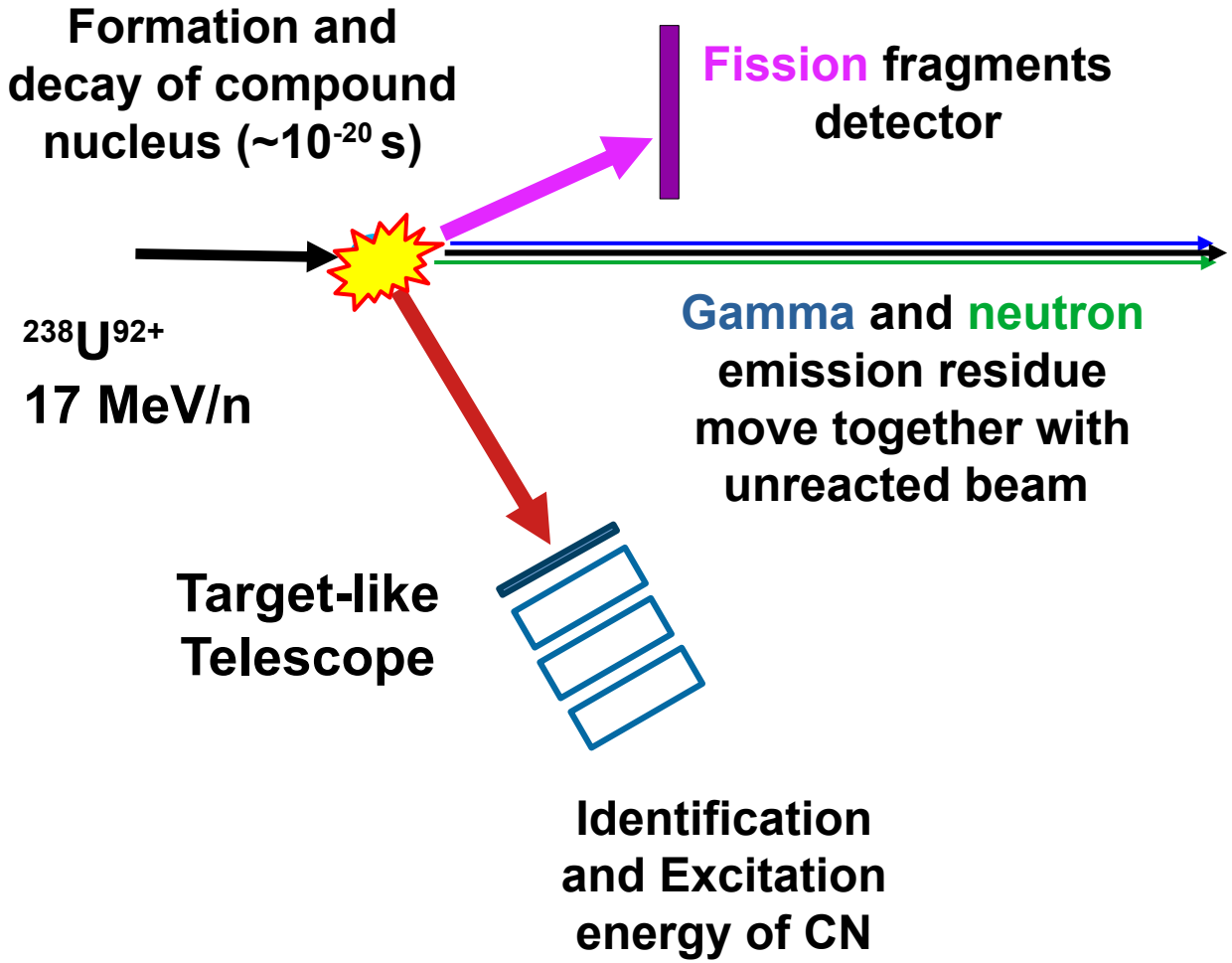

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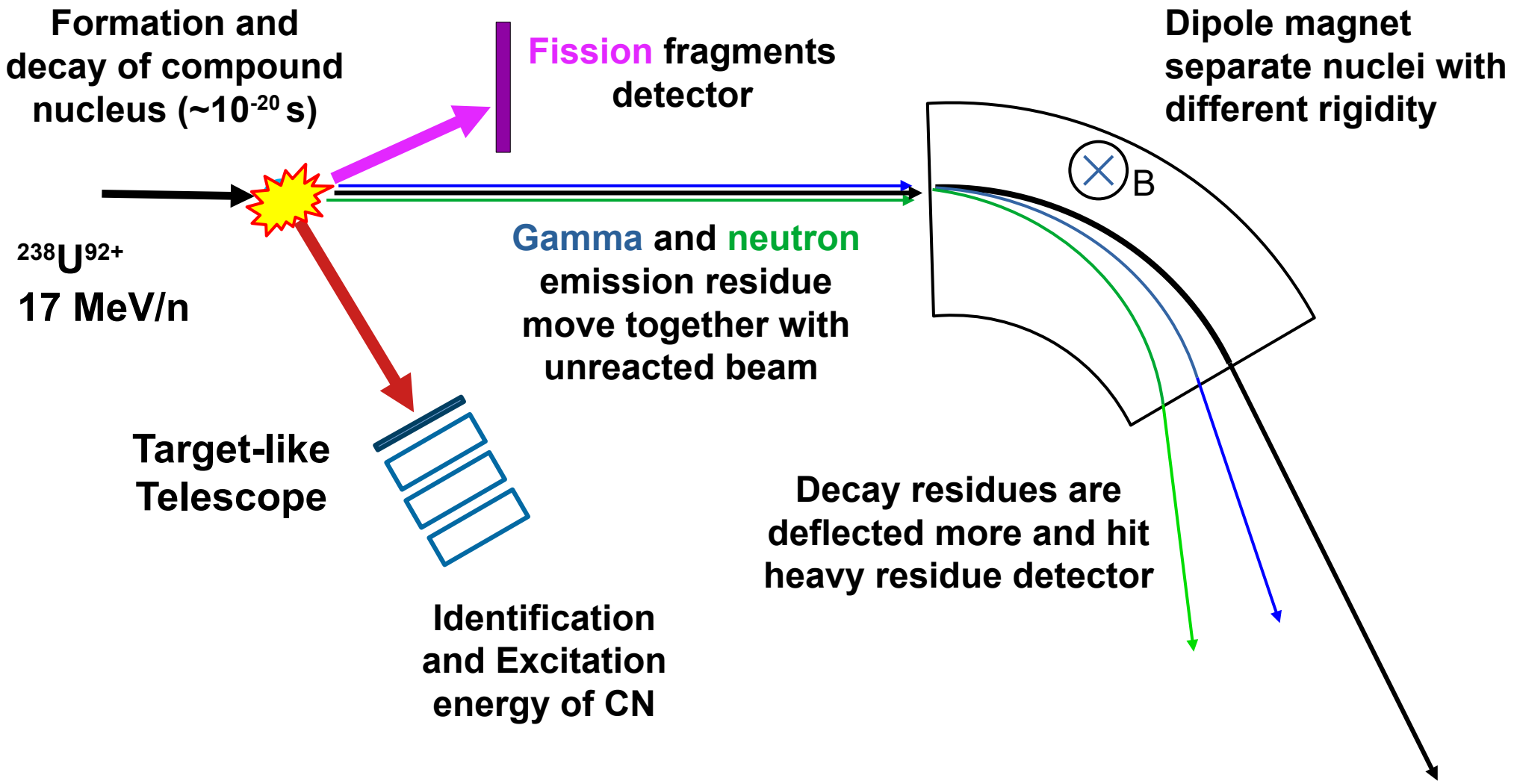

