Indirect measurements of neutron-induced cross sections at storage rings

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and the NucAr collaboration

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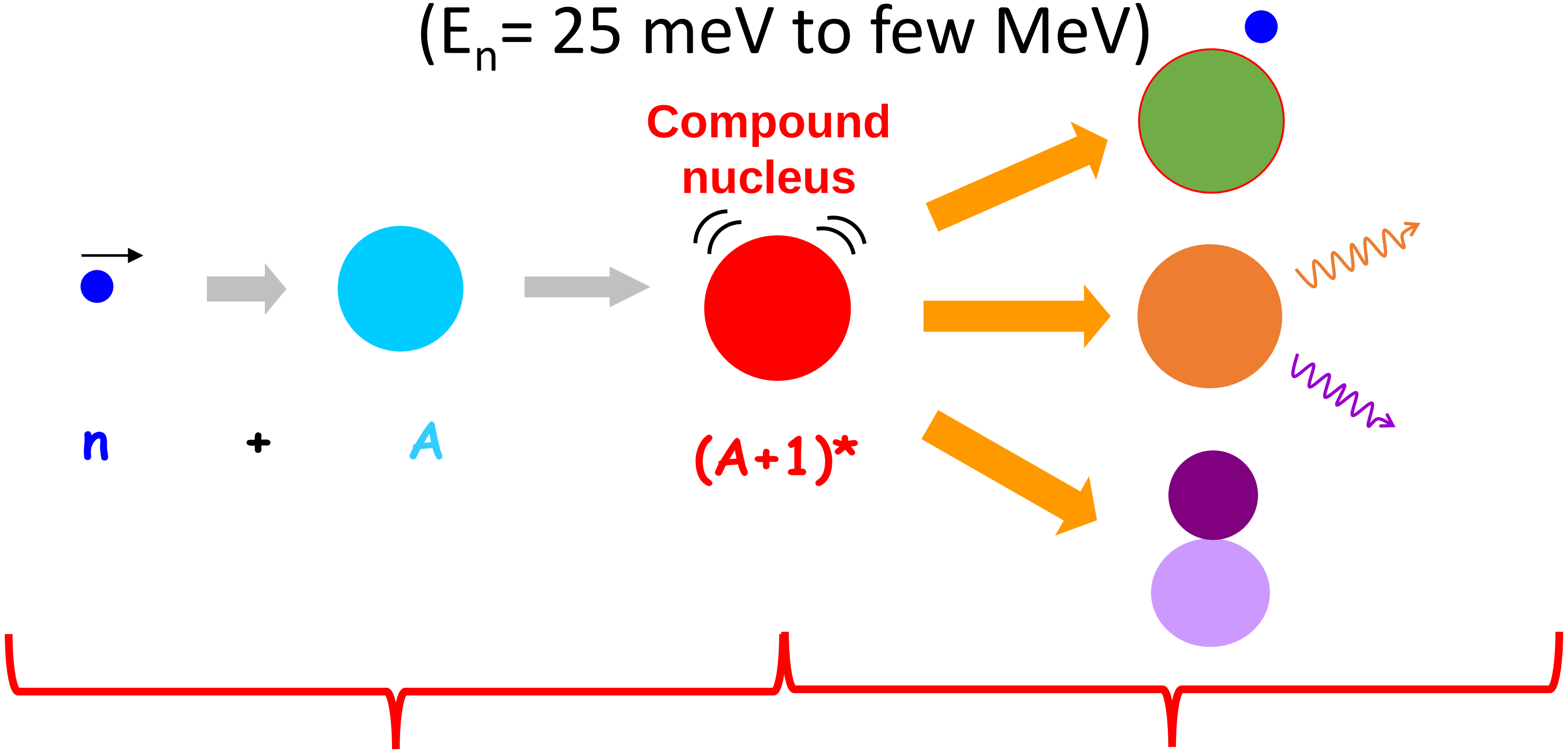
Neutron-induced reactions

(E$_n$= 25 meV to few MeV)

