



Investigating the surrogate-reaction via the simultaneous measurement of gamma-emission and fission probabilities

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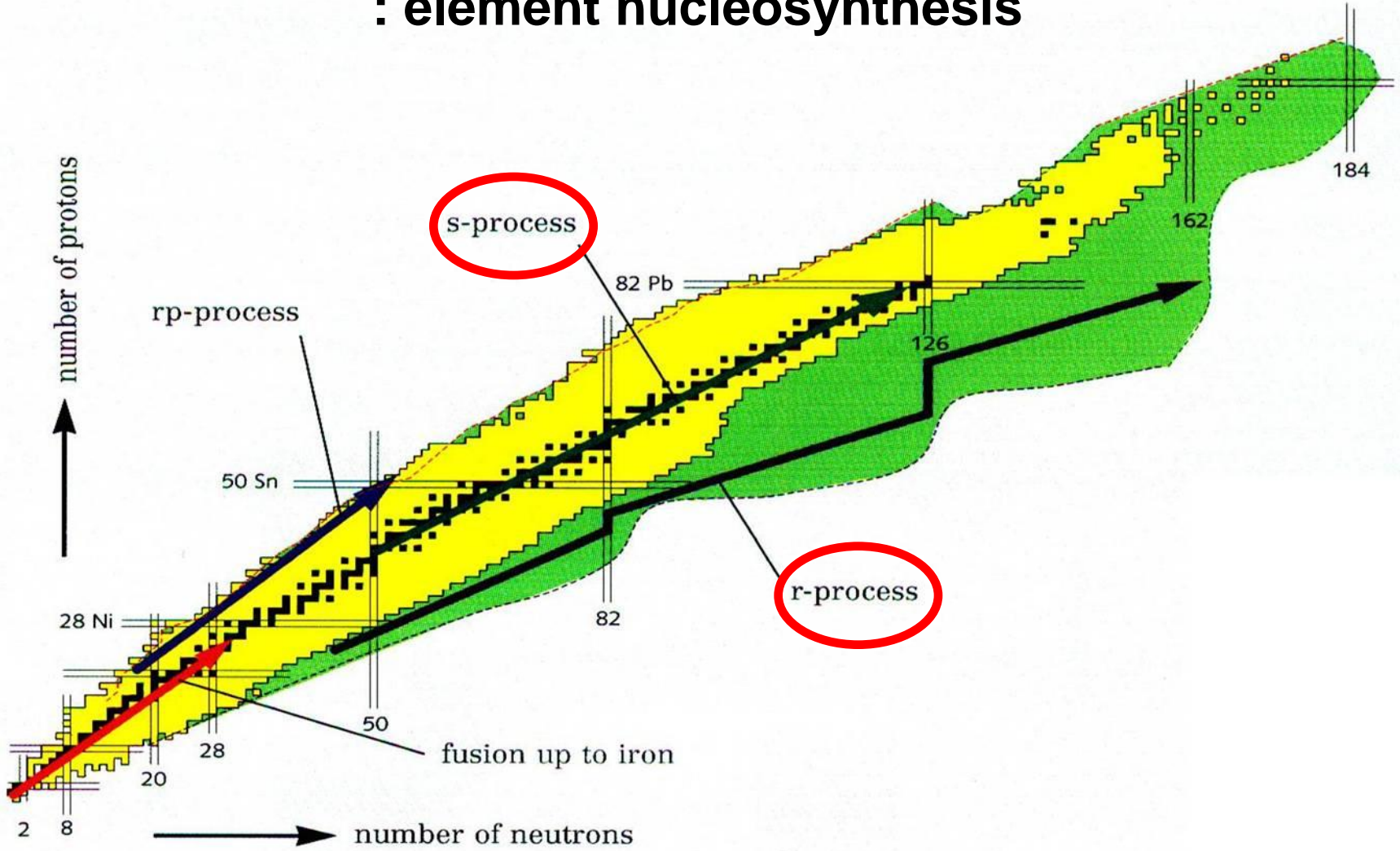
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Need for neutron-induced cross sections of short-lived nuclei : element nucleosynthesis



Need for neutron-induced cross sections on short-lived nuclei : transmutation of nuclear waste

The image shows a periodic table with a red oval highlighting the actinide region (elements 89-103). The table includes various isotopes with their half-lives and decay modes. The highlighted area is labeled "Minor actinides".

		Bk 238 144 s		Bk 240 5 m	Bk 241 4.6 h	Bk 242 7 m	Bk 243 4.5 h	Bk 244 4.35 h	Bk 245 4.90 d	Bk 246 1.80 d	Bk 247 1380 a	Bk 248 > 9 a	Bk 249 320 d
		Cm 237 ?	Cm 238 2.4 s	Cm 239 3 h	Cm 240 27 d	Cm 241 32.8 d	Cm 242 162.94 d	Cm 243 29.1 a	Cm 244 18.10 a	Cm 245 8500 a	Cm 246 4730 a	Cm 247 1.56 · 10 ⁷ a	Cm 248 3.40 · 10 ⁶ a
Am 234 2.32 m	Am 235 10.3 m	Am 236 2.9 m	Am 237 73.0 m	Am 238 1.63 h	Am 239 11.9 h	Am 240 50.8 h	Am 241 432.2 a	Am 242 141 a	Am 243 7370 a	Am 244 26 m	Am 245 2.05 h	Am 246 25 m	Am 247 22 m
Pu 233 20.9 m	Pu 234 8.8 h	Pu 235 25.3 m	Pu 236 2.858 a	Pu 237 45.2 d	Pu 238 87.74 a	Pu 239 2.411 · 10 ⁴ a	Pu 240 6563 a	Pu 241 14.35 a	Pu 242 3.750 · 10 ⁵ a	Pu 243 4.956 h	Pu 244 8.00 · 10 ⁷ a	Pu 245 10.5 h	Pu 246 10.85 d
Np 232 14.7 m	Np 233 36.2 m	Np 234 4.4 d	Np 235 396.1 d	Np 236 2.144 · 10 ⁶ a	Np 237 2.117 d	Np 238 2.355 d	Np 239 7.22 m	Np 240 65 m	Np 241 13.9 m	Np 242 2.2 m	Np 243 1.85 m	Np 244 2.29 m	
U 231 4.2 d	U 232 68.9 a	U 233 1.592 · 10 ⁵ a	U 234 0.0054 a	U 235 7.038 · 10 ⁸ a	U 236 120 ns	U 237 6.75 d	U 238 99.2742 a	U 239 2.342 · 10 ⁴ a	U 240 2.342 · 10 ⁴ a	U 241 2.342 · 10 ⁴ a	U 242 16.8 m		
Pa 230 17.4 d	Pa 231 3.276 · 10 ⁴ a	Pa 232 1.31 d	Pa 233 27.0 d	Pa 234 1.17 m	Pa 235 6.70 h	Pa 236 9.1 m	Pa 237 8.7 m	Pa 238 2.3 m	Pa 239 1.8 h				
Th 229 7880 a	Th 230 7.54 · 10 ⁴ a	Th 231 25.5 h	Th 232 1.405 · 10 ¹⁰ a	Th 233 22.3 m	Th 234 24.10 d	Th 235 7.1 m	Th 236 37.5 m	Th 237 5.0 m	Th 238 9.4 m				

Minor actinides

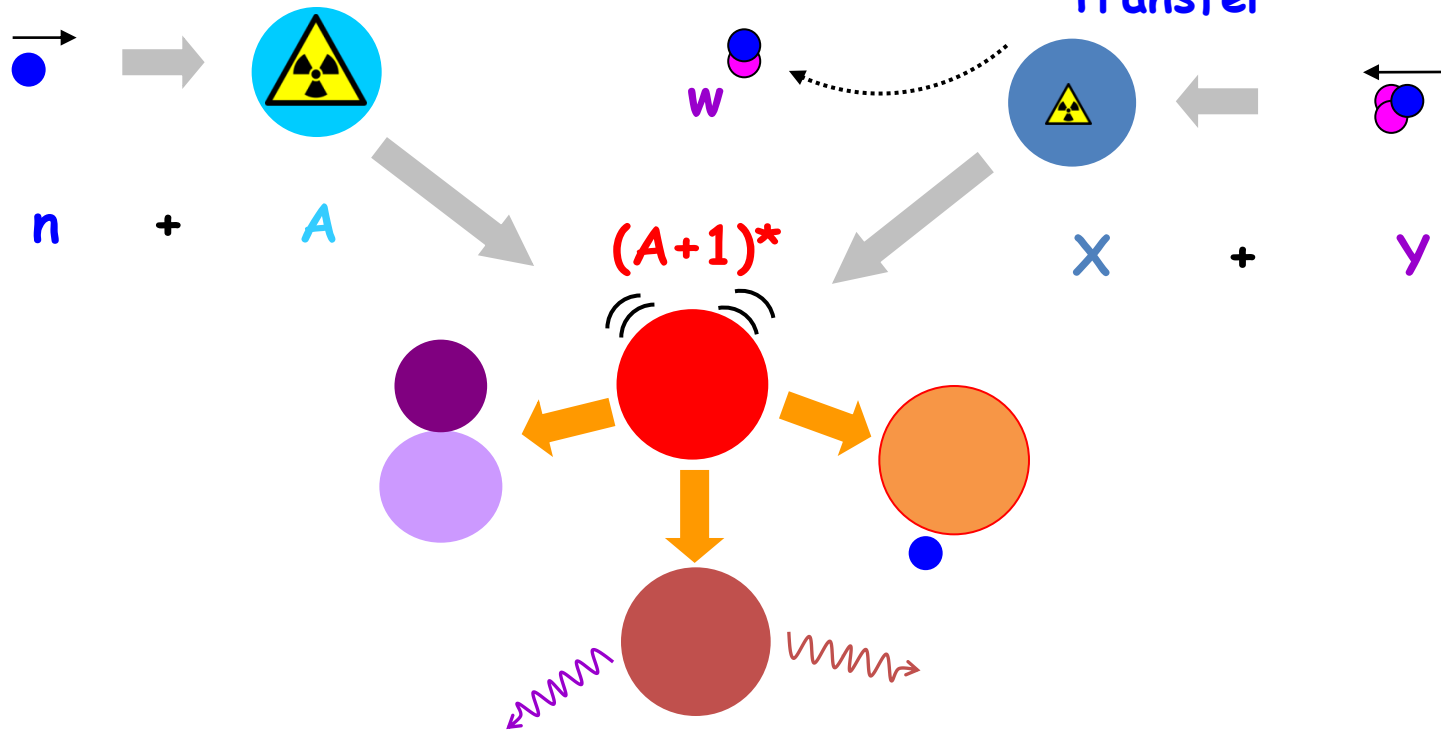
Neutron-induced fission and capture cross sections of short-lived nuclei needed. Very difficult or even impossible to measure!