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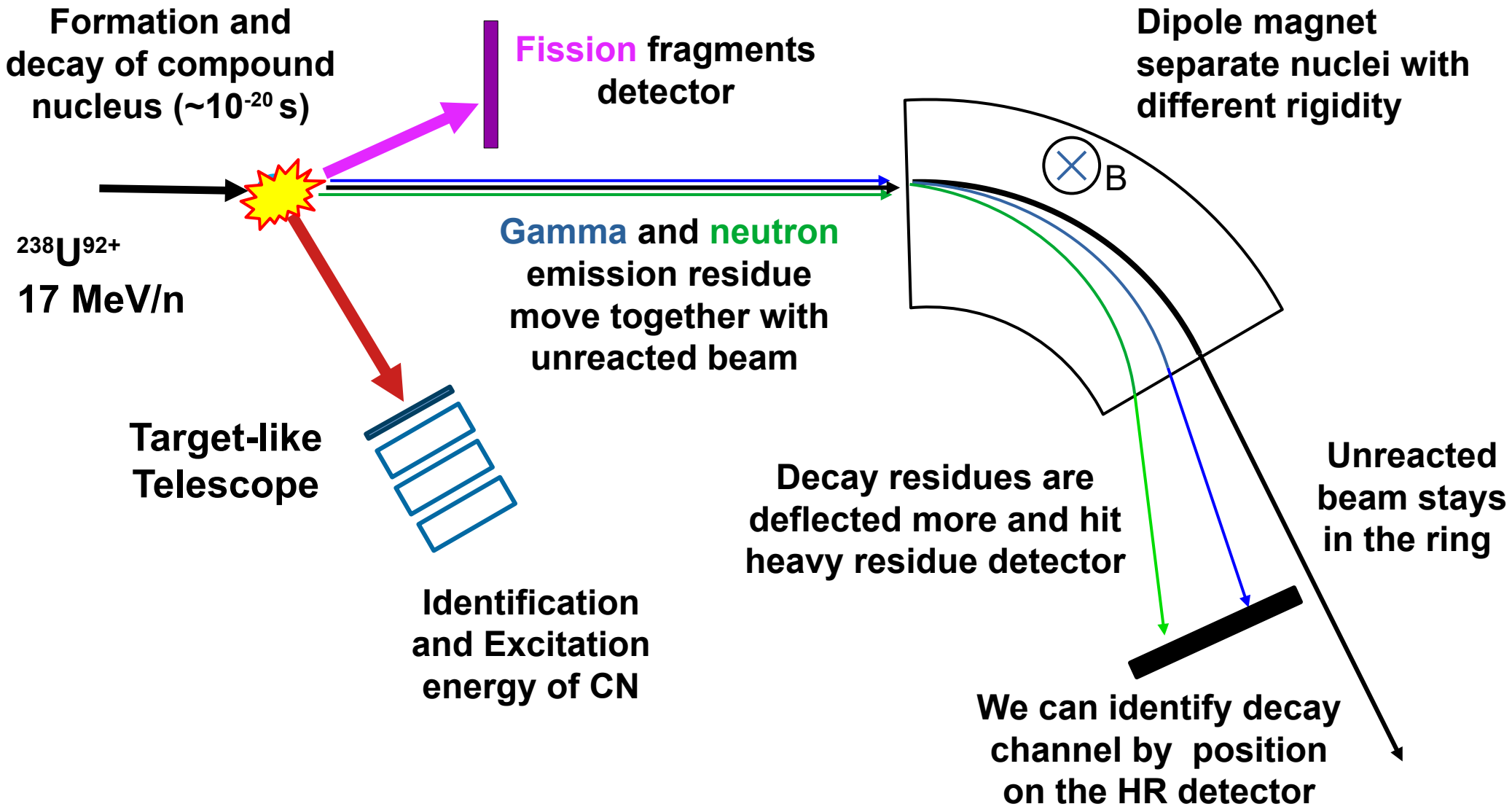

