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

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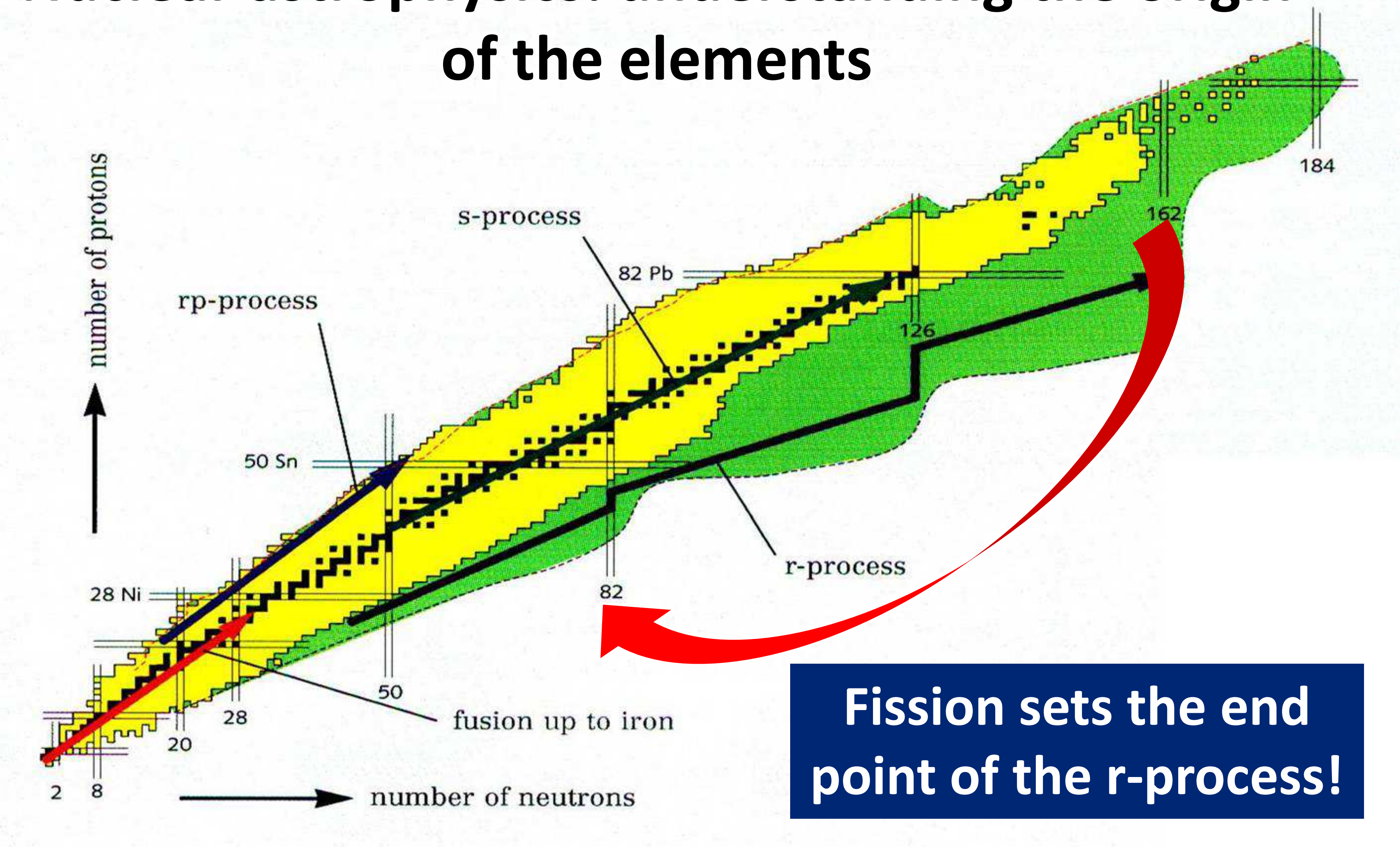
Need for neutron-induced cross sections on short-lived nuclei : reactor physics

Very difficult or even impossible to measure!

Nuclear astrophysics: understanding the origin of the elements

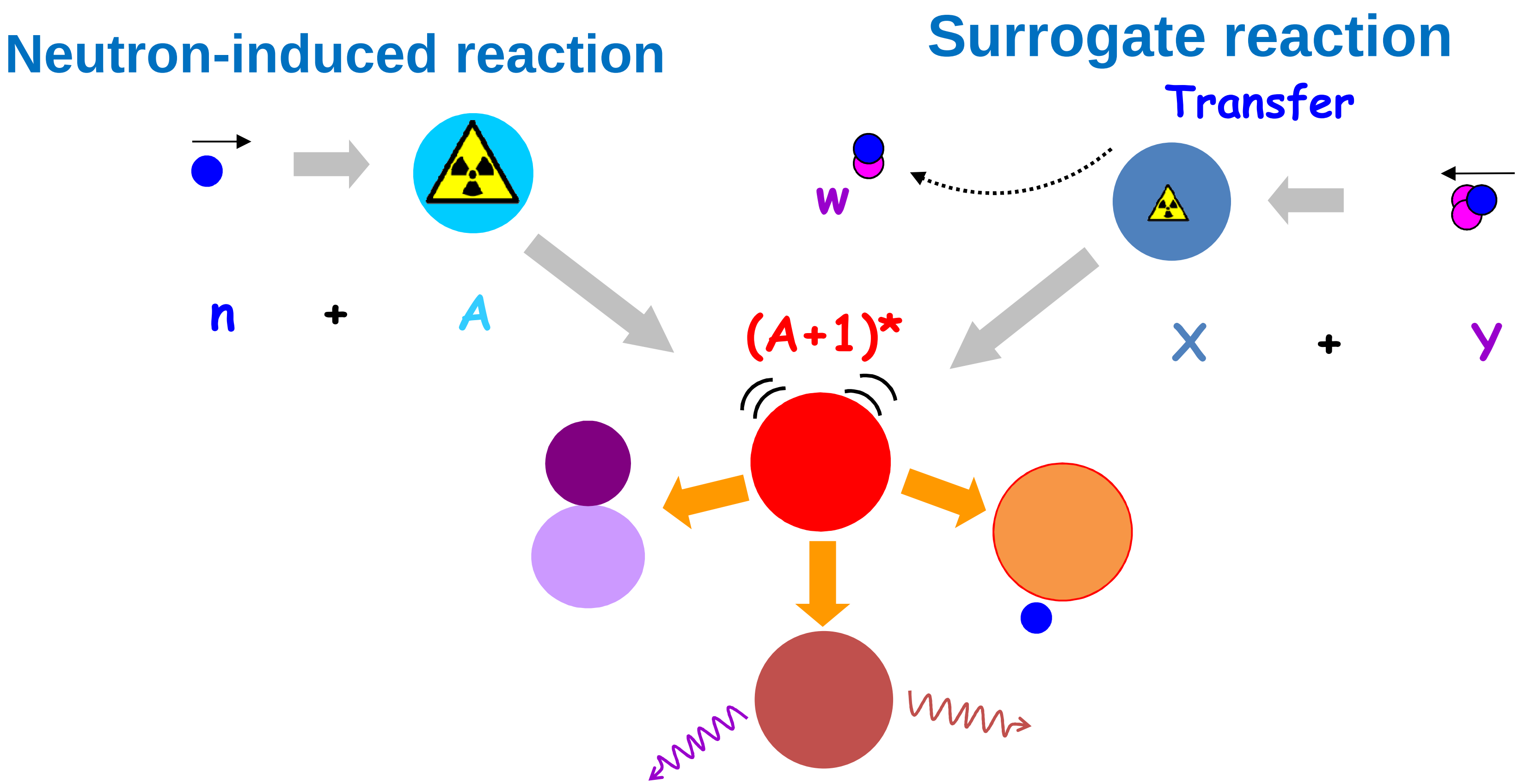


Fission sets the end point of the r-process!

"The fundamental role of fission during r-process nucleosynthesis in neutron star mergers" , S. Goriely, Eur. Phys. J. A (2015) 51: 22

Surrogate-reaction method

Cramer and Britt (Los Alamos 1970…!!)