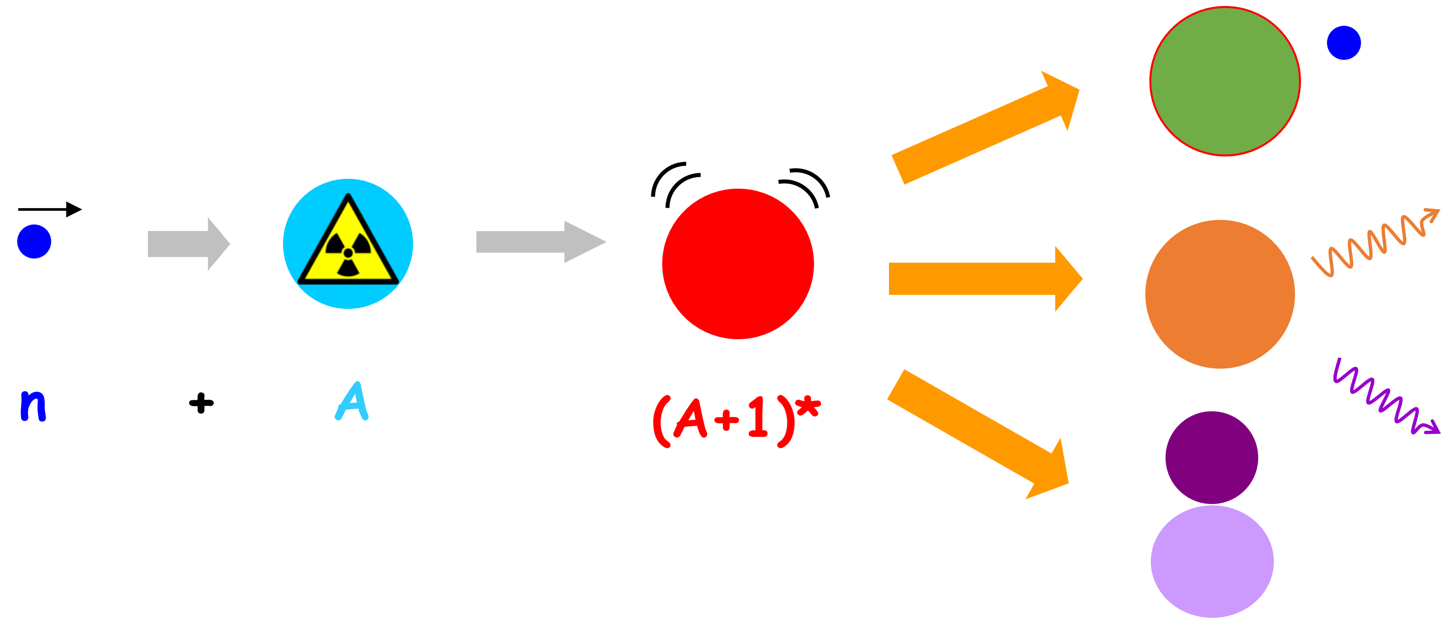


Step 1: Formation **Step 2: Decay**

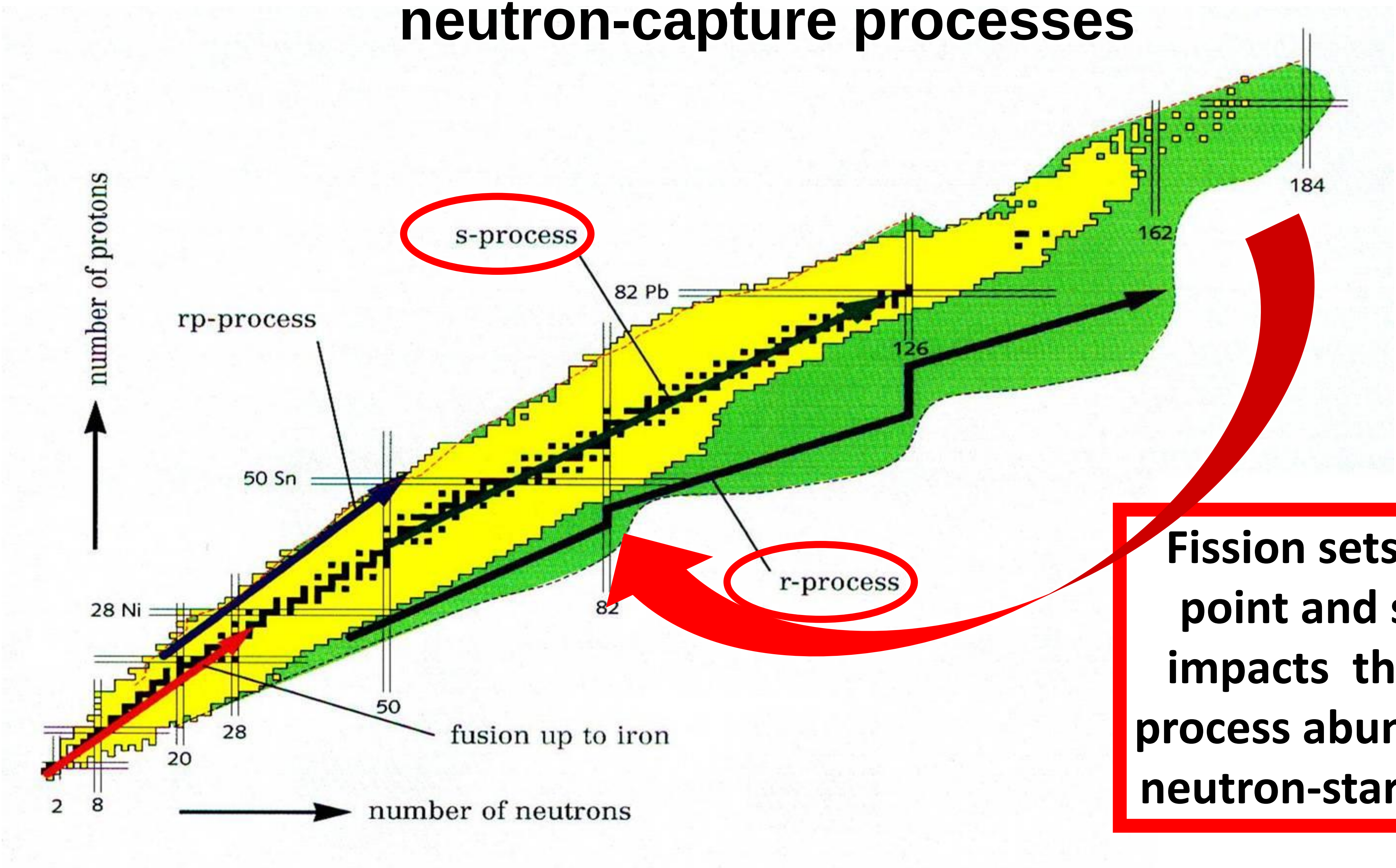
$$\sigma^{A}_{n,decay}(E_n)=\sigma^{A+1}_{formation}(E_n)\cdot P^{n}_{decay}(E_n)$$

$$\sigma^{A}_{n,\gamma}(E_n)=\sigma^{A+1}_{formation}(E_n)\cdot P^{n}_{\gamma}(E_n)$$

Need for neutron cross sections of short-lived nuclei



Synhtesis of heavy elements: slow and rapid neutron-capture processes

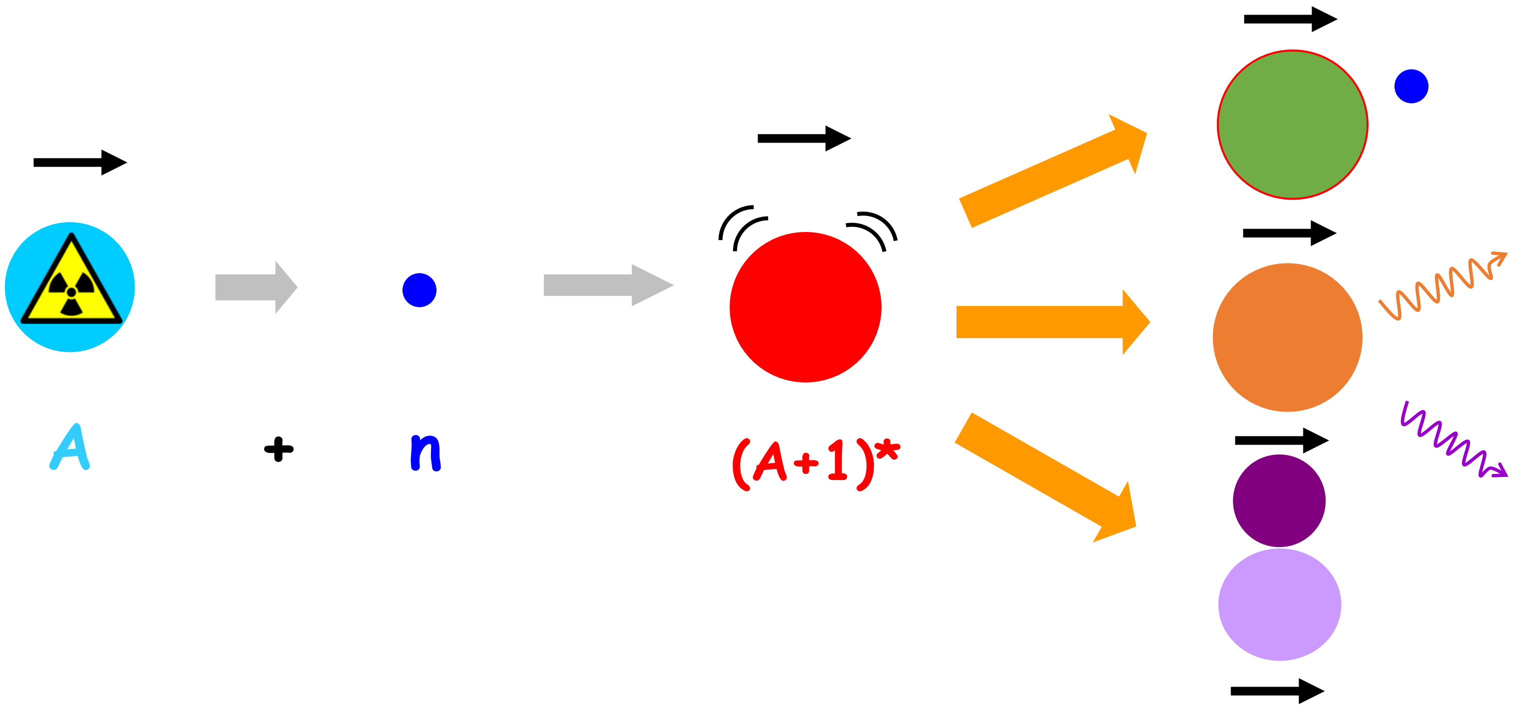


Fission sets the end point and strongly impacts the final r-process abundances in neutron-star mergers!