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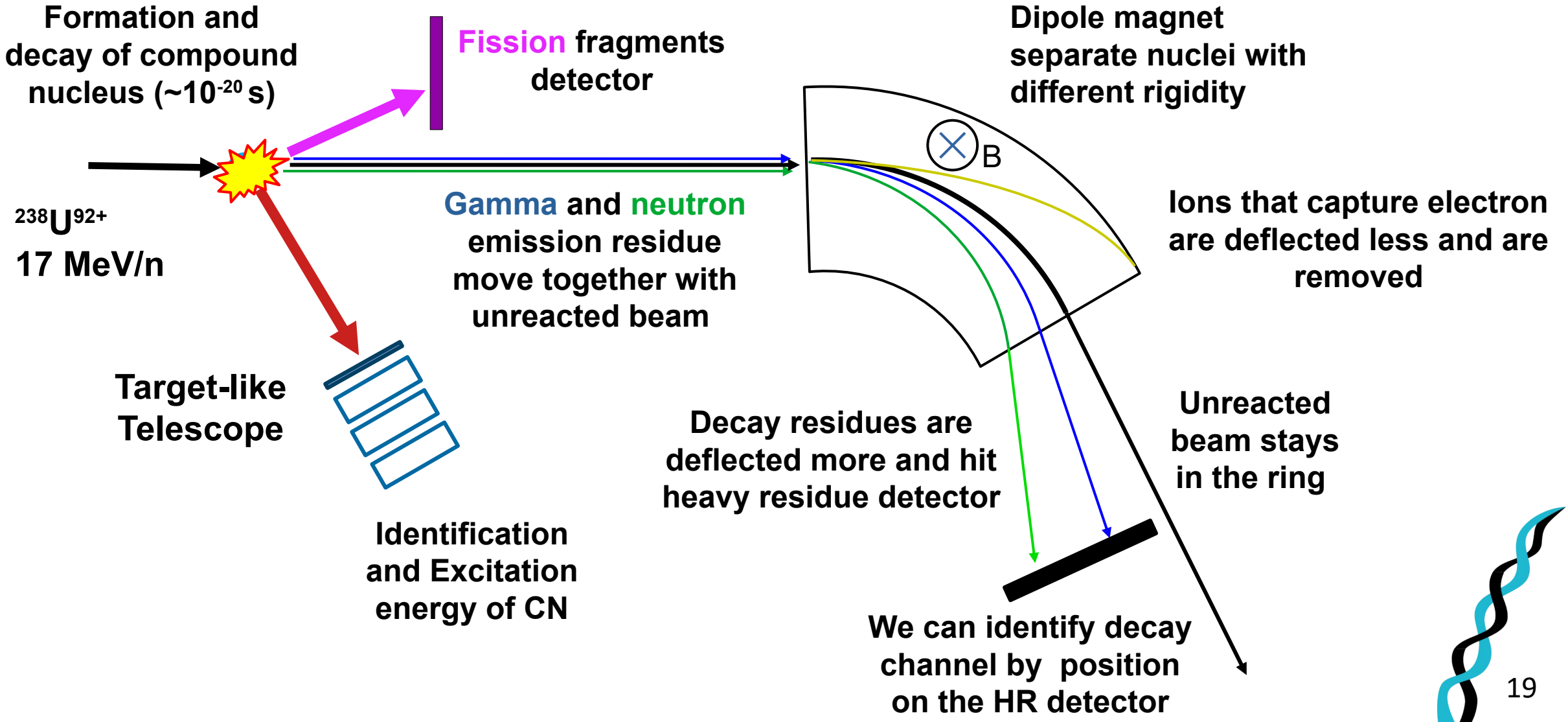
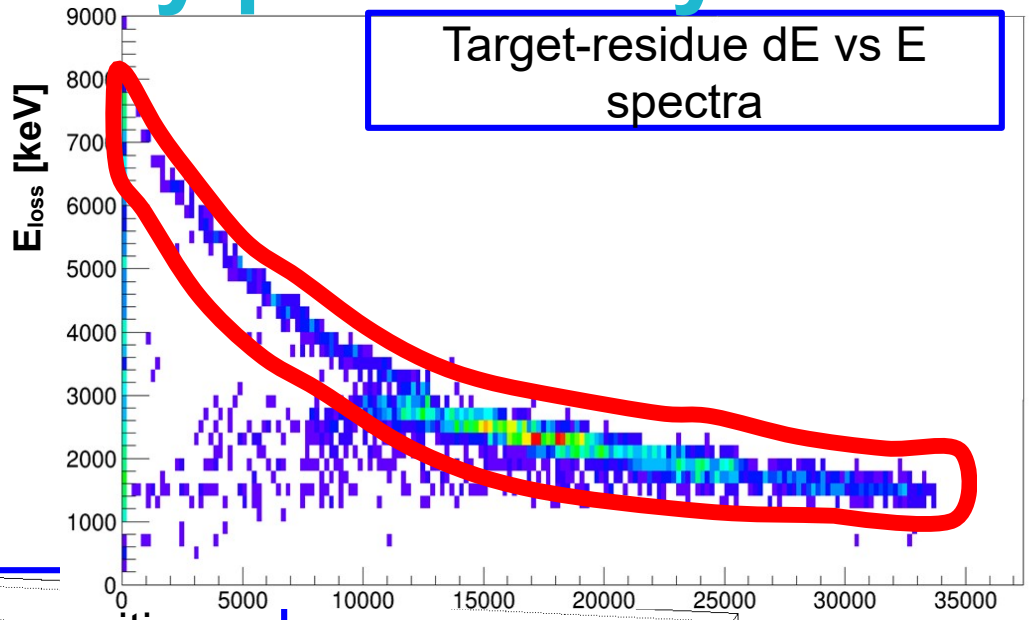
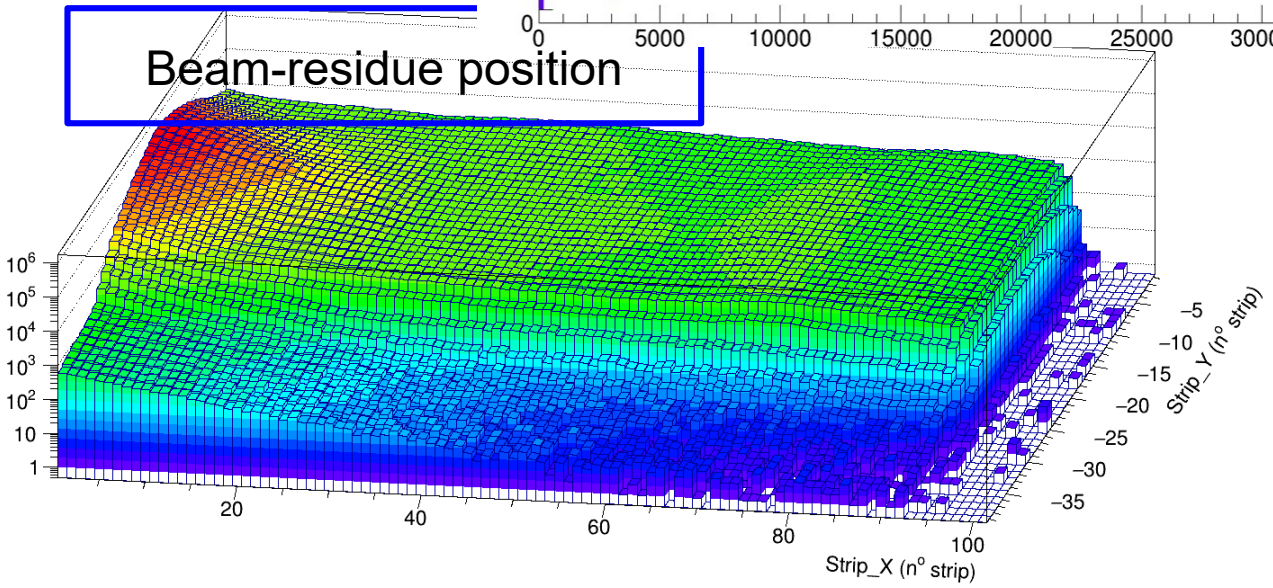