Surrogate-reaction method

Cramer and Britt (Los Alamos 1970...!!)

Neutron-induced reaction

Surrogate reaction



$$\sigma_{n,decay}^A(E^*) = \underbrace{\sigma_{CN}^{A+1}(E^*)}_{\substack{\text{Theory} \\ \text{Optical model}}} \cdot \underbrace{P_{decay}^{surro}(E^*)}_{\text{Experiment}}$$

Validity of the surrogate method

$$\sigma_{n,decay}^A(E^*) = \sigma_{CN}^{A+1}(E^*) \cdot P_{decay}^{surro}(E^*)$$

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

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

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

Populated J and π distributions are equal

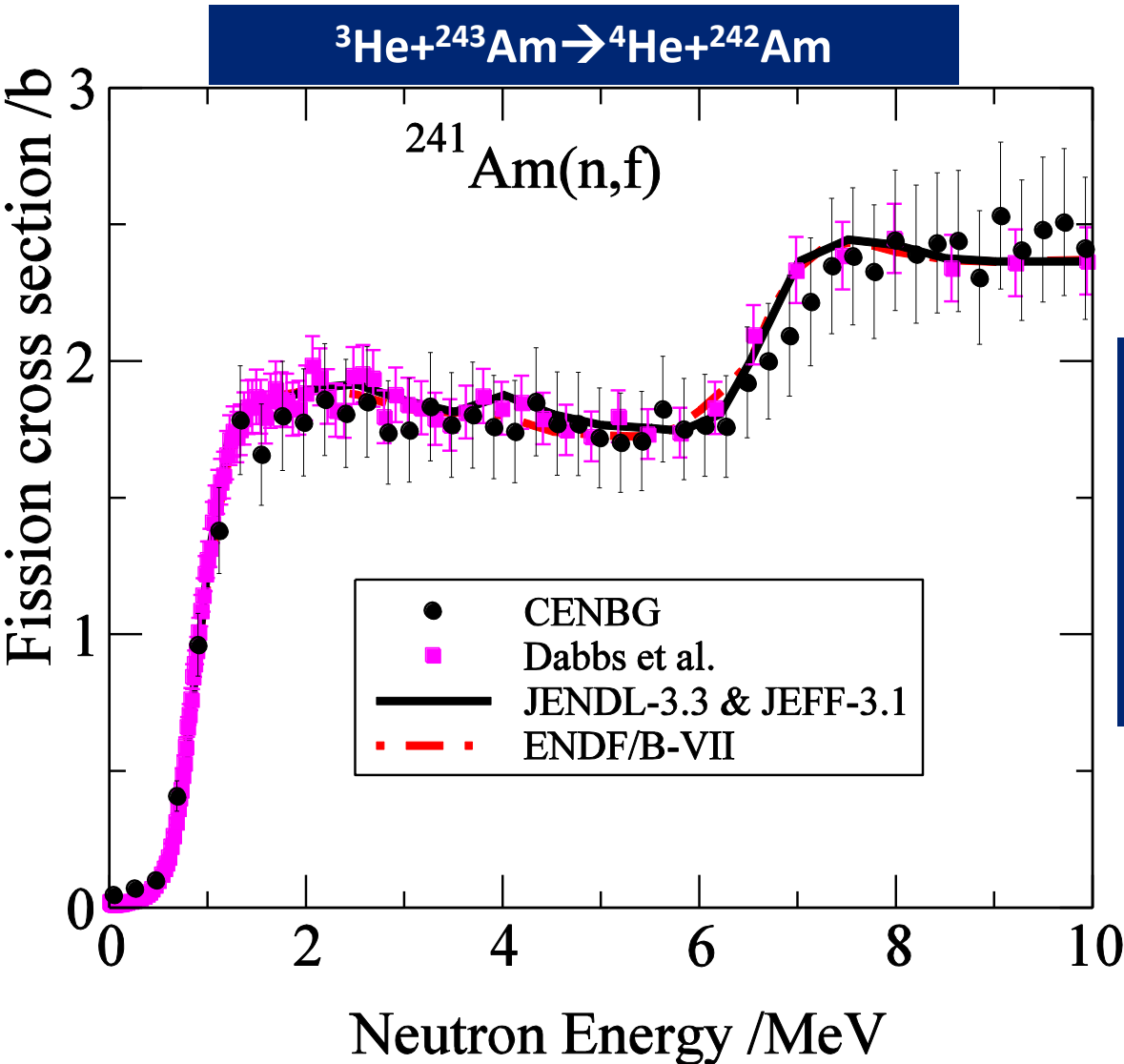
OR

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!

Results for fission



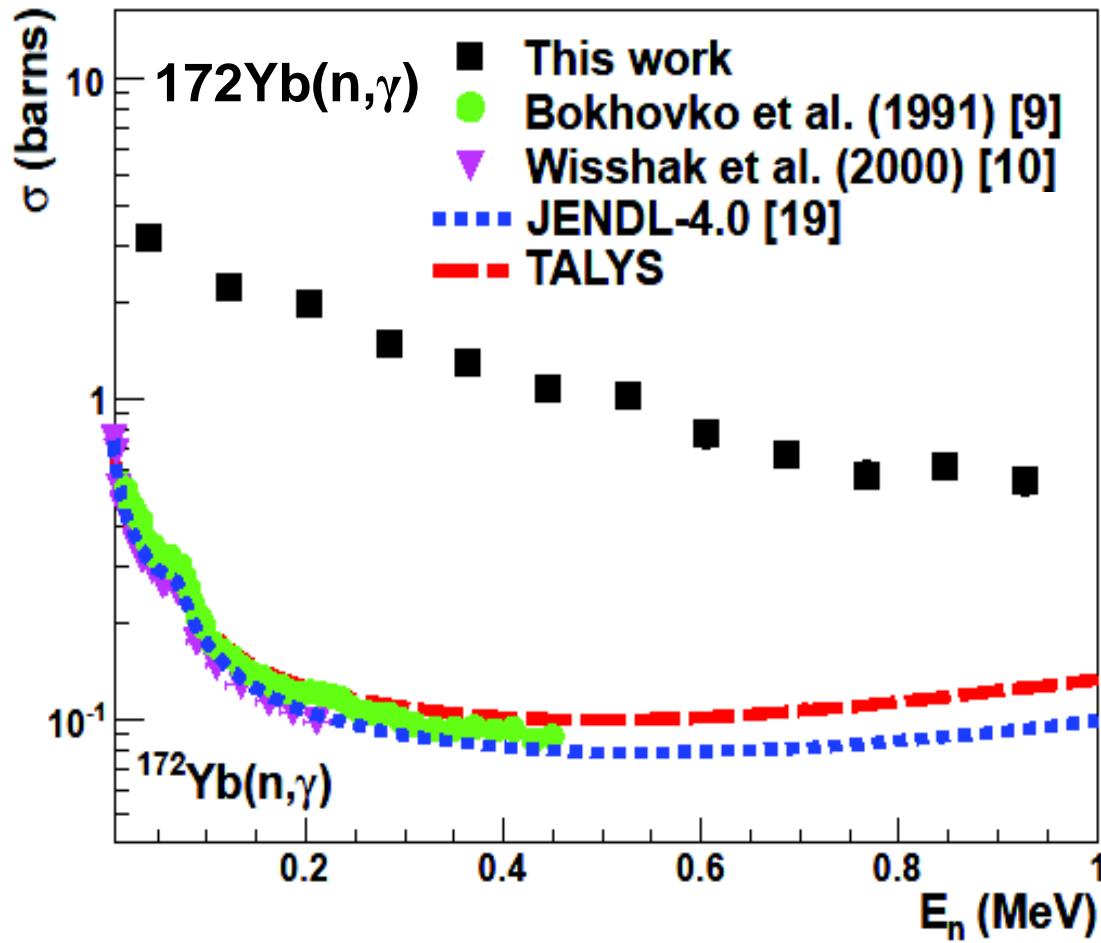
General finding: the cross sections obtained with surrogate method are in good agreement with n-induced data for fission!

