Indirect measurements of neutron-induced cross sections at storage rings

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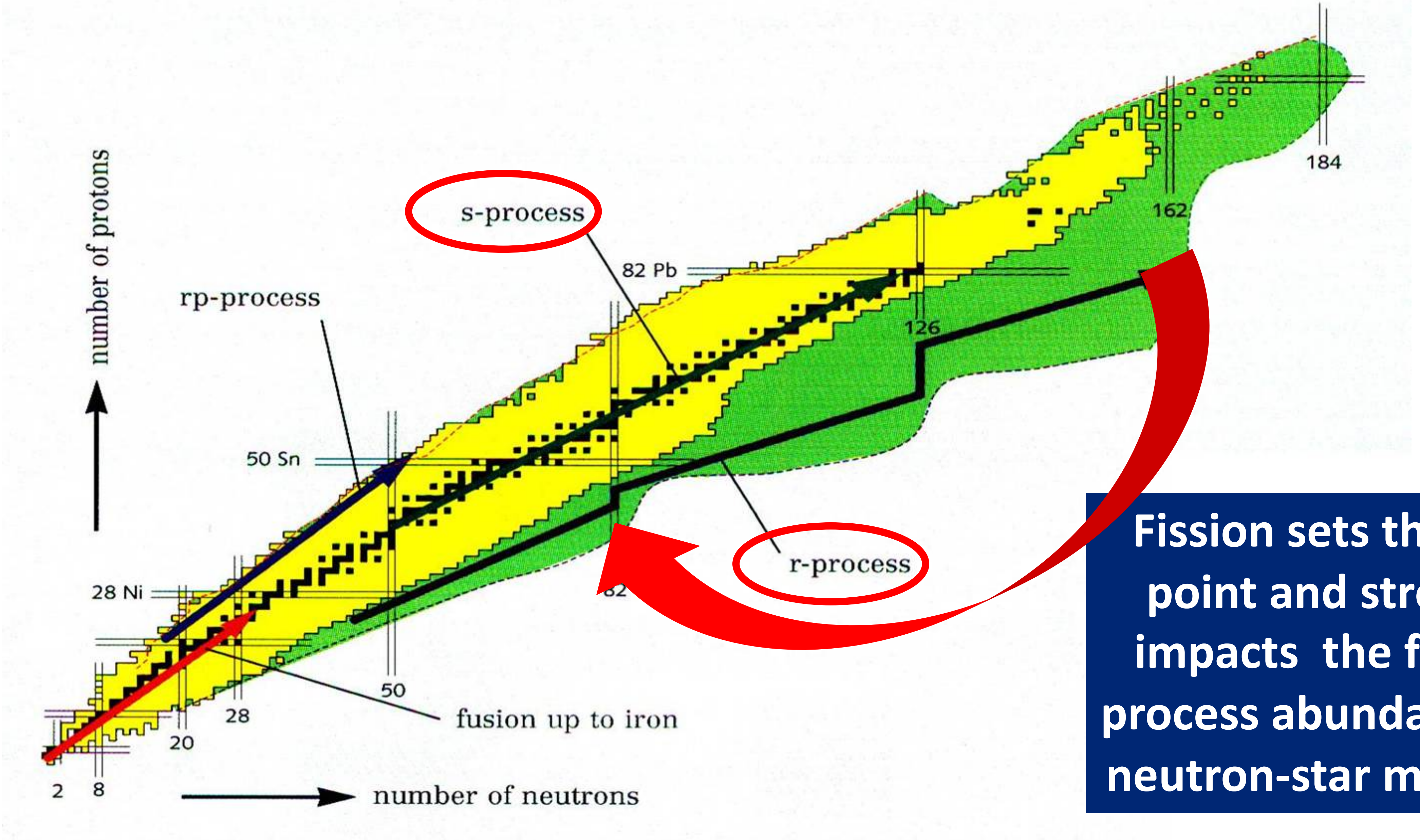
Need for neutron-induced cross sections on short-lived nuclei : s- and r-process nucleosynthesis