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

Theory
Optical model

Experiment

Validity of the surrogate 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

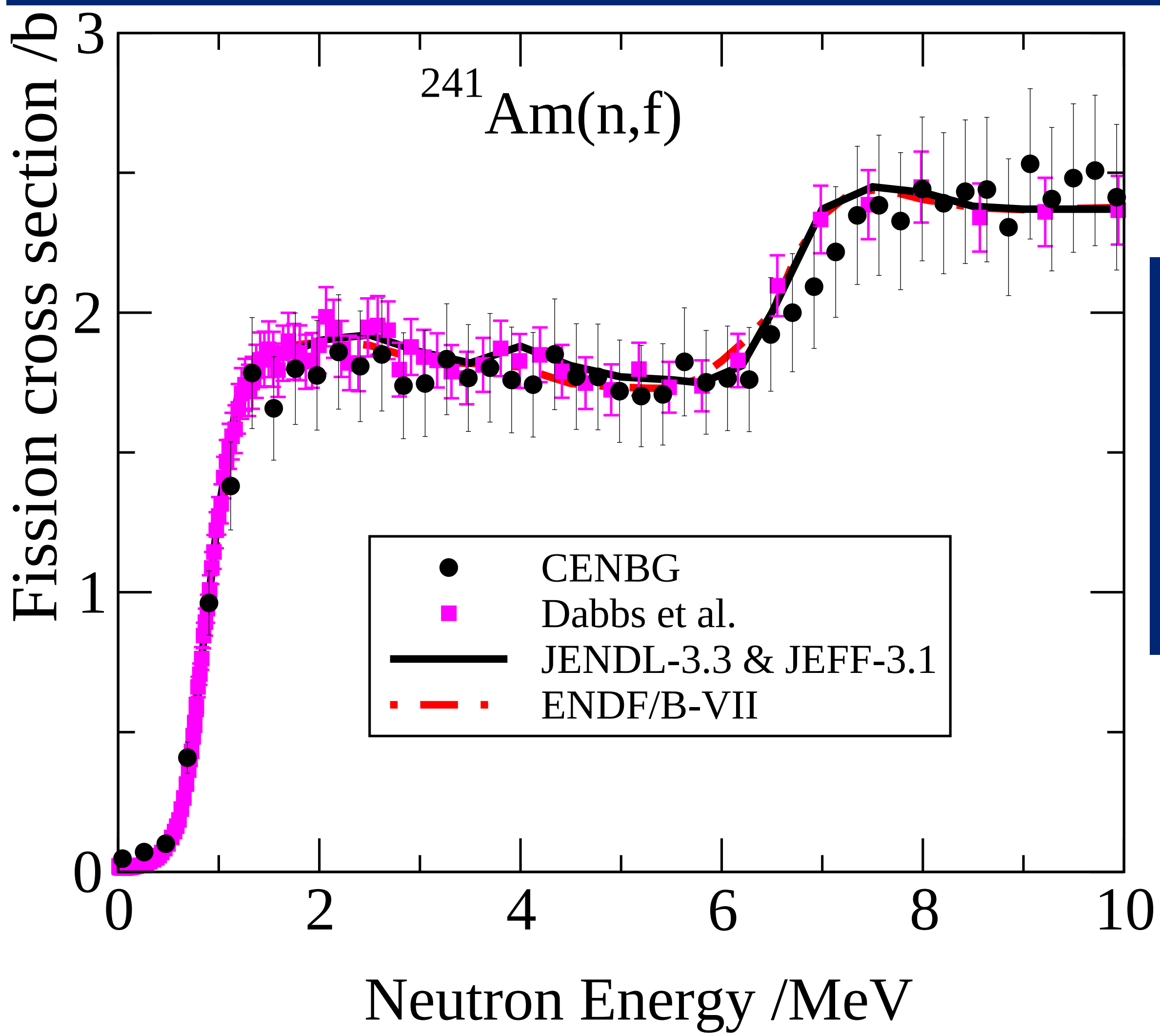
OR

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!

Results for fission

$^{3}He+^{243}Am(7370\ y) \rightarrow ^{4}He+^{242}Am \Leftrightarrow n+^{241}Am(432.2\ y)$



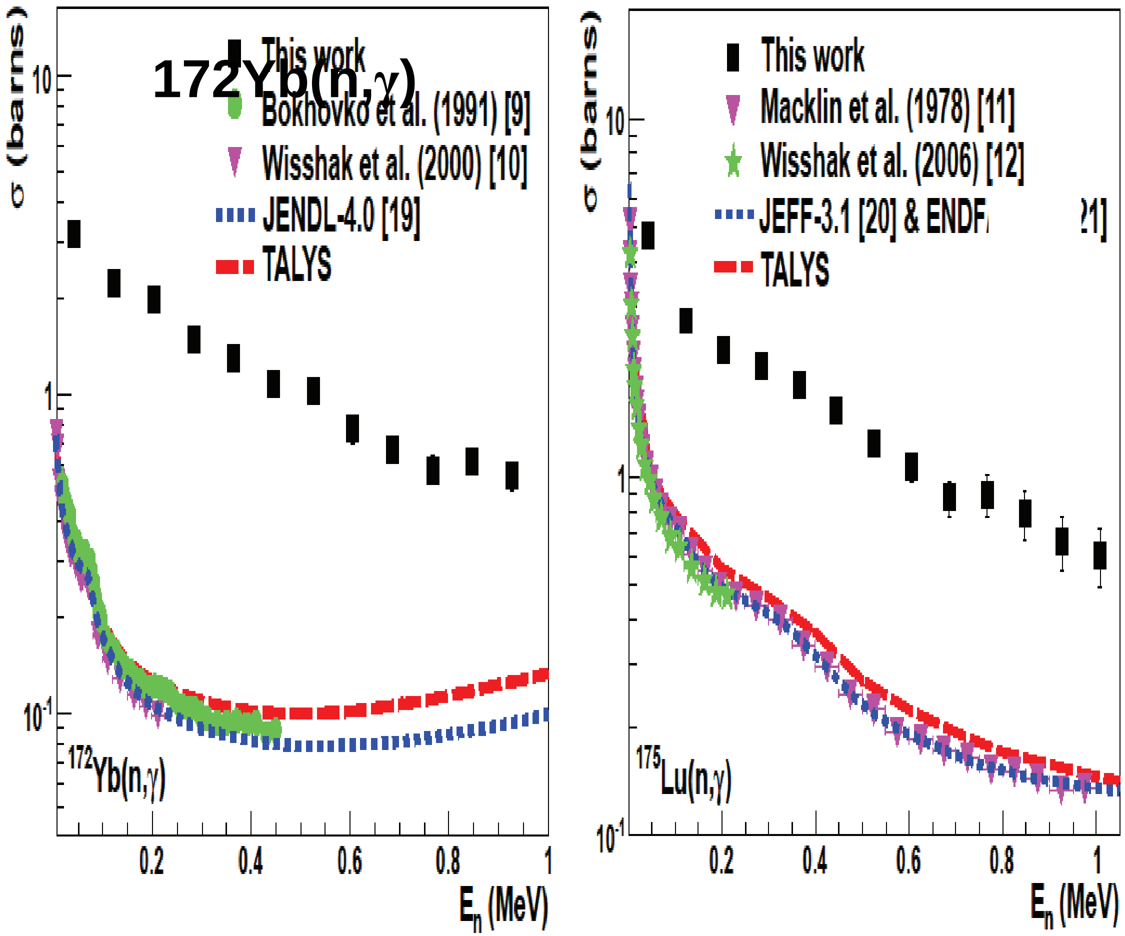
General finding: the cross sections obtained with surrogate method are in good agreement with n-induced data for fission!