G. Kessedjian et al., Phys. Lett. B 692 (2010) 297

G. Kessedjian et al., Phys. Rev. C 91 (2015) 044607

Results for radiative capture

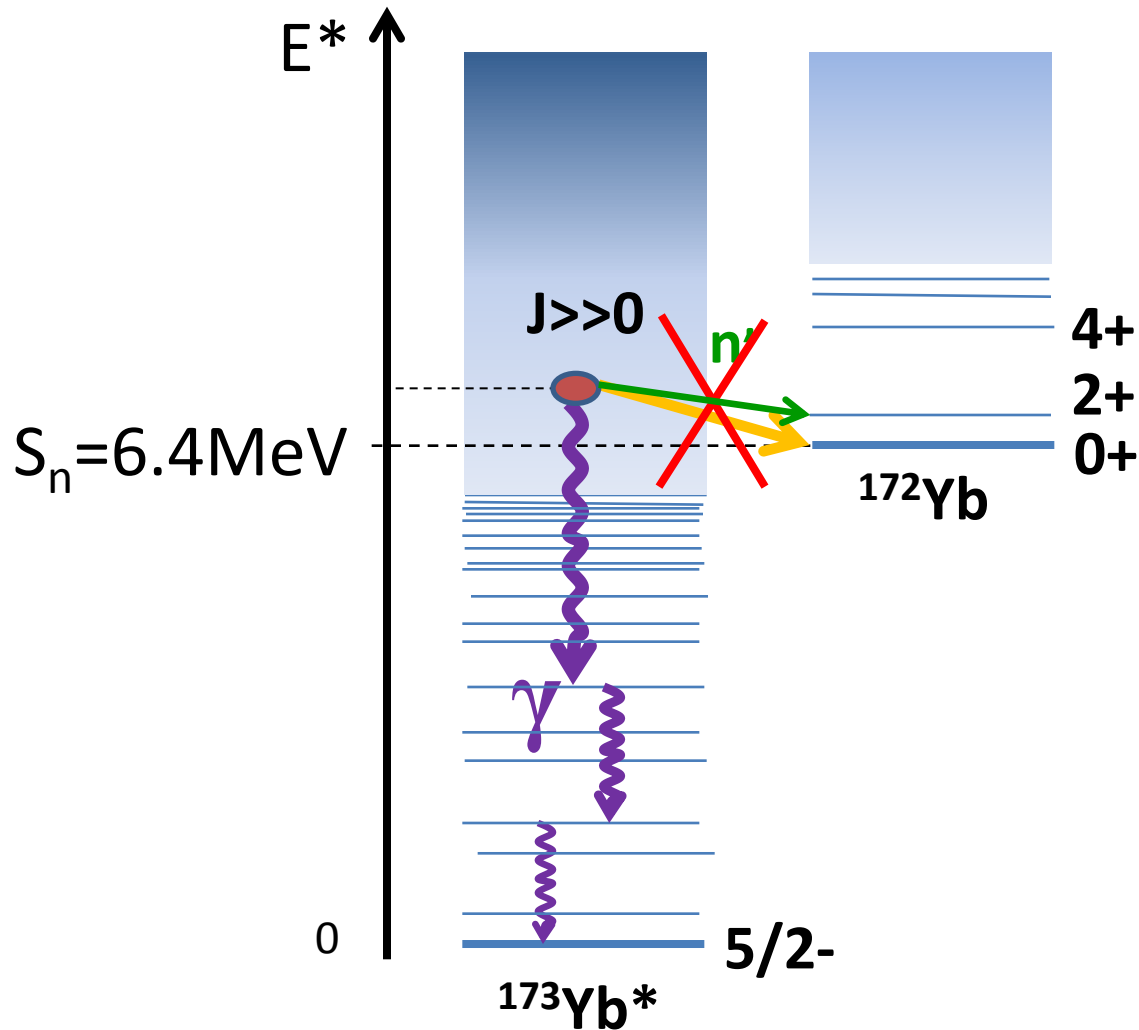
$3\text{He} + {}^{174}\text{Yb} \rightarrow 4\text{He} + {}^{173}\text{Yb}$



The cross sections obtained with surrogate method are in clear disagreement with n-induced data for capture!

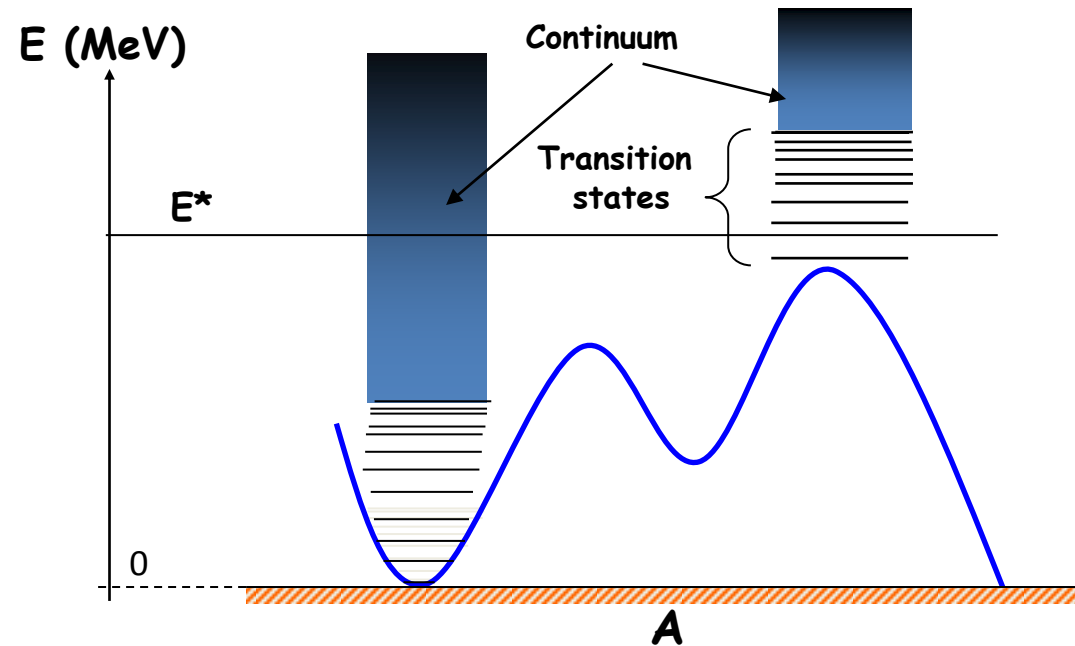
G. Boutoux et al., Phys. Lett. B 712 (2012) 319

Why do we obtain such discrepancies?



Strong sensitivity of neutron emission to $J\pi$

Fission seems to be much less sensitive to spin/parity differences, why?