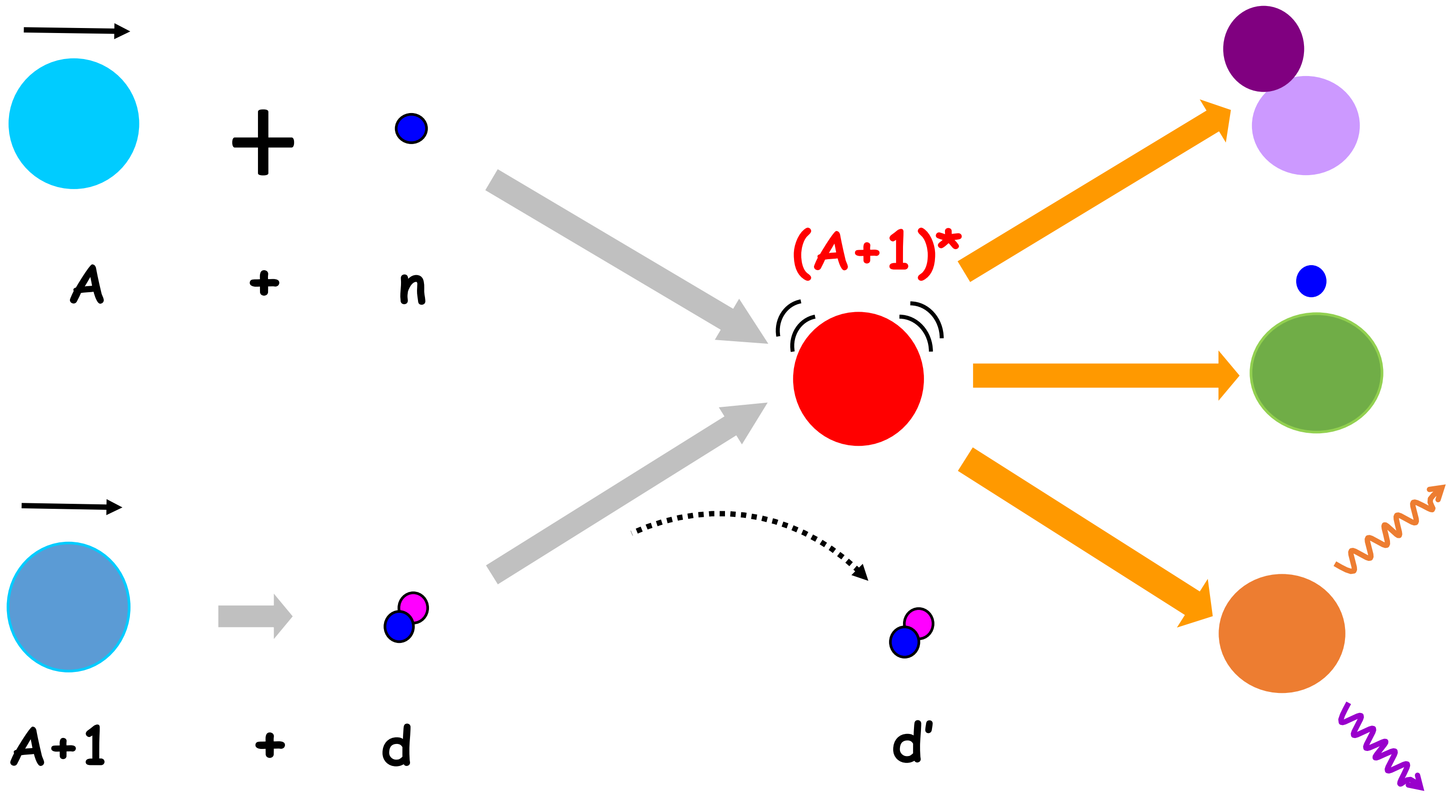


Fission sets the end point and strongly impacts the final r-process abundances in neutron-star mergers!

Applications in nuclear technology, reactor physics

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

Surrogate-reaction method in inverse kinematics



Other reactions possible: (d,p), (d,t)…

$$\sigma^{A}_{n,decay}(E^*) = \underbrace{\sigma^{A+1}_{CN}(E^*)}_{\text{Theory}} \cdot \underbrace{P^{surro}_{decay}(E^*)}_{\text{Experiment}}$$

Validity of the surrogate-reaction method

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

Neutron-induced and surrogate reaction must lead to the formation of a compound nucleus :
Decay only depends on *E, *J* and π !!**

