Insensitivity of the fission threshold to the angular momentum

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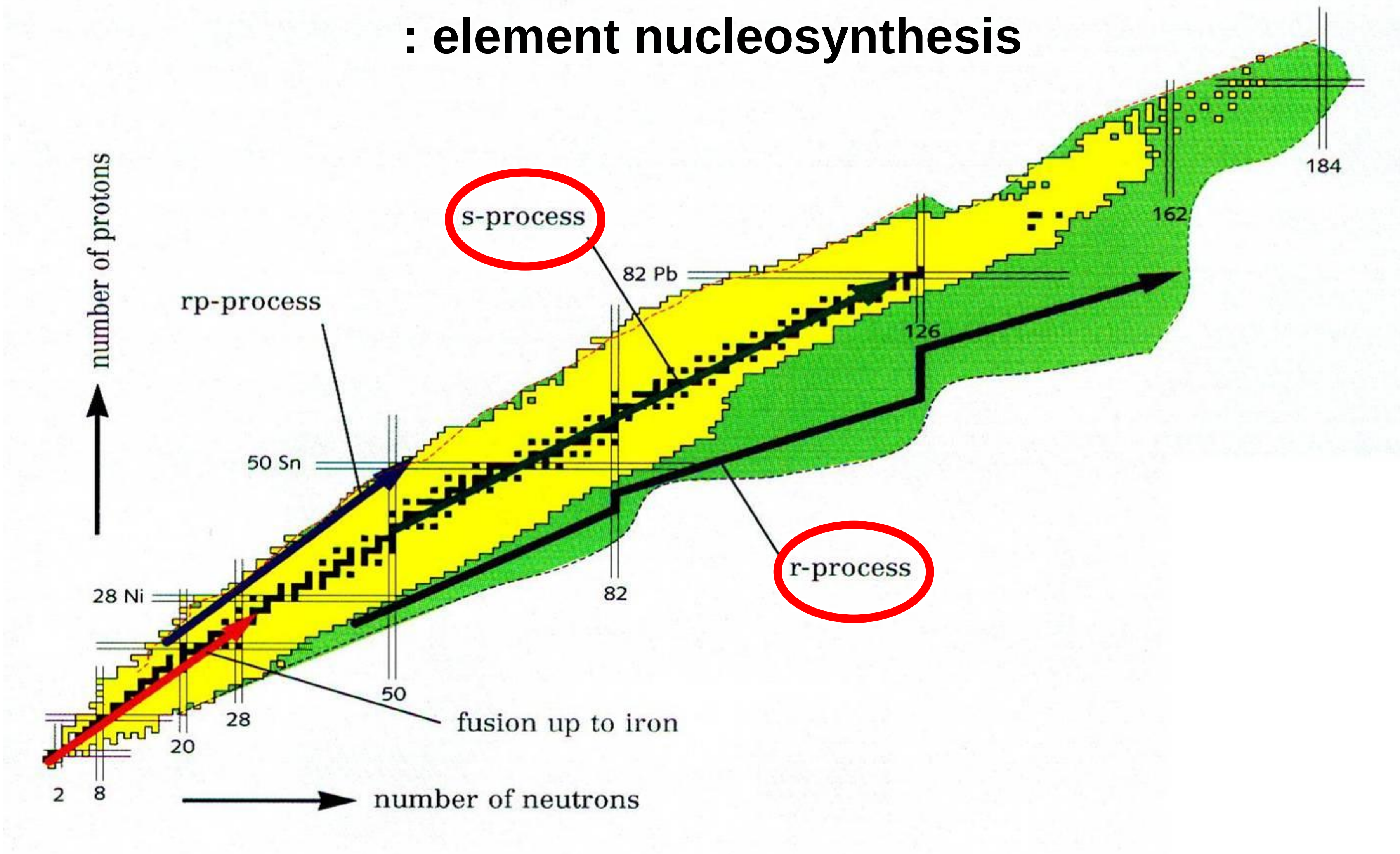
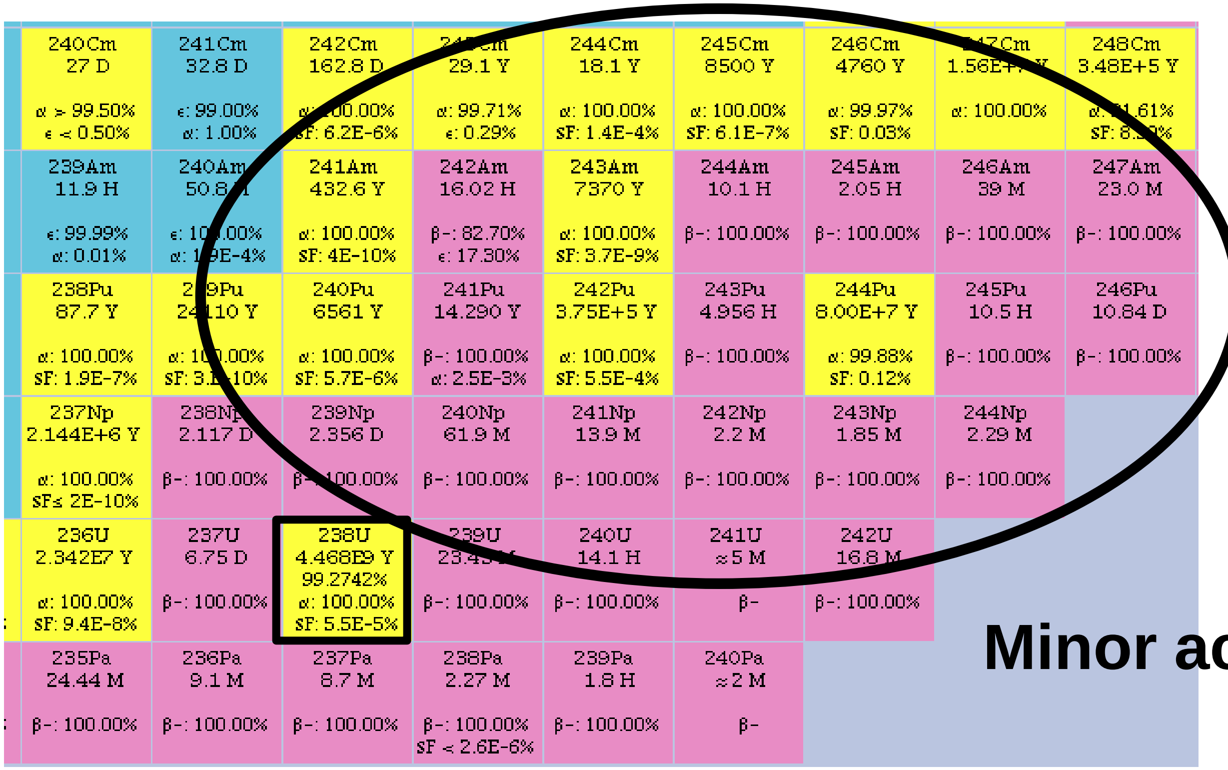
The context:

Study of the surrogate reaction method, an indirect method to infer neutron-induced cross sections of short-lived nuclei

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



Minor actinides

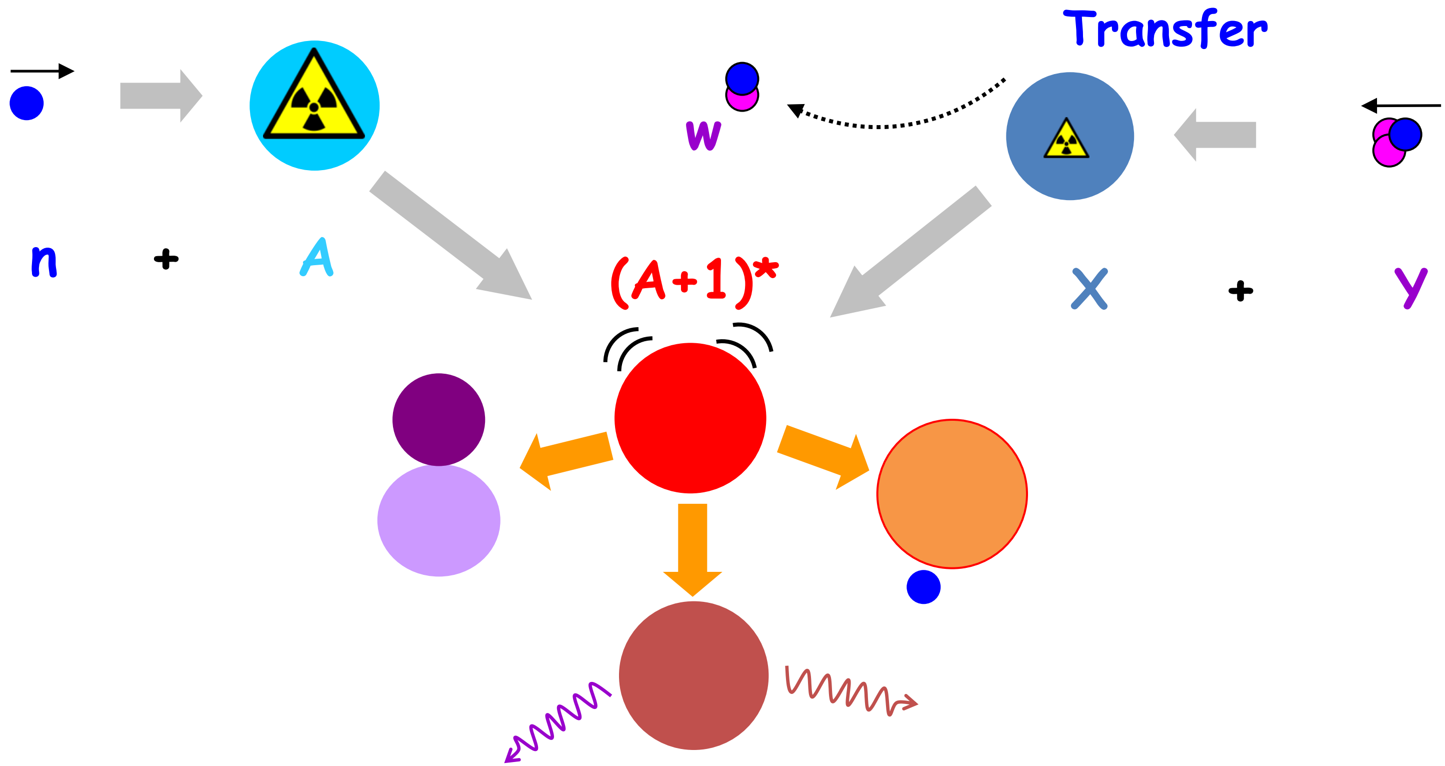
Neutron-induced fission and capture cross sections of short-lived nuclei needed.
Very difficult or even impossible to measure!

Surrogate-reaction method

Cramer and Britt (Los Alamos 1970…!!)

Neutron-induced reaction

Surrogate reaction



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

Theory
Optical model

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 achieve statistical equilibrium (compound nucleus formation):
Decay only depends on *E, *J* and π !!**

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

Populated *J* and π distributions are equal

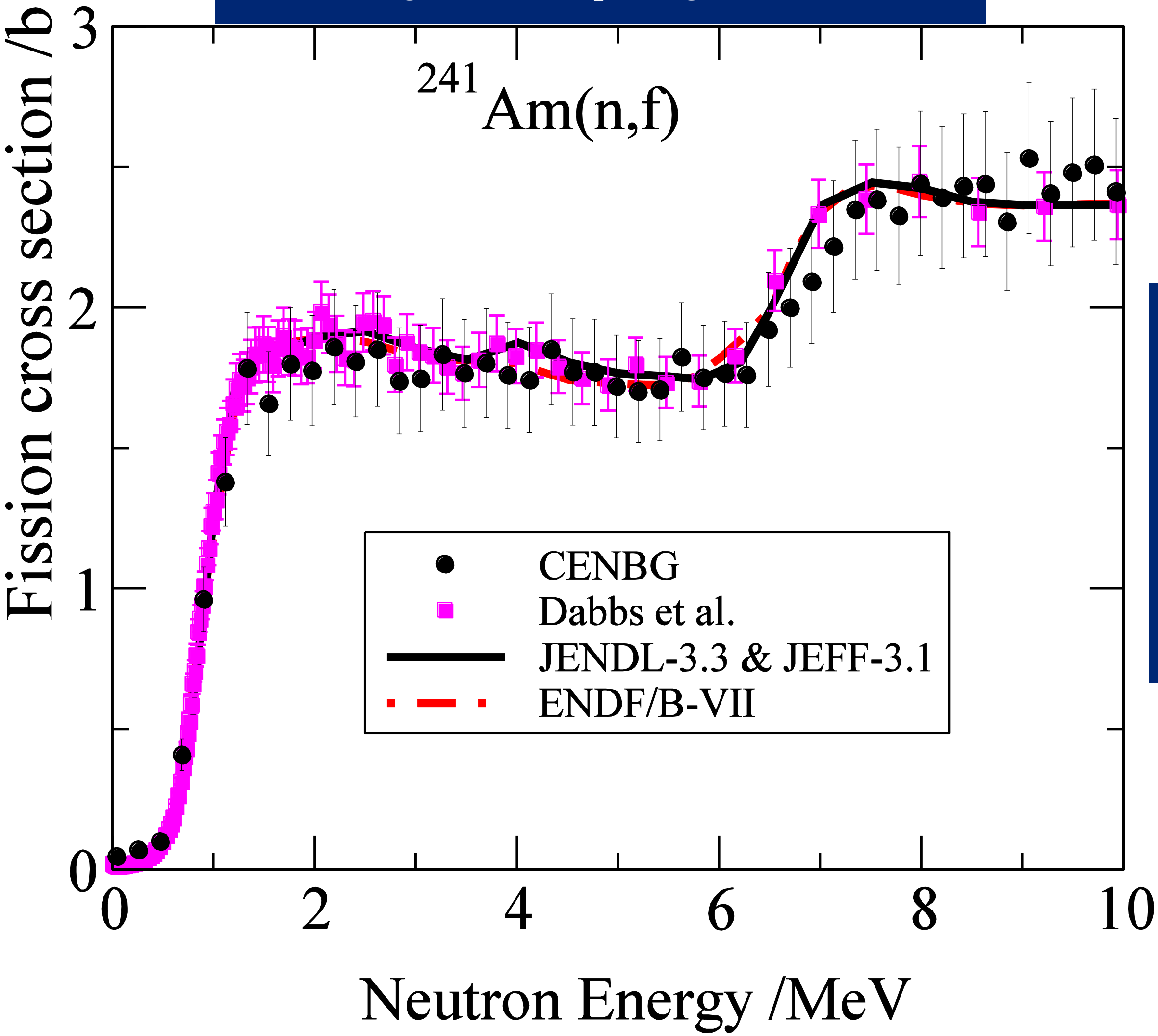
OR

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

$^{3}He+^{243}Am \rightarrow ^{4}He+^{242}Am$

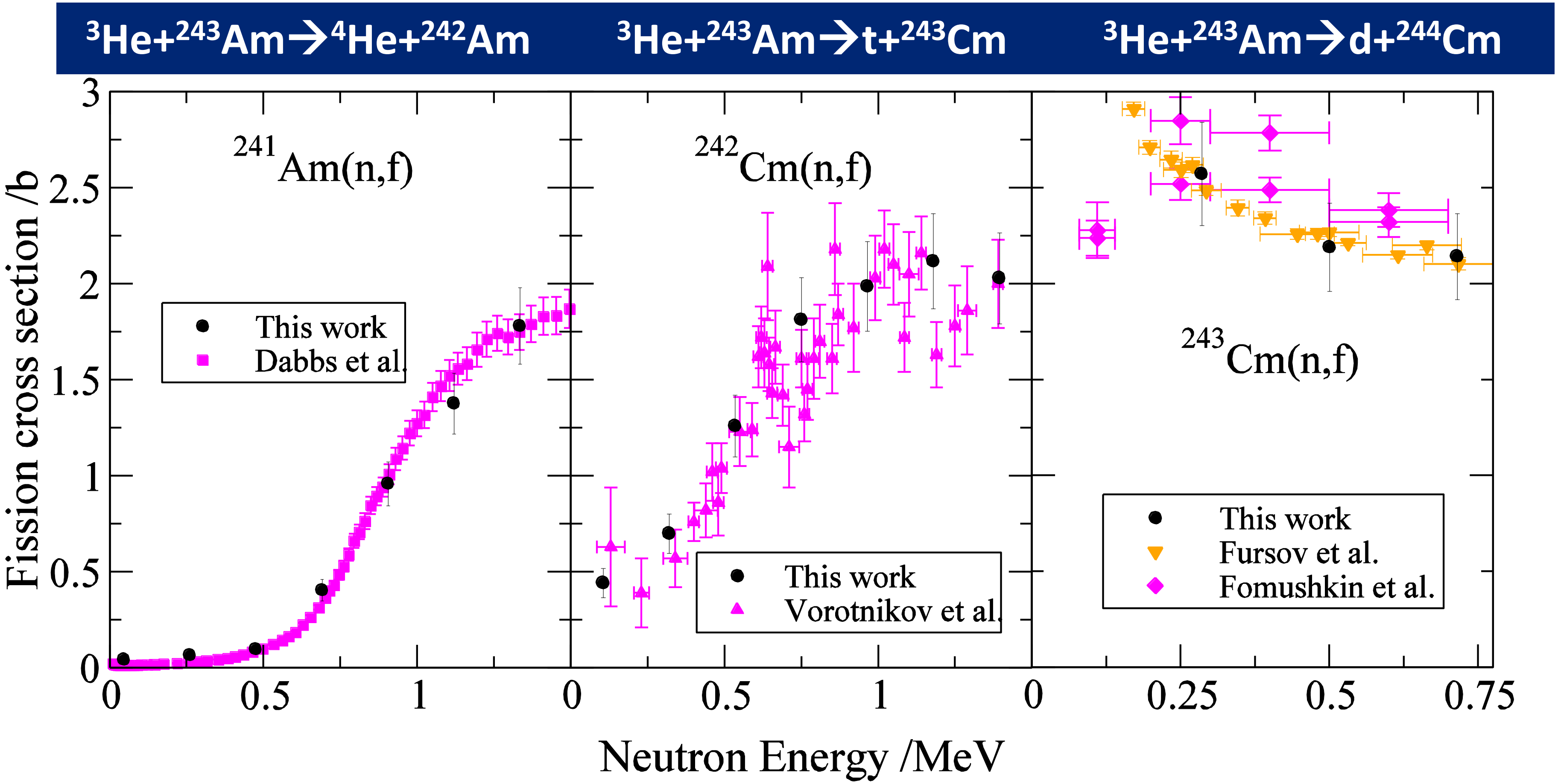


General finding: the cross sections obtained with surrogate method are in good agreement with n-induced data for fission!