Reactor physics: fast reactors, transmutation, new fuel cycles

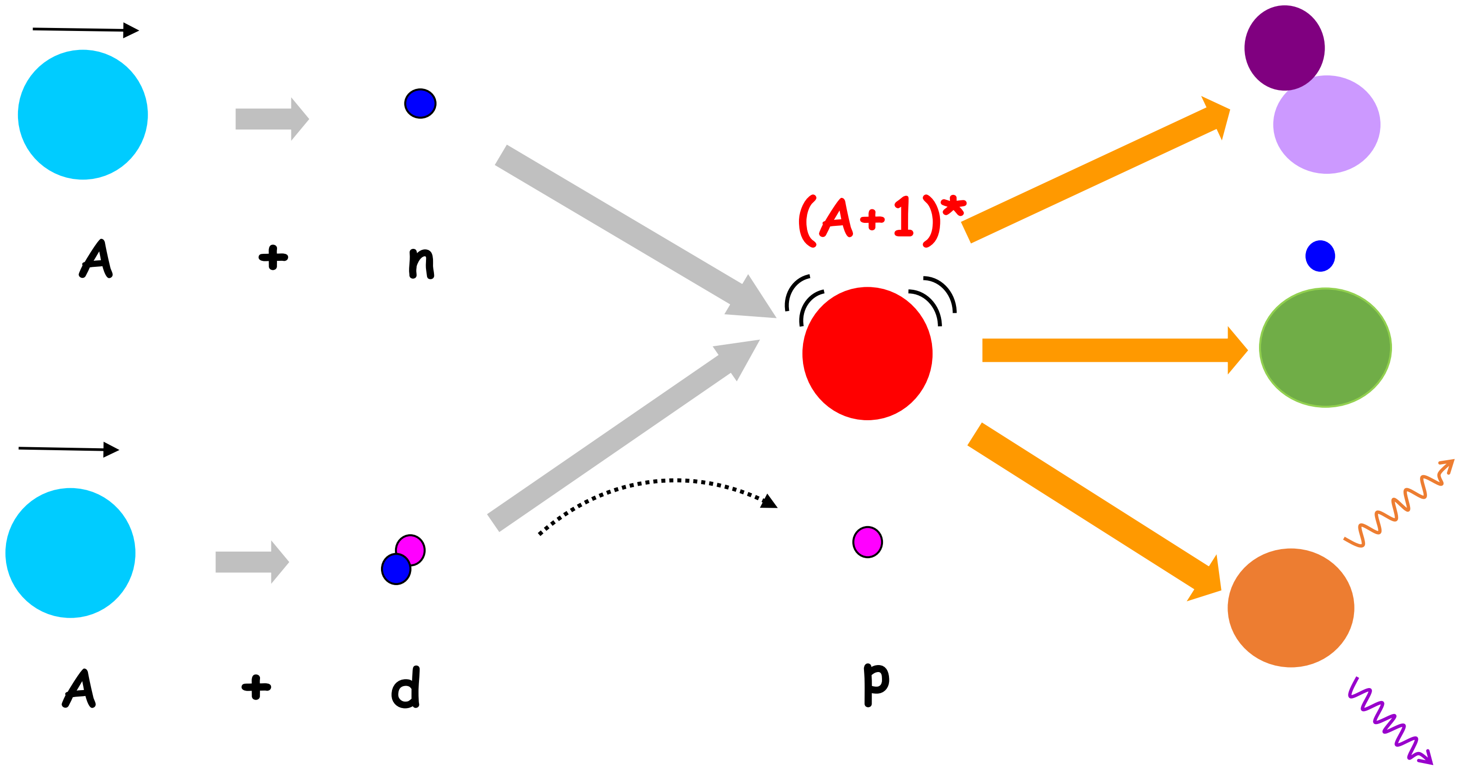
Very difficult or even impossible to measure with standard techniques →difficulty to produce and handle the needed targets!

Solution: measurements in inverse kinematics…



…but free-neutron targets are not yet available!

Surrogate-reaction method in inverse kinematics

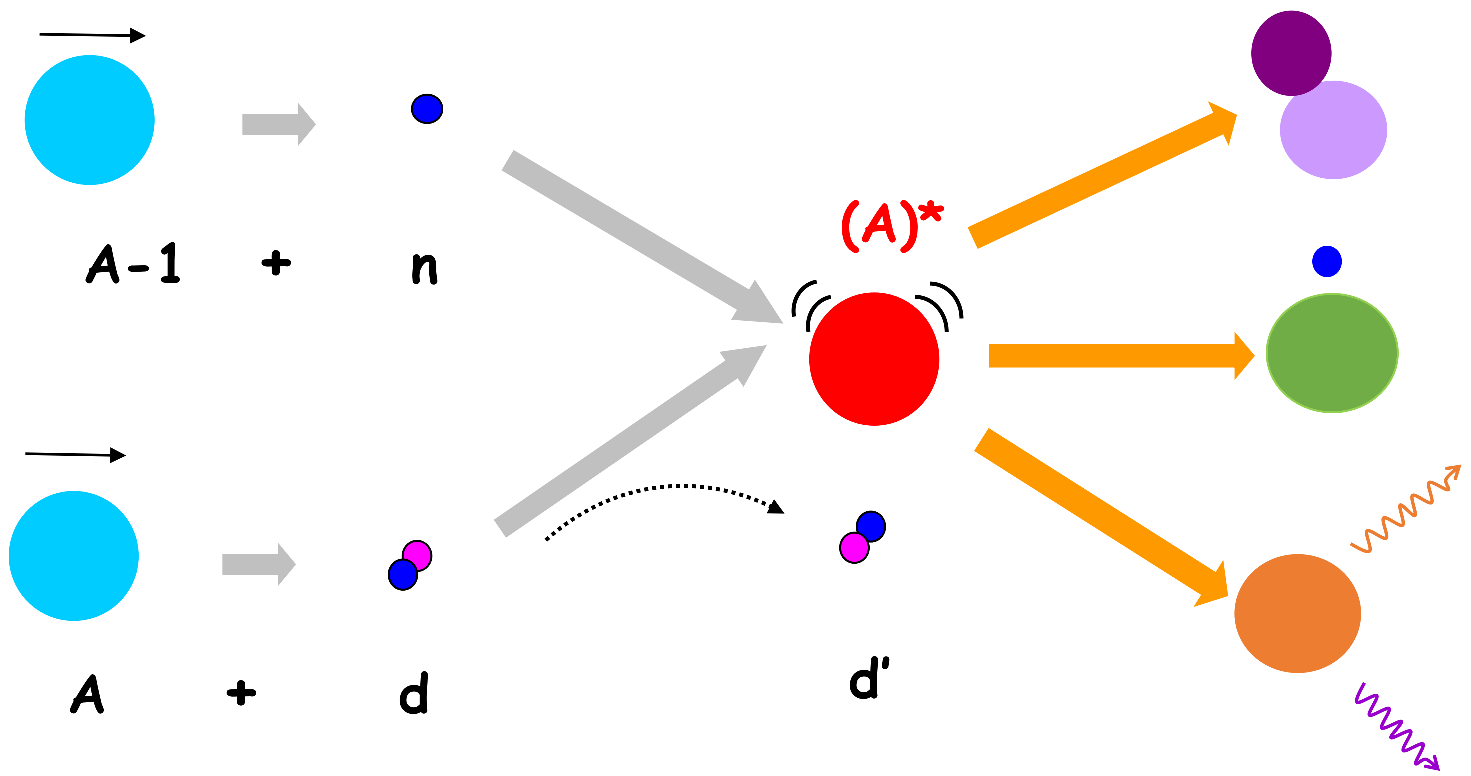


$$\sigma^{A}_{n,decay}(E^*) = \sigma^{A+1}_{formation}(E^*) \cdot P^{surro}_{decay}(E^*)$$