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

Populated *J* and π distributions are equal

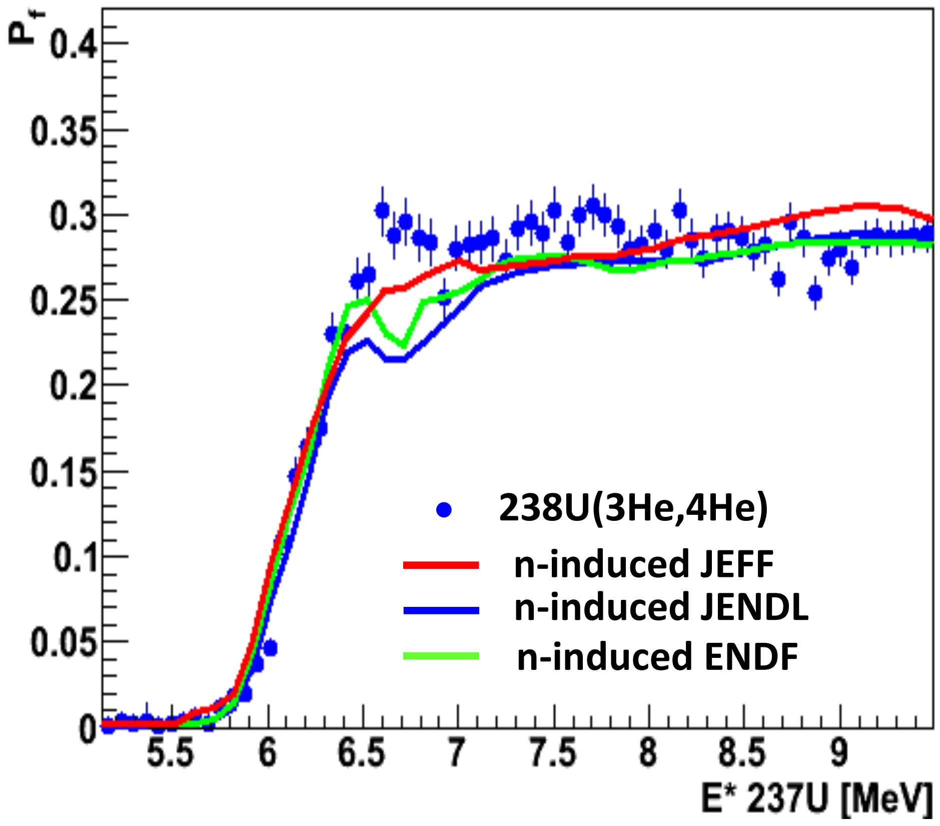
OR

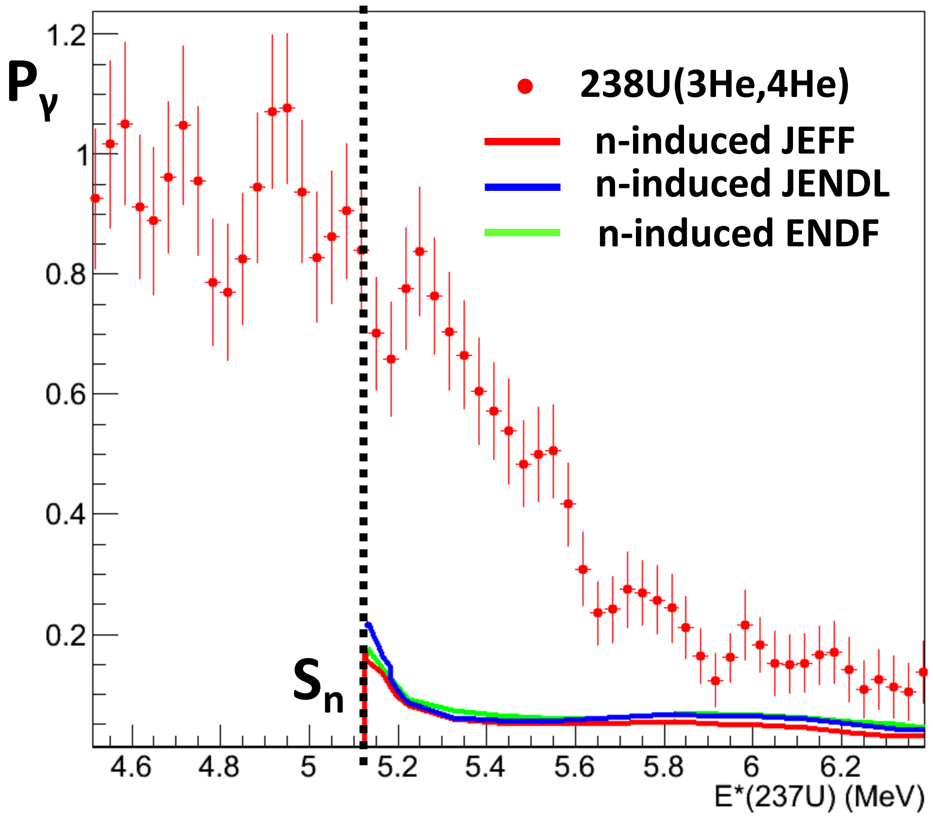
Decay independent of *J* and π (Only valid at high E* in the Weisskopf-Ewing limit)

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!

Preliminary results!