# How to get the $^{208}$Pb(p,p') decay probability?

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

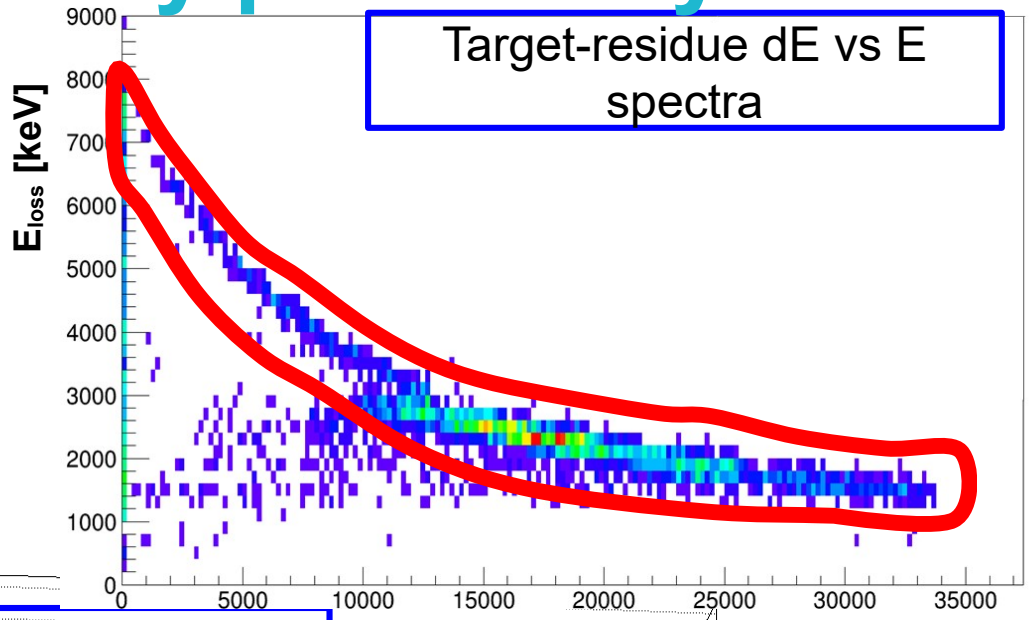


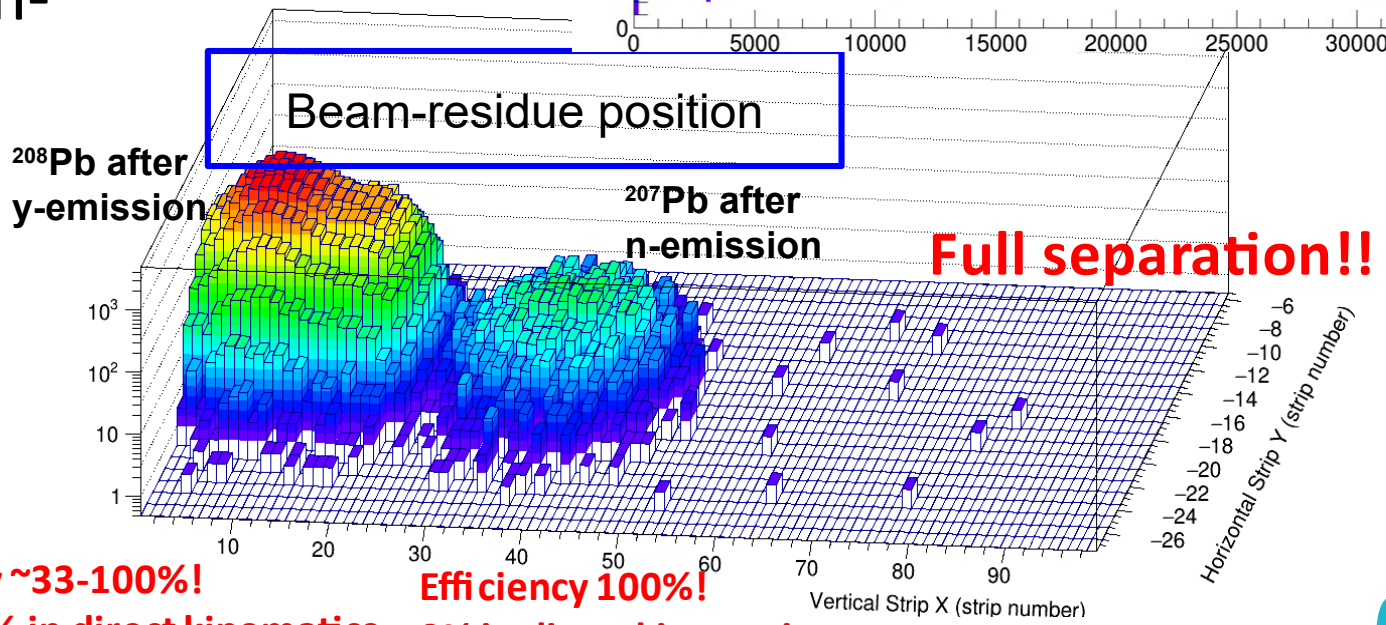



# How to get the $^{208}$Pb(p,p') decay probability?

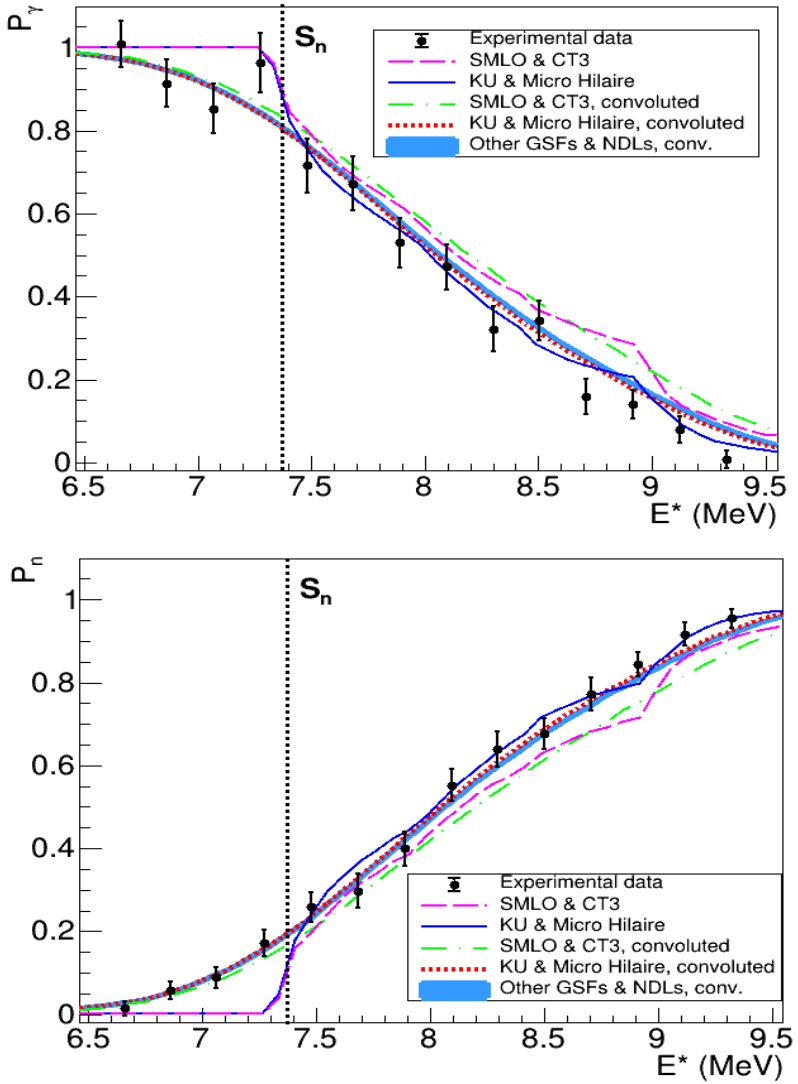
- We select the reaction based on the signals from telescope
  - We calculate excitation energy E*
- We look for coincidences in fission detectors or beam-residue detector