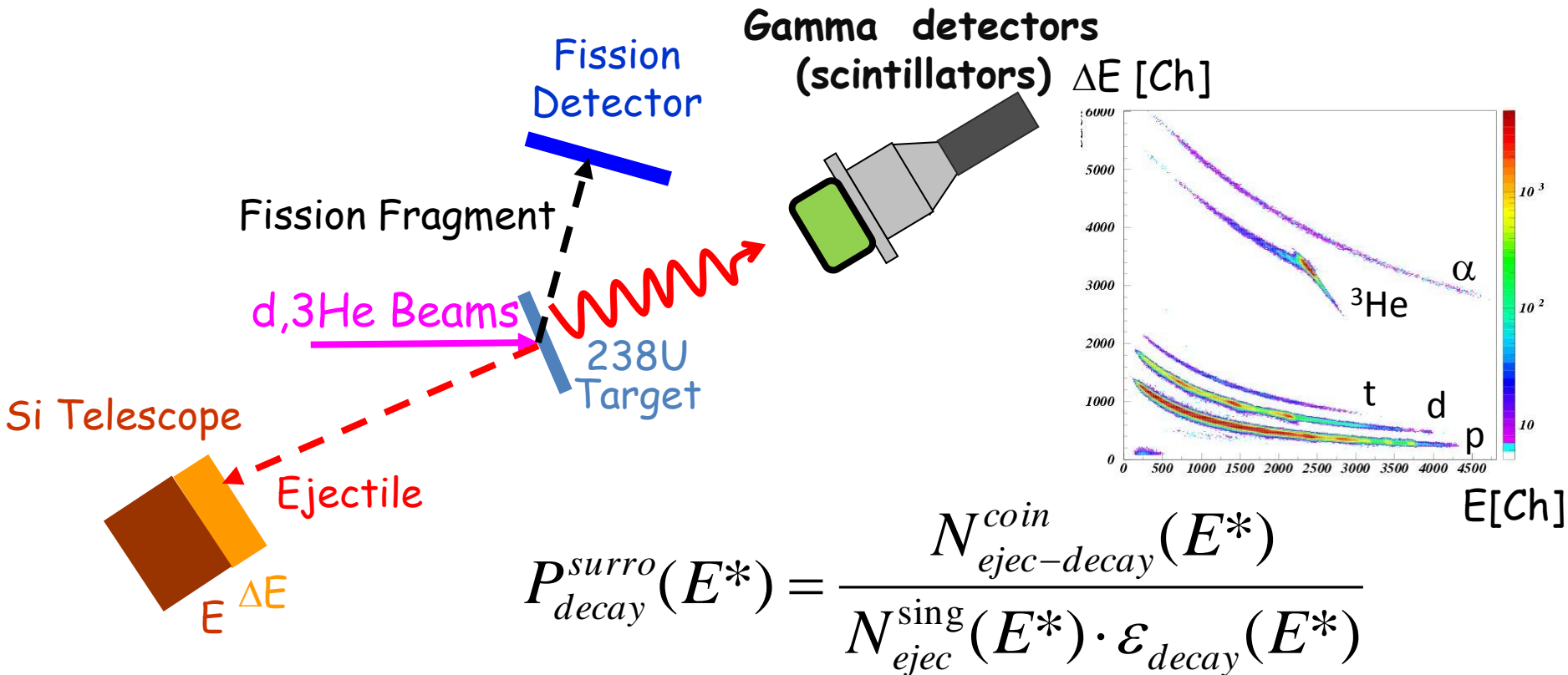
The top of the fission Barrier is also a region of low density of states!

First step to understand:

Simultaneous measurement of fission and gamma-decay probabilities!

Never done before!

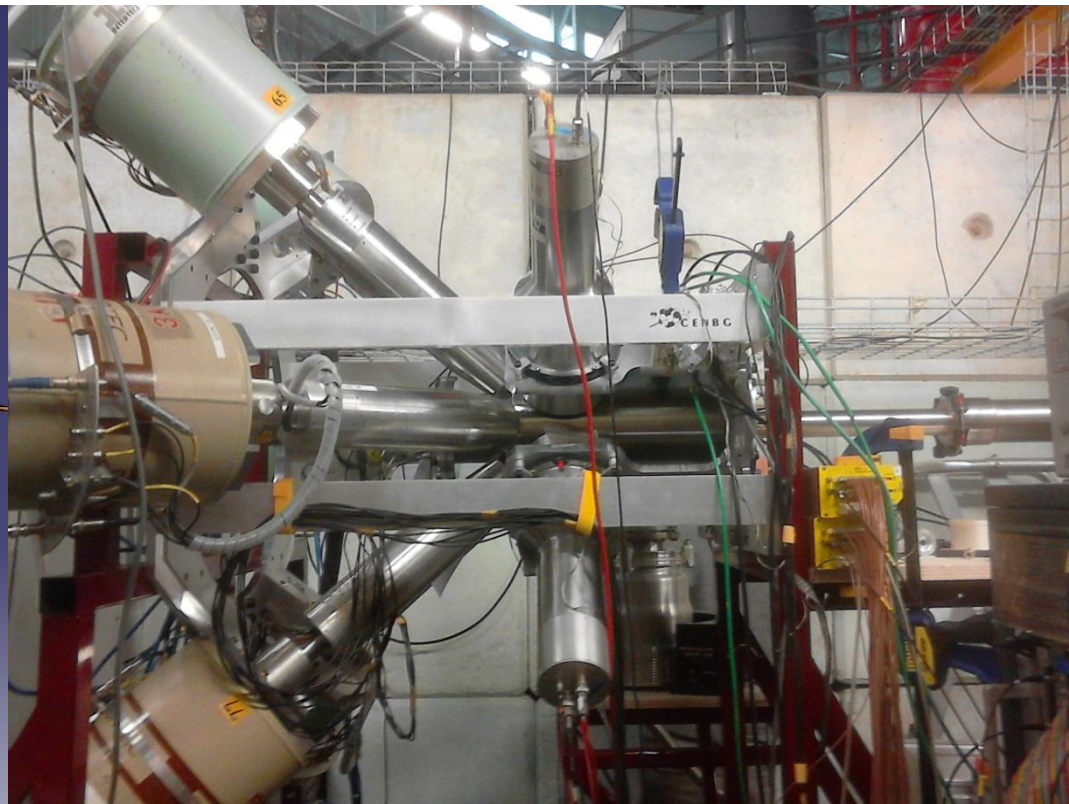
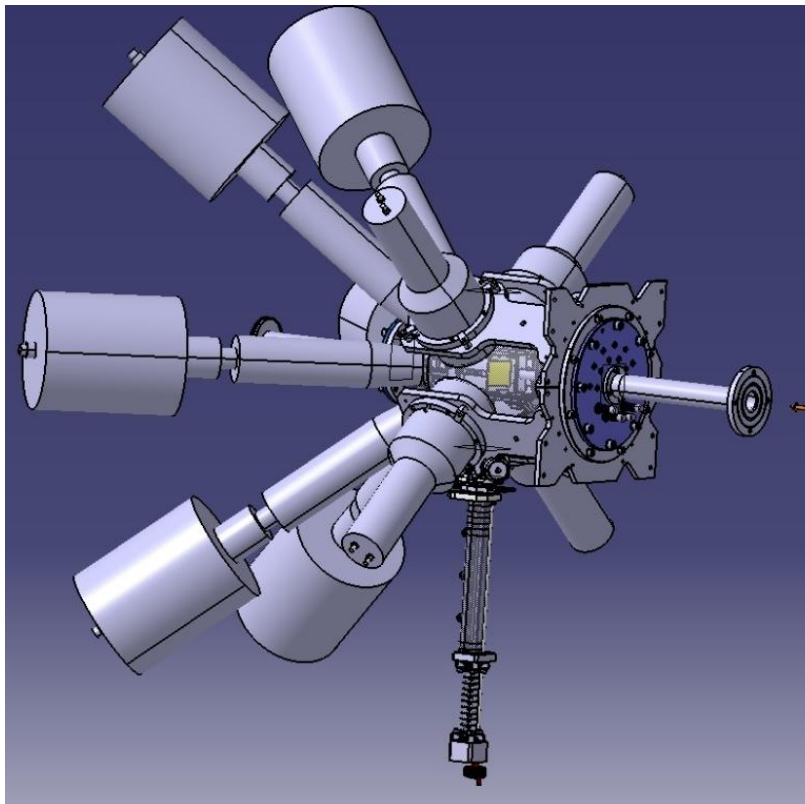
Setup for simultaneous measurement of fission and gamma-decay probabilities



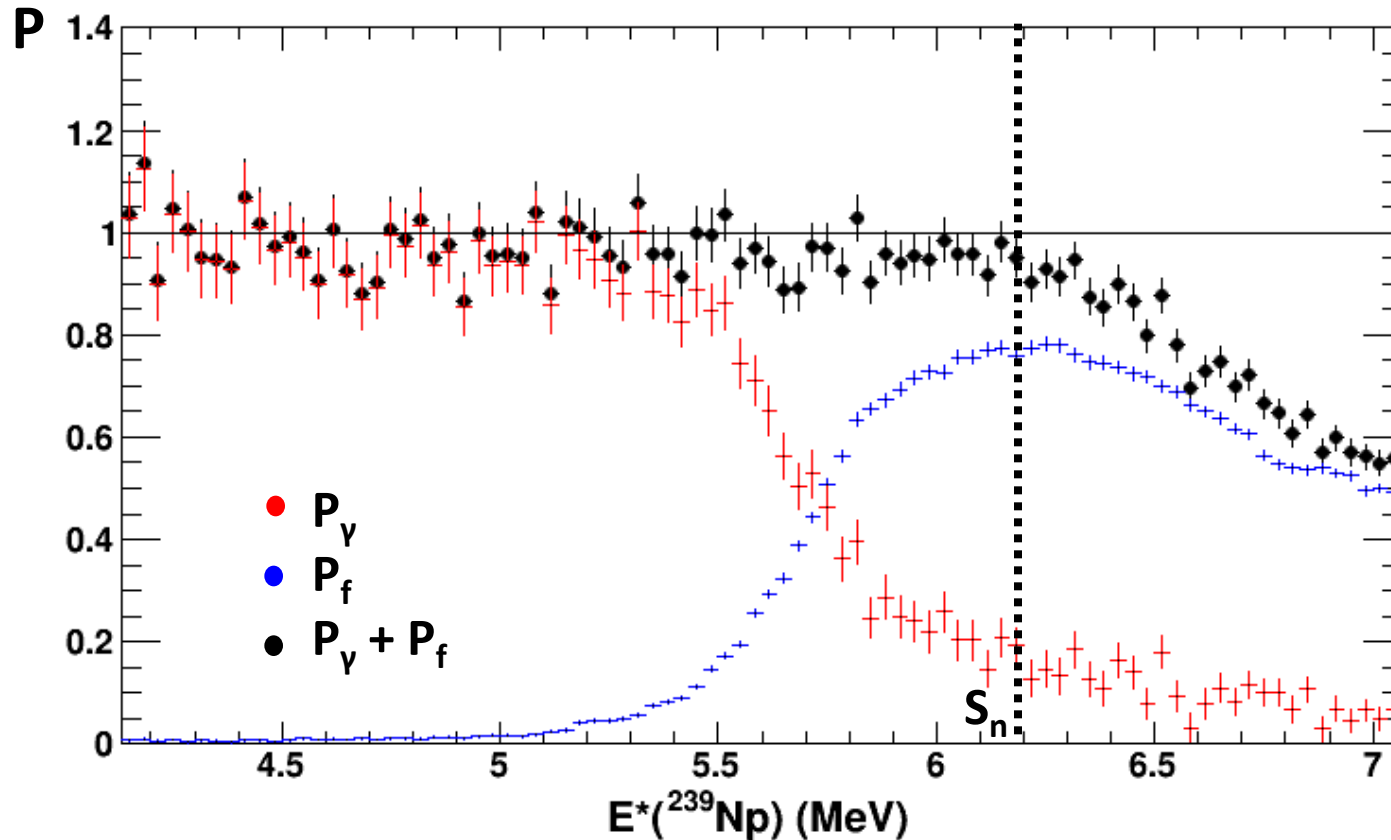
Challenge: removal of gamma rays emitted by the fission fragments !