3He + 238U-> 4He + 237U ↔ n + 236U

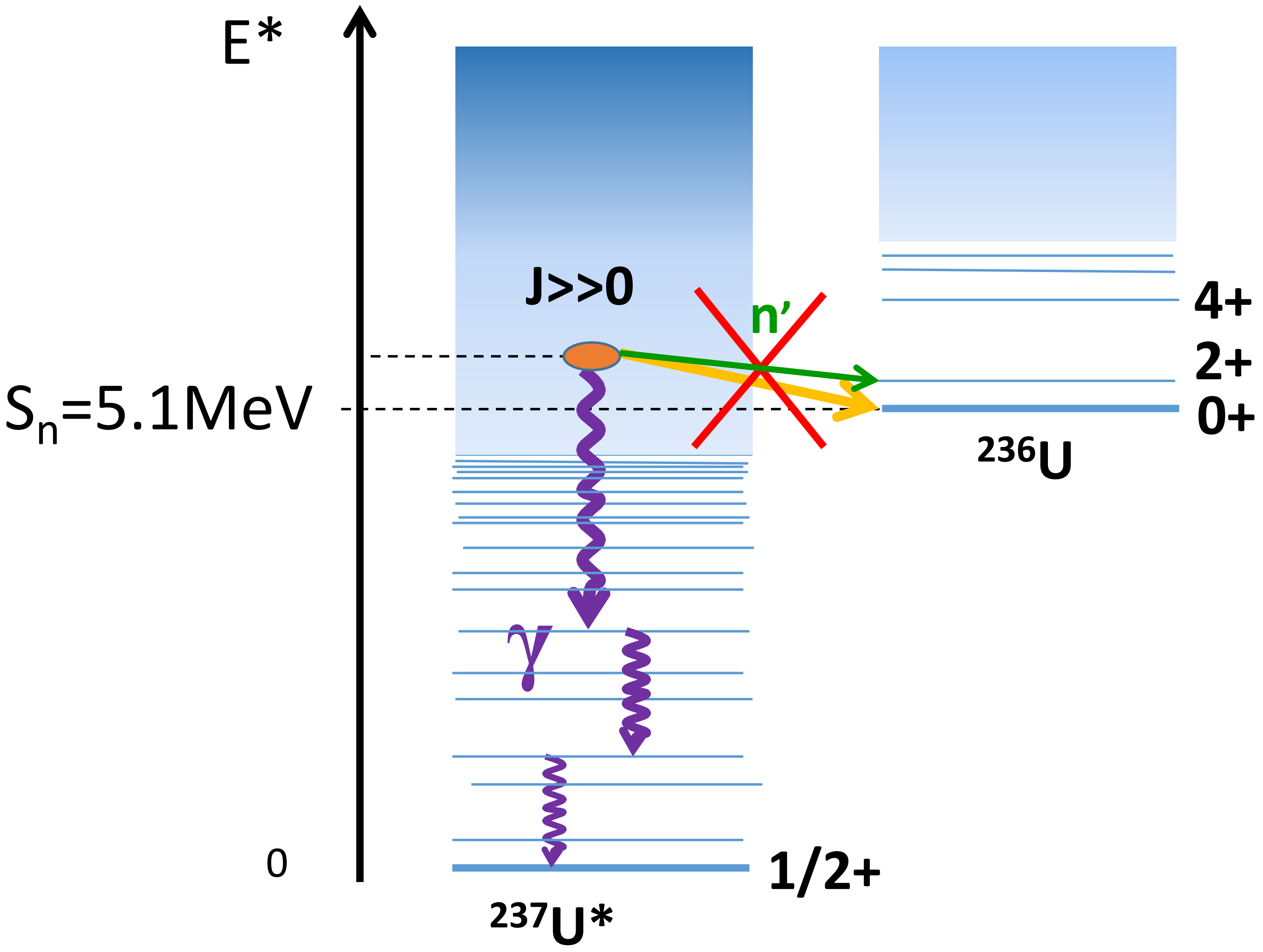




General finding : Good agreement for fission probabilities

but strong disagreement for γ-emission probabilities

Why do we obtain such discrepancies?

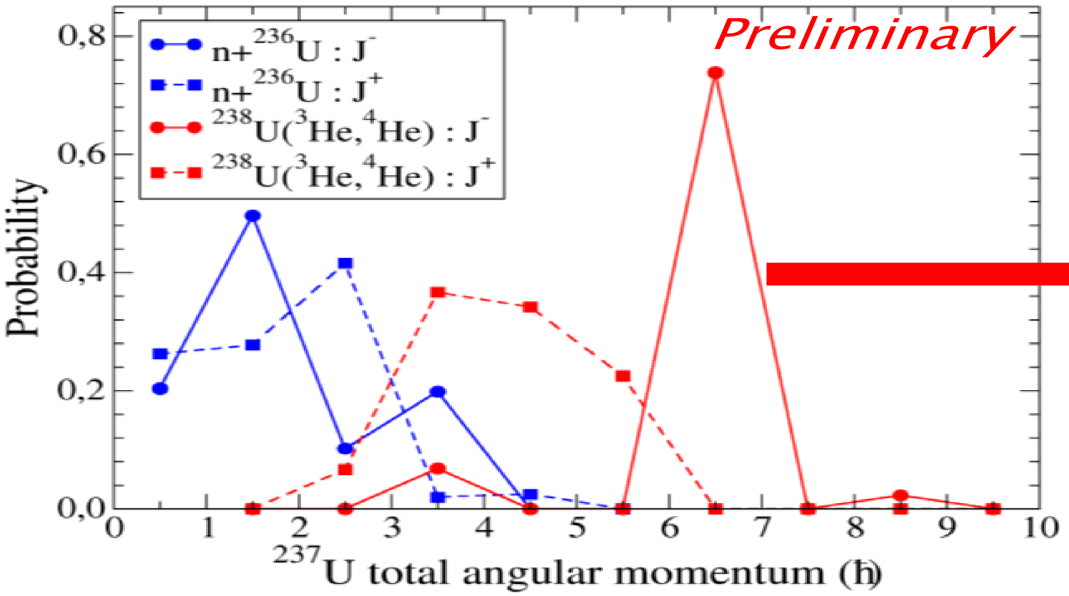


Strong sensitivity of neutron emission to Jπ !