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

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

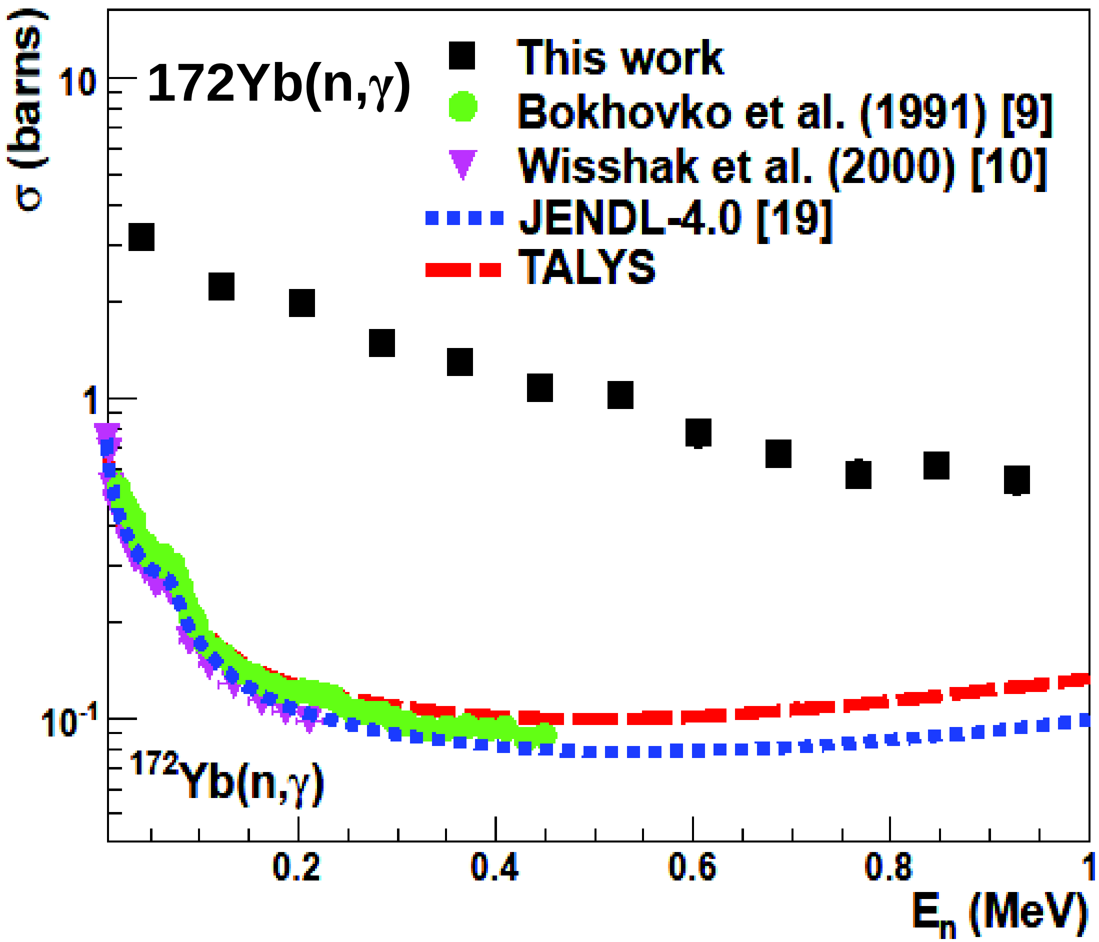
Focus on the fission threshold



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

Results for radiative capture

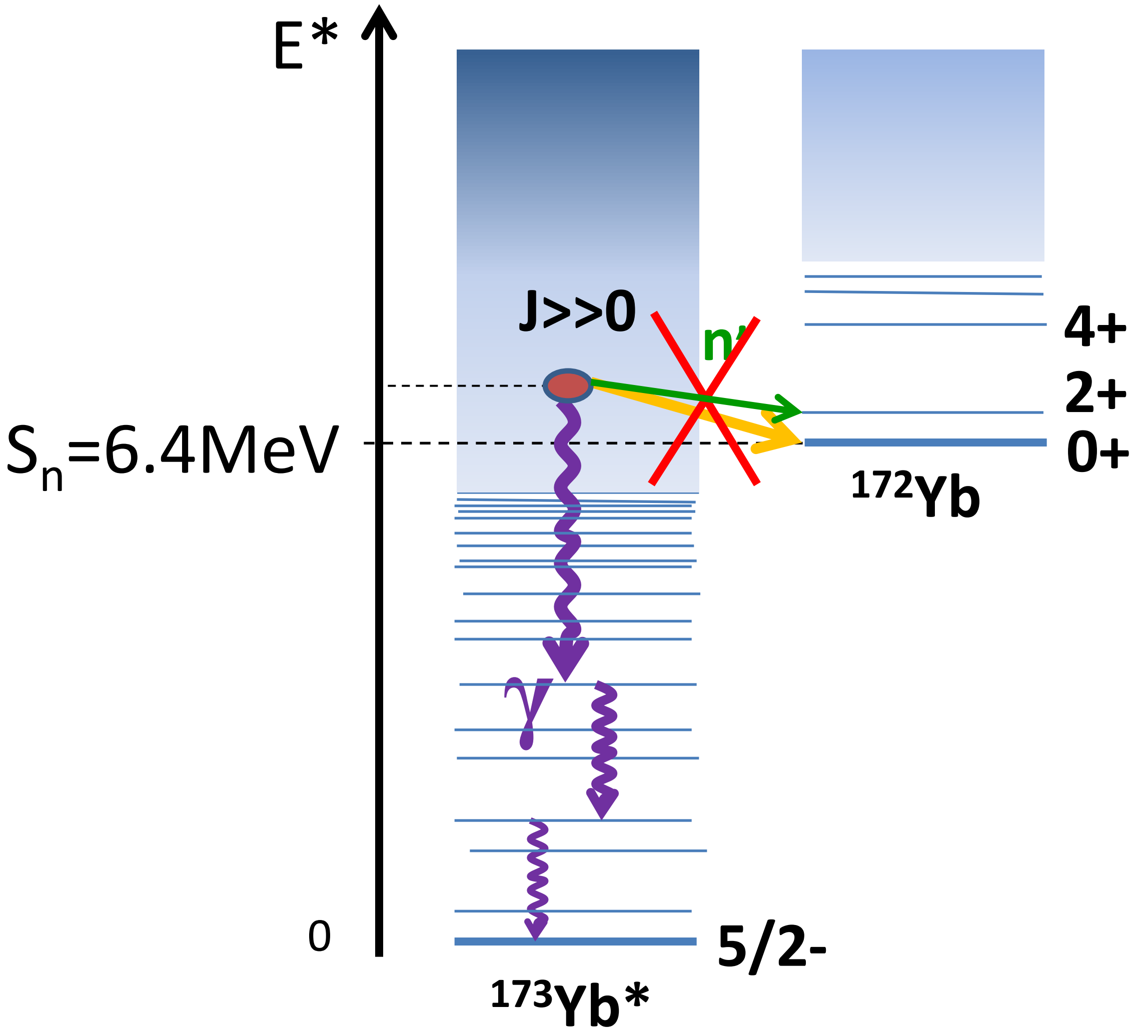
3He + 174Yb -> 4He + 173Yb



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

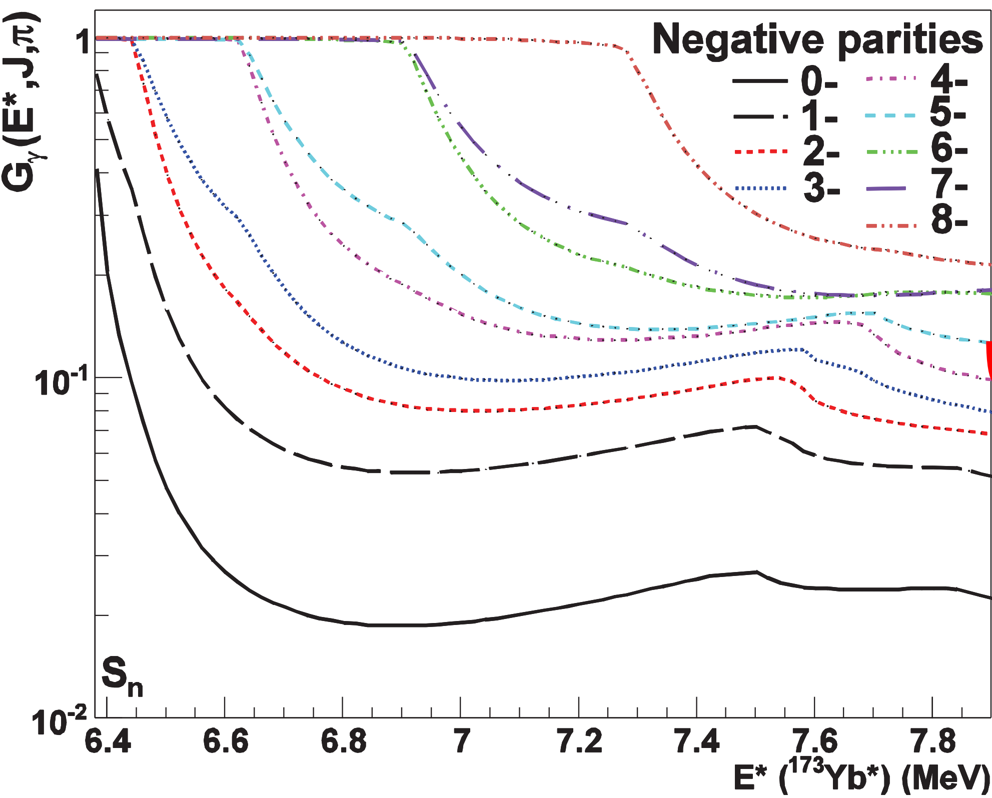
Why do we obtain such discrepancies?



Strong sensitivity of neutron emission to Jπ

Gamma-emission probabilities: a sensitive "spinmeter"

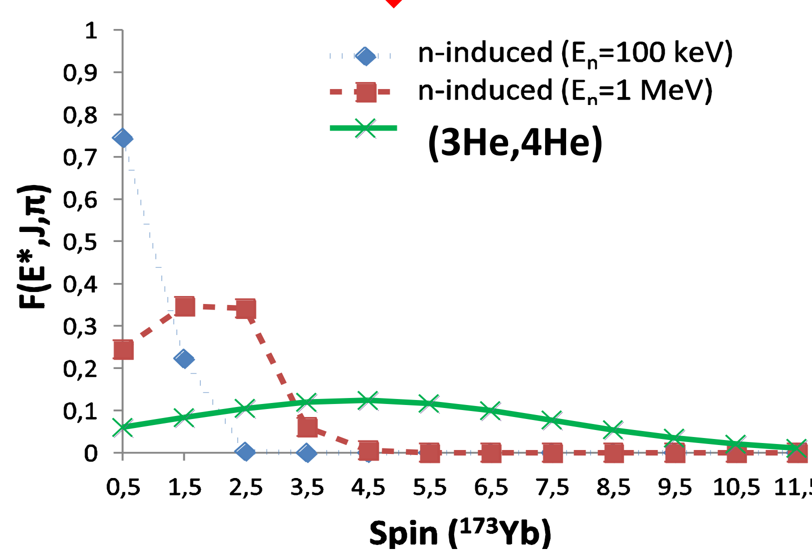
Hauser Feshbach calculation performed with TALYS by CEA evaluator P. Romain



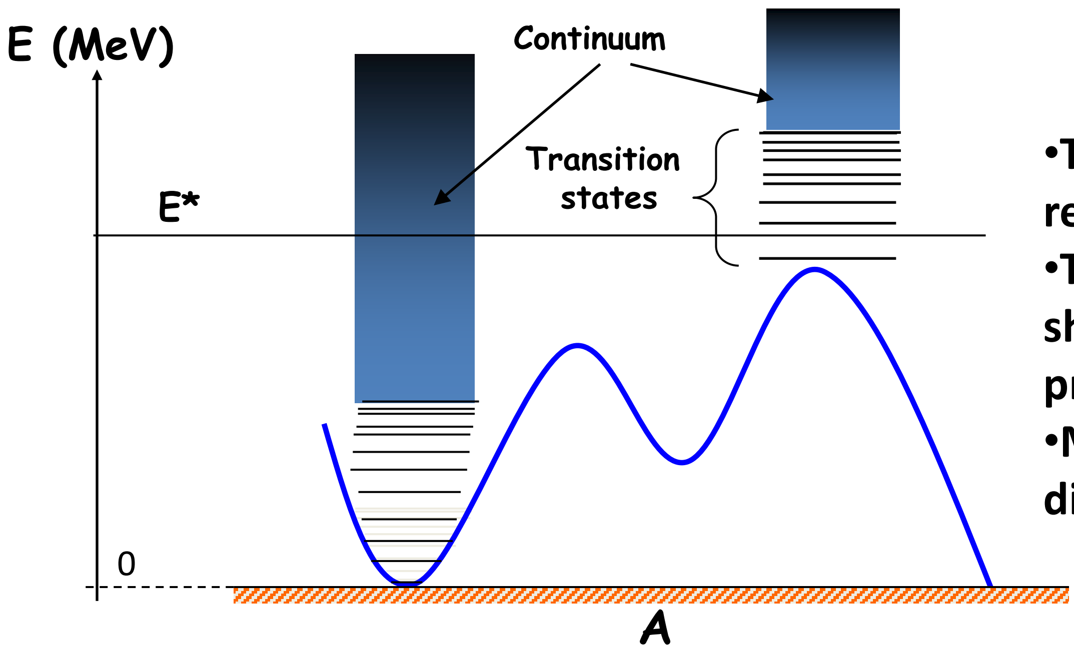
$$P_\gamma(E^*) = \sum_{J^\pi} F_S^{CN}(E^*,J^\pi)\cdot G_\gamma(E^*,J^\pi)$$

$$P_\gamma(E^*) = \sum_{J^\pi}\left[\frac{1}{2\sigma\sqrt{2\pi}}e^{-\frac{(J-\bar{J})^2}{2\sigma^2}}\right]\cdot G_\gamma(E^*,J^\pi)$$

Fit to the measured Pγ to infer <J> and σ_J



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



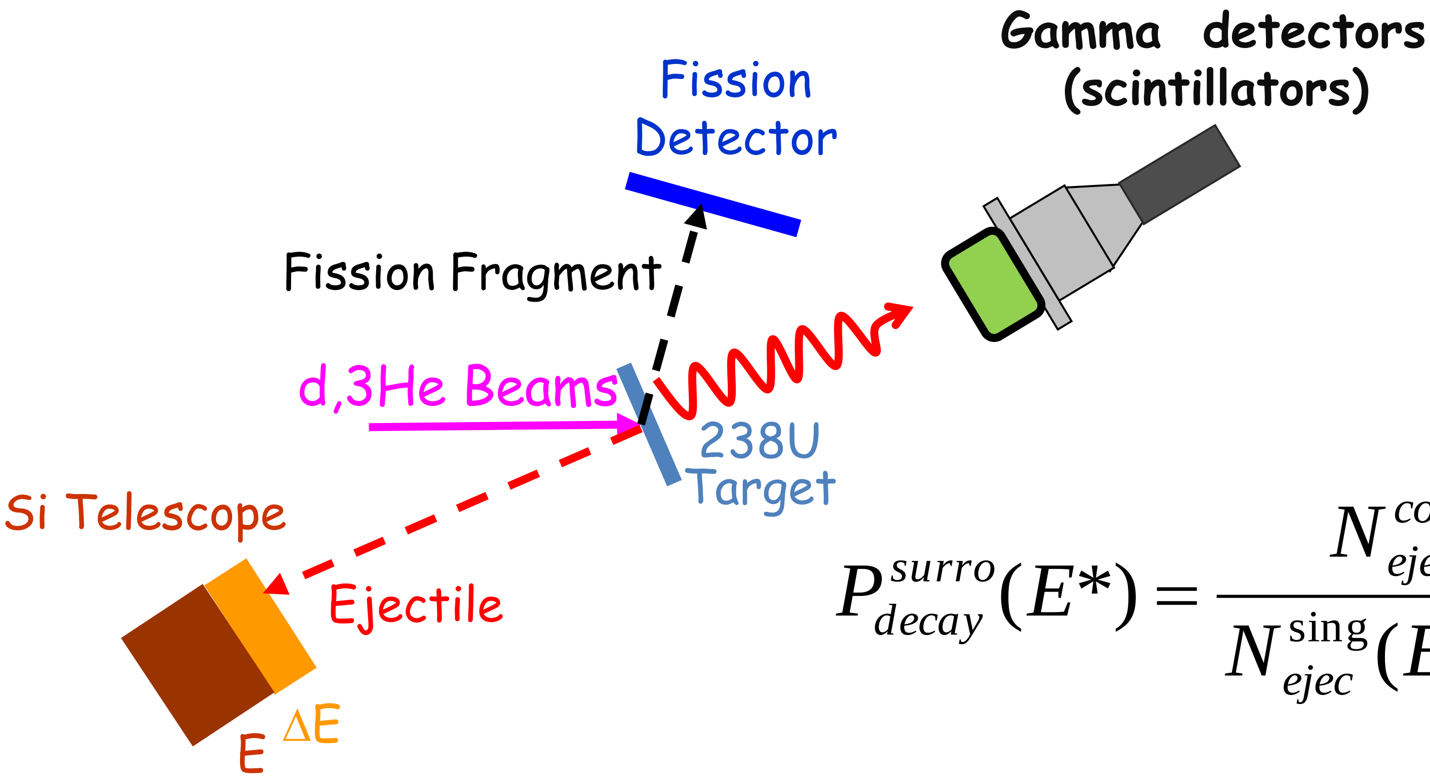
- The top of the fission Barrier is also a region of low density of states!
- The neutron-emission suppression should also affect the fission probability!
- Maybe the spins populated are not so different ...?