Theory

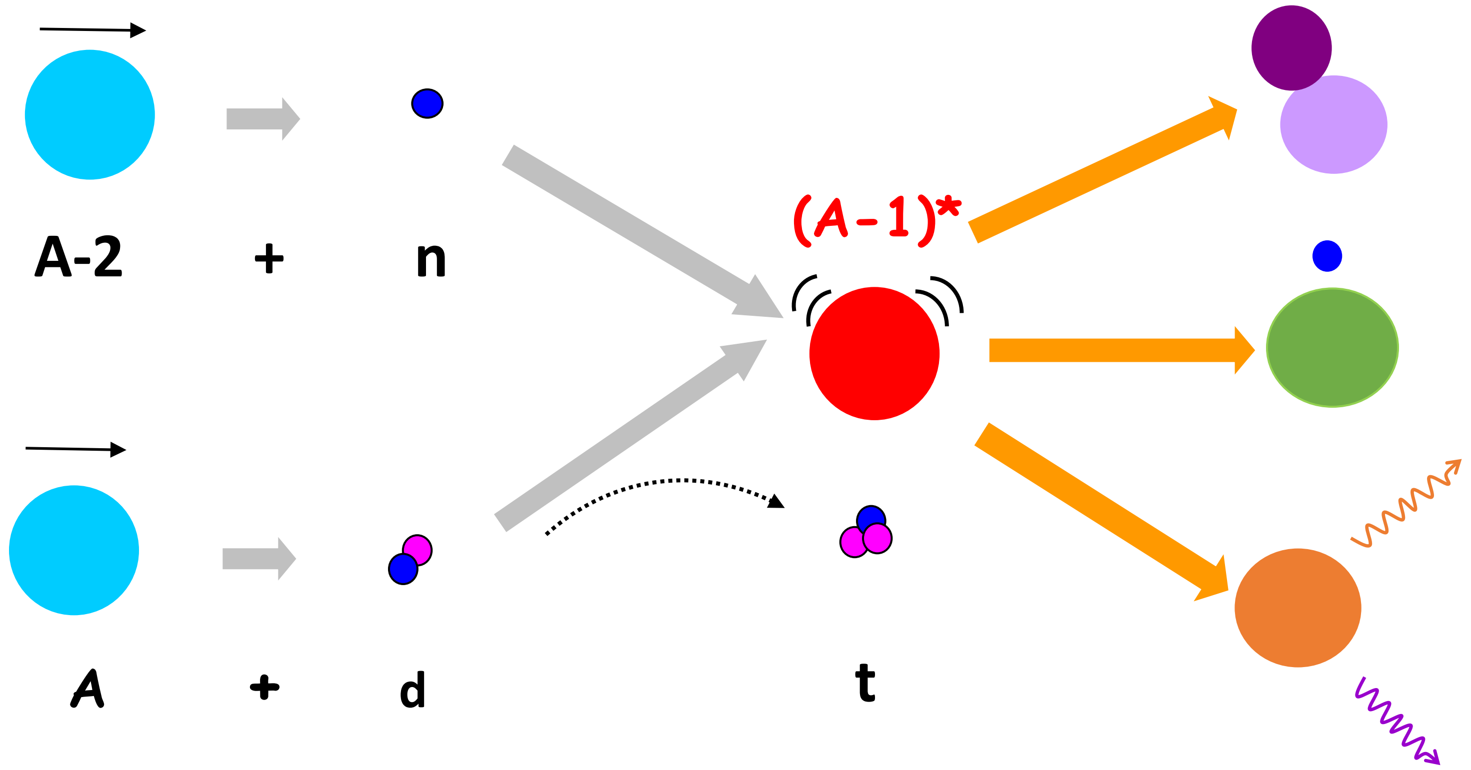
Experiment

Several reactions can be studied in the same experiment!



$$\sigma_{n,decay}^{A-1}(E^*) = \underbrace{\sigma_{formation}^{A}(E^*)}_{\text{Theory}} \cdot \underbrace{P_{decay}^{surro}(E^*)}_{\text{Experiment}}$$

Several reactions can be studied in the same experiment!



$$\sigma^{A-2}_{n,decay}(E^*) = \sigma^{A-1}_{formation}(E^*) \cdot P^{surro}_{decay}(E^*)$$

Theory

Experiment

Validity of the surrogate-reaction method

$$\sigma^{A}_{n,decay}(E^*) = \sigma^{A+1}_{formation}(E^*) \cdot P^{surro}_{decay}(E^*)$$

1. Neutron-induced and surrogate reaction must lead to the formation of a compound nucleus :

Decay only depends on *E, *J* and π !**

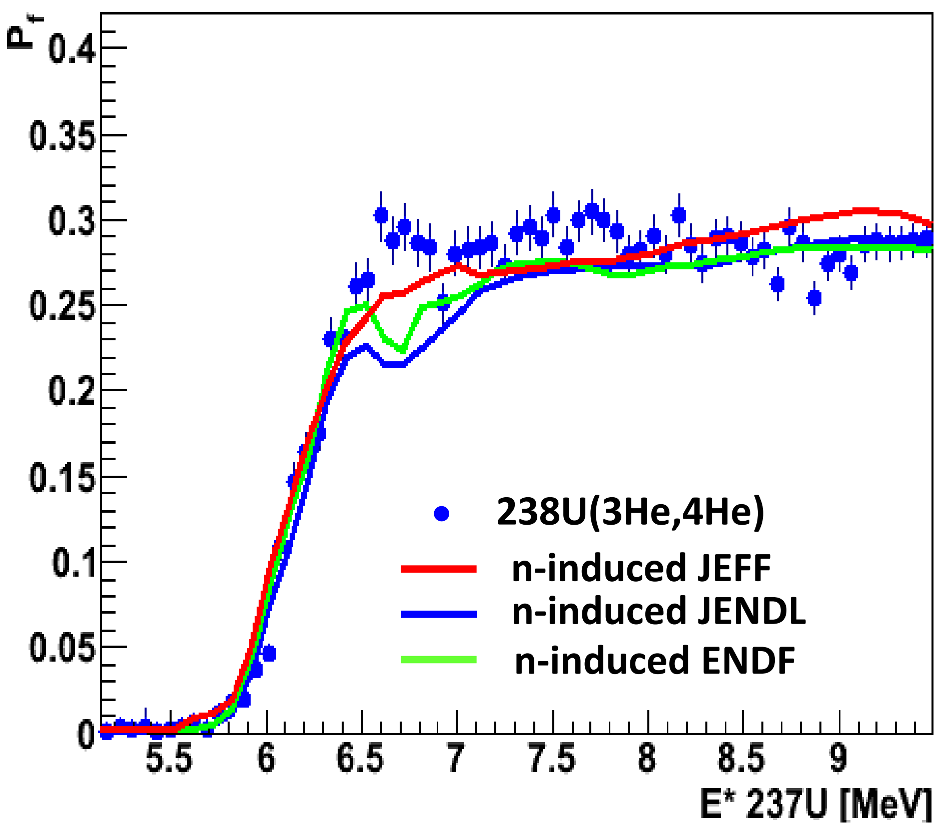
2. $P^{surro}_{decay}(E^*) = P^{n}_{decay}(E^*)$