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

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

Results for radiative capture

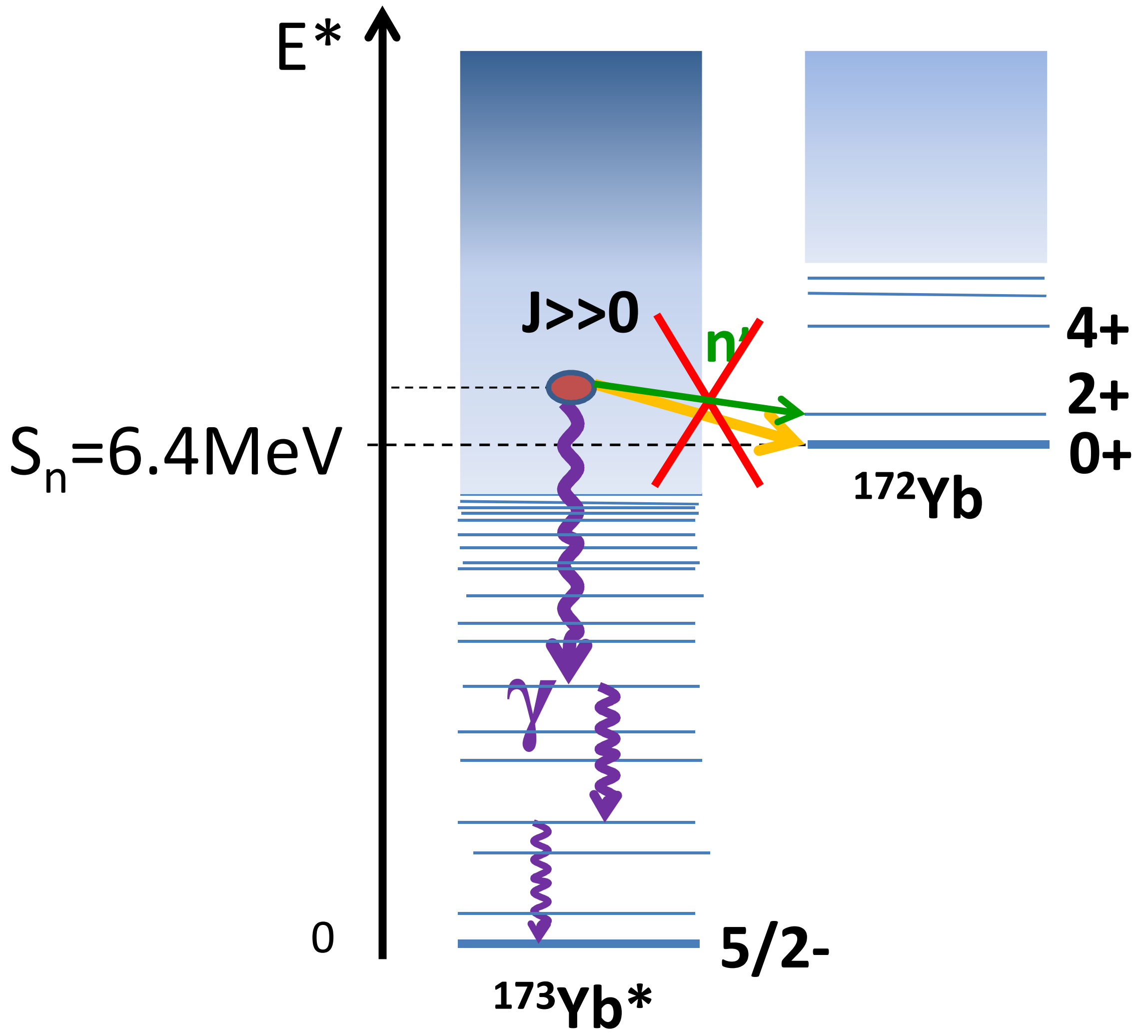
3He + 174Yb -> 4He + 173Yb



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

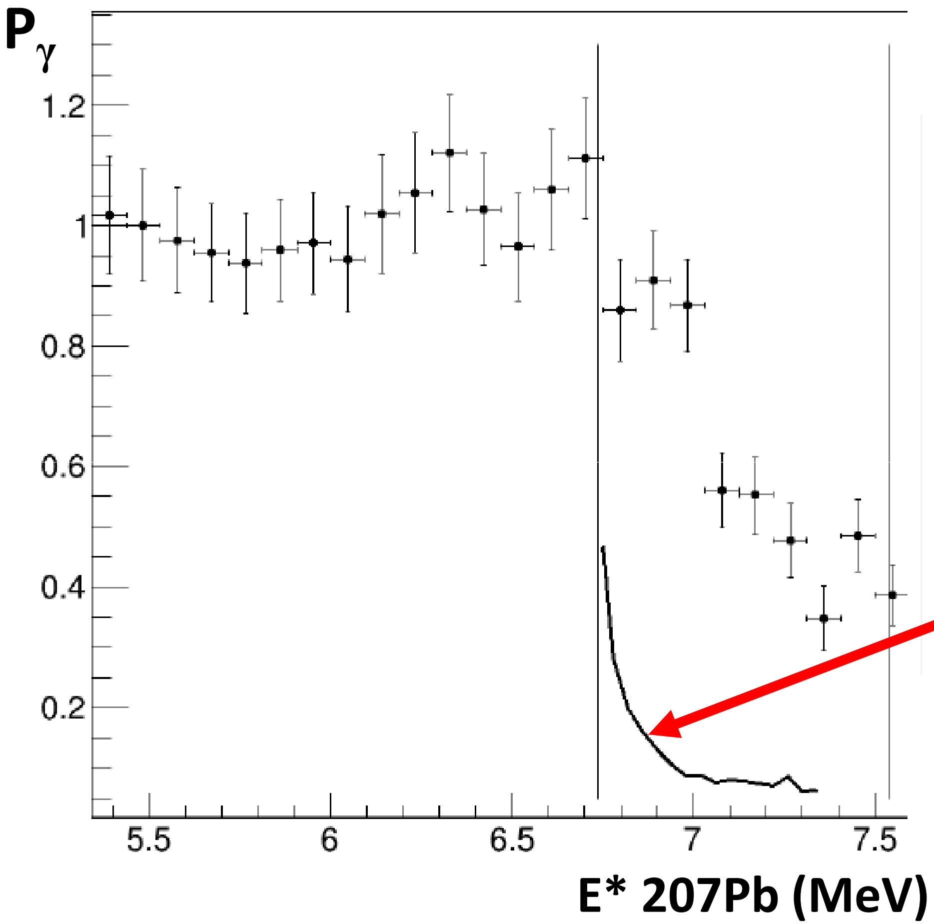
Why do we obtain such discrepancies?

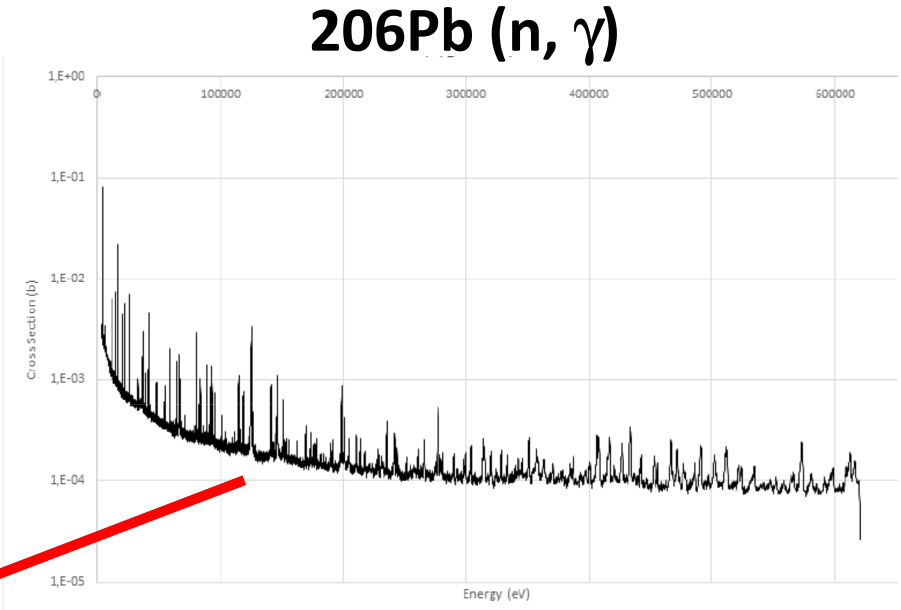


Strong sensitivity of neutron emission to Jπ

Preliminary results!

3He + 208Pb-> 4He + 207Pb<-> n + 206Pb



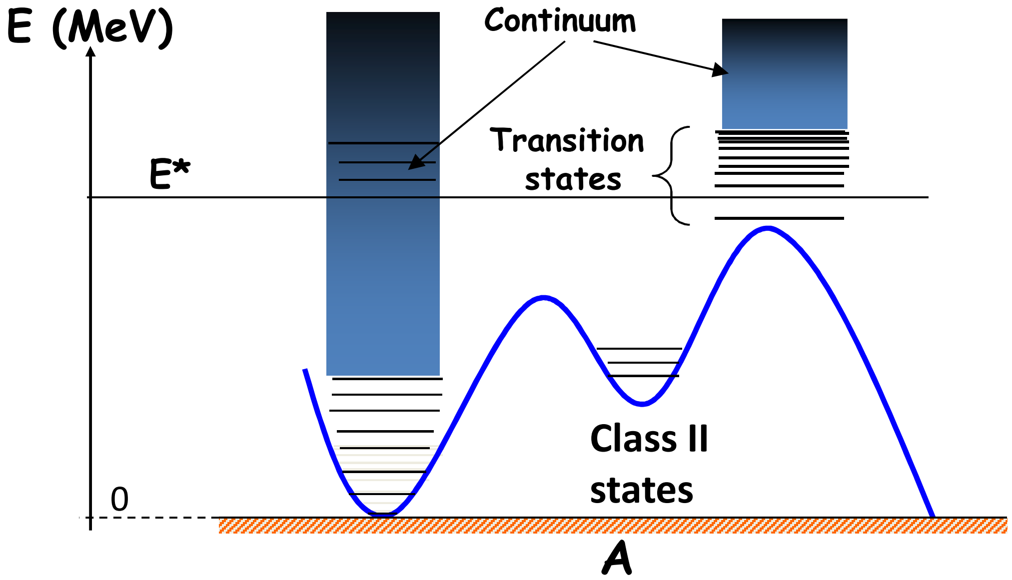


(n,gamma) cross section convoluted with our E* resolution (~100 keV) and divided by CN xs formation.

Can we apply the statistical model to try to reproduce our gamma-emission probability?