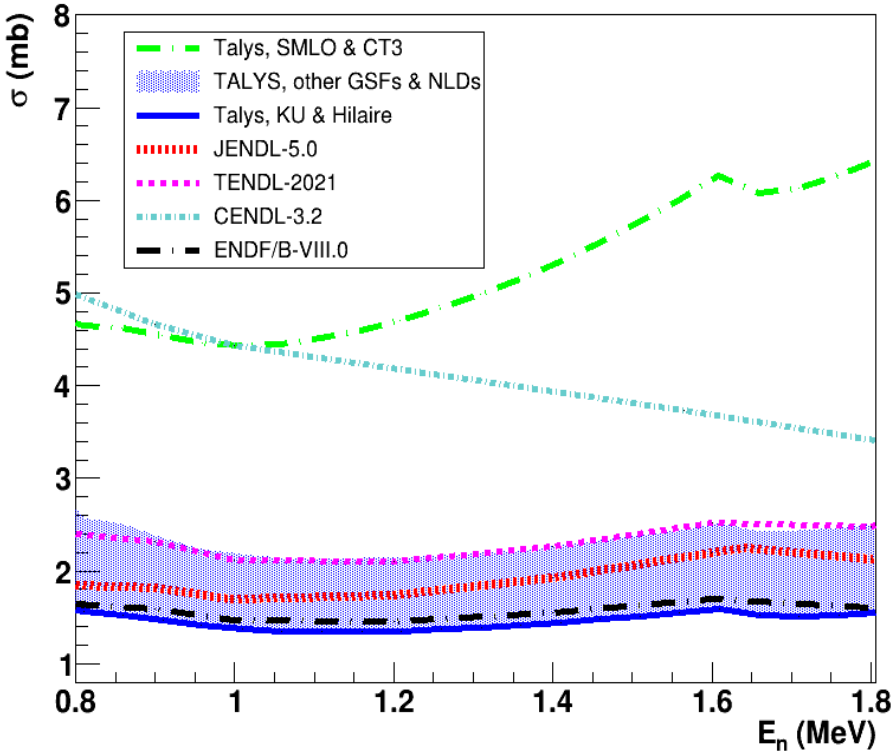
$$P_\chi(E^*) = \frac{N_{c,\chi}(E^*)}{N_s(E^*) \cdot \varepsilon_\chi(E^*)}$$