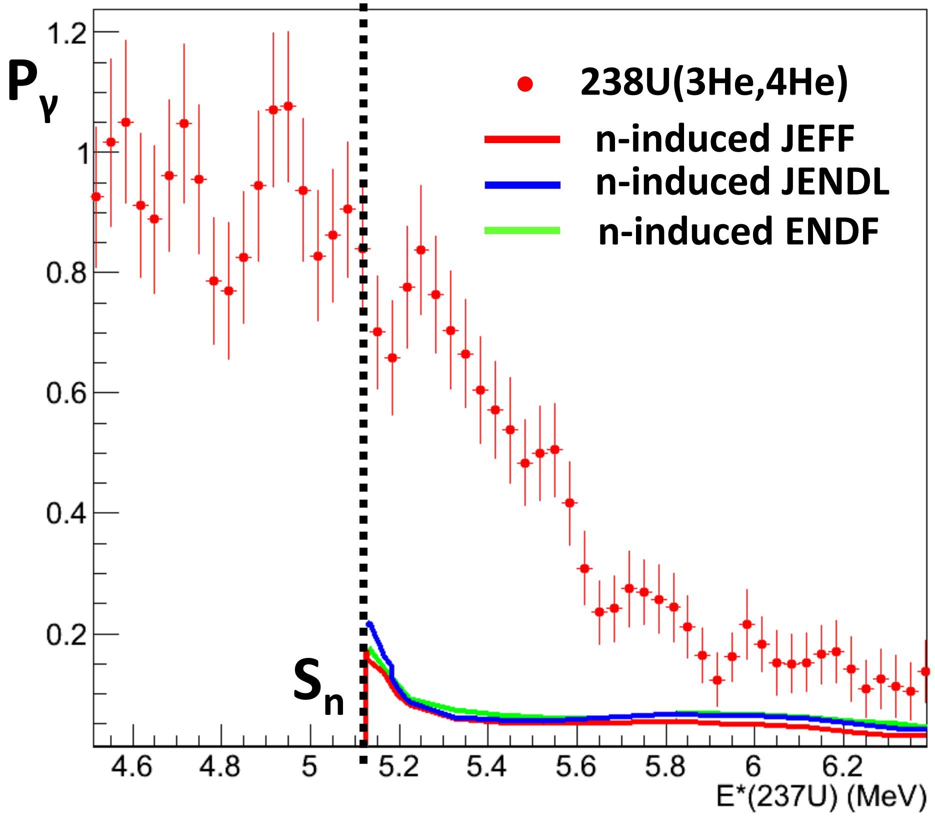
But P_{decay} can depend on *J* and π , and the populated *J* and π can be different for the n-induced and surrogate reactions

Not possible to say a priori if a reaction meets these conditions.
Data obtained with the surrogate method need
to be compared to neutron-induced data!

Representative results

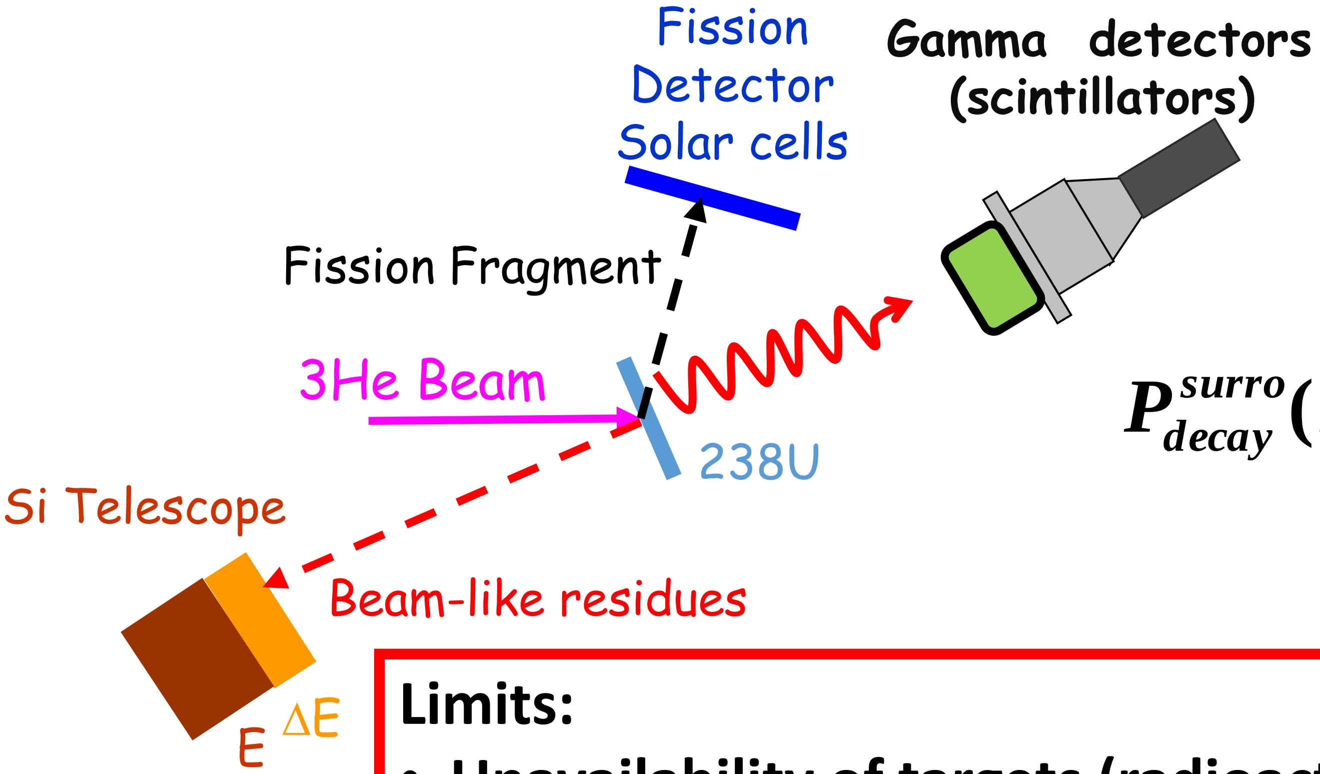
3He+238U→4He+237U ⇔ n+236U→237U





Good agreement for fission probabilities but strong disagreement for γ-emission probabilities. Not understood, need systematic studies involving nuclei with different nuclear structure and different reactions to define how to use surrogate reactions when no neutron data exist.