PhD Thesis of R. Perez, University of Bordeaux

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



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

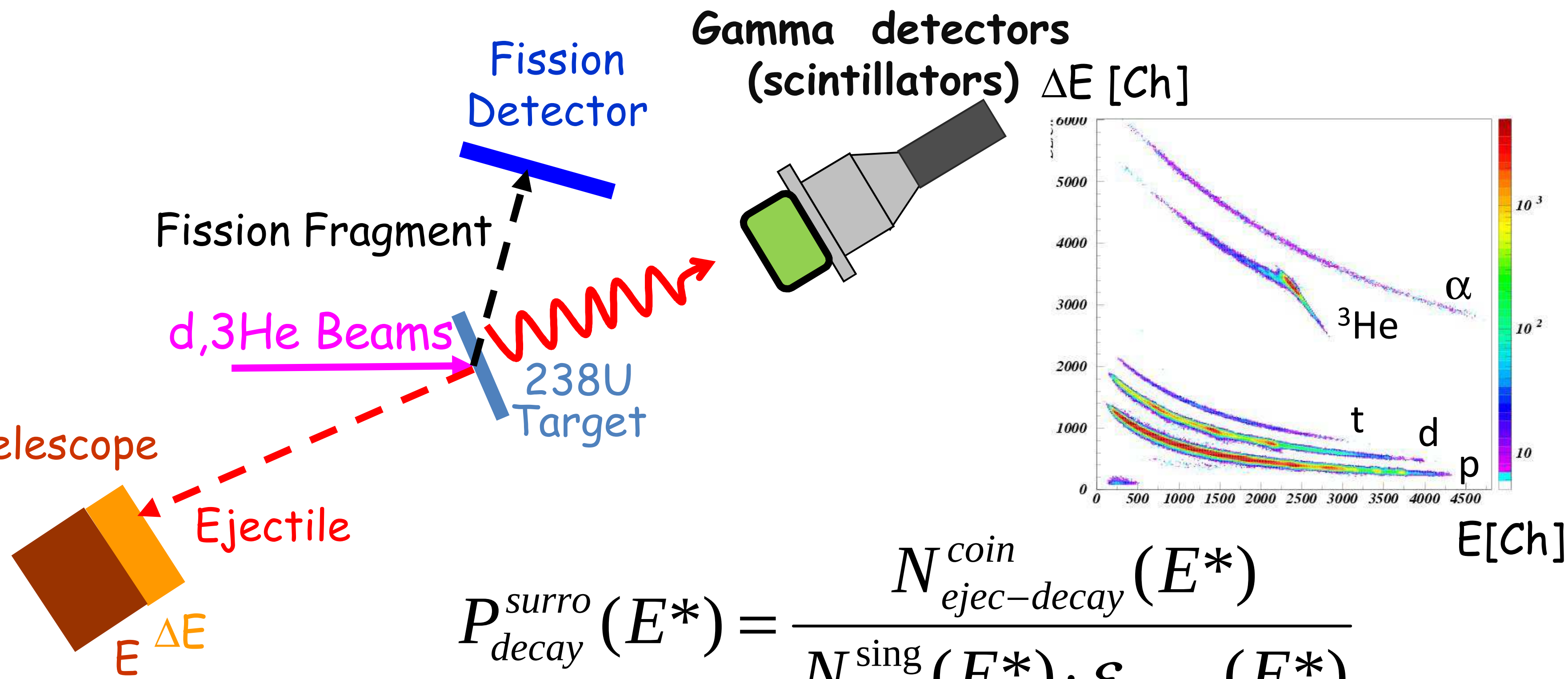
The suppression of neutron emission should also affect the fission probability!

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

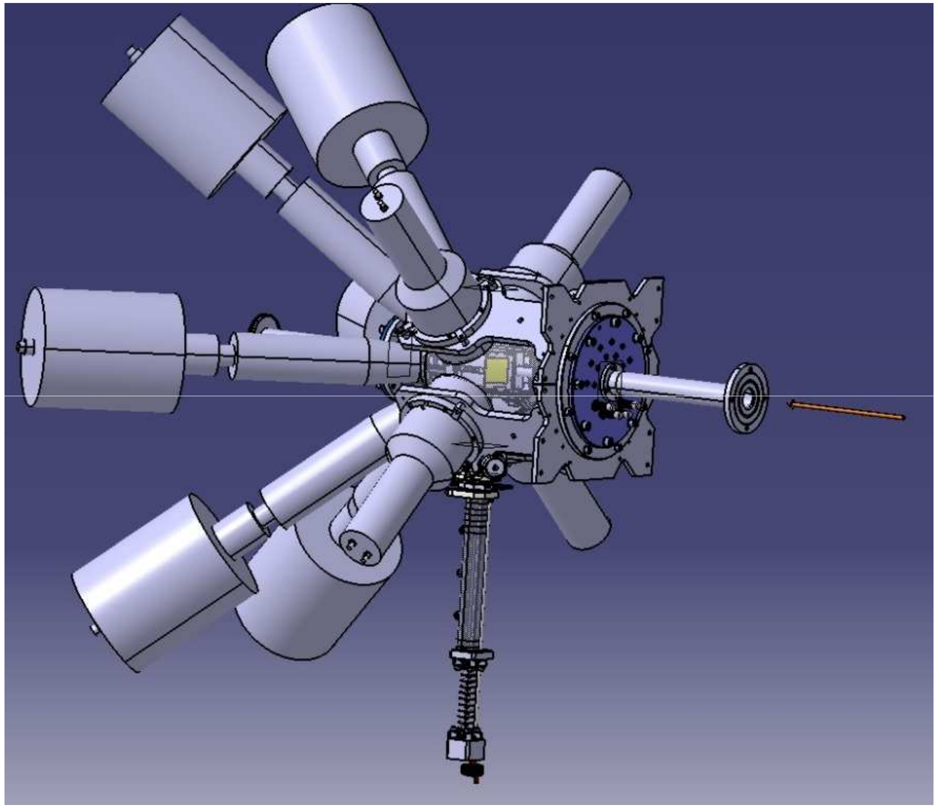


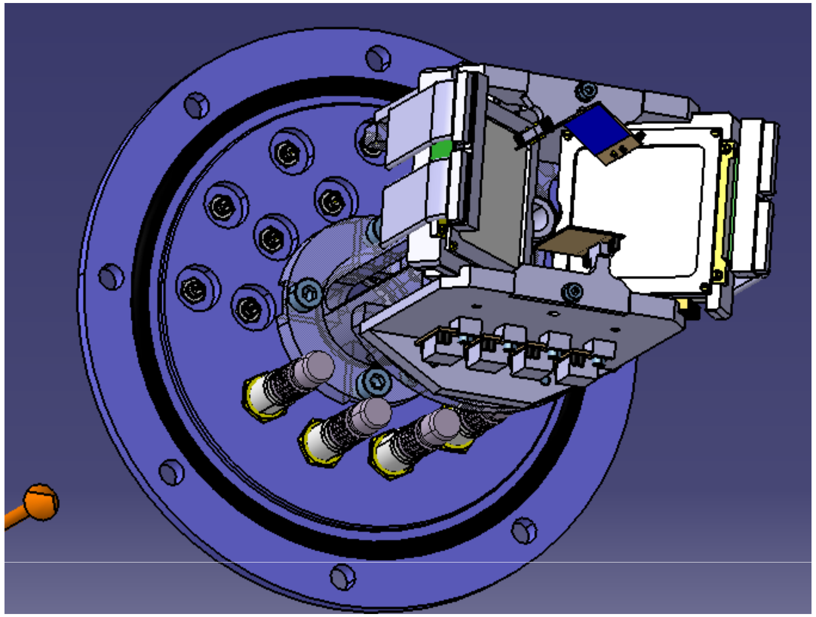
$$P_{decay}^{surro}(E^*) = \frac{N_{ejec-decay}^{coin}(E^*)}{N_{ejec}^{sing}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

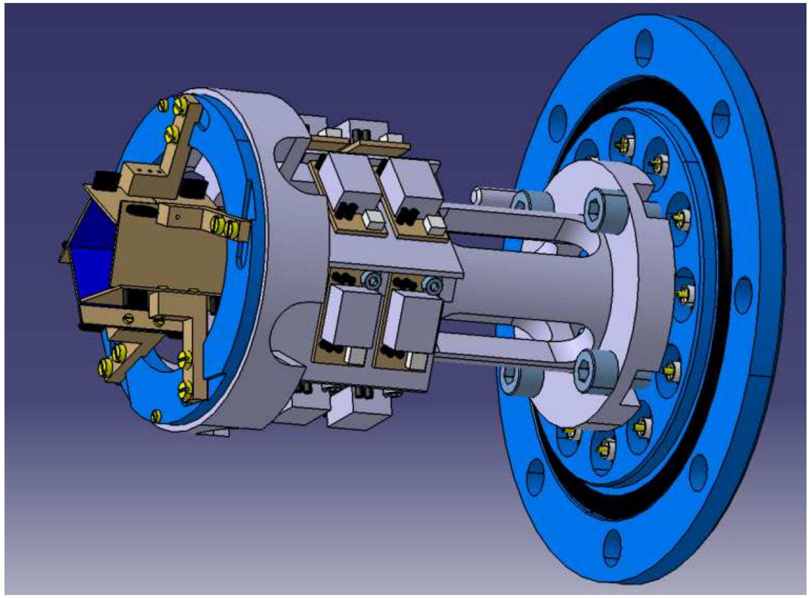
Challenge: removal of gamma rays emitted by the fission fragments !