$$N_{ejec-\gamma}^{coin}(E^*) = N_{ejec-\gamma}^{coin,tot}(E^*) - \frac{N_{ejec-f-\gamma}^{coin}(E^*)}{\epsilon_f(E^*)}$$

Setup used for experiment at the Orsay tandem



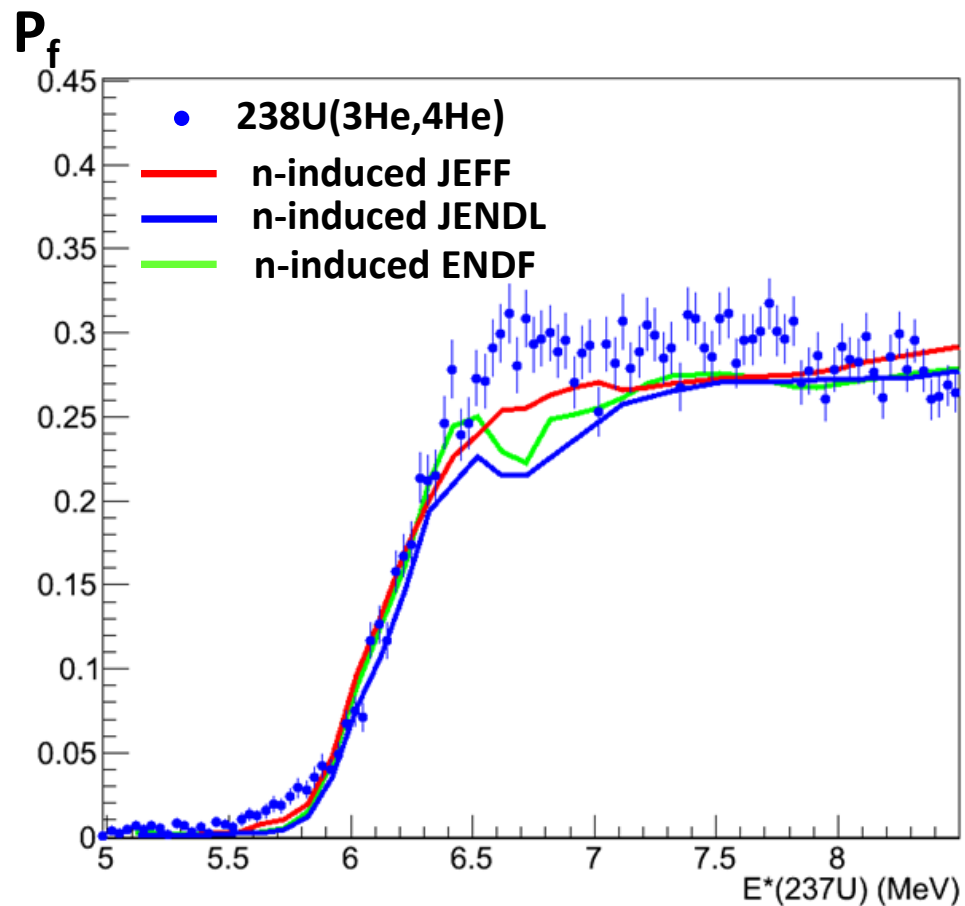
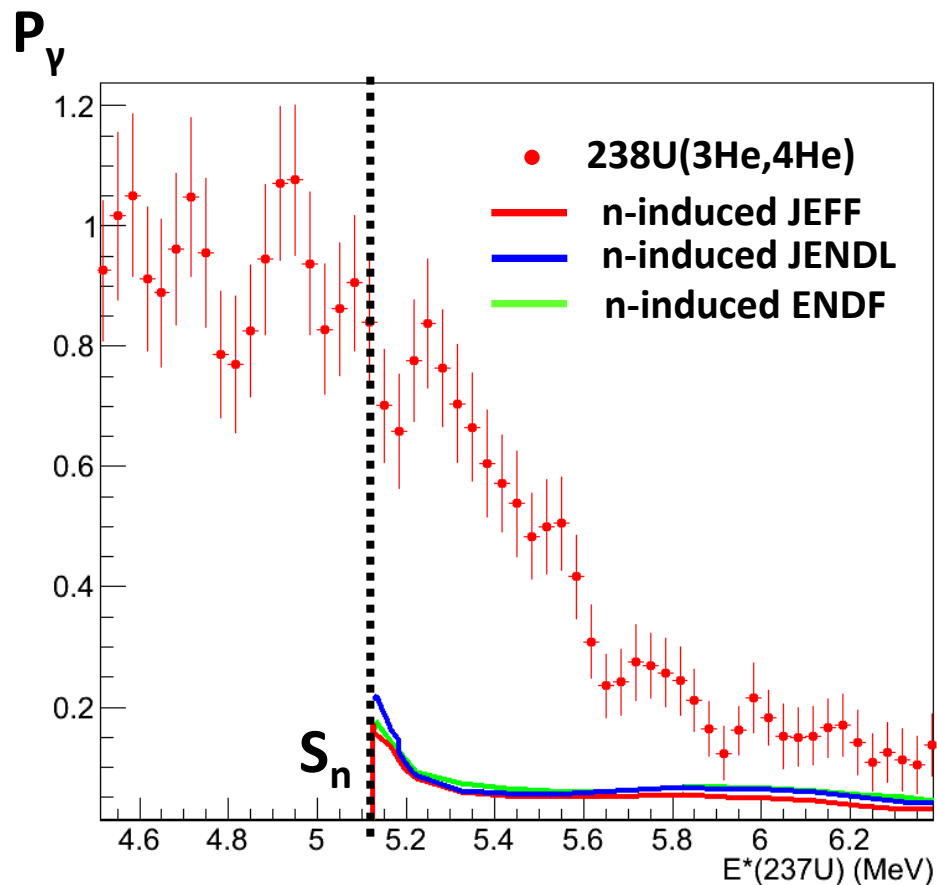
Preliminary results!



$P_f + P_\gamma = 1$ at $E^* < S_n$:
Validation of analysis procedure!