Measurement of fission and gamma-emission probabilities in direct kinematics



$$P_{decay}^{surro}(E^*) = \frac{N_{beamlike-decay}^{coin}(E^*)}{N_{beamlike}^{sing}(E^*)\cdot\varepsilon_{decay}(E^*)}$$

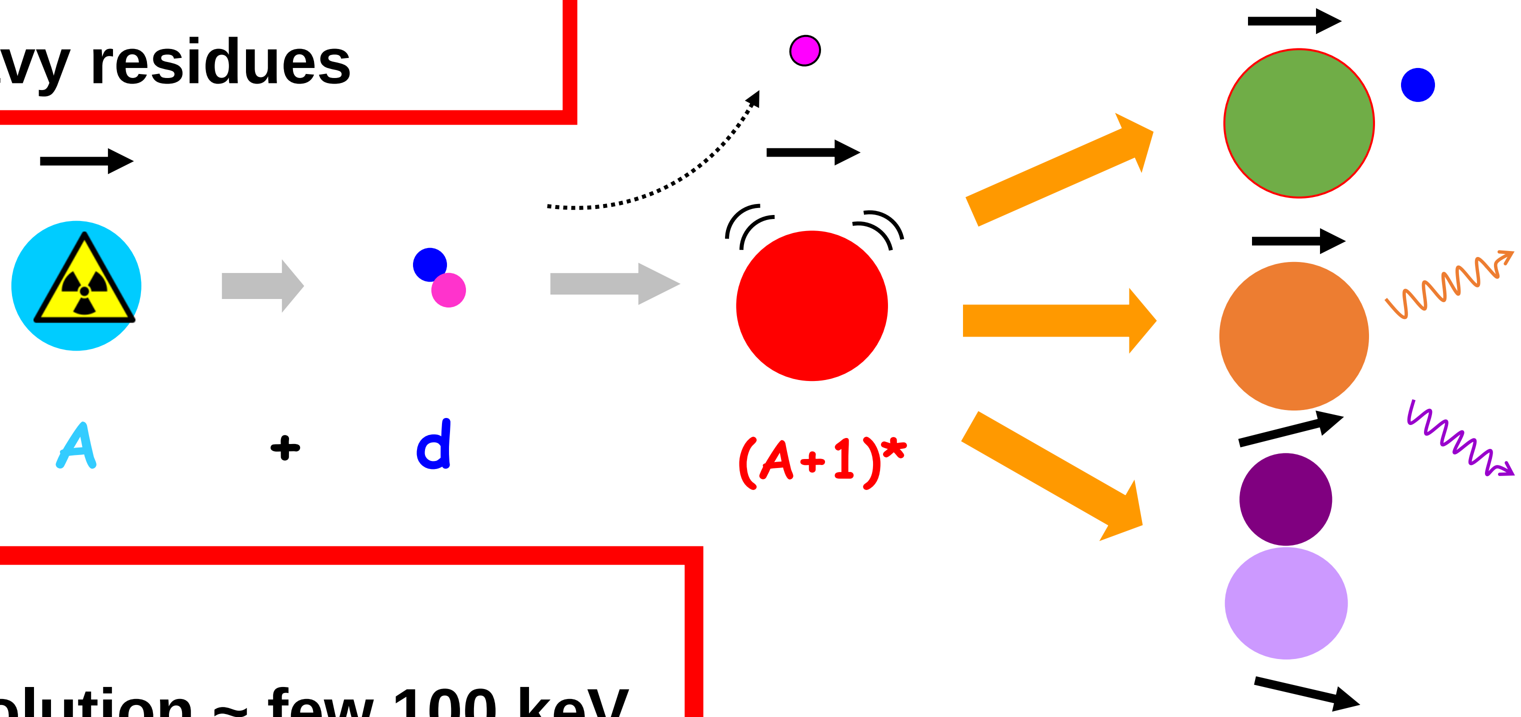
Limits:

- **Unavailability of targets (radioactive samples)**
- **Target contaminants and target support**
- **P_γ : discrimination of γ's from fission fragments, very low detection efficiency**
- **P_n: measurement of low-energy neutrons and neutron efficiency**

Advantages of Inverse kinematics:

-Access to very short-lived nuclei

-Detection of heavy residues



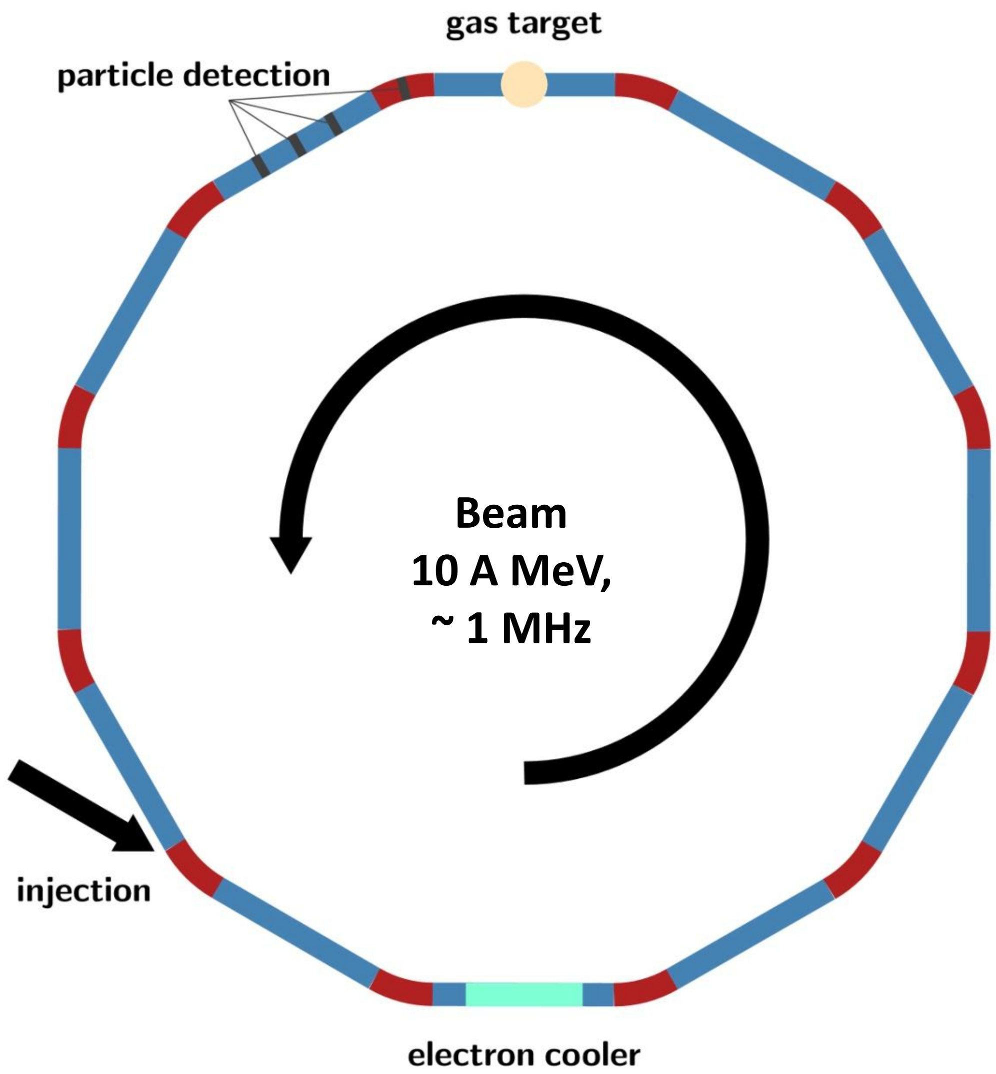
BUT!

- **Required E* resolution ~ few 100 keV, $E^*=f(E_{beam}, E_{target\_like}, \theta)$**
- **Target contaminants and target windows have to be avoided**

STORAGE RINGS!