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

Setup used for experiment at the Orsay tandem



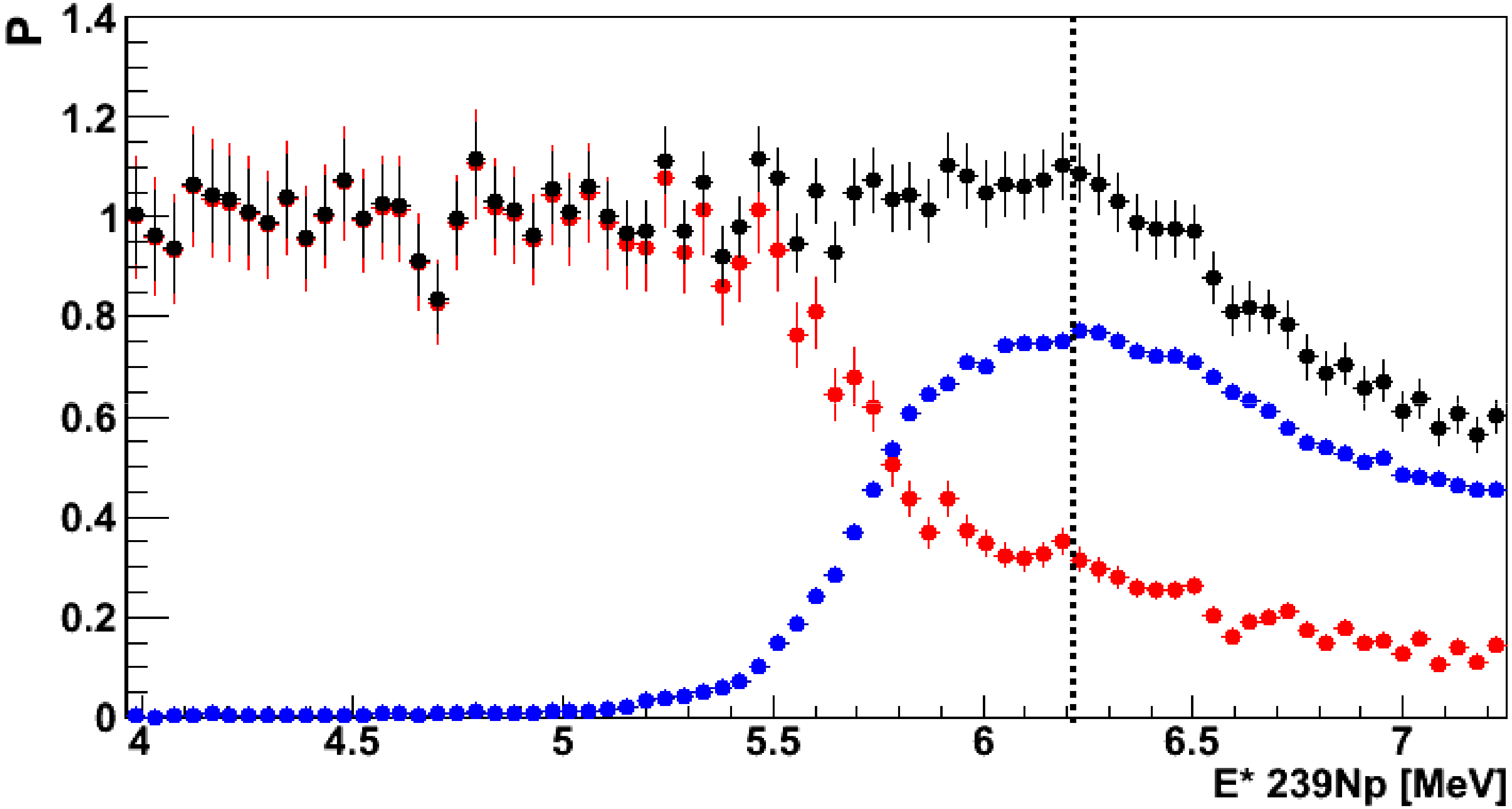




Fission efficiency ~ 65%
Gamma detection efficiency ~ 6%

Preliminary results!

3He + 238U-> d + 239Np ↔ n + 238Np (2,1d)

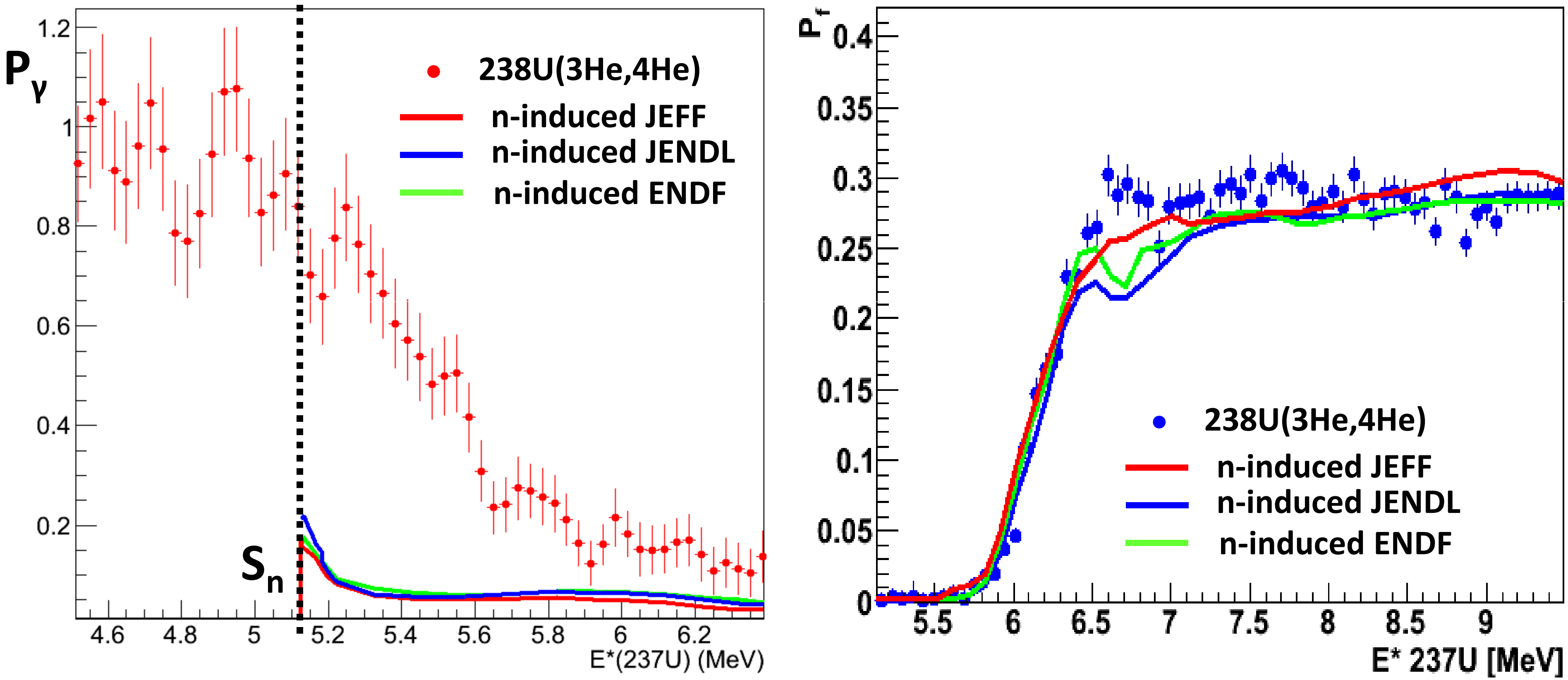


$P_f + P_\gamma = 1$ at $E^* < S_n$:
Validation of analysis procedure!

P. Marini et al., to be published

Preliminary results!