P. Marini et al., to be published

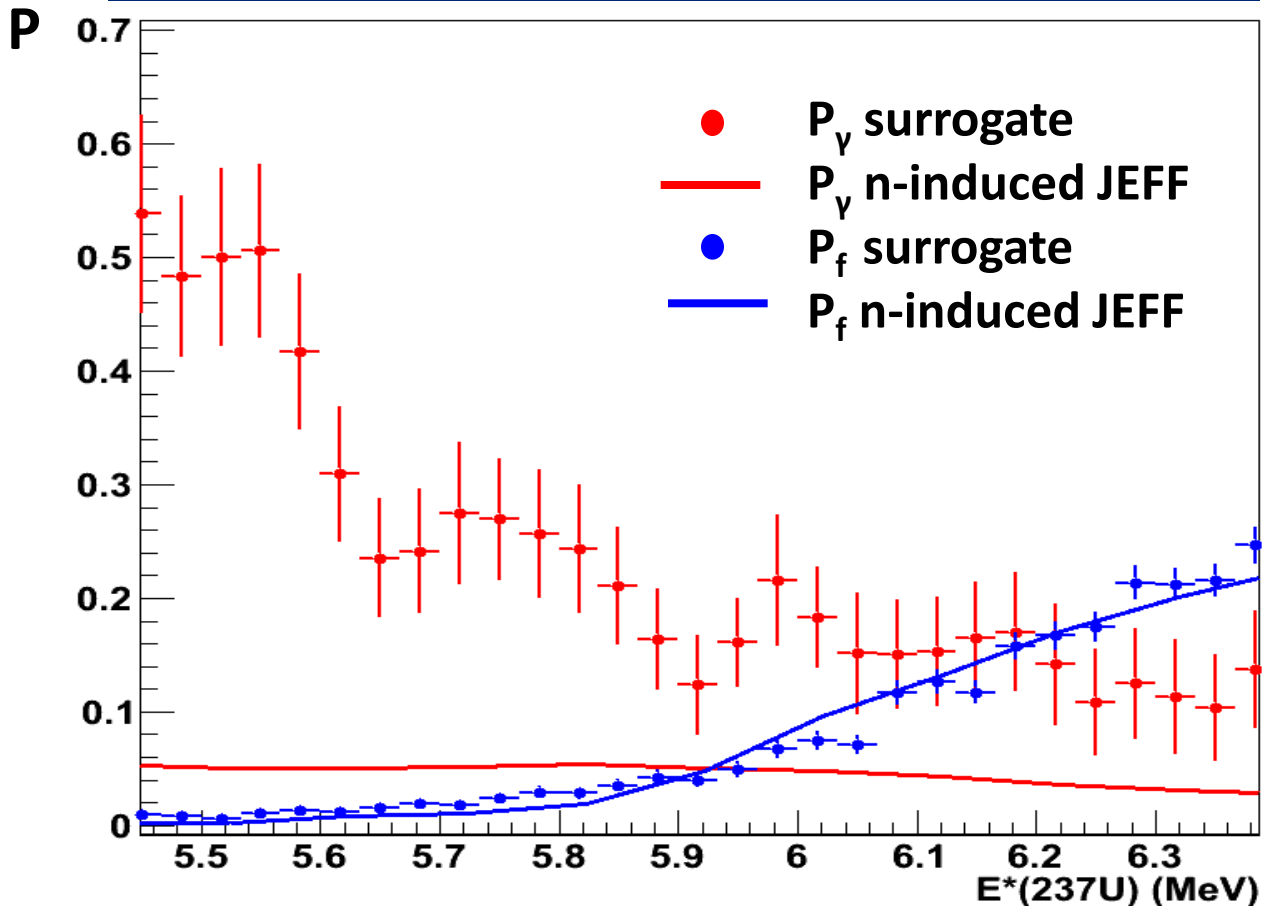
Preliminary results!



P. Marini et al., to be published

Focus on the overlap region

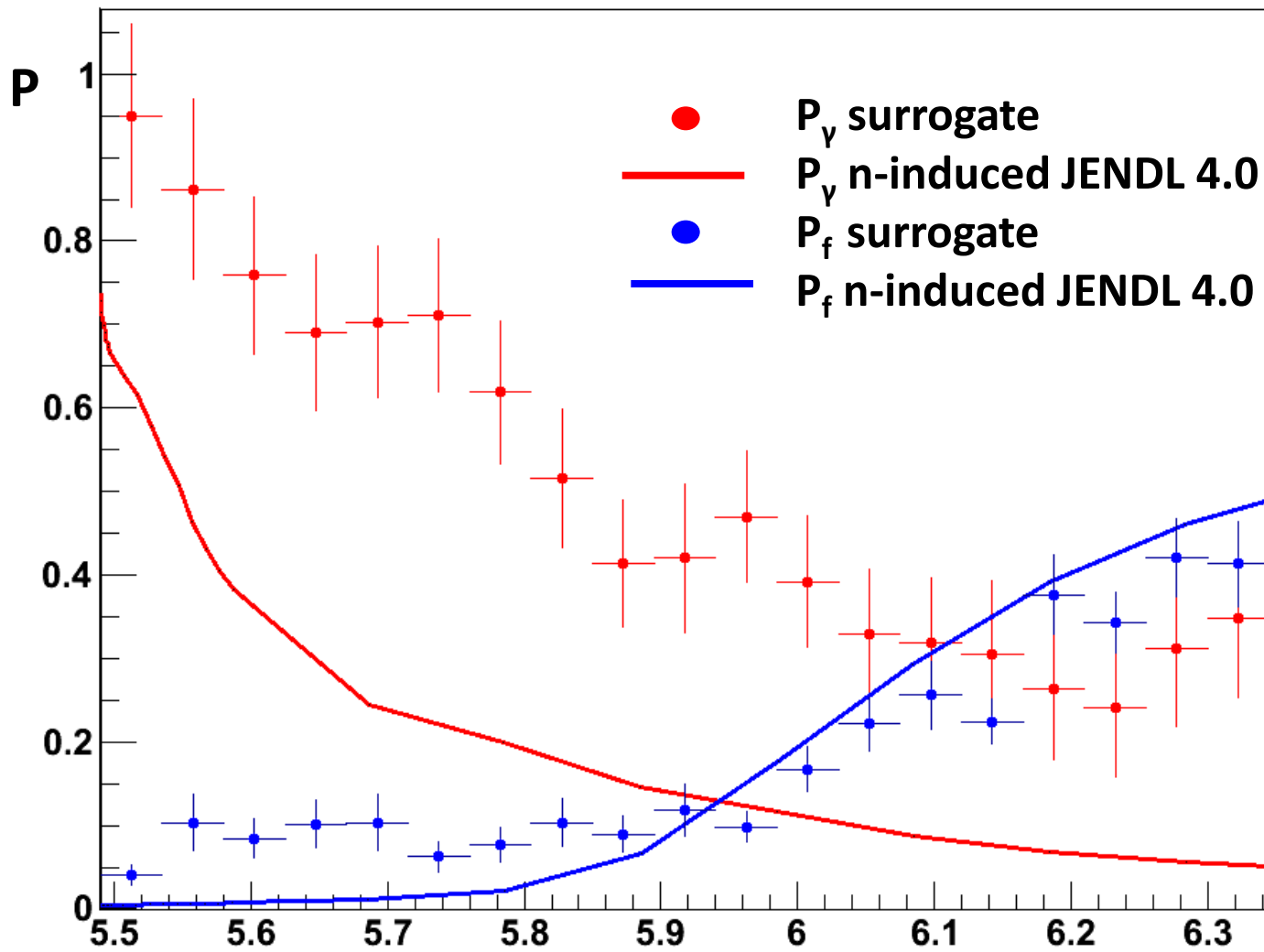
Preliminary results!



The fission probability is much less sensitive to the entrance channel than the gamma-decay probability!

P. Marini et al., to be published

Preliminary results!

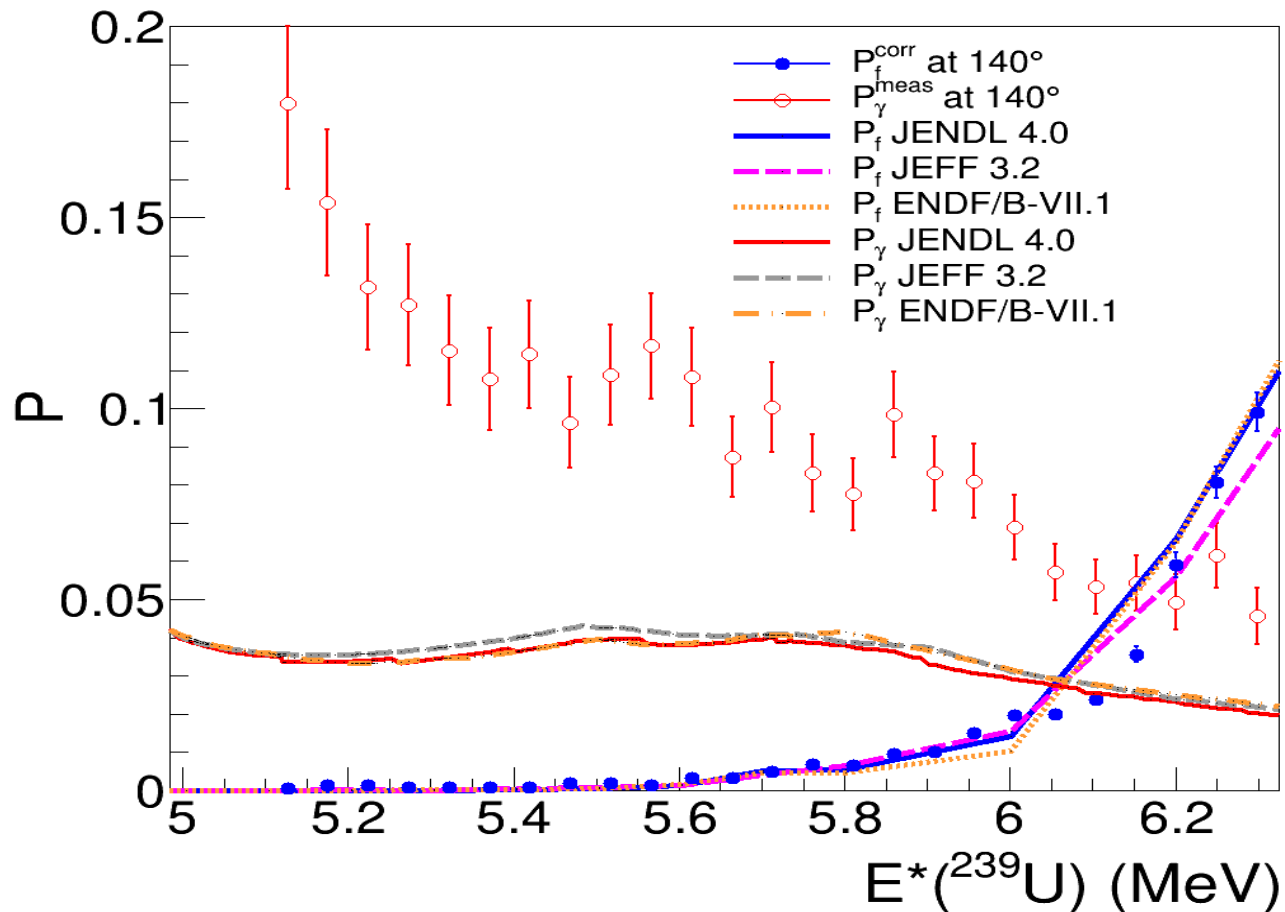


P. Marini et al., to be published

$E^*({}^{238}\text{Np})$ (MeV)