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

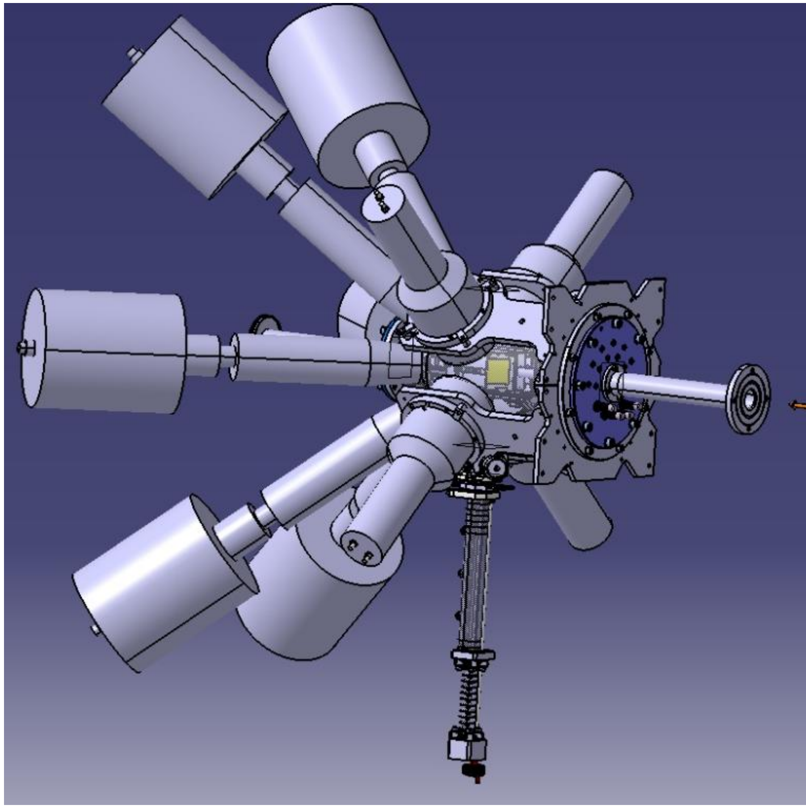


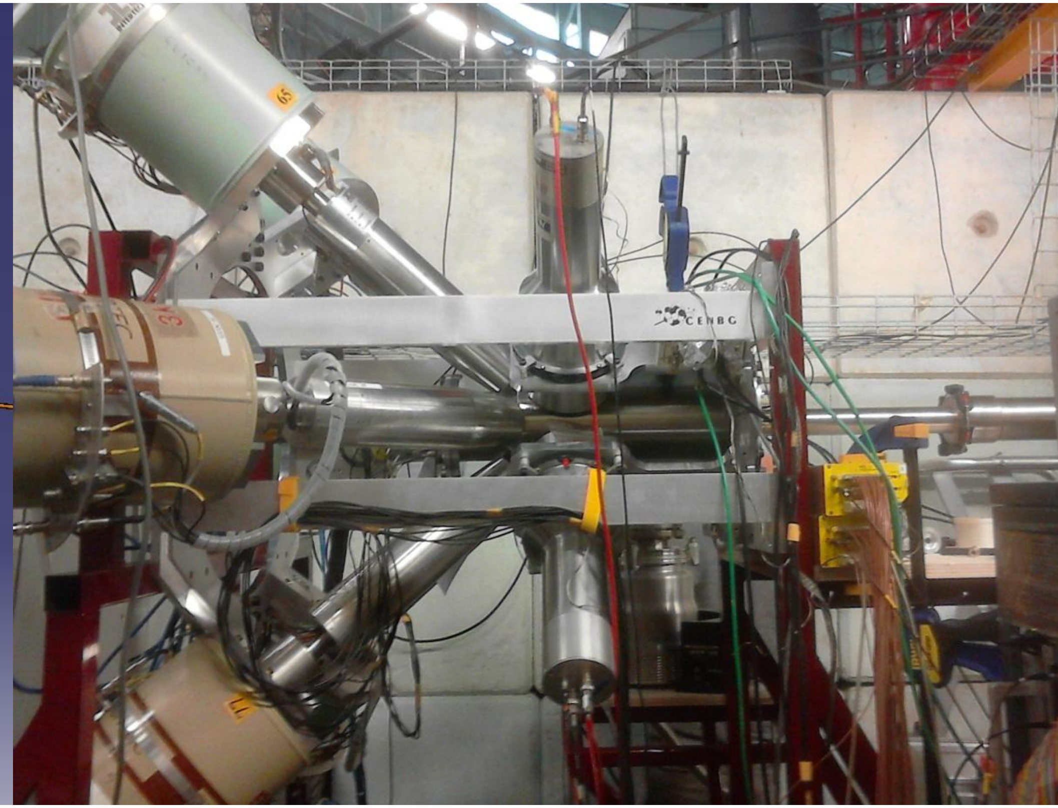
$$P^{surro}_{decay}(E^*) = \frac{N^{coin}_{ejec-decay}(E^*)}{N^{sing}_{ejec}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

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

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

Setup used for experiment at the Orsay tandem in April 2015

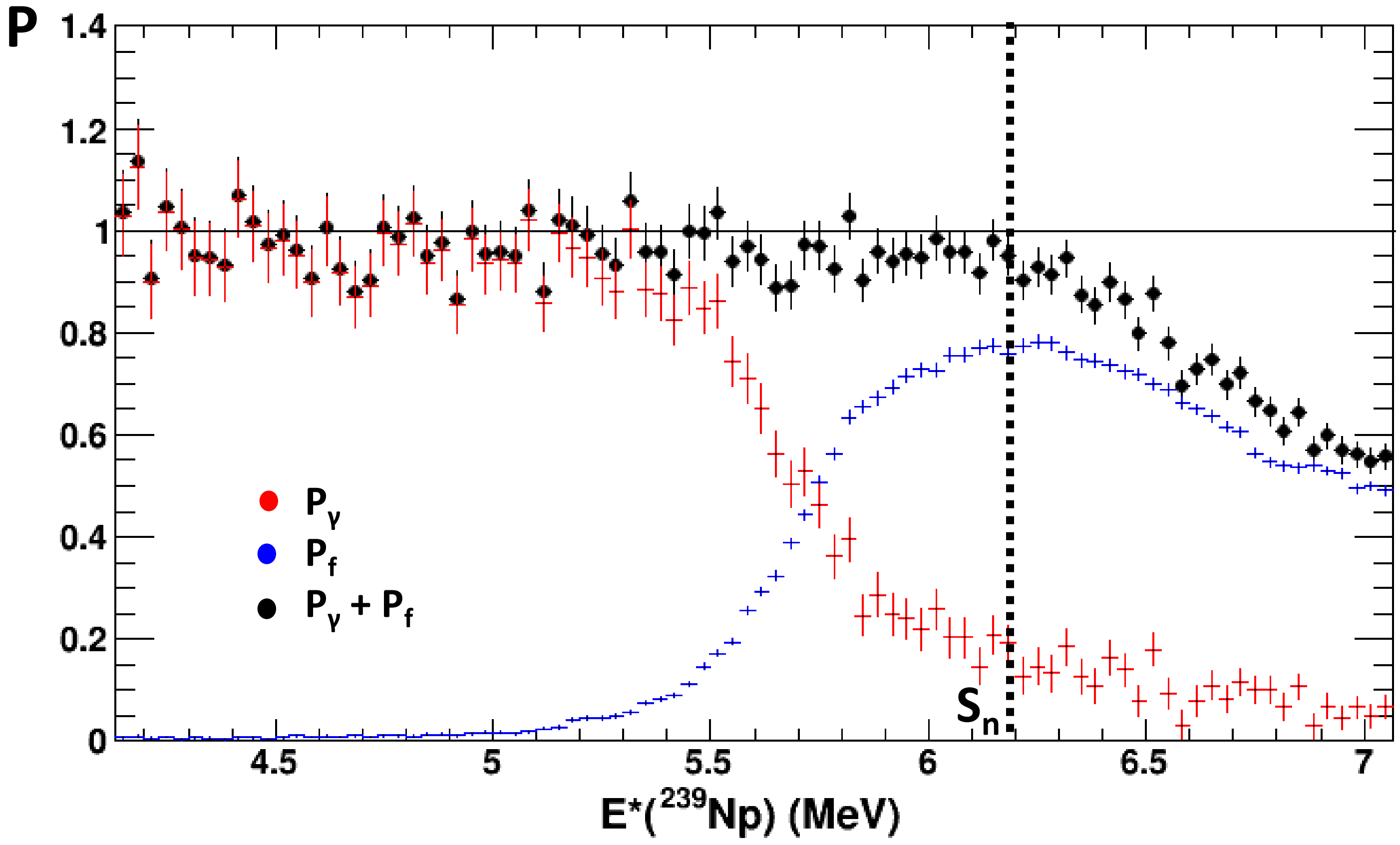




Results

Preliminary results!

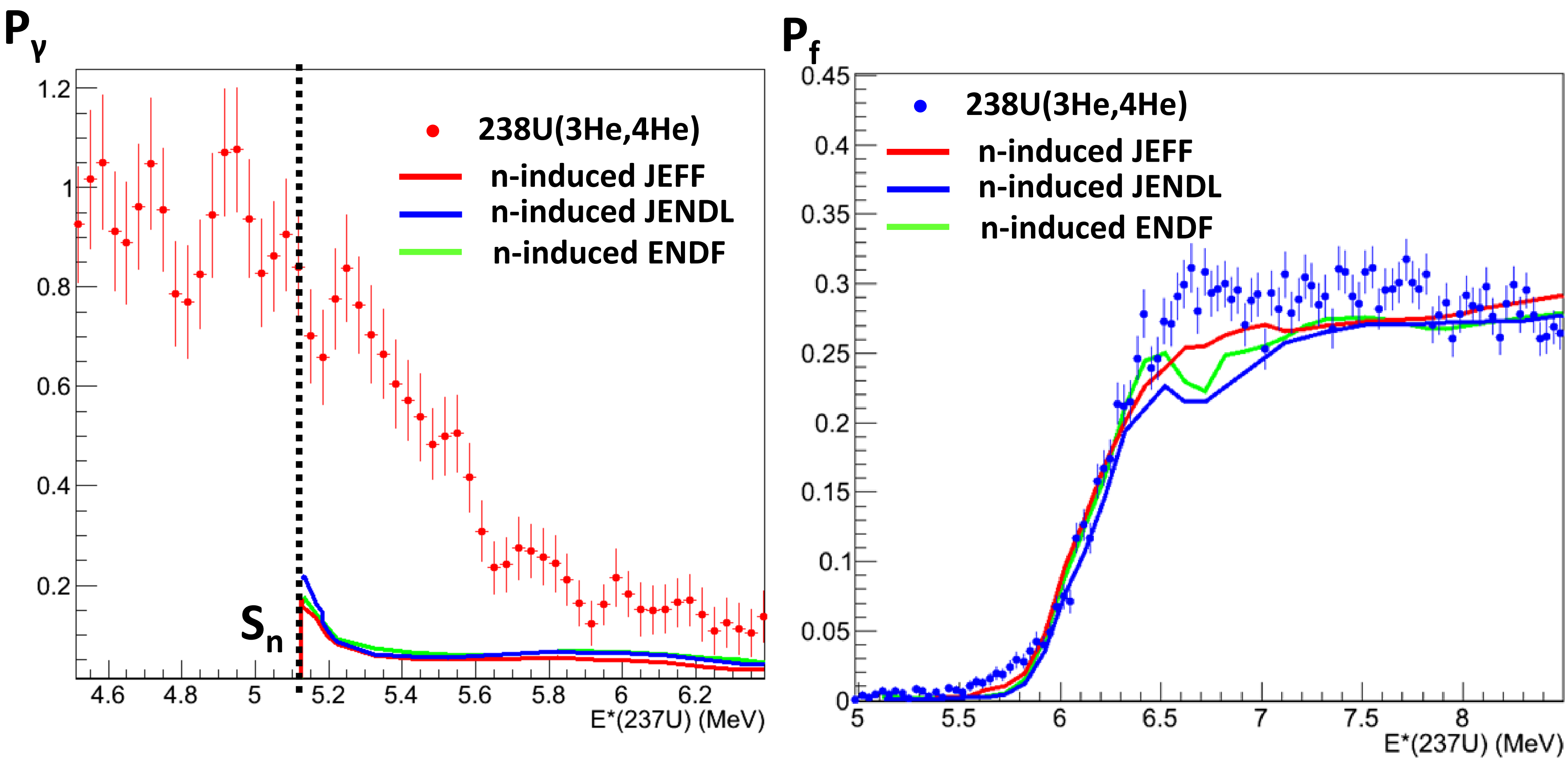
3He + 238U-> d + 239Np ↔ n + 238Np (2,1d)



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

Preliminary results!

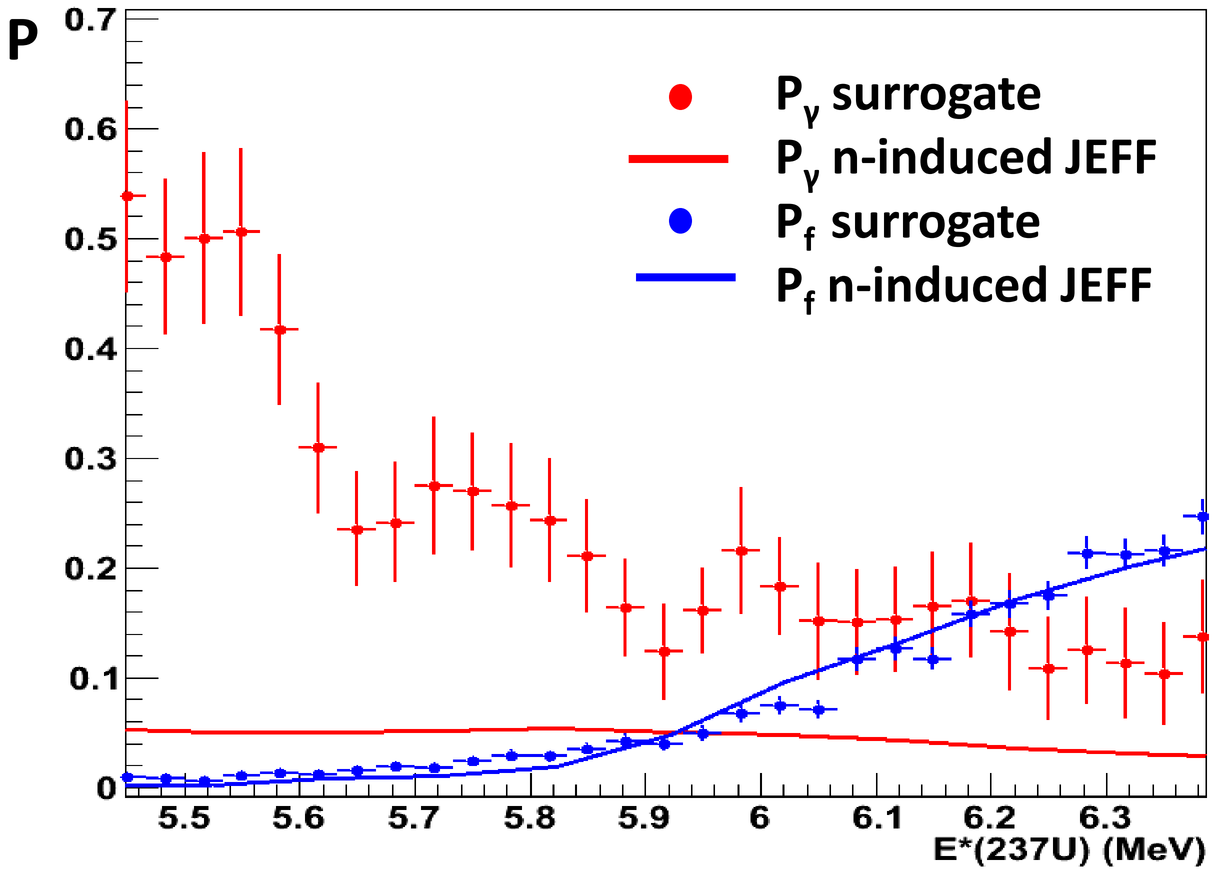
3He + 238U-> 4He + 237U ↔ n + 236U



Focus on the overlap region

Preliminary results!