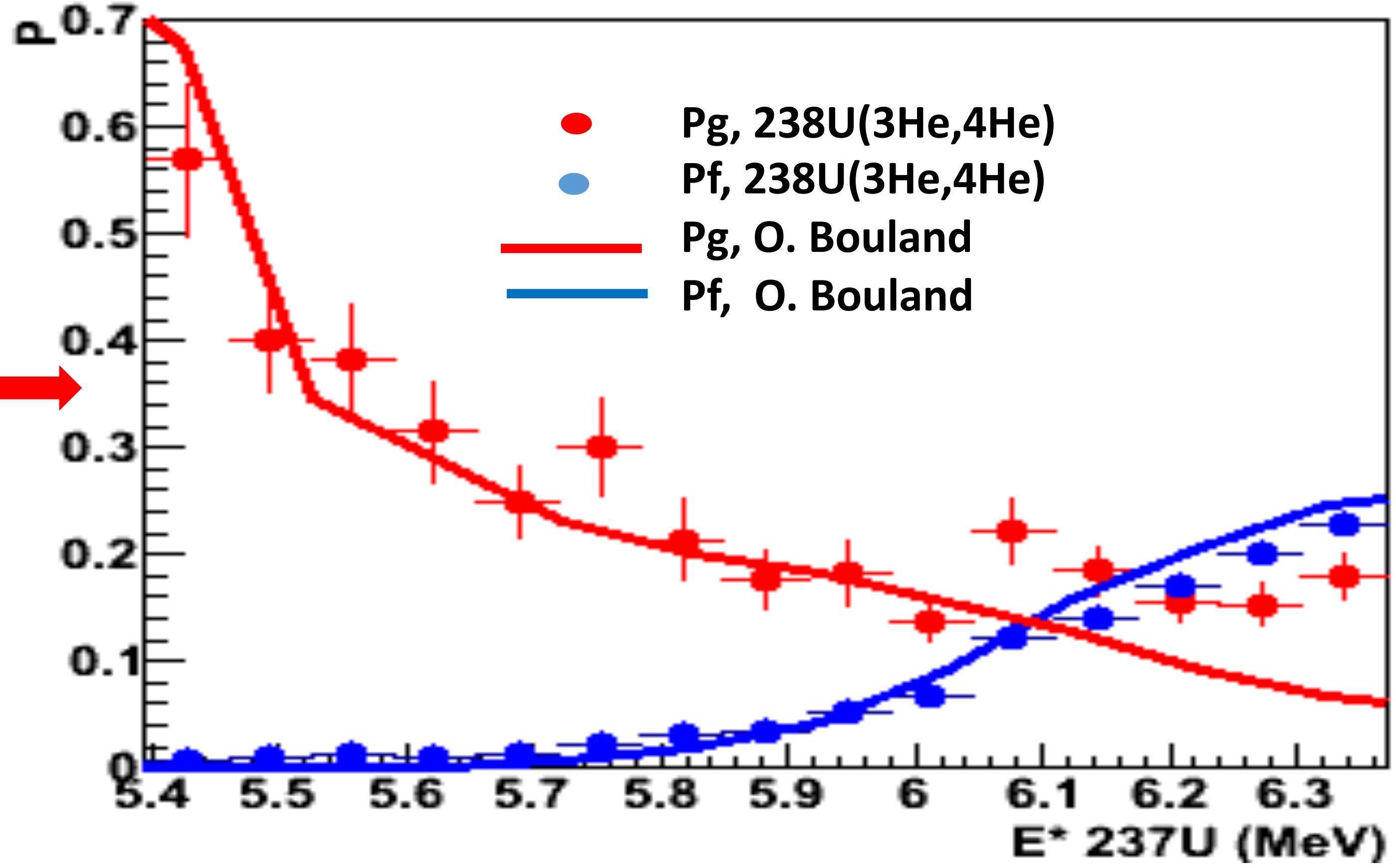
Preliminary results!