Advantages of heavy-ion storage rings

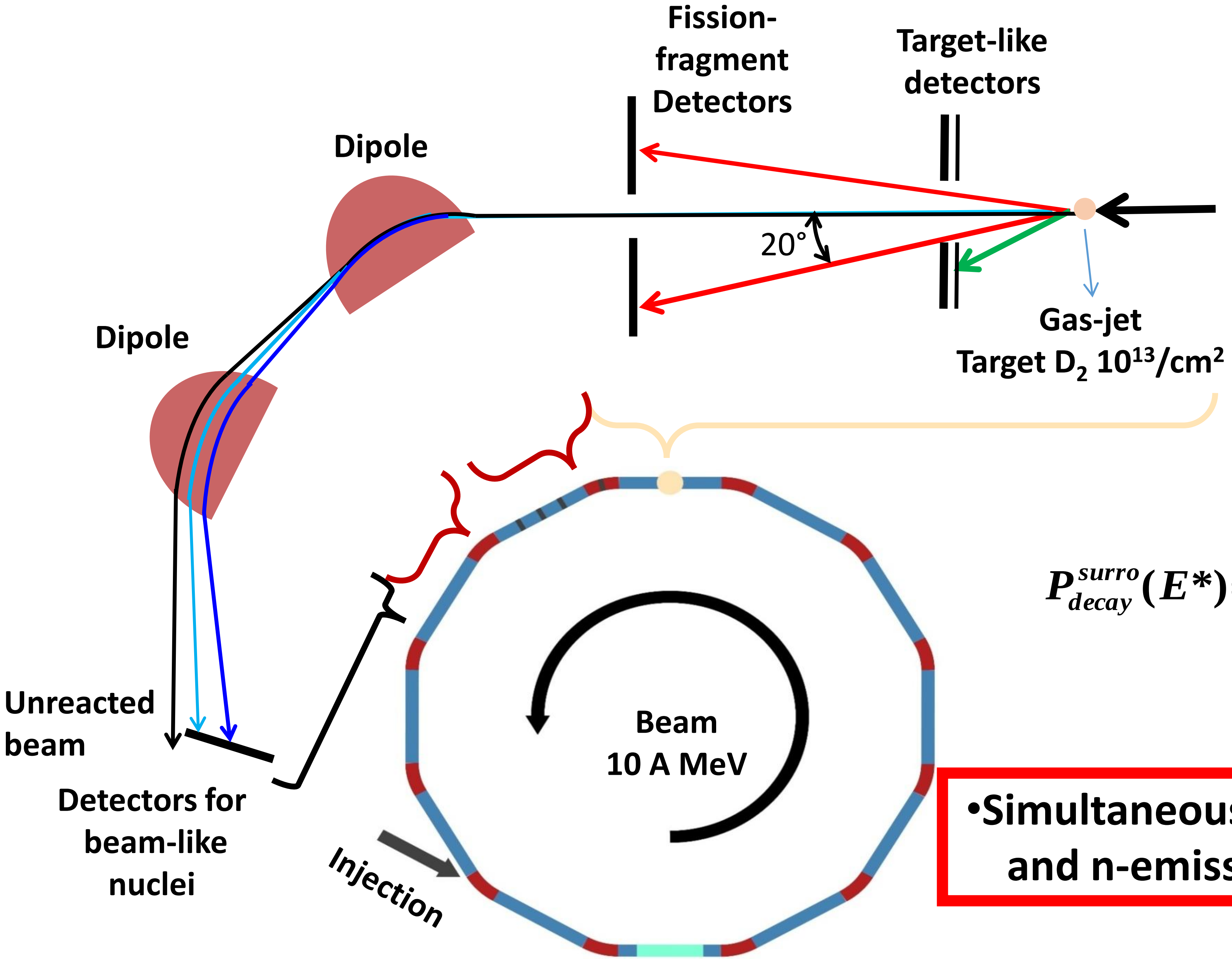
The CRYRING at GSI/FAIR



- **Beam cooling → Excellent energy and position resolution of the beam, restored after each passage through the target, negligible straggling effects and energy-loss effects**
- **Use of ultra-thin in-ring gas-jet targets ~10^{13}/cm^2. Effective target thickness increased by ~10^6 due to revolution frequency (at 10 A MeV)**
- **Pure targets, pure beams, (no backing, no contaminants)**

Challenge: Detectors in Ultra-High Vacuum (10^{-11}-10^{-12} mbar)!

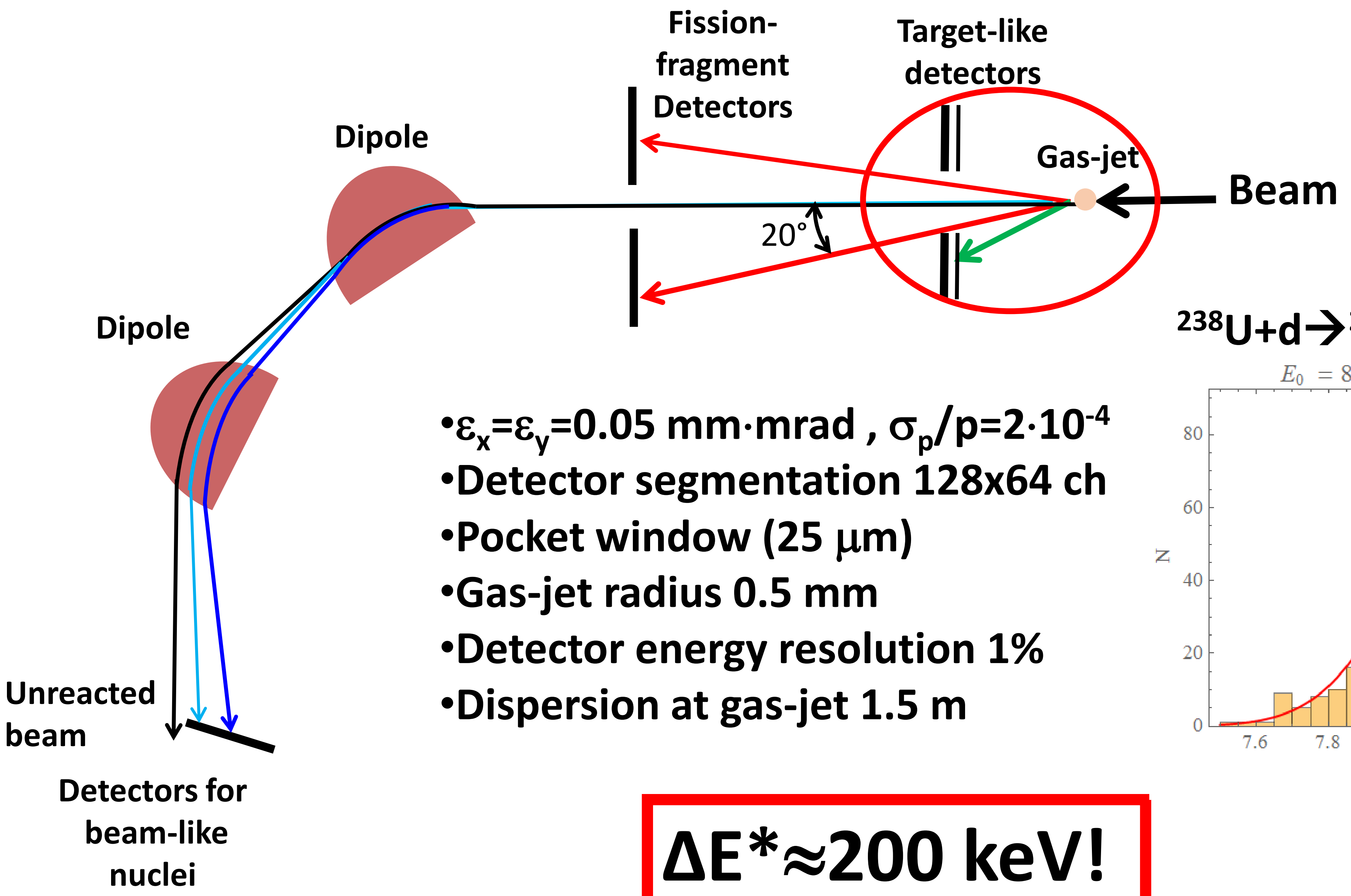
Set-up at the CRYRING



$$P_{decay}^{surro}(E^*) = \frac{N_{targetlike-decay}^{coin}(E^*)}{N_{targetlike}^{sing}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