3He + 238U-> 4He + 237U ↔ n + 236U

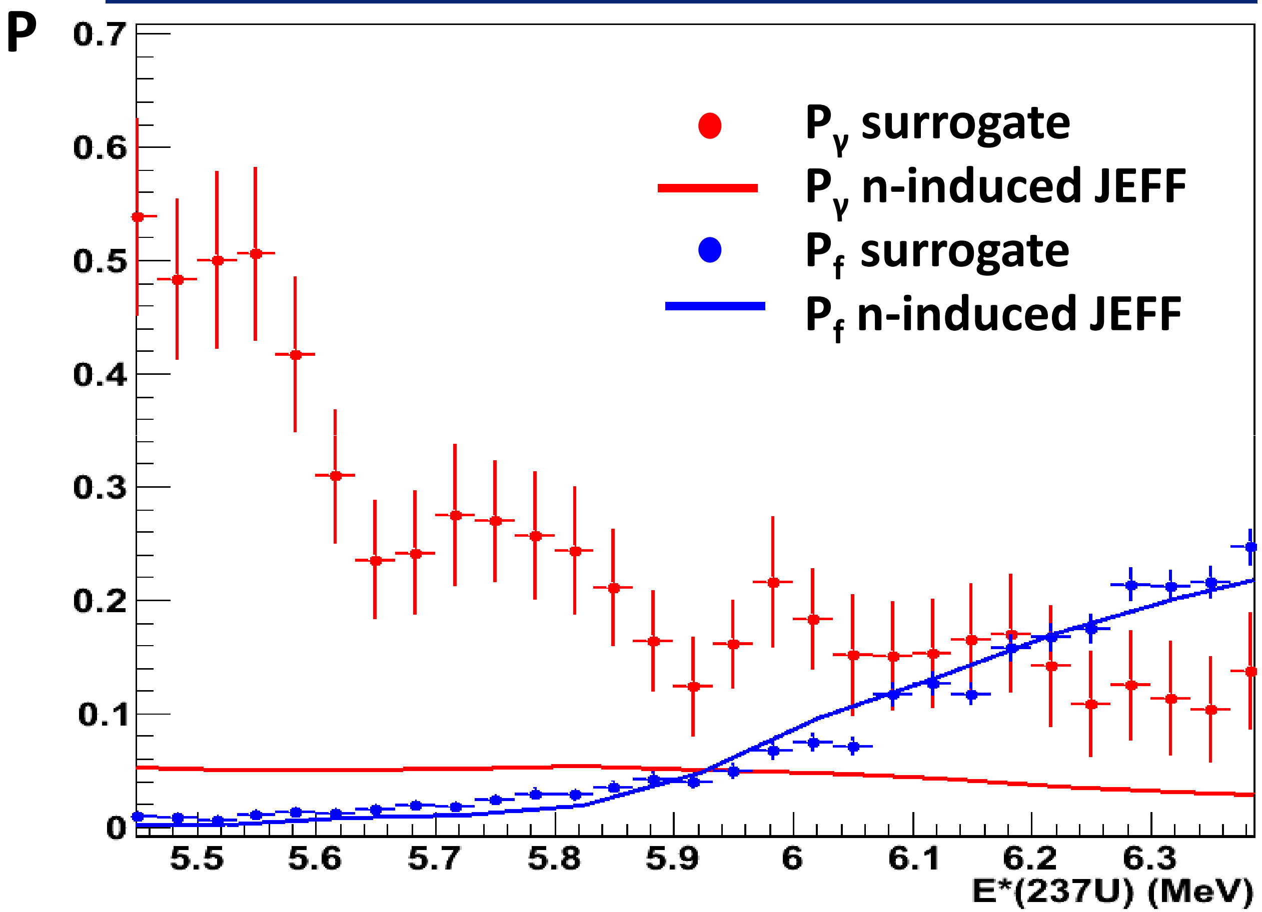


P. Marini et al., to be published

Focus on the overlap region

Preliminary results!

3He + 238U-> 4He + 237U ↔ n + 236U

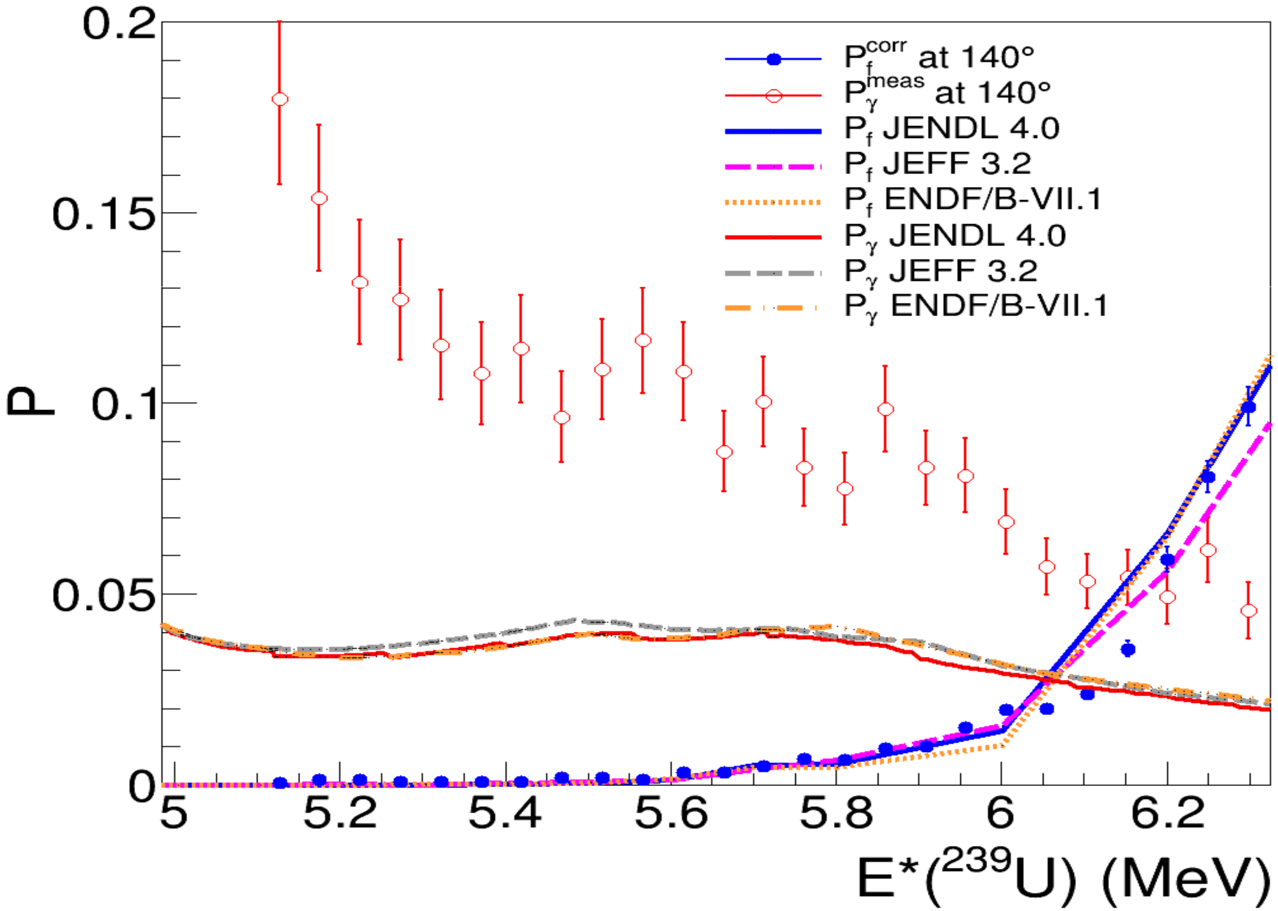


The fission probability is much less sensitive to the entrance channel than the gamma-decay probability!

P. Marini et al., to be published

d + 238U-> p + 239U ↔ n + 238U

→Problem: deuteron breakup, corrected with method based on CDCC and DWBA by J. Lei and A. Moro Phys. Rev. C 92(2015) 044616
Breakup fusion contribution :Imaginary part of the n-238U optical potential was divided into two , one part corresponding to CN formation



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

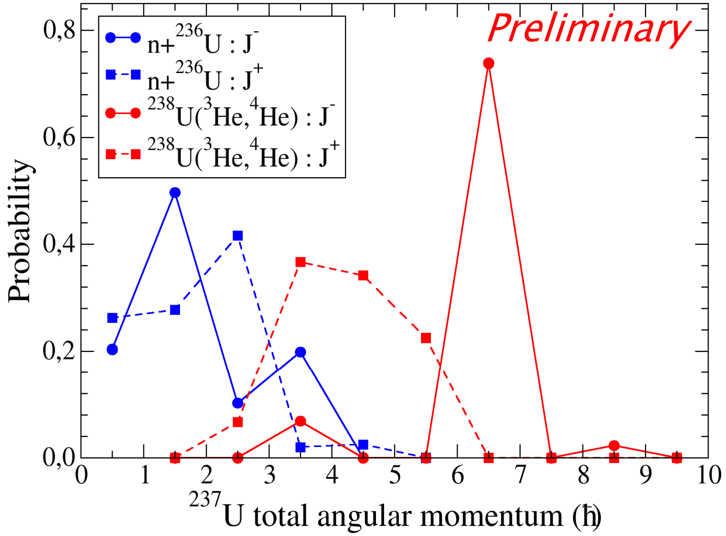
Can we explain these results within the framework of the statistical model?

$$P_{surro,decay}(E^*) = \sum_{J^\pi} P_{surro}^{form}(E^*, J^\pi) \cdot G_{decay}(E^*, J^\pi)$$