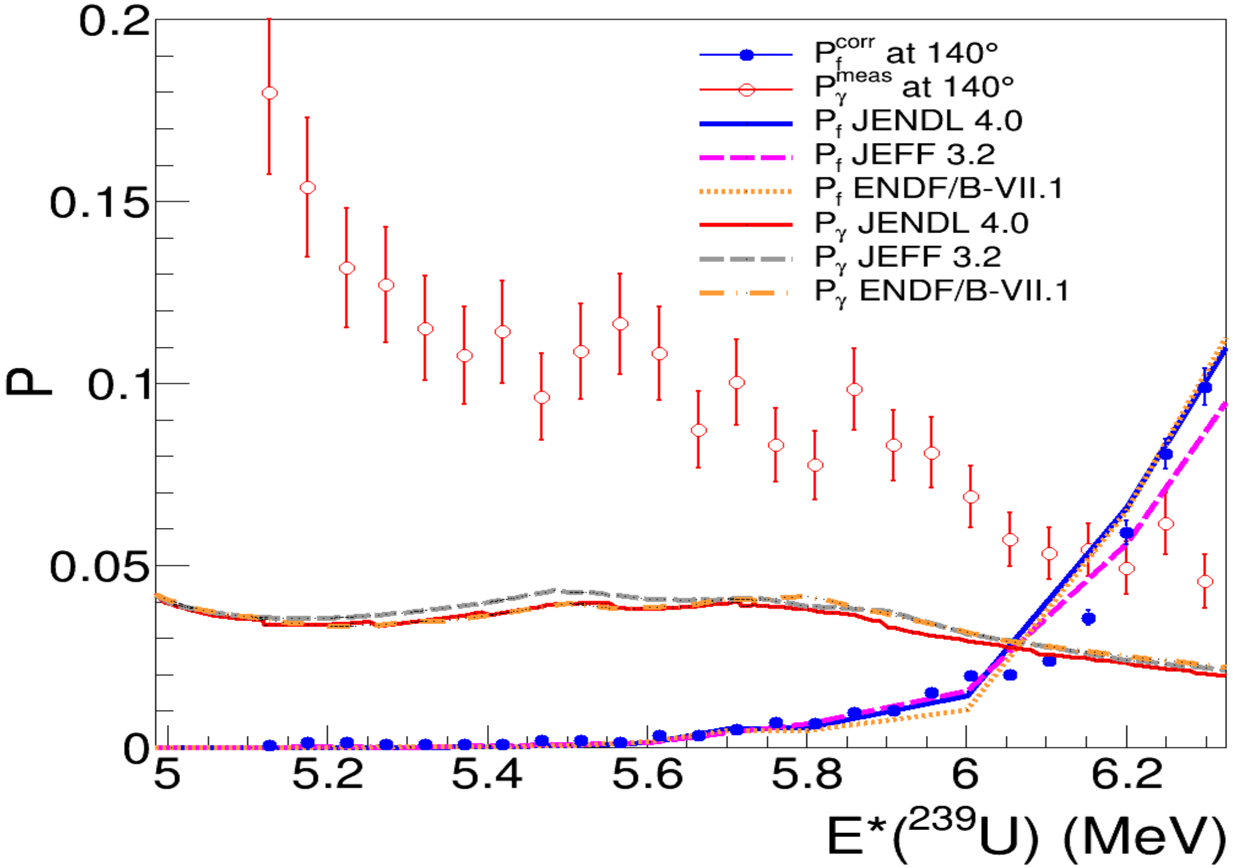
3He + 238U-> 4He + 237U ↔ n + 236U



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

Focus on the overlap region

d + 238U-> p + 239U ↔ n + 238U



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

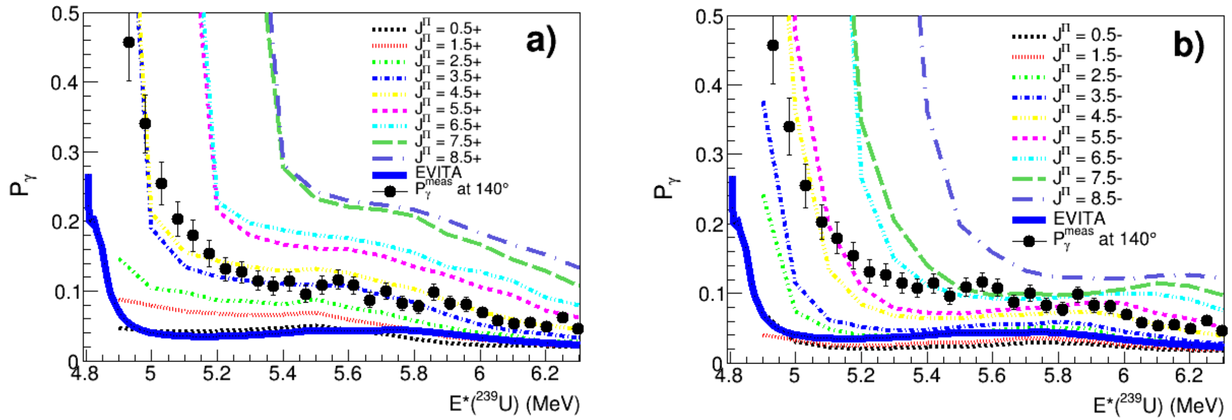
Q. Ducasse et al., Nucl. Instrum. Meth. A 826 (2016) 60

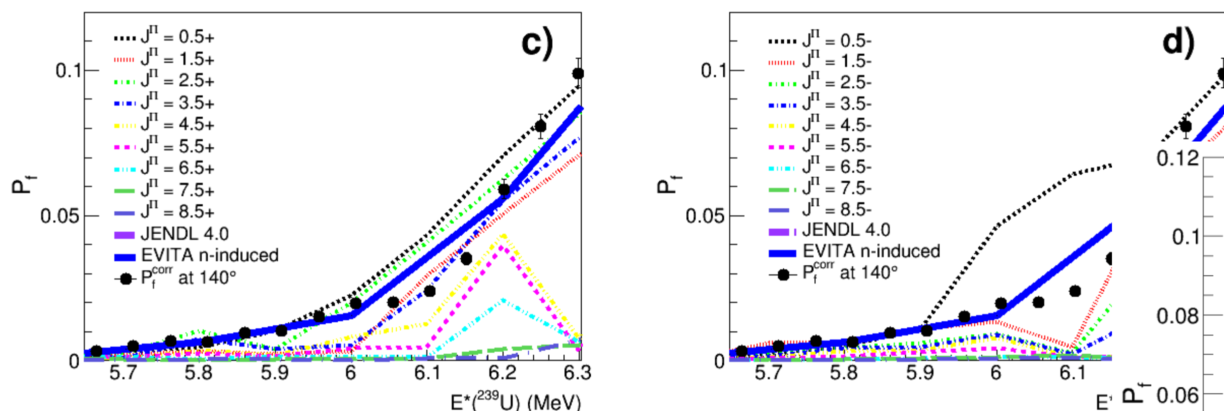
Q. Ducasse et al., submitted to Phys. Rev. C

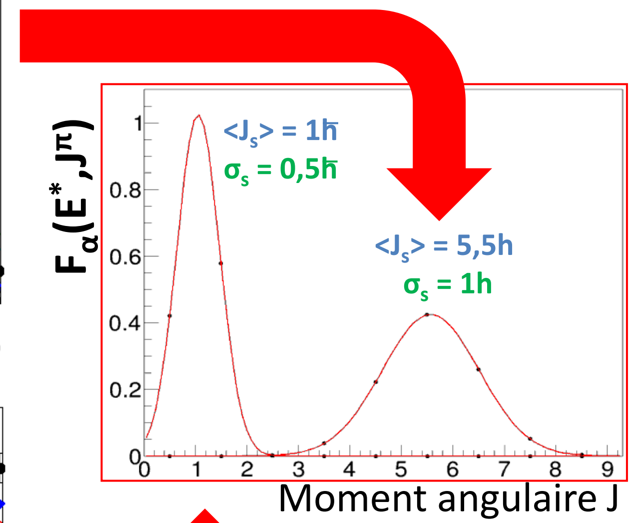
Can we explain these results within the framework of the statistical model?

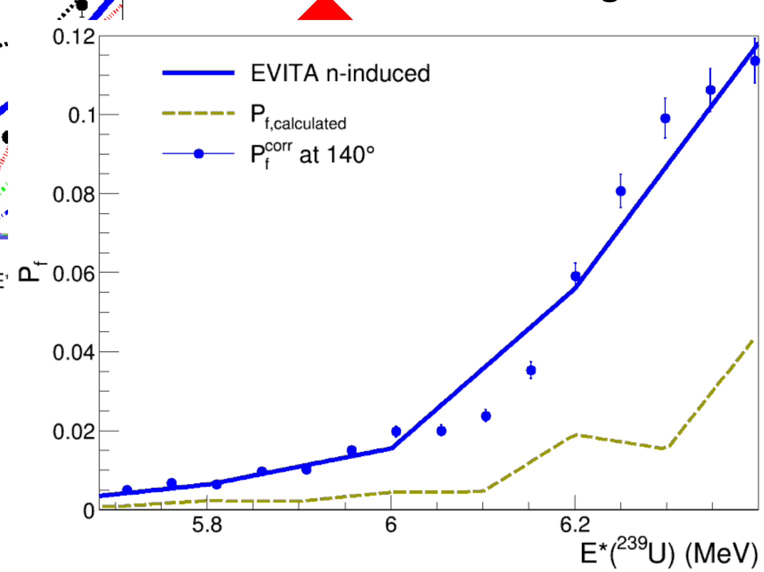
238U(d,p)

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



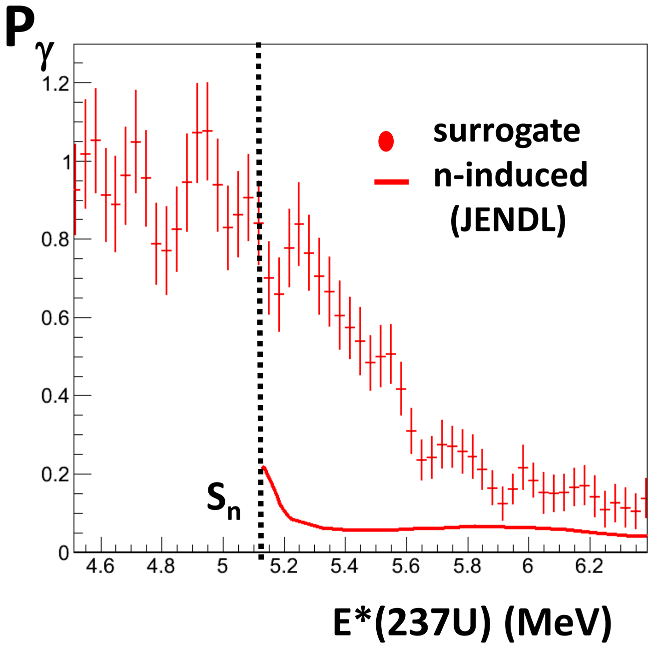




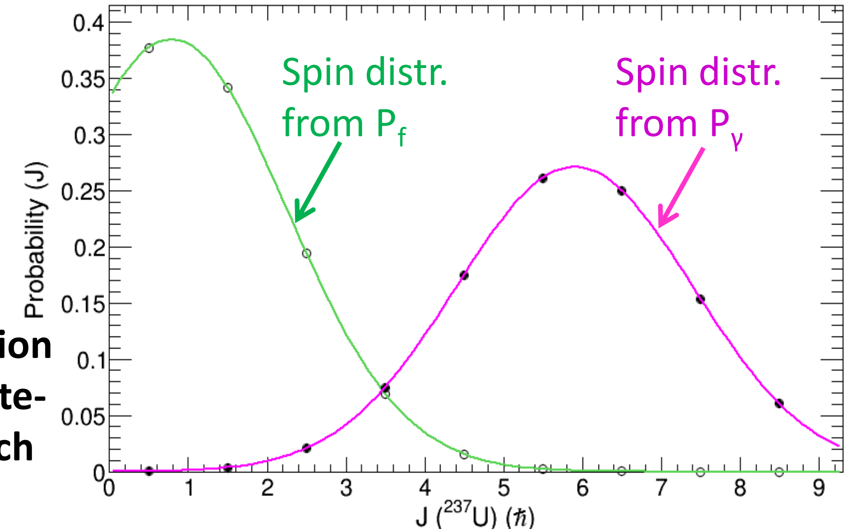


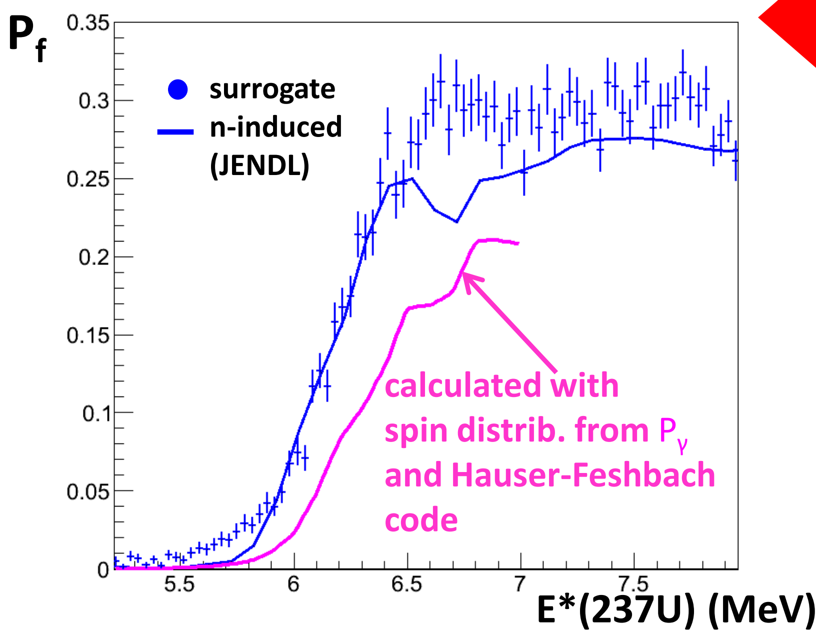
Q. Ducasse et al., submitted to Phys. Rev. C

238U(3He,4He)



Deduce spin distribution with the help of monte-carlo Hauser Feshbach code EVITA

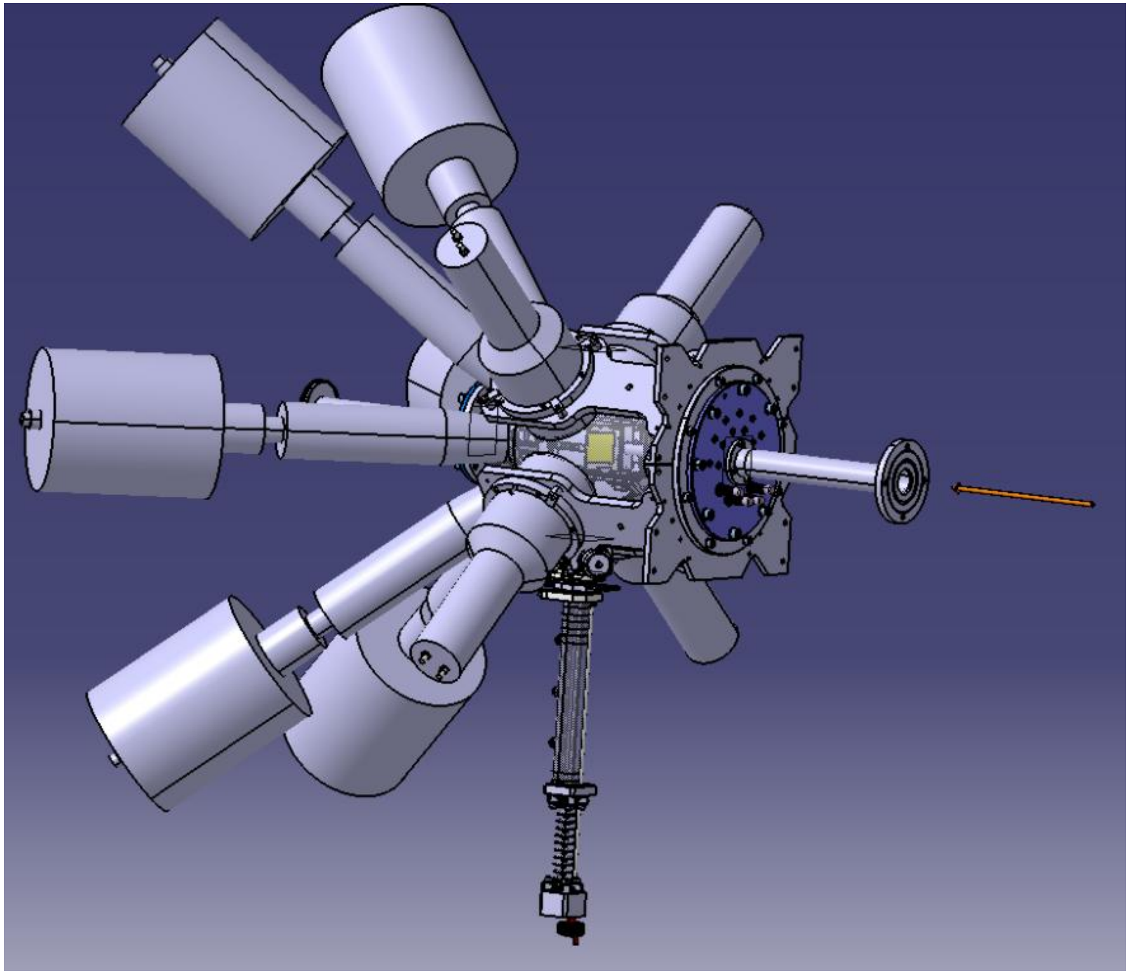




The calculations predict a strong sensitivity of the fission threshold to angular momentum in contradiction with our results!

Perspectives

3He + 240Pu-> 3He' + 240Pu ↔ n + 239Pu



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

Good-quality n-induced data available!