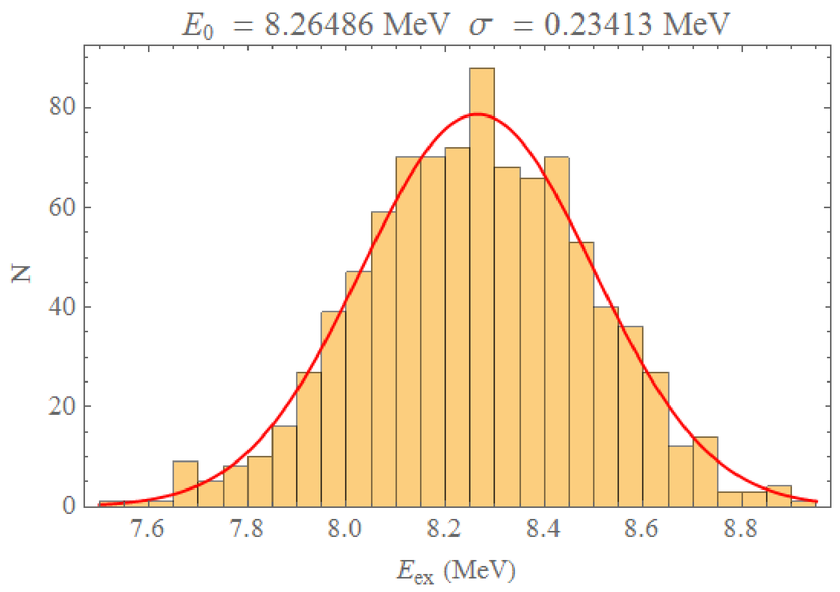
•Simultaneous measurement of fission, γ- and n-emission probabilities, unique!

Detailed Geant 4 simulations: excitation-energy resolution



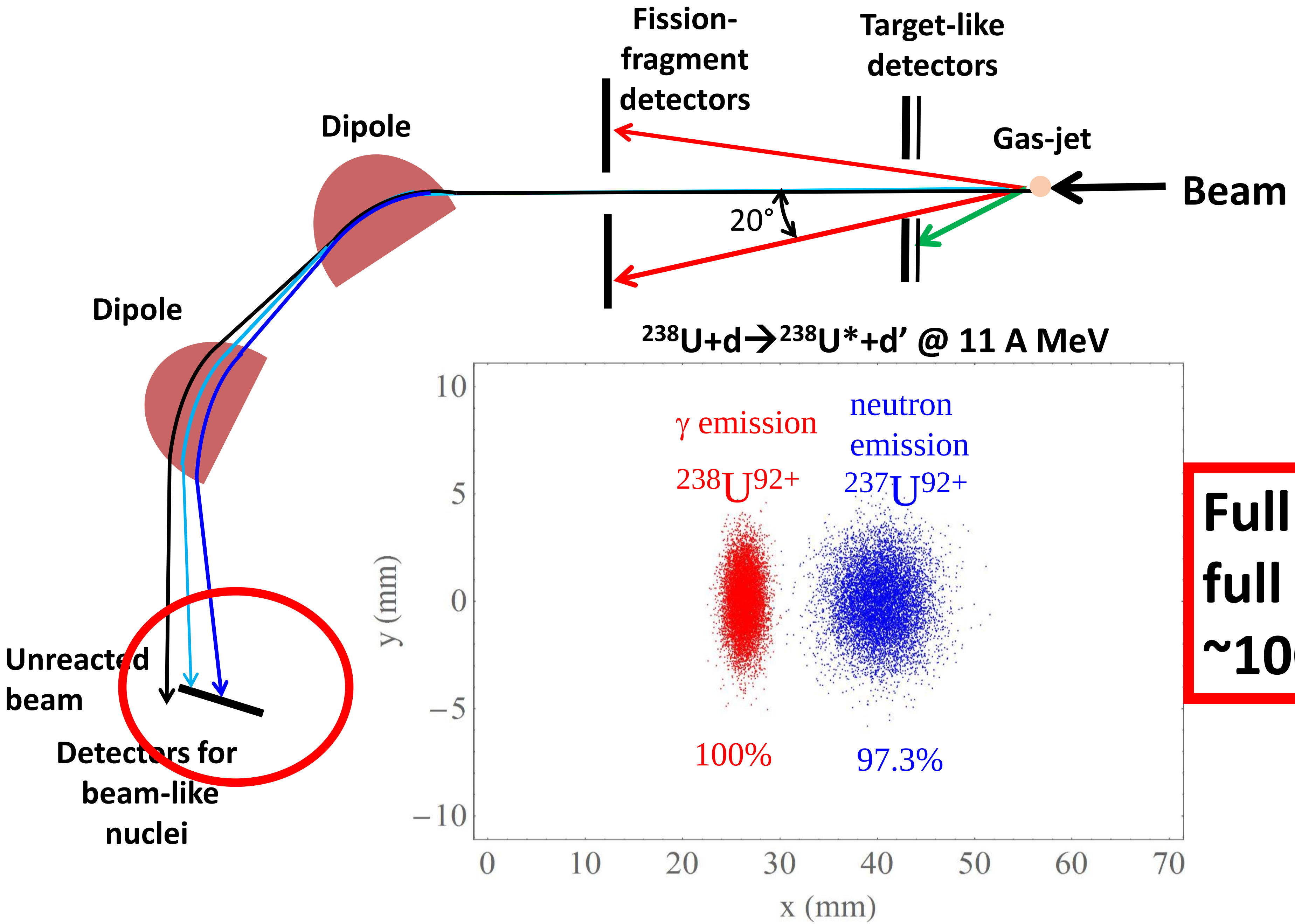
- $\varepsilon_x = \varepsilon_y = 0.05$ mm·mrad , $\sigma_p/p = 2 \cdot 10^{-4}$
- Detector segmentation 128x64 ch
- Pocket window (25 μm)
- Gas-jet radius 0.5 mm
- Detector energy resolution 1%
- Dispersion at gas-jet 1.5 m

$^{238}U + d \rightarrow {}^{238}U^* + d'$ @ 11 A MeV



ΔE*≈200 keV!

Detailed Geant 4 simulations: separation of beam-like residues



Full separation and full transmission: ~100% efficiency!

Conclusions

- **Surrogate reactions in inverse kinematics are the most promising indirect method to infer neutron cross sections of short-lived nuclei which are crucial for nuclear astrophysics and applications in nuclear technology.**
- **CRYRING is the ideal place to carry out high-resolution surrogate reaction studies in inverse kinematics:**
  - **→ E* resolution of few100 keV**
  - **→No target contaminants or backing, pure beams**
  - **→Simultaneous measurement of all decay probabilities with ~ 100% efficiency**
- **Numerous measurements with stable and radioactive beams will be possible**
- **Applications for funding submitted, TDR will be prepared for end 2019, submission of proposal to next PAC**