- Closest reaction to a neutron-induced reaction in inverse kinematics
- Problem: deuteron breakup, corrected with method based on DWBA by J. Lei and A. Moro Phys. Rev. C 92(2015) 044616
(Other approaches to breakup in talks by B. Carlson, M. Avrigeanu)

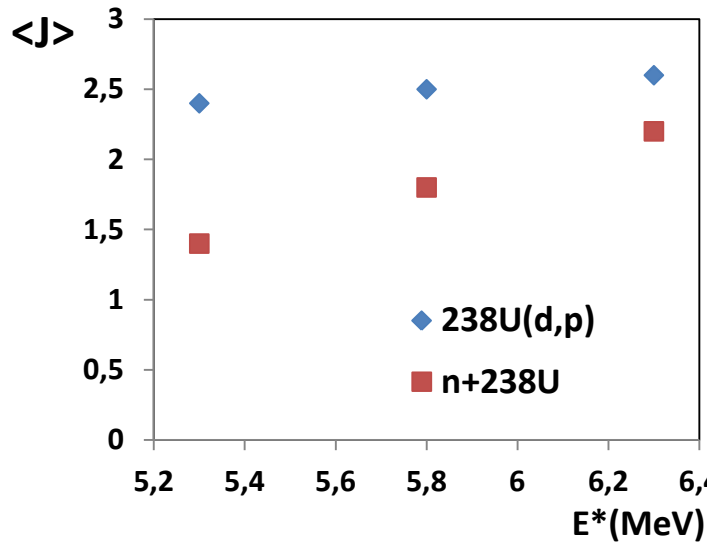


Q. Ducasse et al., Phys. Rev. C 94 (2016) 024614

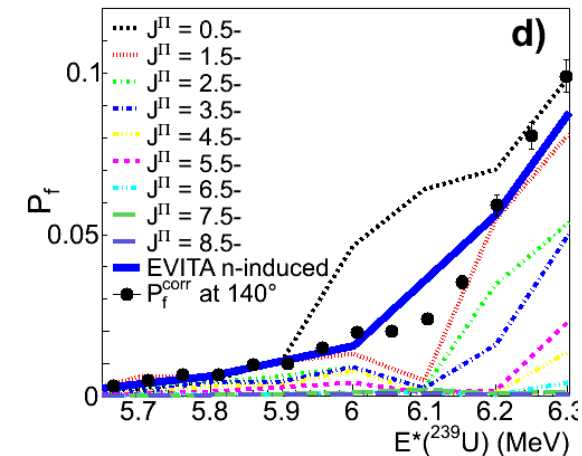
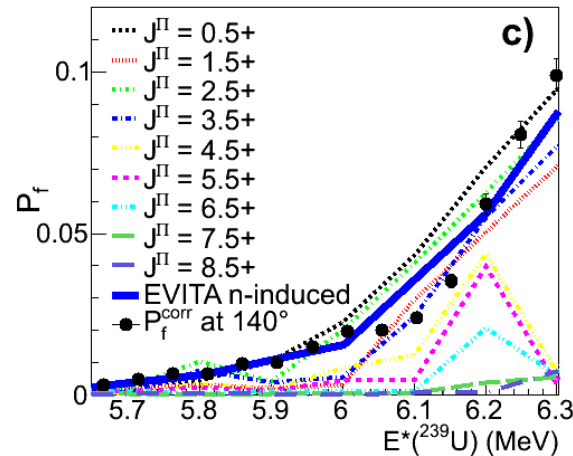
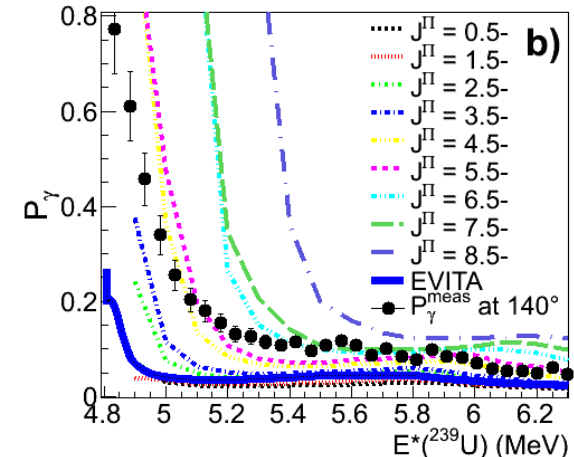
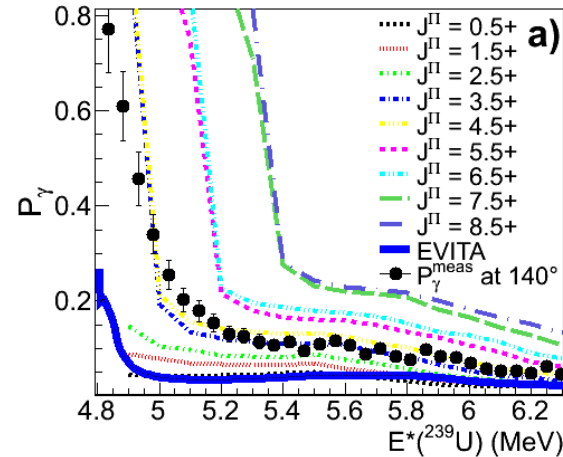
**Can we explain these results within the
framework of the statistical model?**

238U(d,p)

Calculated average spin of 239U



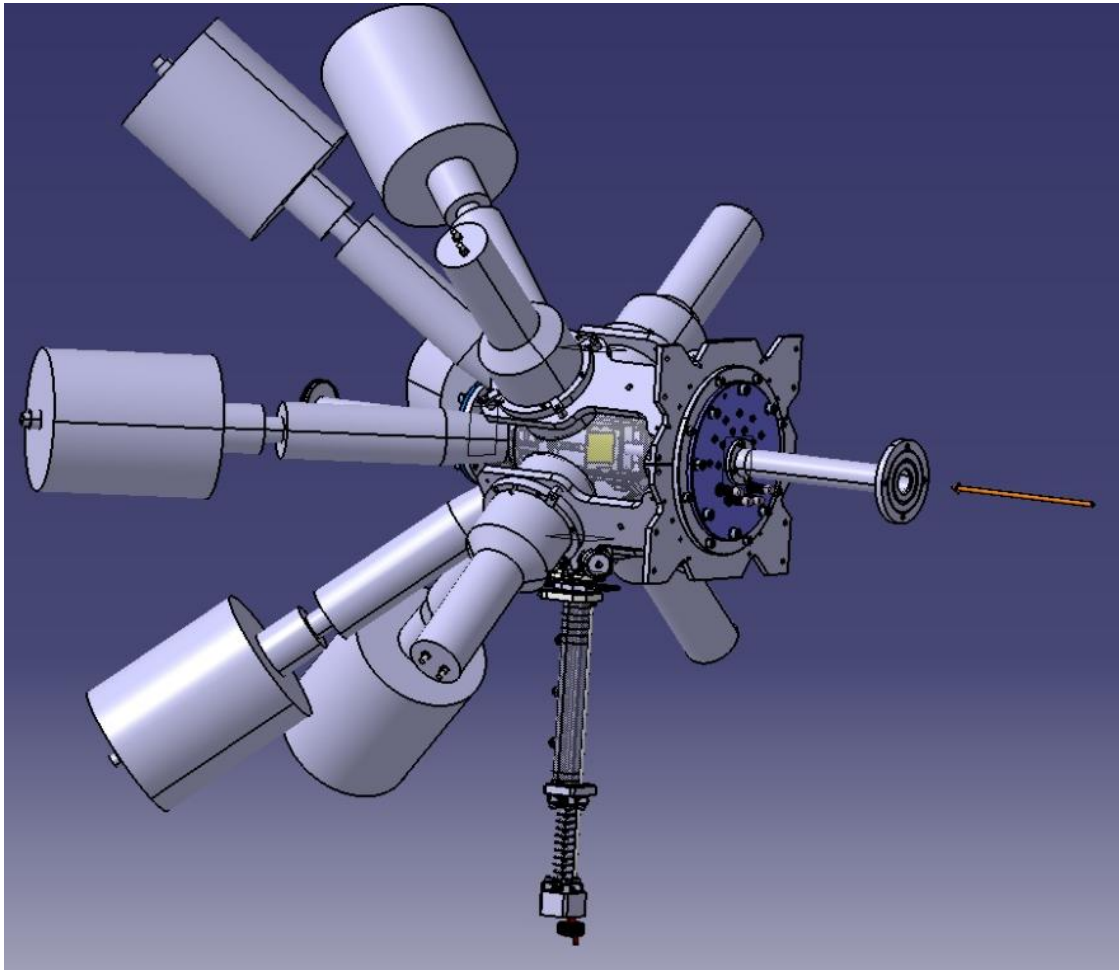
Monte-carlo Hauser Feshbach code EVITA
(Based on TALYS and run by CEA evaluator B. Morillon)