- **Longer term: Perform systematic studies in other regions of the chart of nuclei, isomeric beams**

→Experiments in inverse kinematics with RIBs

Conclusions…

- **First simultaneous measurement of gamma-decay and fission probabilities for surrogate reactions**

- **The fission threshold is much less sensitive than the gamma-decay probability to the differences in the entrance channel.**

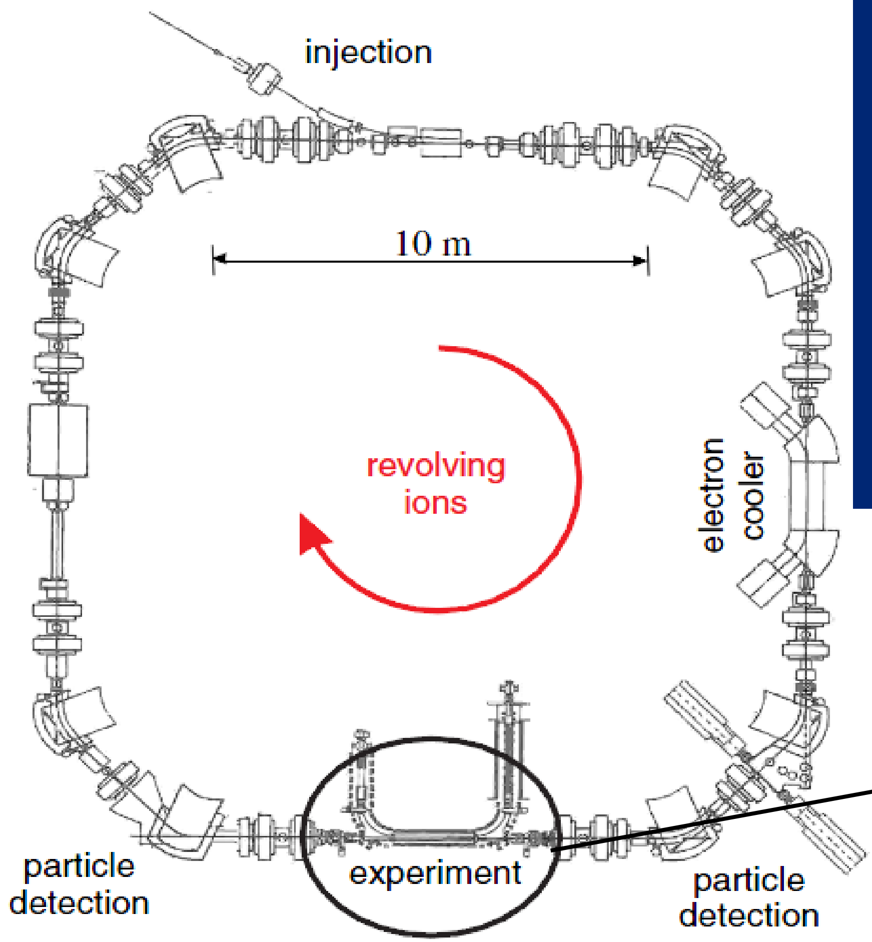
- **This finding cannot be explained by statistical model calculations performed with TALYS**

- **Can we explain the results with appropriate schemes of transition states?**

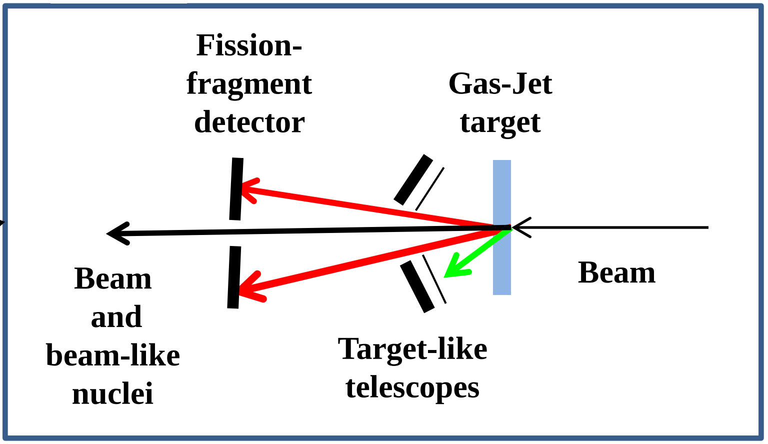
Acknowledgements

- Défi interdisciplinaire NEEDS, projet ACTISUR
- CHANDA FP7-EURATOM 605203
- Université de Bordeaux

Fission-probability measurements inside a storage ring



- Beam-energy resolution of few hundreds keV, beam size 1 mm!!
- In-ring measurements with gas-jet targets (H2, D2, 3He, 4He): Pure targets (no contaminants, no backing), limited straggling
- Increased intensity by 10^6 due to revolution frequency



Systematic measurement of fission probabilities in other regions, also of purified isomeric beams!!
Experiments at GSI and in the longer term HIE-ISOLDE (2023)

Transfer-induced reactions in inverse kinematics with radioactive ion beams

HIE-ISOLDE, actinide and pre-actinide beams:

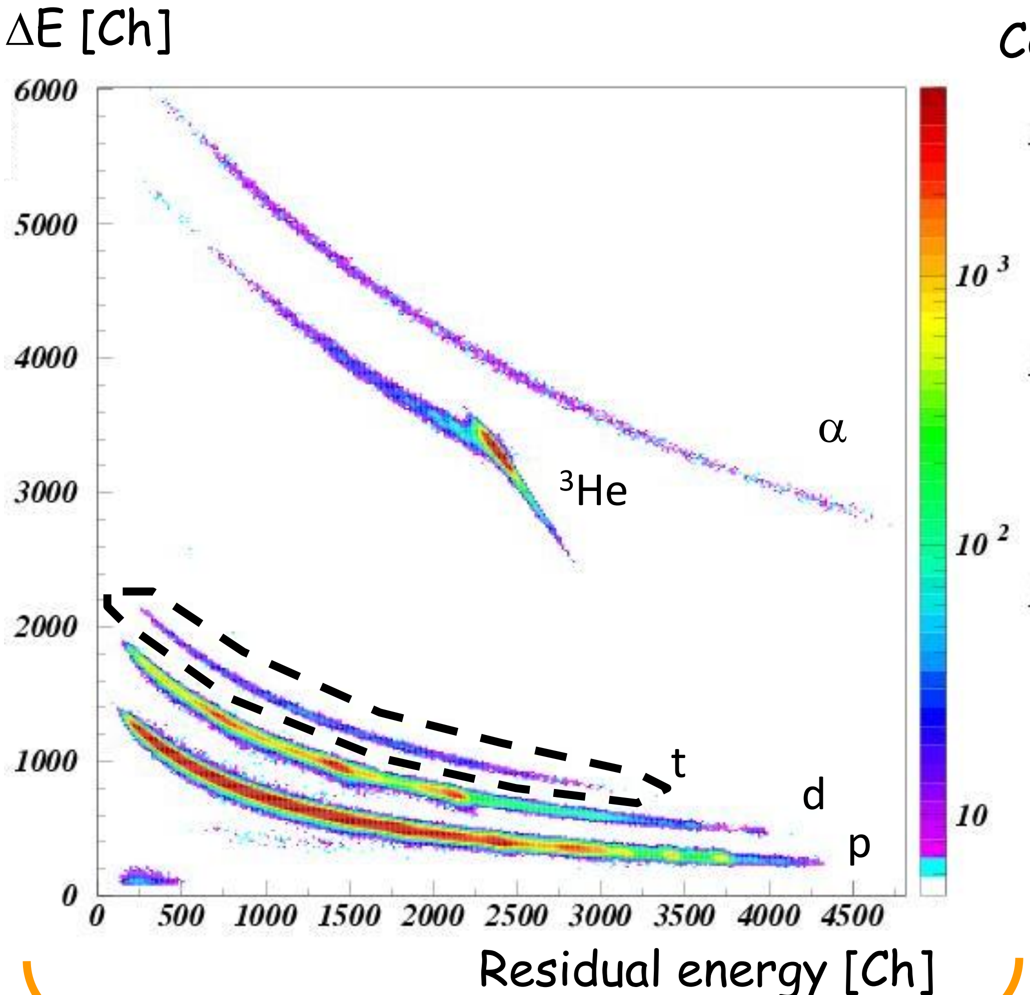
Element	Isotopic chain	Half lifes
Rn (Z=86)	$^{204-212}$Rn $^{219-221}$Rn	2.4h $\leq T_{1/2} \leq$ 28.5min 3.96s $\leq T_{1/2} \leq$ 25min
Fr (Z=87)	$^{207-213}$Fr $^{220-228}$Fr	14.8s $\leq T_{1/2} \leq$ 20min 27.4s $\leq T_{1/2} \leq$ 21.8min
Ra (Z=88)	$^{221-222,224-226,228}$Ra	28s $\leq T_{1/2} \leq$ 1600y

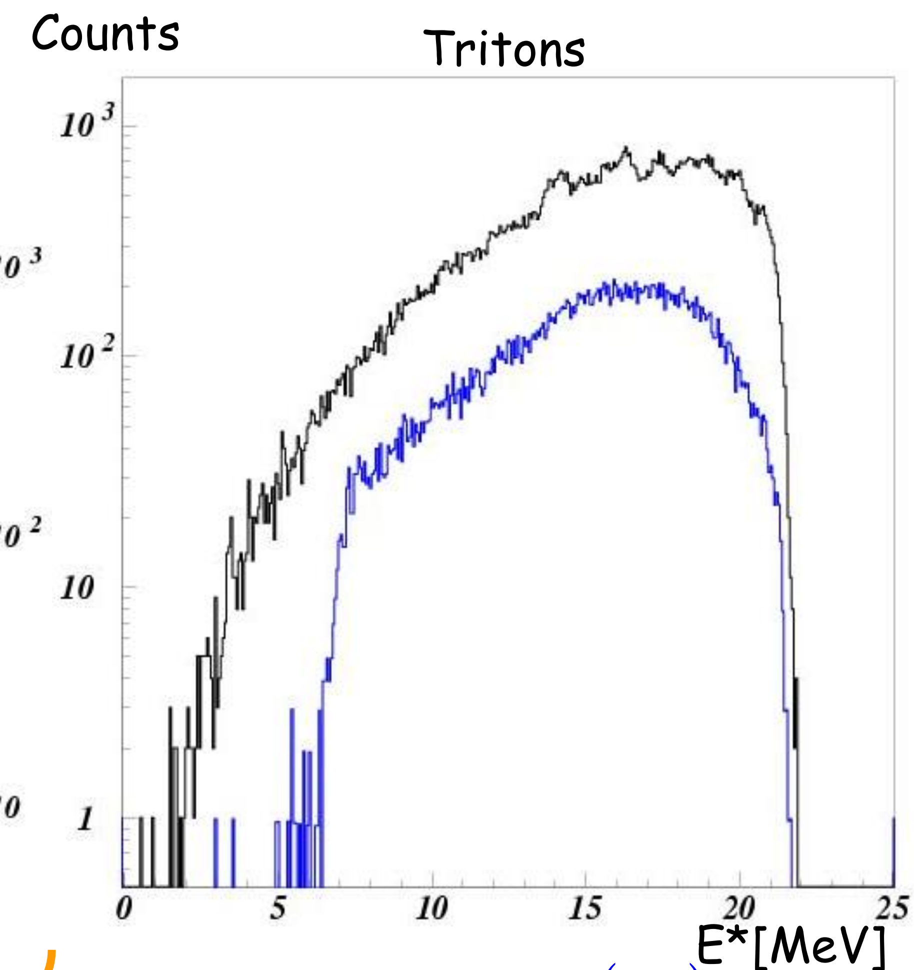
10 A MeV and high intensities

BUT…

Limited beam quality: dispersion in energy > 2MeV and size > few mm

Fission probability

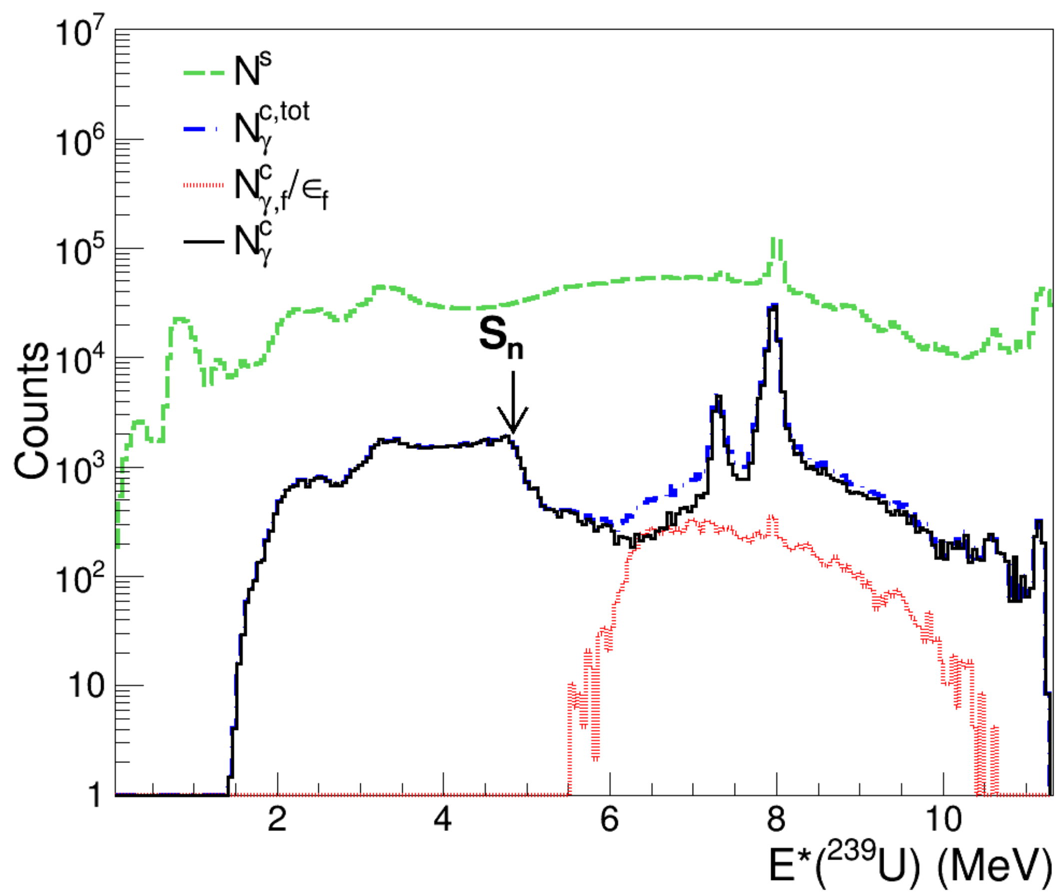




Light-particle kinematics + Q-values
E* of the CN

$$P_f\left(E^*\right) = \frac{N_{coin}\left(E^*\right)}{N_{CN}\left(E^*\right)\cdot Eff\left(E^*\right)}$$