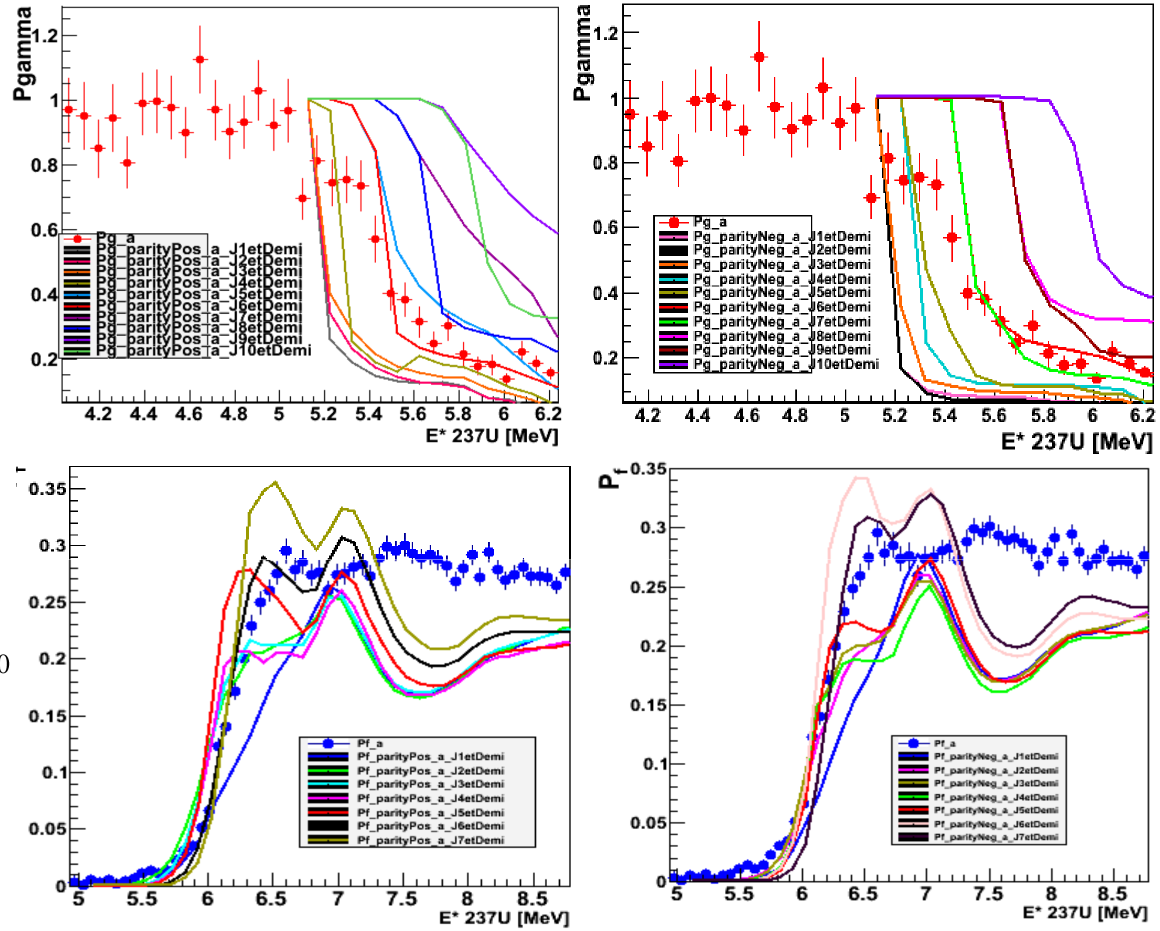
Interpretation of results: 238U(3He,4He)237U

Preliminary calculations based on extended R-Matrix theory

Preliminary DWBA calculations



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

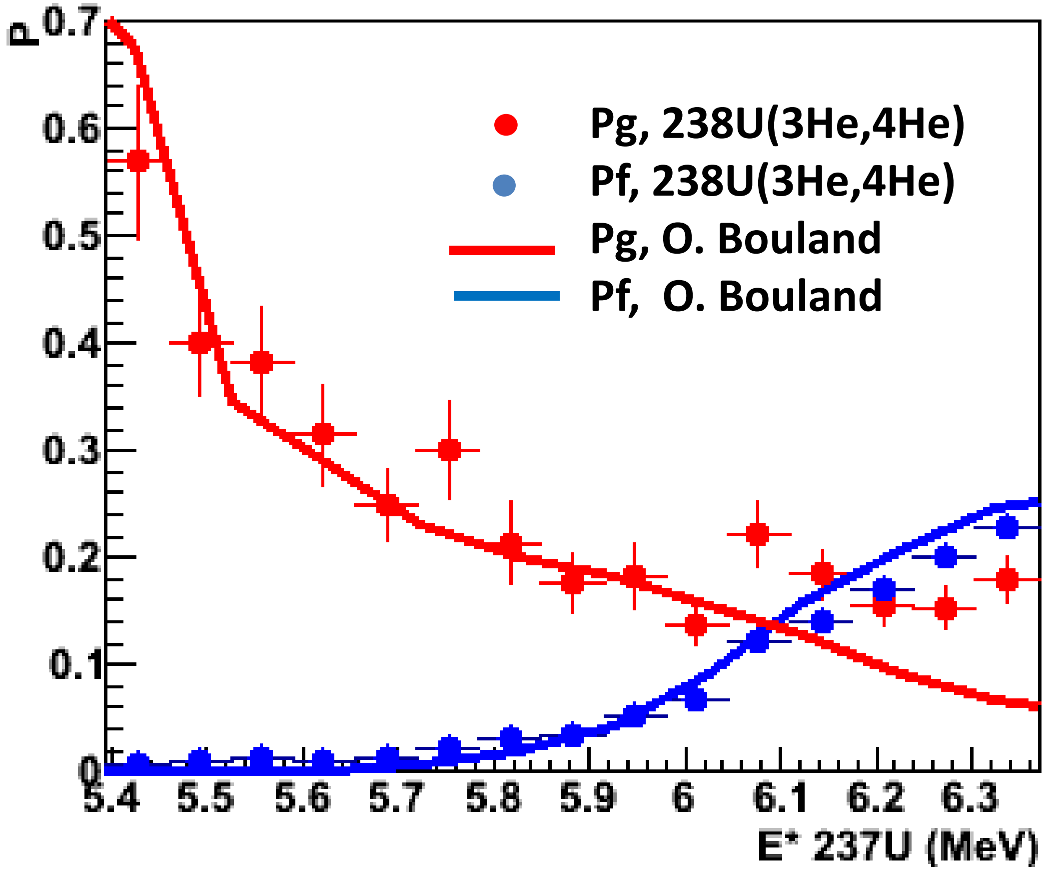


O. Bouland, contribution to ND2016
O. Bouland et al., PRC 88 (2013) 054612

$$P_{surro,decay}(E^*) = \sum_{J^\pi} P_{surro}^{form}(E^*, J^\pi) \cdot G_{decay}(E^*, J^\pi)$$

Preliminary results!

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



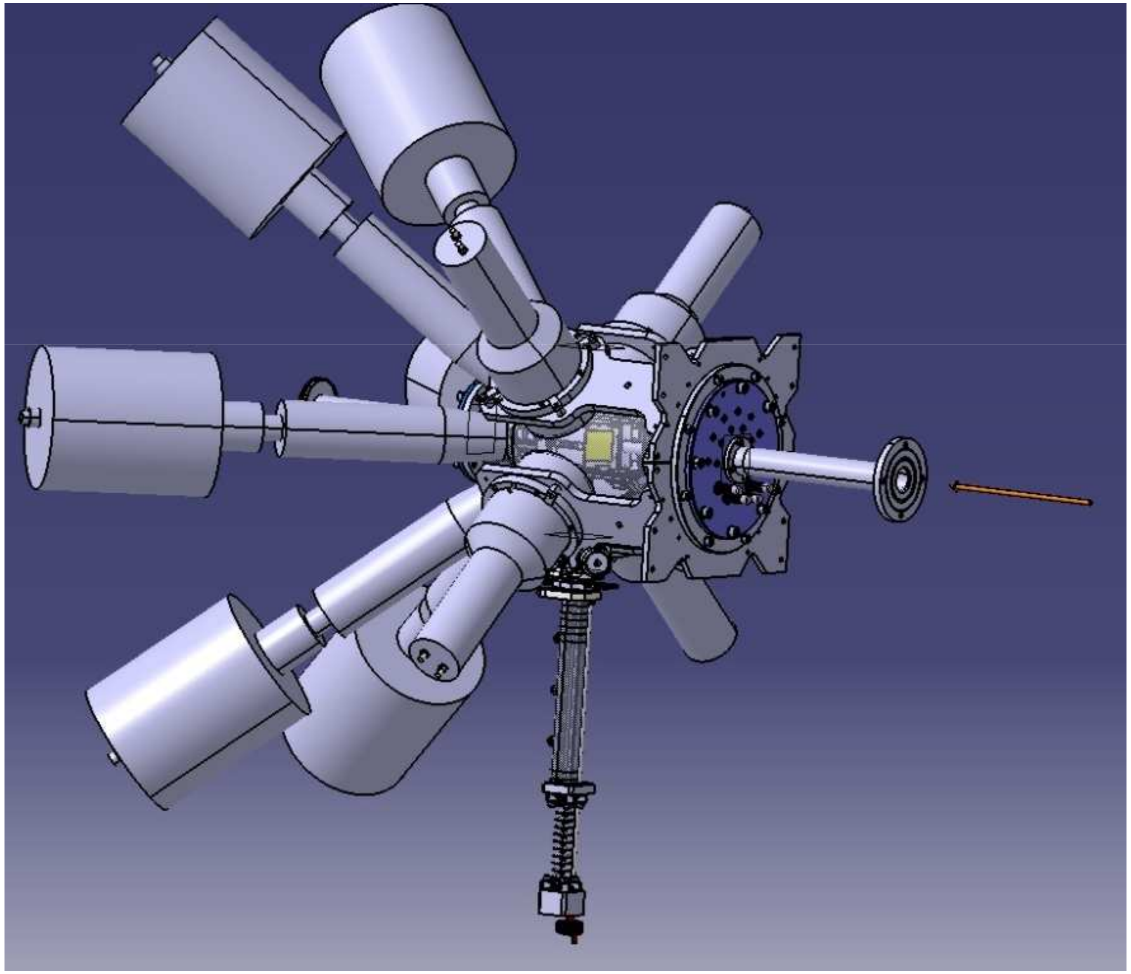
O. Bouland, contribution to ND2016

Surrogate data can be used to tune model parameters in order to infer n-induced cross sections.