3He + 238U-> 4He + 237U

Populated spin/parity distributions



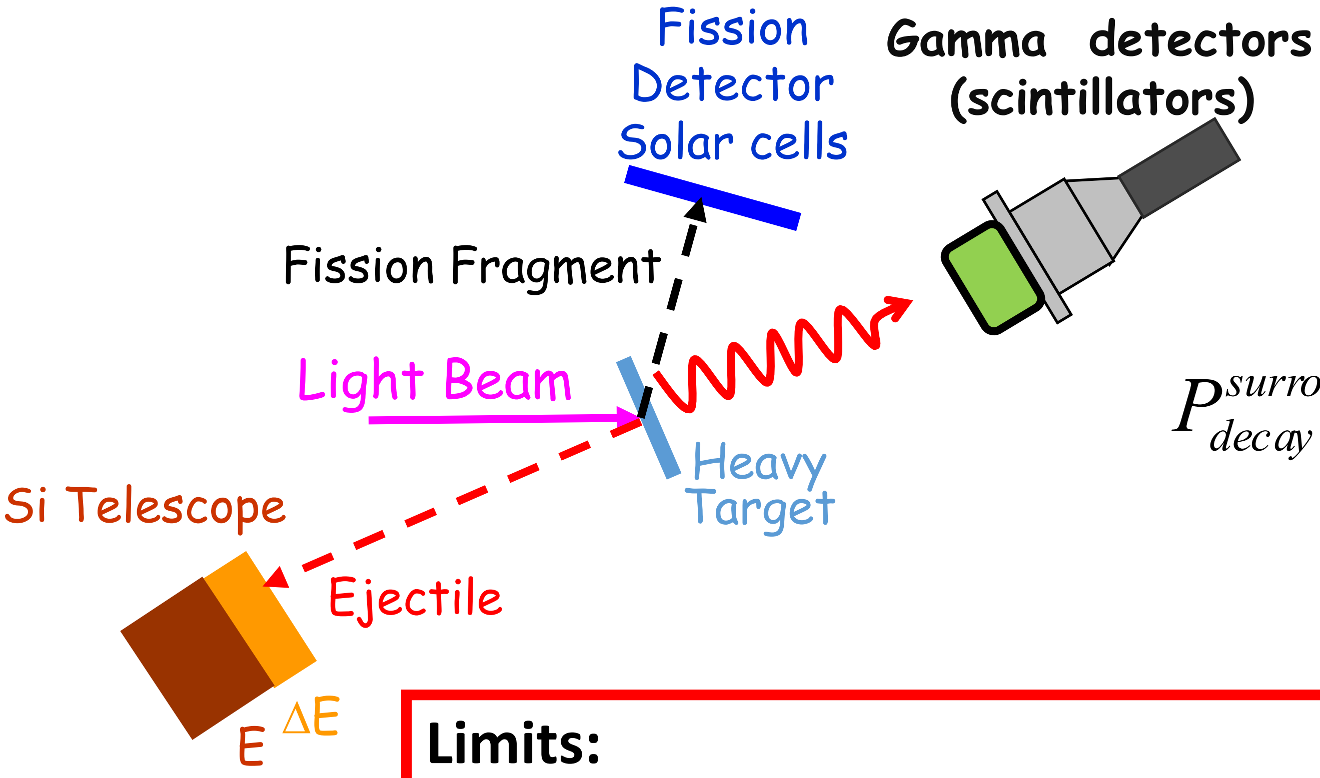
I. Thompson, J. E. Escher,
UCRL-TR-225984 (2006)



O. Bouland & B.Jurado, contribution to ND2016

Pγ is much more sensitive to J^{π} than P_f but it is possible to correct for J^{π} effects

Setup for measurement of fission and gamma-emission probabilities in direct kinematics



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

Limits:

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

Advantages of Inverse kinematics:

-Access to very short-lived nuclei

-Detection of heavy residues

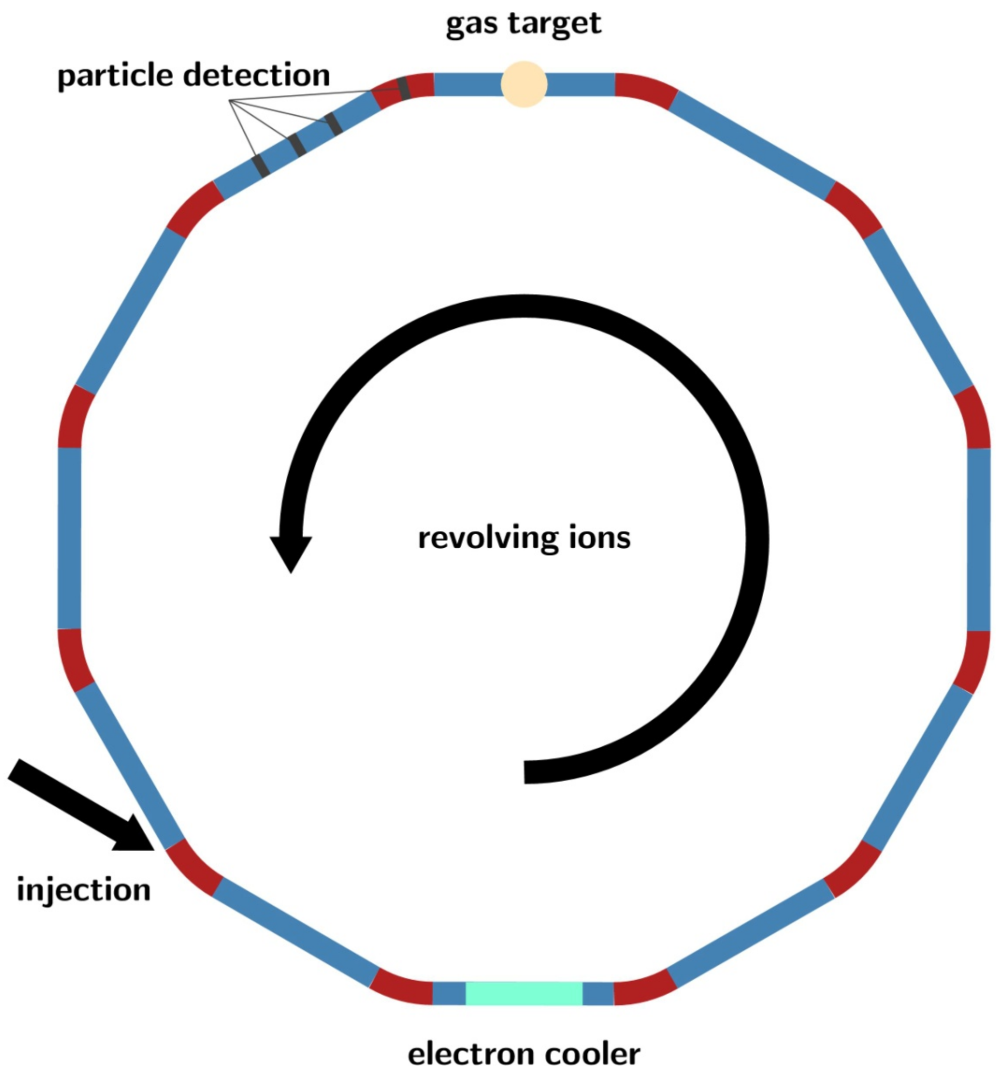
BUT

- **Required E* resolution $\leq$ 100 keV**
- **Target contaminants and target windows have to be avoided**

STORAGE RINGS!