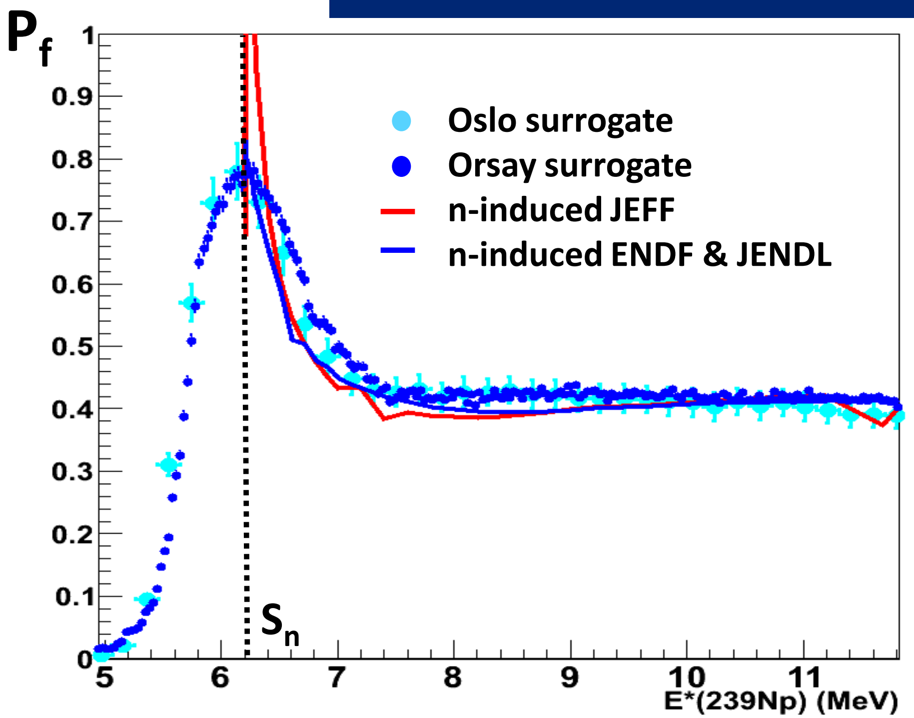
$$E^* = \frac{A}{A+1}E_n + B_n$$

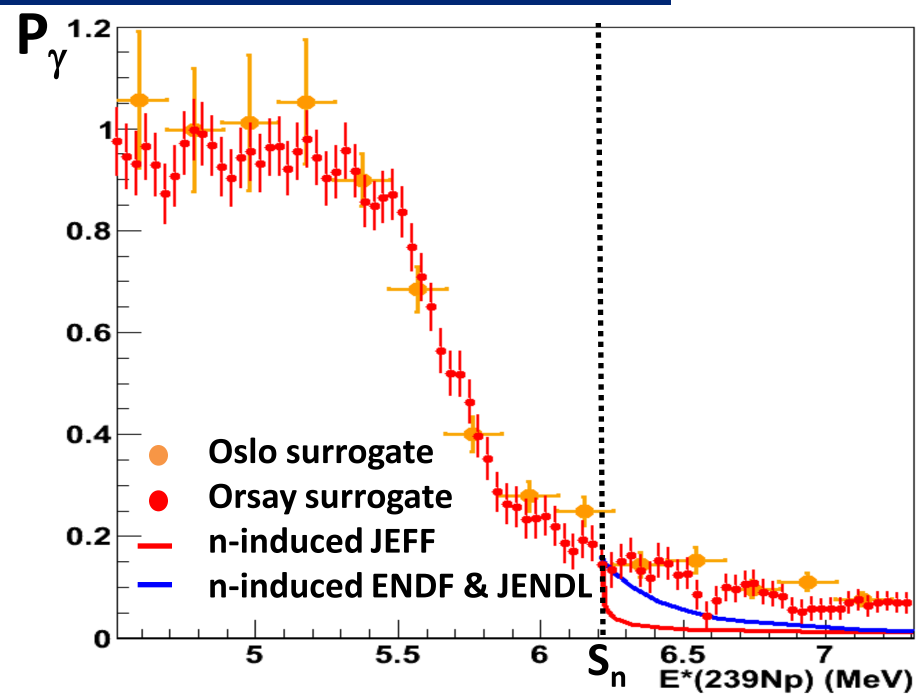


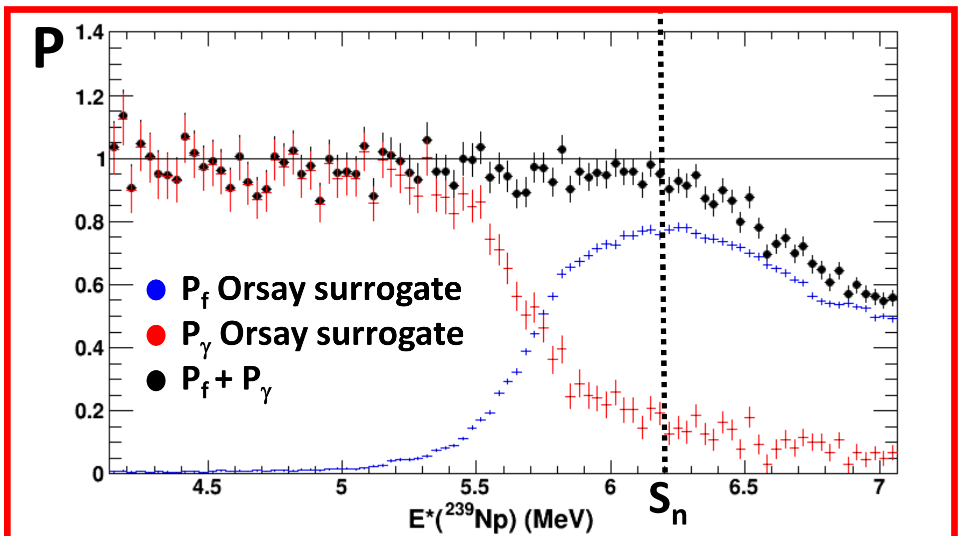
N^s
$N_\gamma^{c,tot}$
$N_{\gamma,f}^c/\epsilon_f$
N_γ^c
S_n
Counts
$E^*(^{239}U)$ (MeV)
1
10
10^2
10^3
10^4
10^5
10^6
10^7
2
4
6
8
10

Preliminary results!

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







$P_f + P_\gamma = 1$ at E*<Sn :
validation
of analysis procedure!!

Validity of the surrogate method: limiting cases

Neutron-induced decay probability

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

Surrogate decay probability

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

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

$$P_{neutron}^{form}(E^*, J^\pi) = P_{surro}^{form}(E^*, J^\pi)$$

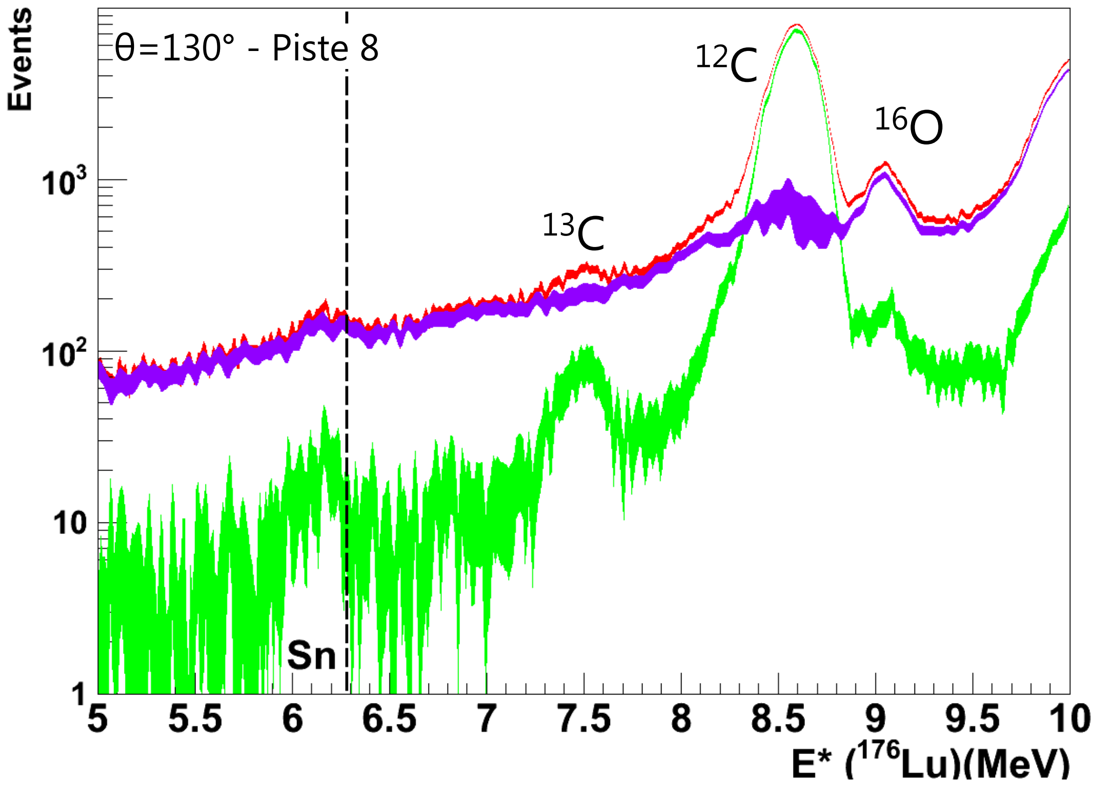
or

$$G_{decay}(E^*, J^\pi) = G_{decay}(E^*)$$

$N_{SINGLES}(E^*)$

Soustraction des contaminants:

- Réactions contaminantes avec le support en C et les impuretés (O).
- Les éjectiles émis dans ces réactions donne une mauvaise identification du noyau excité!

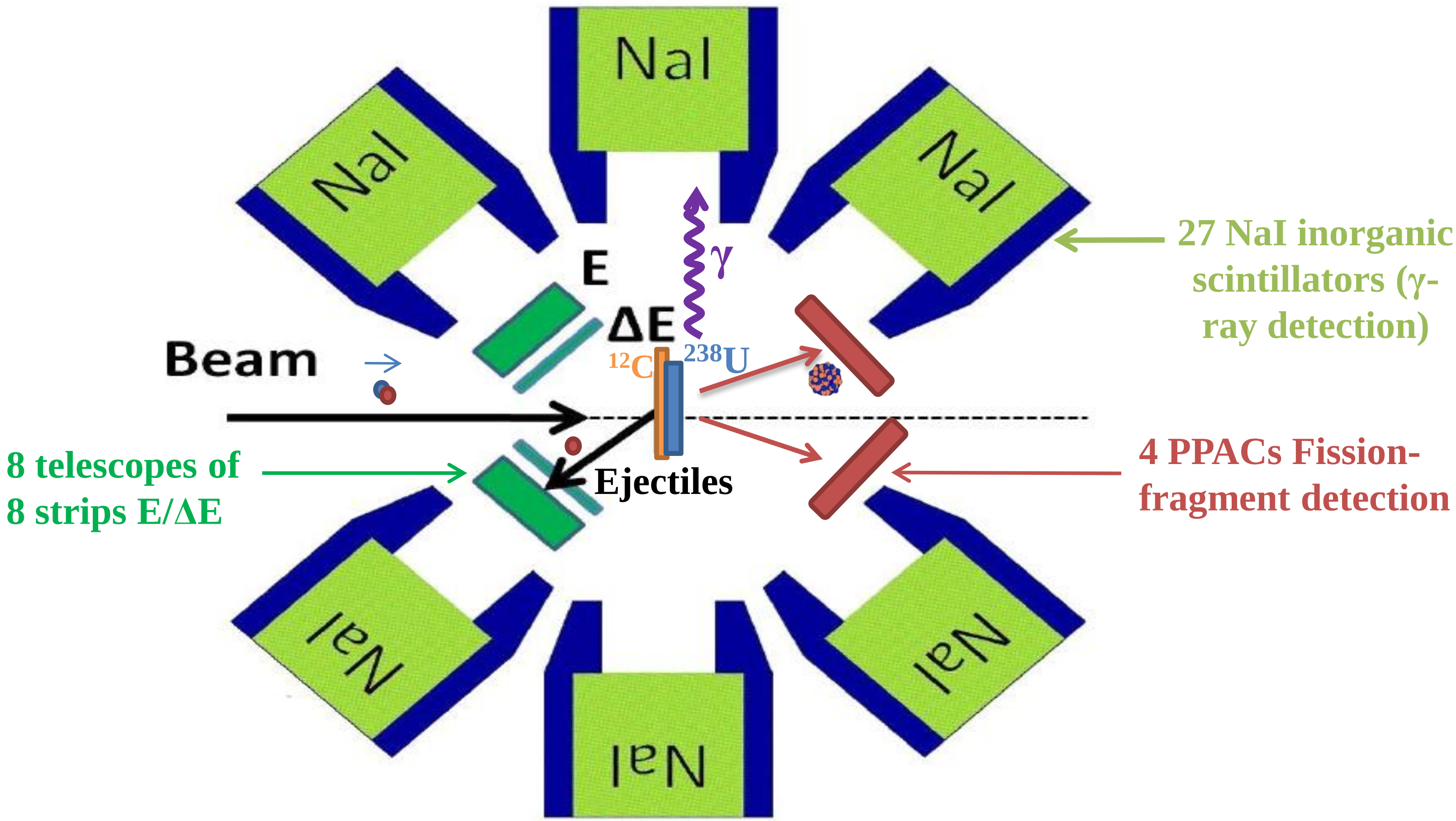


$N_{SINGLES}$ = $N_{SINGLES}$ brut - $N_{SINGLES}$ support C

→ Rejet systématique des zones contaminées par ^{12}C et ^{16}O.

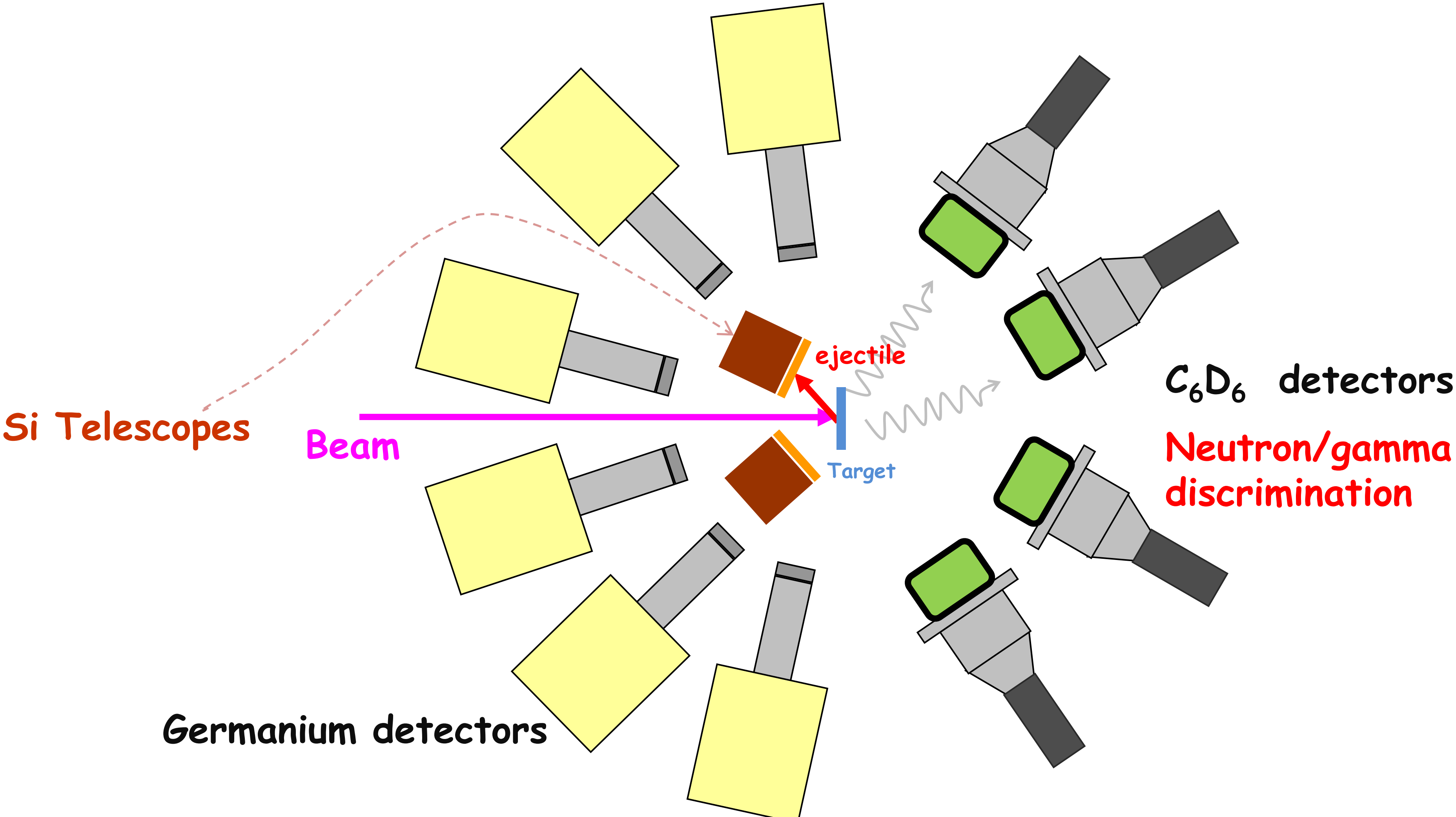
→ Bonne soustraction du ^{13}C dans la zone d'intérêt (S_n<E*<S_n+1 MeV)

Experimental set-up at the Oslo cyclotron



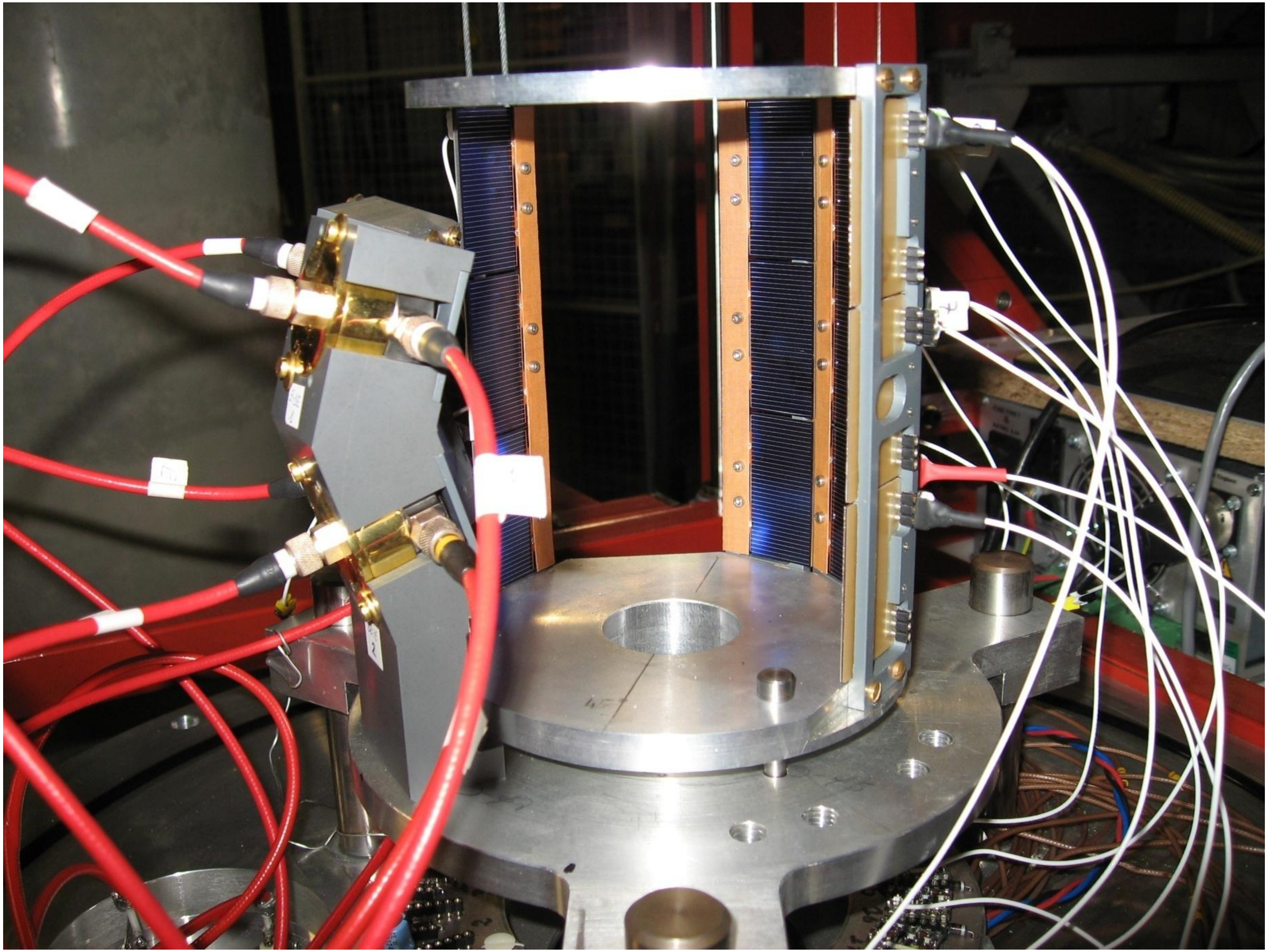
Simultaneous measurement of fission and gamma-decay probabilities!