Perspectives: Determine full spin & parity distribution and couple it to the HF results to see if we can reproduce our data

Q. Ducasse et al., Phys. Rev. C 94 (2016) 024614

Perspectives



**${}^{240}\text{Pu}$: Even-even
fissioning nucleus
expected to be more
sensitive to spin/parity
differences!**

**Good-quality n-induced
data available!**

Perspectives

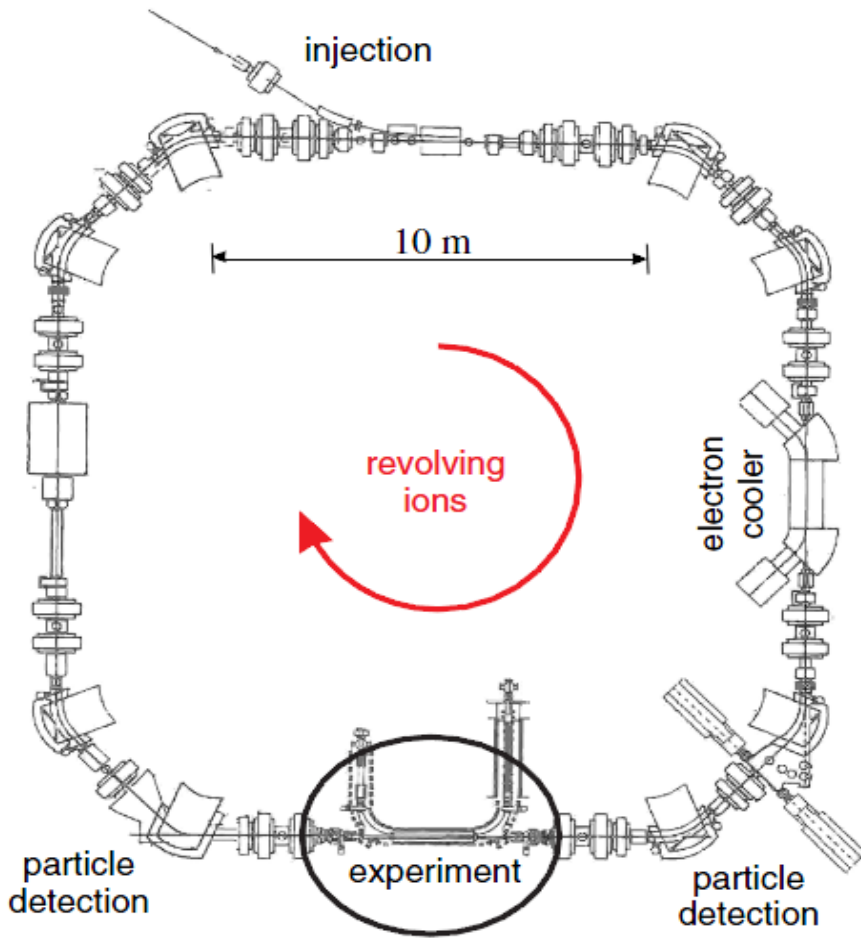
Measurements in direct kinematics are limited by the availability and the quality of the targets!



Experiments in inverse kinematics with RIBs!

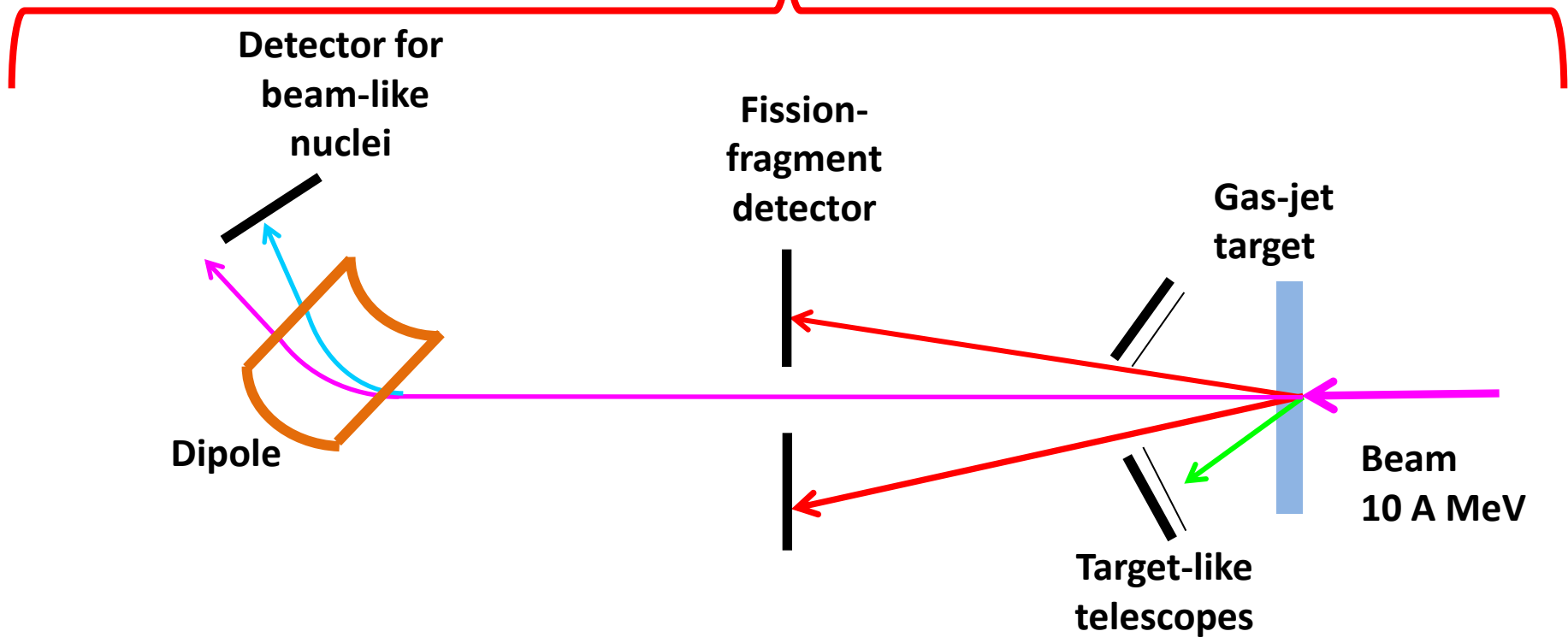
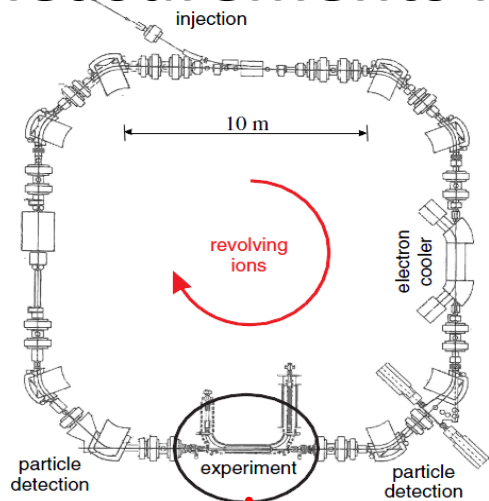
But, RIBs have low quality: large dispersion in energy (few MeV) and size (few mm)

Decay-probability measurements inside a storage ring



- Excellent beam –energy definition, beam-energy resolution of few hundreds keV at 10 A MeV, beam size 1 mm!!
- In-ring measurements with gas-jet targets (H₂, D₂, ³He, ⁴He). Effective target thickness increased by $\sim 10^6$ due to revolution frequency
- Pure beams, pure targets (no contaminants, no backing)!
- Pure isomeric beams!
- Measurements possible at the ESR at GSI in the near future

Decay-probability measurements inside a storage ring



Conclusions...

- **First simultaneous measurement of gamma-decay and fission probabilities for surrogate reactions**
- **The fission probability is much less sensitive to the populated angular momentum than the gamma-decay probability**
- **No obvious explanation yet, our data are useful to establish to which extent the surrogate method can be used to infer fission cross sections in regions where no data are available.**
- **Very promising perspectives open up for decay probability measurements in inverse kinematics with RIBs at storage rings**

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