Advantages of heavy-ion storage rings

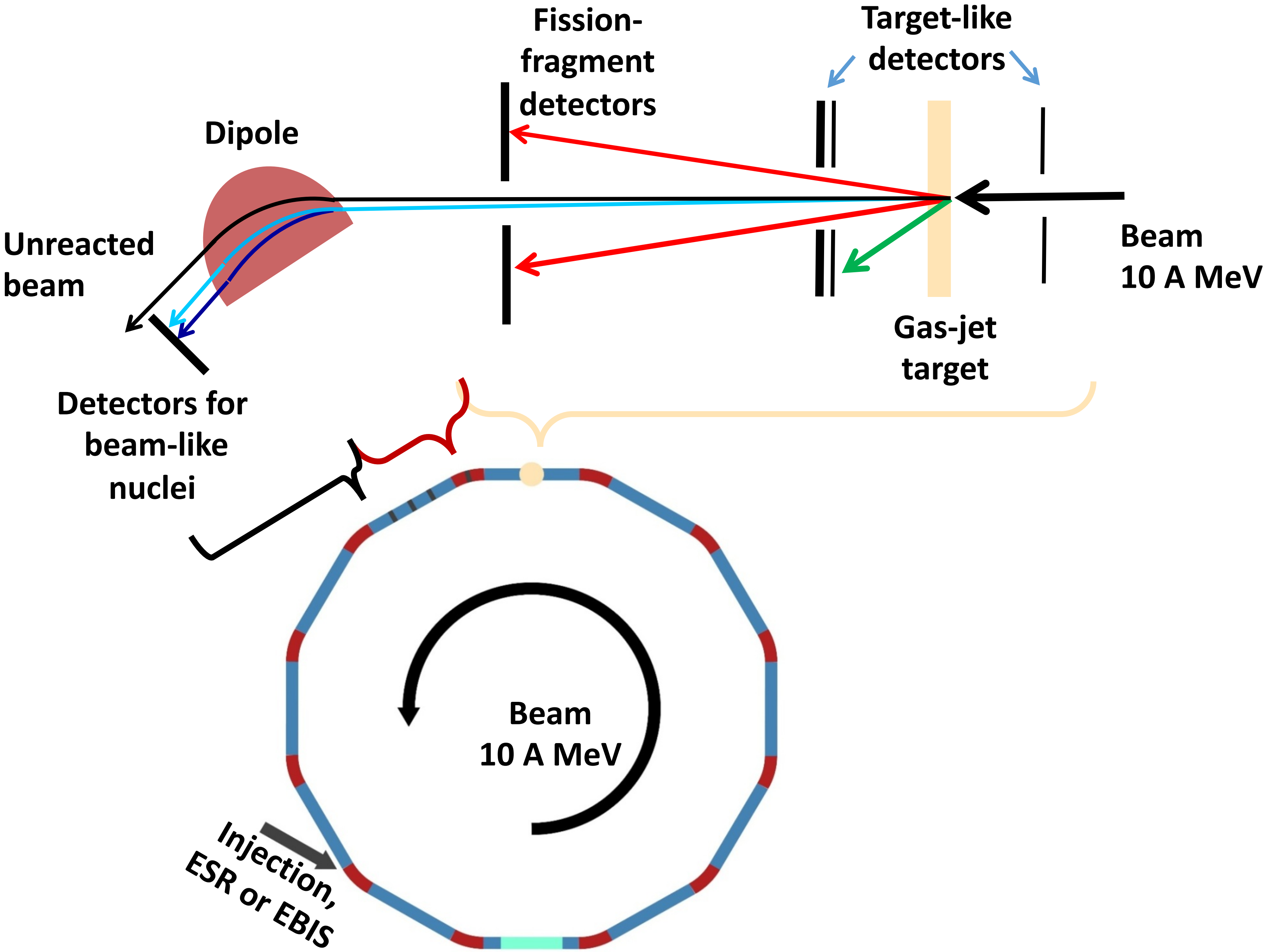
The CRYRING at GSI/FAIR



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

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

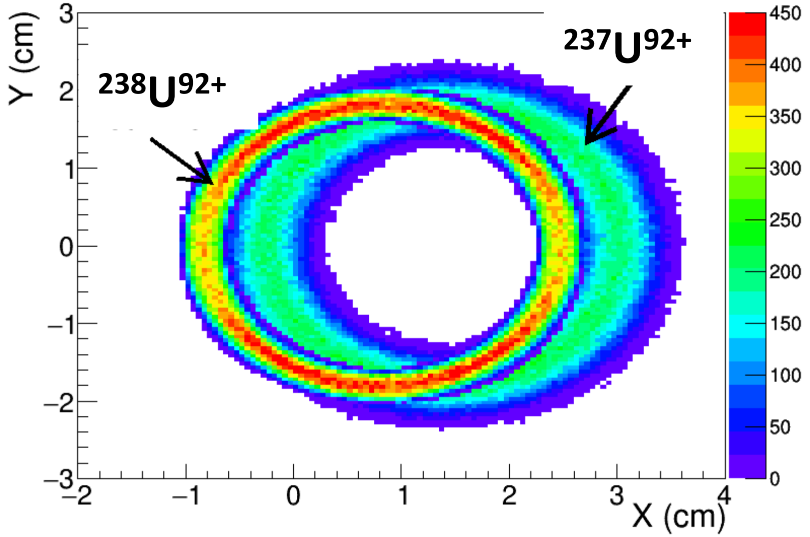
Set-up for decay-probability measurements at storage rings



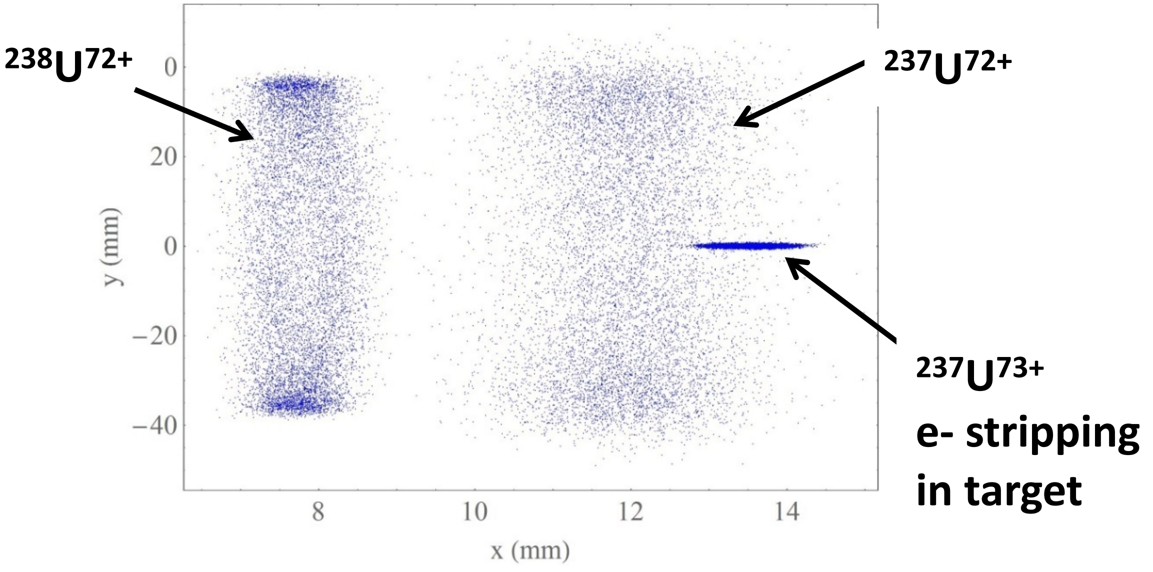
Results of feasibility studies

- Ultra-thin gas-jet target + cooled beams + highly segmented target-like detectors (128X128 ch) → E* resolution ~ 100 keV!
- Fission detection efficiency up to 95 %!
- Possible to separate heavy residues produced after γ and neutron emission

MOCADI Simulation for CRYRING, 238U(d,d')



G4beamline simulation for the ISR, 238U(d,d')



Simulation by Manfred Grieser!

- Detection efficiencies of heavy residues: 30 -90%!

Decay probabilities for ALL open channels can be measured simultaneously with good E* resolution, unique!

First measurements with stable beams

- **Validate the technology by comparing with decay probabilities measured in direct kinematics:**

→ $^{181}Ta(d,d')$

→ $^{238}U(d,d')$

- **Study of the (d,p) reaction in several regions by comparing with well known neutron cross sections**

→ $^{181}Ta(d,p)$

→ $^{197}Au(d,p)$

→ $^{208}Pb(d,p)$

→ $^{238}U(d,p)$

- **Study of the (d,d') reaction in the Zr region**

→ $^{94}Zr(d,d')$ ⇔ $n+^{93}Zr$, deduce $^{93}Zr(n,\gamma)$ and compare with available data

→ $^{96}Zr(d,d')$ ⇔ $n+^{95}Zr$ ($T_{1/2}$=64 d), deduce $^{95}Zr(n,\gamma)$, which is unknown and very important for the s-process!

Conclusions

Storage rings are the ideal devices to carry out high resolution surrogate reaction studies in inverse kinematics:

→No target contaminants or backing, pure (isomeric) beams

→E* resolution ~ 100 keV

→Simultaneous measurement of all decay probabilities with very large efficiencies