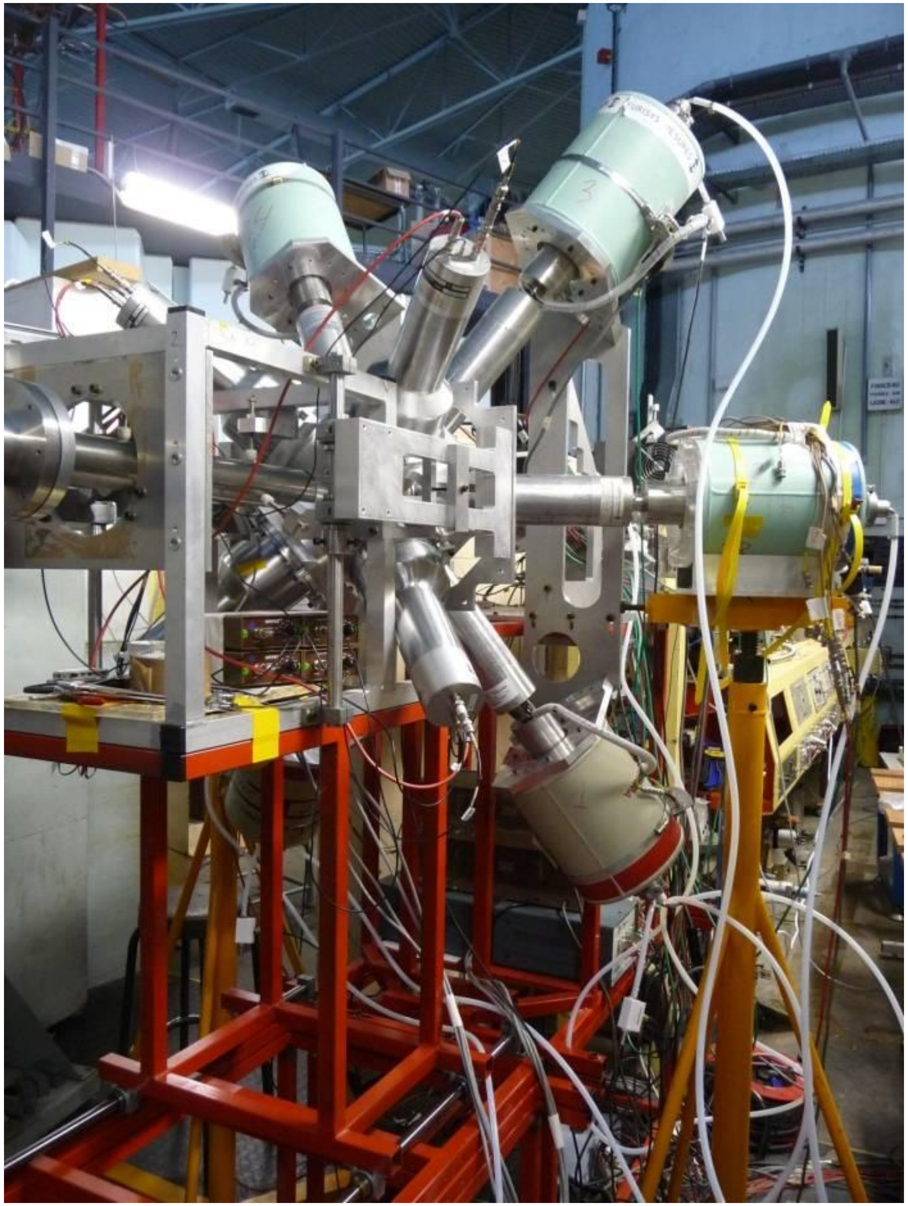
Experimental set-up for gamma-decay probability measurements at IPN Orsay



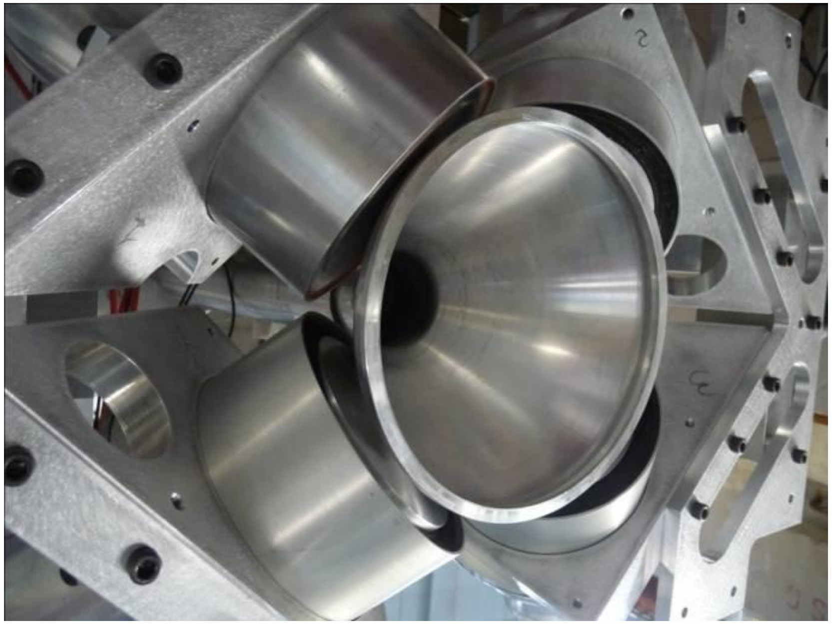
Ge --> verify the gamma-decay probabilities measured with the scintillators!
No gamma-ejectile coincidences coming from contaminants, from nucleus A-1!

Experimental set-up for fission

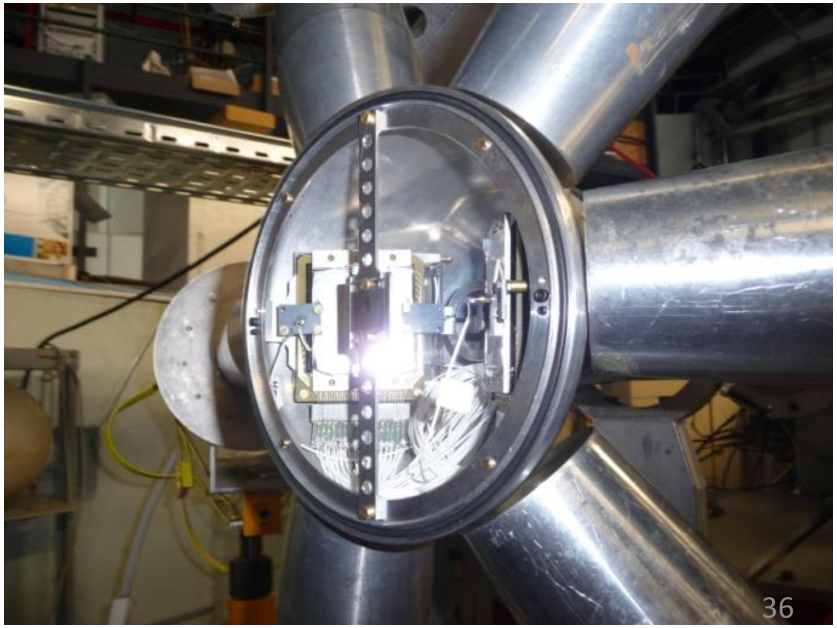




Dispositif expérimental
@ TANDEM (IPN Orsay, FRANCE)



Scintillateurs C6D6 x4



Détecteurs Germanium x6

Difficulties in the prediction of spin-parity distributions in surrogate reactions

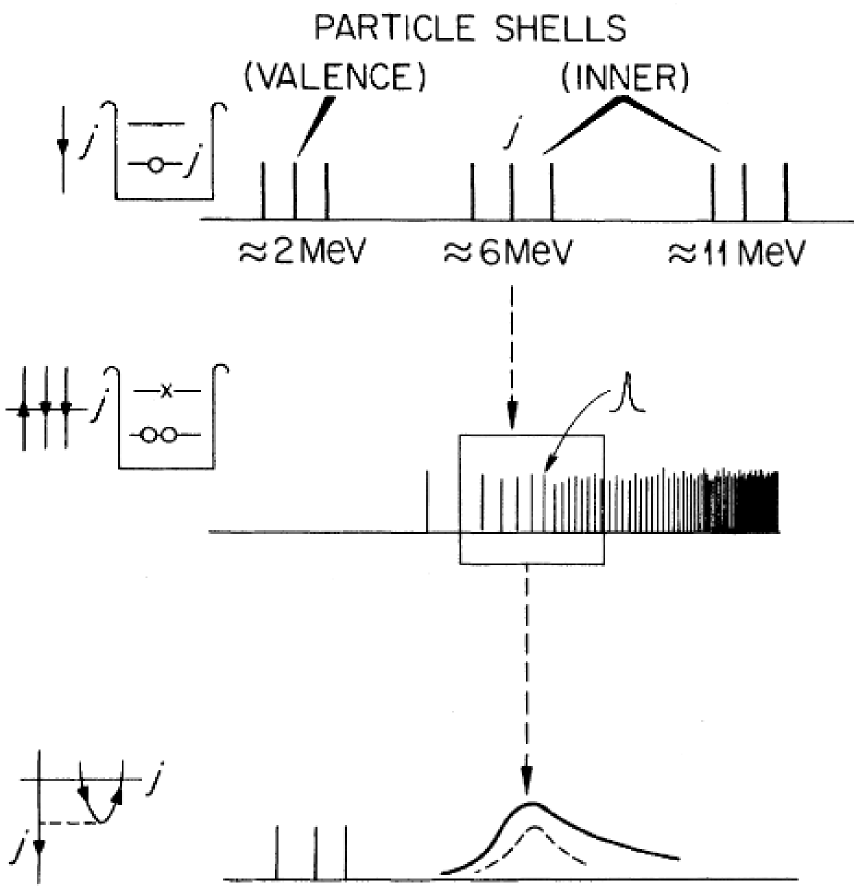


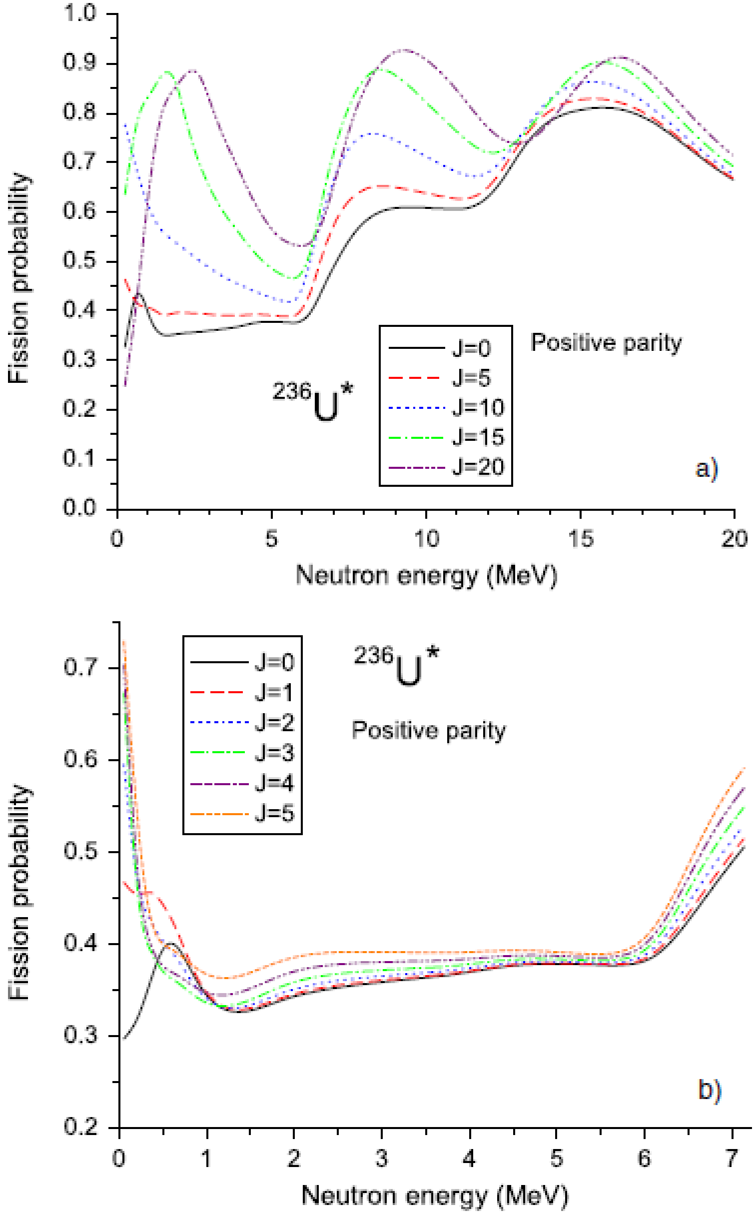
FIG. 4. Schematic illustration of the damping or spreading of the inner shell hole strength (top of figure) into the 2h-1p "sea" of levels (middle of figure) by the inelastic scattering of the hole state (bottom of figure).

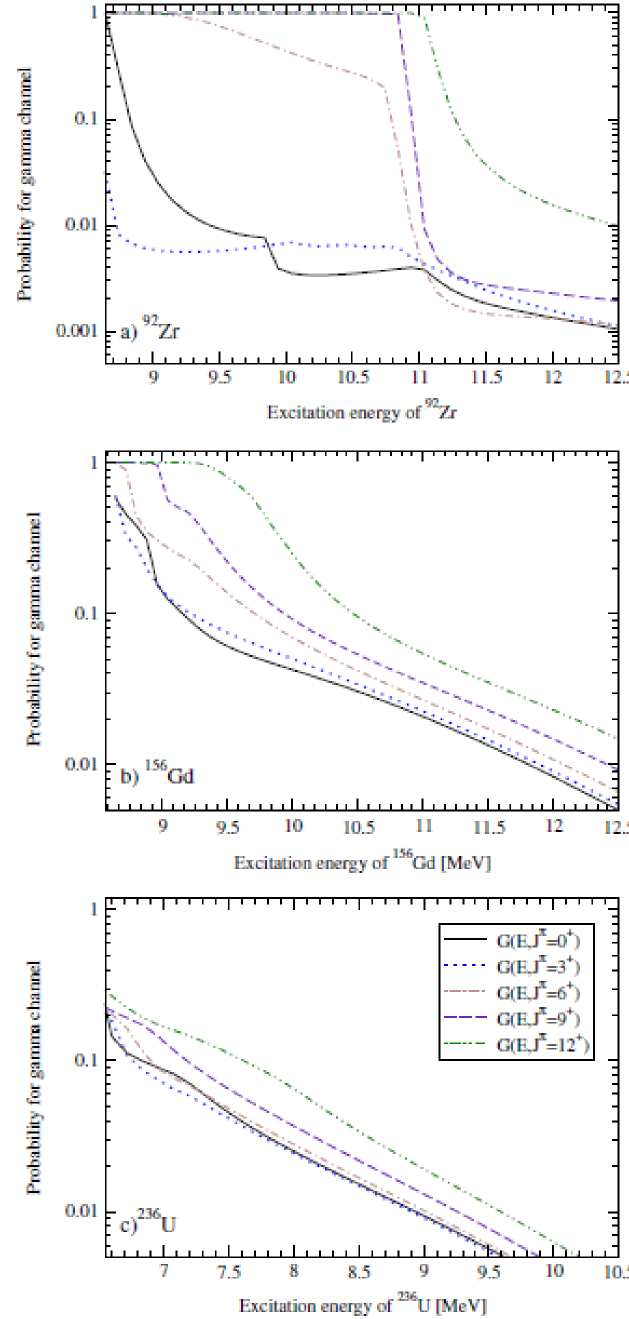
Population of single particle states by the surrogate reactions.
Structure information on unbound states in the continuum needed!