Perspectives

4He+240Pu

4He + 240Pu-> 4He’ + 240Pu* ↔ n + 239Pu



240Pu: Even-even fissioning nucleus expected to be more sensitive to spin/parity differences!

Good-quality n-induced data available!

Experiment expected in April 2017 at the Tandem of the IPN Orsay

Perspectives

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

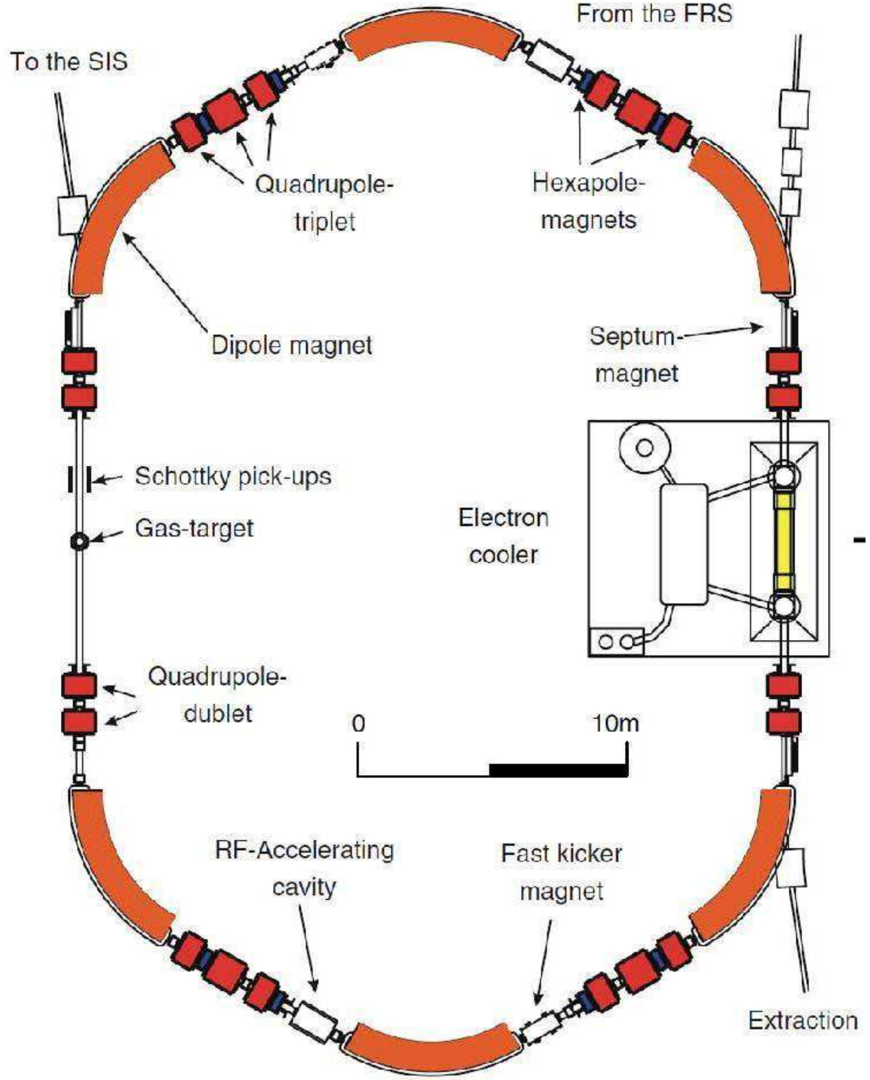
↓

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

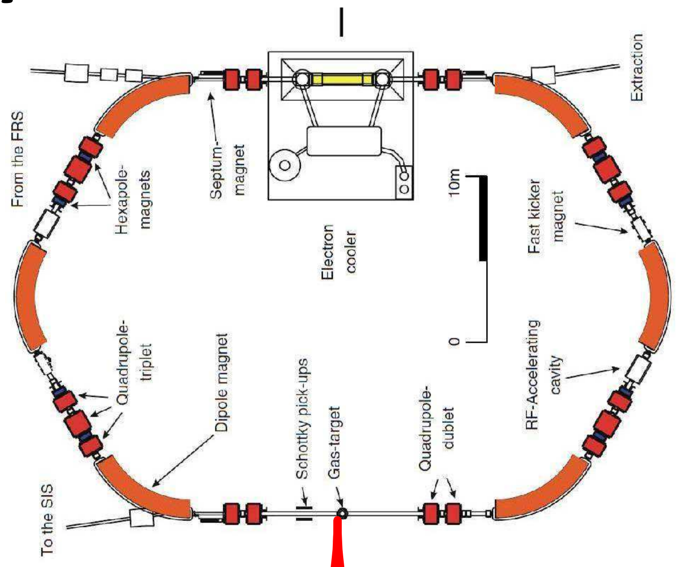
Experimental Storage Ring (ESR) at GSI

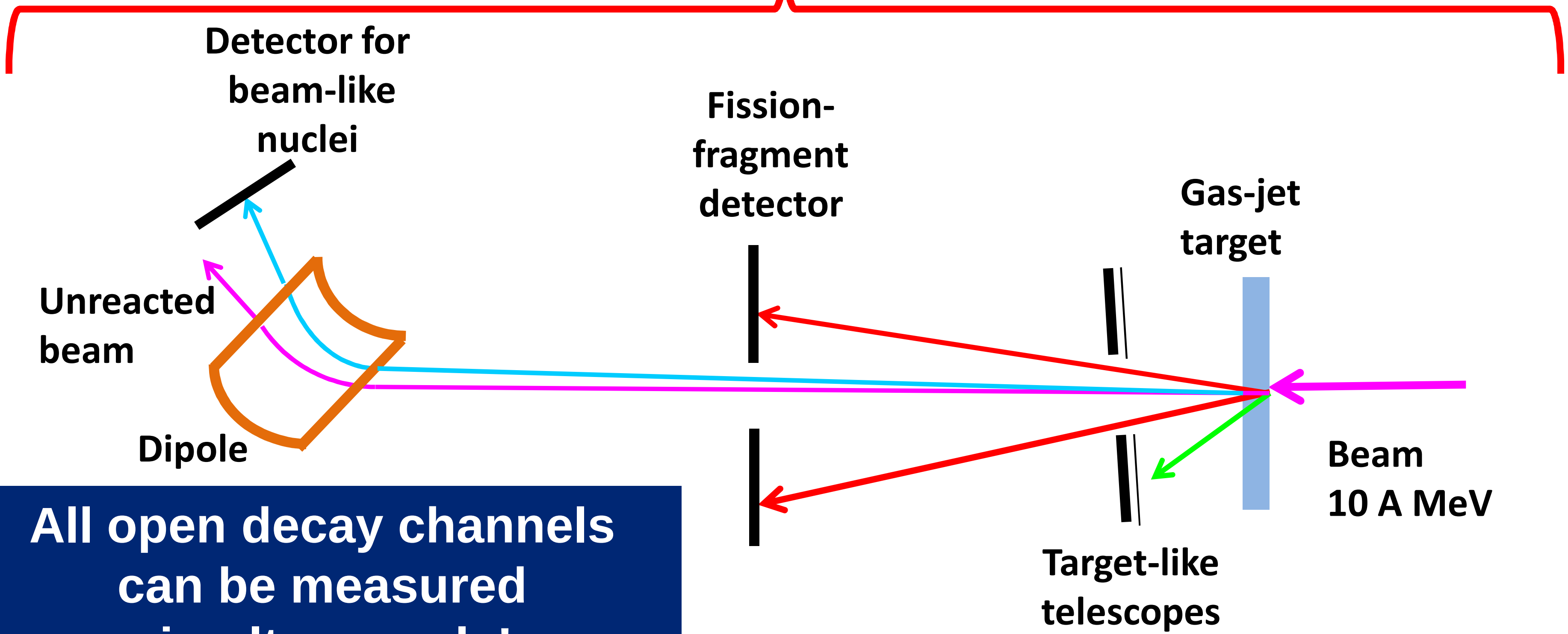


- Excellent beam –energy definition, beam-energy resolution of few hundreds keV at 10 A MeV, beam size 1 mm!!
- In-ring measurements with gas-jet targets (H2, D2, 3He, 4He) with $10^{14}/cm^2$. Effective target thickness increased by ~10^6 due to revolution frequency
- Pure beams, pure targets (no contaminants, no backing)!
- Pure isomeric beams!
- Measurements possible at the ESR at GSI in the near future

First reaction cross-section measurement at the ESR!
B. Mei et al., Phys. Rev. C 92 (2015) 035803

Decay-probability measurements inside a storage ring





All open decay channels can be measured simultaneously!

Conclusions and questions…

- **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**

- **Can we use the surrogate method to infer neutron-induced fission cross sections in regions where no data are available?**

- **How well can we predict n-induced CN formation cross sections far from stability?**

- **γ & particle-emission prob. are useful to constrain statistical-model calculations, provided that the populated J^{π} distributions are known. What information do we need to calculate them?**

- **Very promising perspectives open up for decay probability measurements in inverse kinematics with RIBs at storage rings to help answering these questions.**

Acknowledgements

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