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

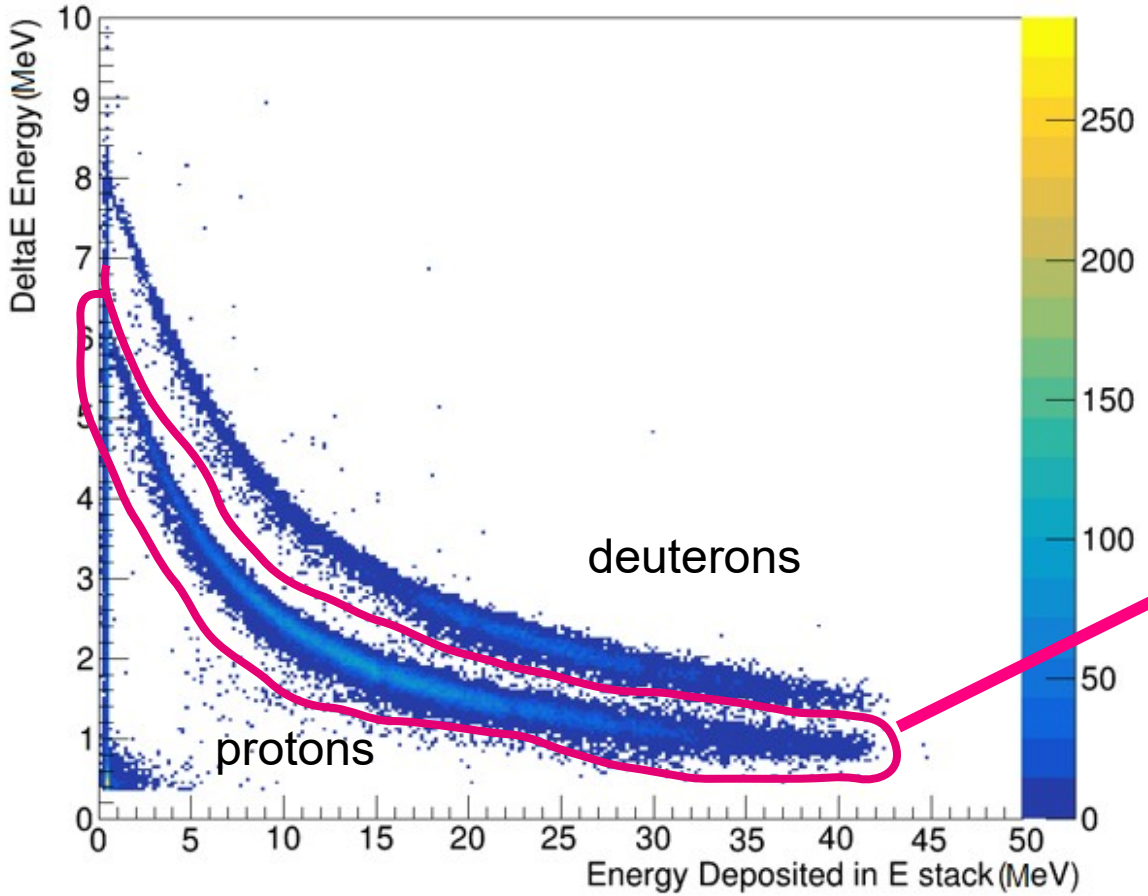


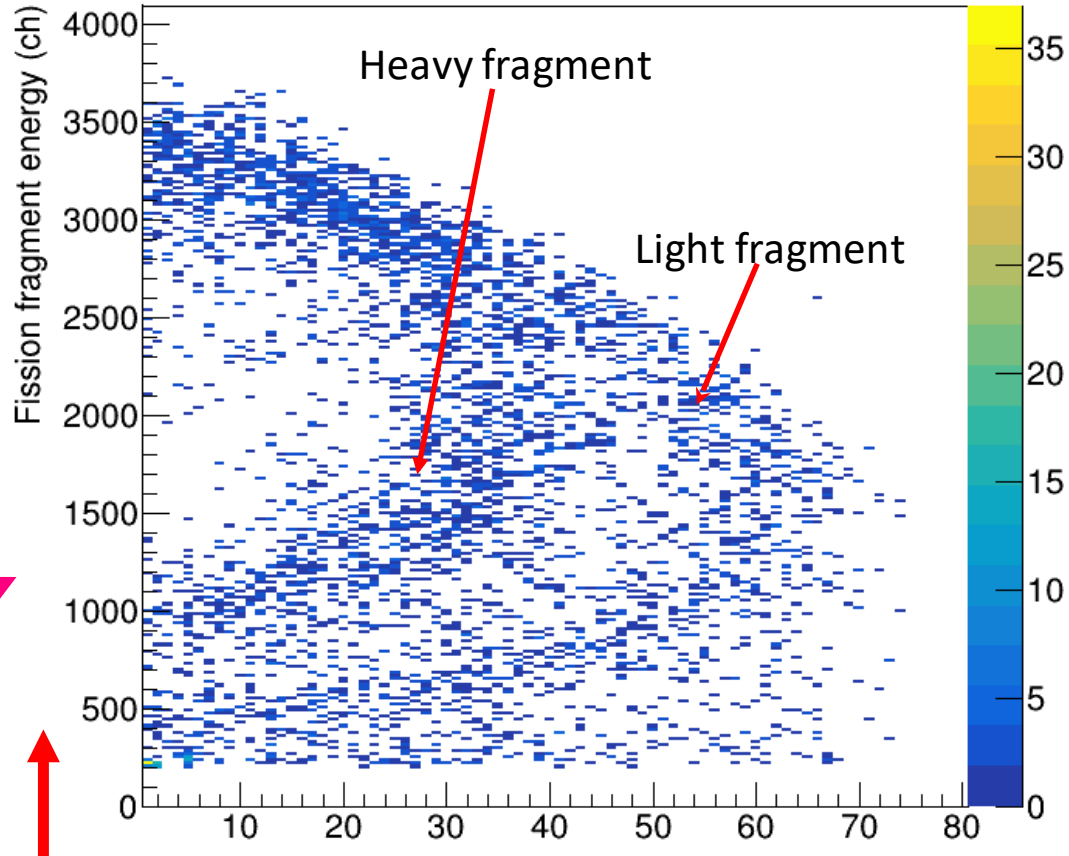

M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501

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

# Preliminary results $^{238}$U(d,p) fission probability of $^{239}$U



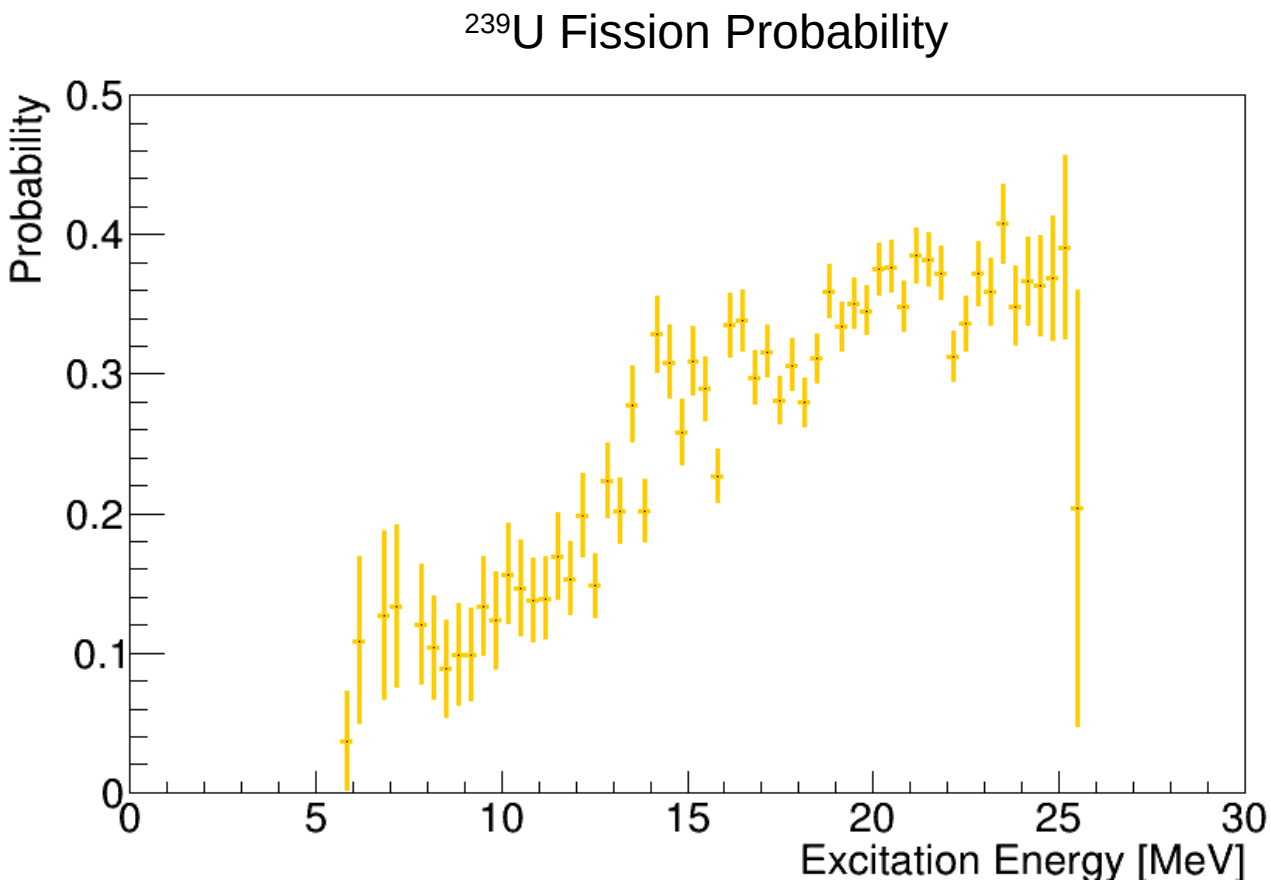

Fission detector




Beam

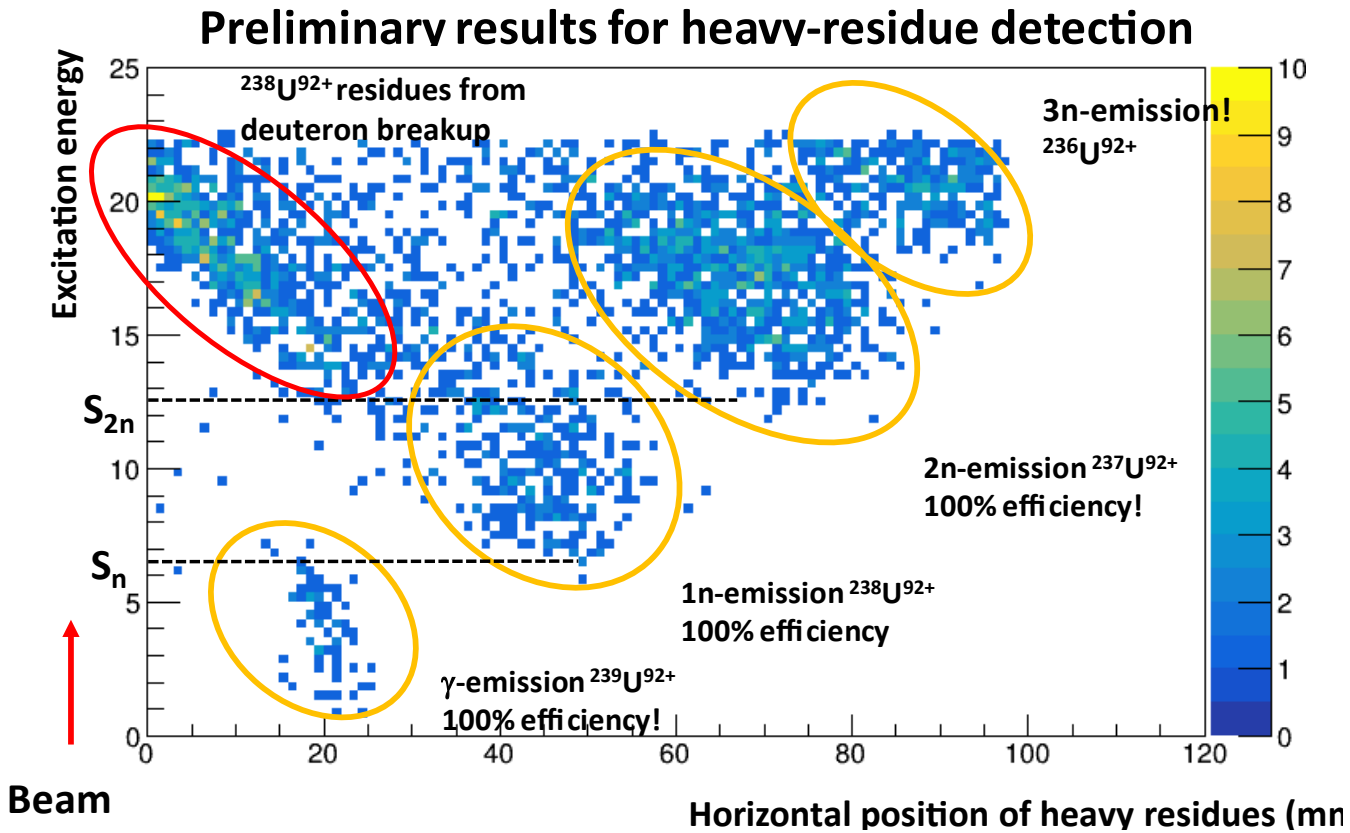
# Preliminary results $^{238}$U(d,p) fission probability of $^{239}$U

- $^{238}$U(d,p,f) Probability
- First time fission studied in storage ring
- Efficiency for fission is about 47%
- 1st 2nd and 3rd chance fission



# Preliminary results for beam-residue detection of $^{238}$U(d,p)

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



# Conclusions and perspectives

- Storage rings offer the ideal conditions to investigate surrogate reactions
- ESR ring and pure gas-jet target enable to measure for the first time fission, gamma, one two and three neutron-emission probabilities!
- Next experiment (2027) infer n-induced cross section for $^{205}$Pb, our first experiment with radioactive beams, new gas target, better resolution and more solid angle

# NECTAR team

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***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***
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NECTAR: Nuclear rEaCTions At storage Rings

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