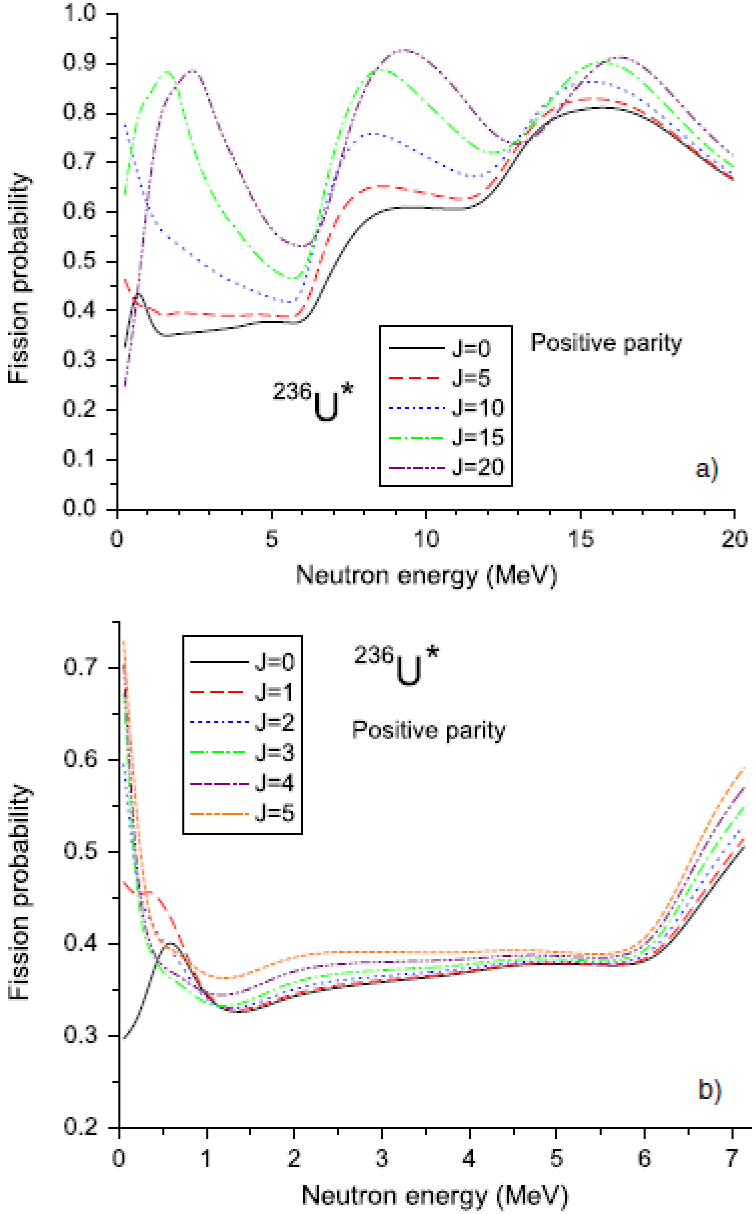
Residual interactions make these states decay into the other (many!) available states at the same energy

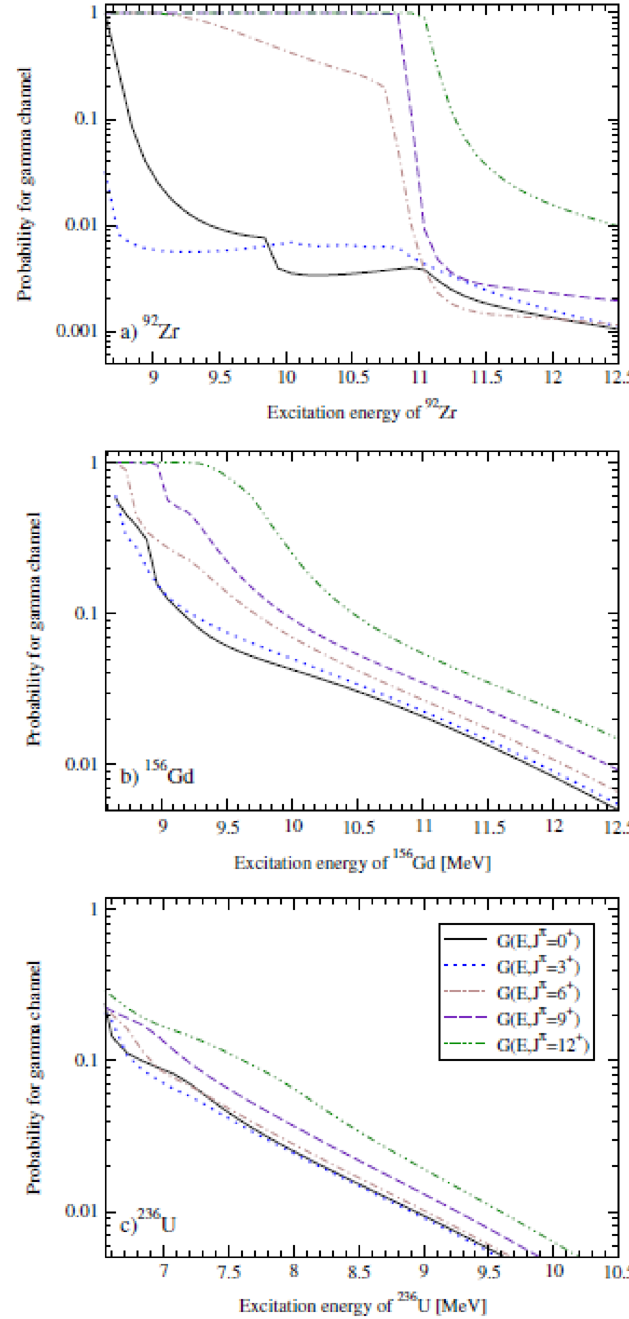
The initial single particle strength is fragmented!
Calculation very difficult!
In addition one has to calculate the probability that this damping leads to the formation of a compound state.

M.B. Lewis, Phys. Rev. C 11 (1975) 145

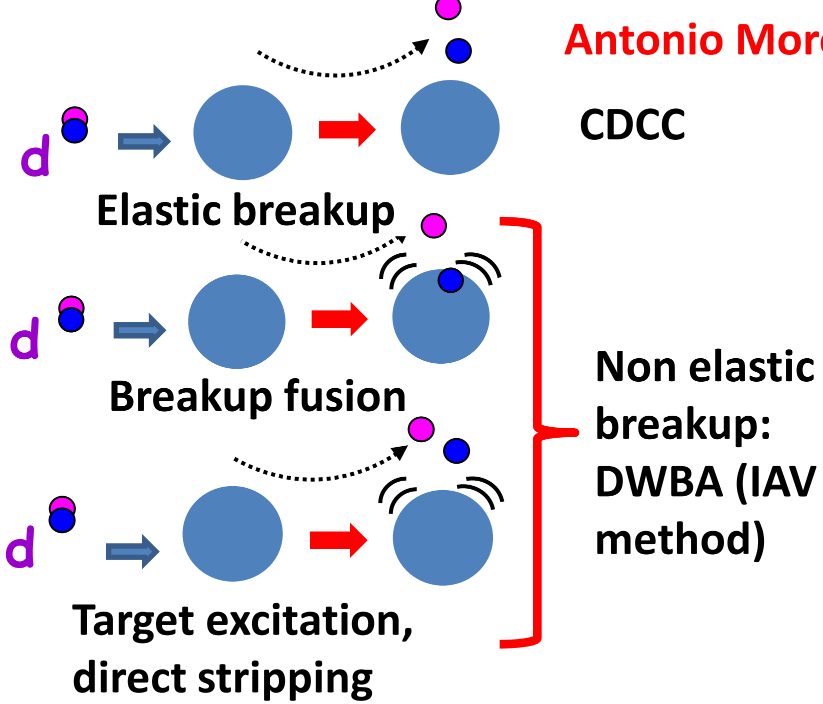

Fission probability
Neutron energy (MeV)
236U*
Positive parity
J=0
J=5
J=10
J=15
J=20
a)
J=0
J=1
J=2
J=3
J=4
J=5
b)

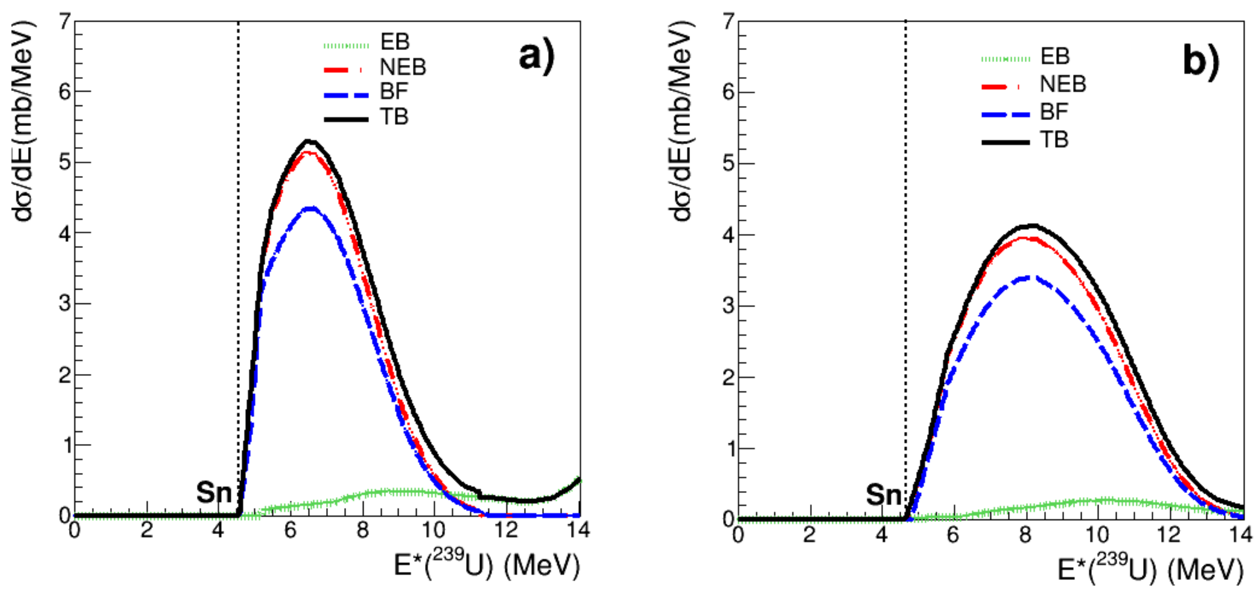

Probability for gamma channel
Excitation energy of 92Zr
a) 92Zr
Excitation energy of 156Gd [MeV]
b) 156Gd
Excitation energy of 236U [MeV]
c) 236U
G(E,J^π=0^+)
G(E,J^π=3^+)
G(E,J^π=6^+)
G(E,J^π=9^+)
G(E,J^π=12^+)

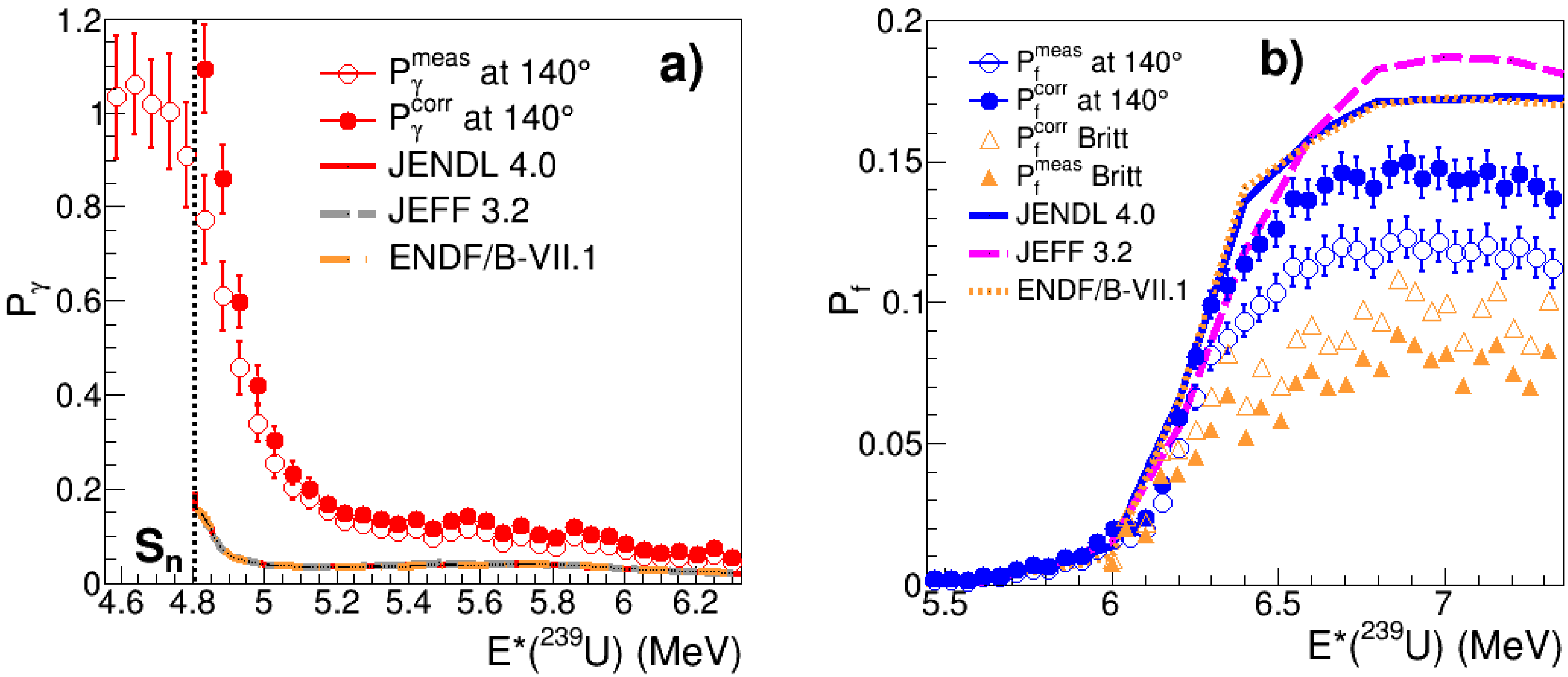

Fission probability
Neutron energy (MeV)
$^{236}U^*$
Positive parity
J=0
J=5
J=10
J=15
J=20
a)
J=0
J=1
J=2
J=3
J=4
J=5
b)


Probability for gamma channel
a) ^{92}Zr
Excitation energy of ^{92}Zr
b) ^{156}Gd
Excitation energy of ^{156}Gd [MeV]
c) ^{236}U
Excitation energy of ^{236}U [MeV]
$G(E, J^\pi=0^+)$
$G(E, J^\pi=3^+)$
$G(E, J^\pi=6^+)$
$G(E, J^\pi=9^+)$
$G(E, J^\pi=12^+)$

Antonio Moro and Jin Lei, Univ. of Sevilla, Spain







a)
P_γ^{meas} at 140°
P_γ^{corr} at 140°
JENDL 4.0
JEFF 3.2
ENDF/B-VII.1
S_n
P_γ
E*(^{239}U) (MeV)
b)
P_f^{meas} at 140°
P_f^{corr} at 140°
P_f^{corr} Britt
P_f^{meas} Britt
JENDL 4.0
JEFF 3.2
ENDF/B-VII.1
P_f
E*(^{239}U) (MeV)

Excitation-energy sharing between CN and ejectile

3He, t, d, p have no bound excited state. 4He first excited state at 20 MeV

When we detect these ejectiles they are in the ground state

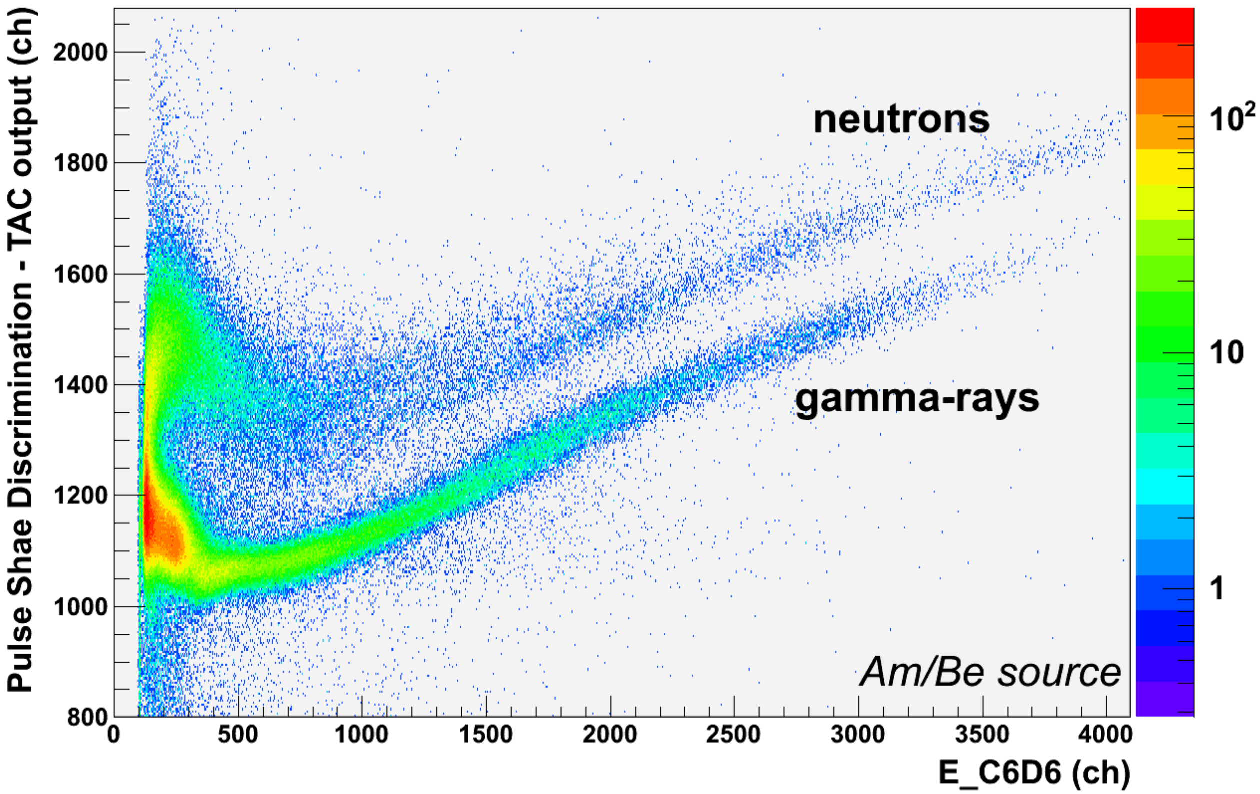
For Eproj ~ 24 MeV and detecting ejectiles at backward angles

No polution of (3He,d) channel observed. Demonstrated by Gavron et al. by comparing fission probabilities of the same compound nucleus formed in (3He,t) and (3He,d) reactions.

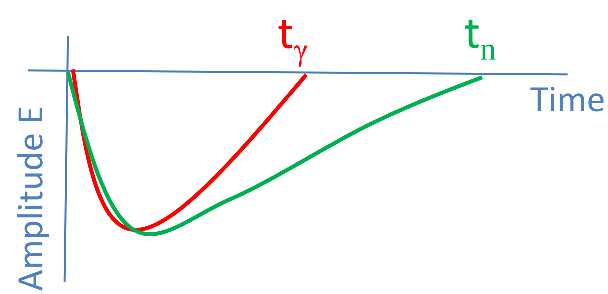
$$P_\gamma(E^*) = \frac{N_{p-\gamma}(E^*)}{N_p(E^*) \cdot \varepsilon_\gamma(E^*)}$$

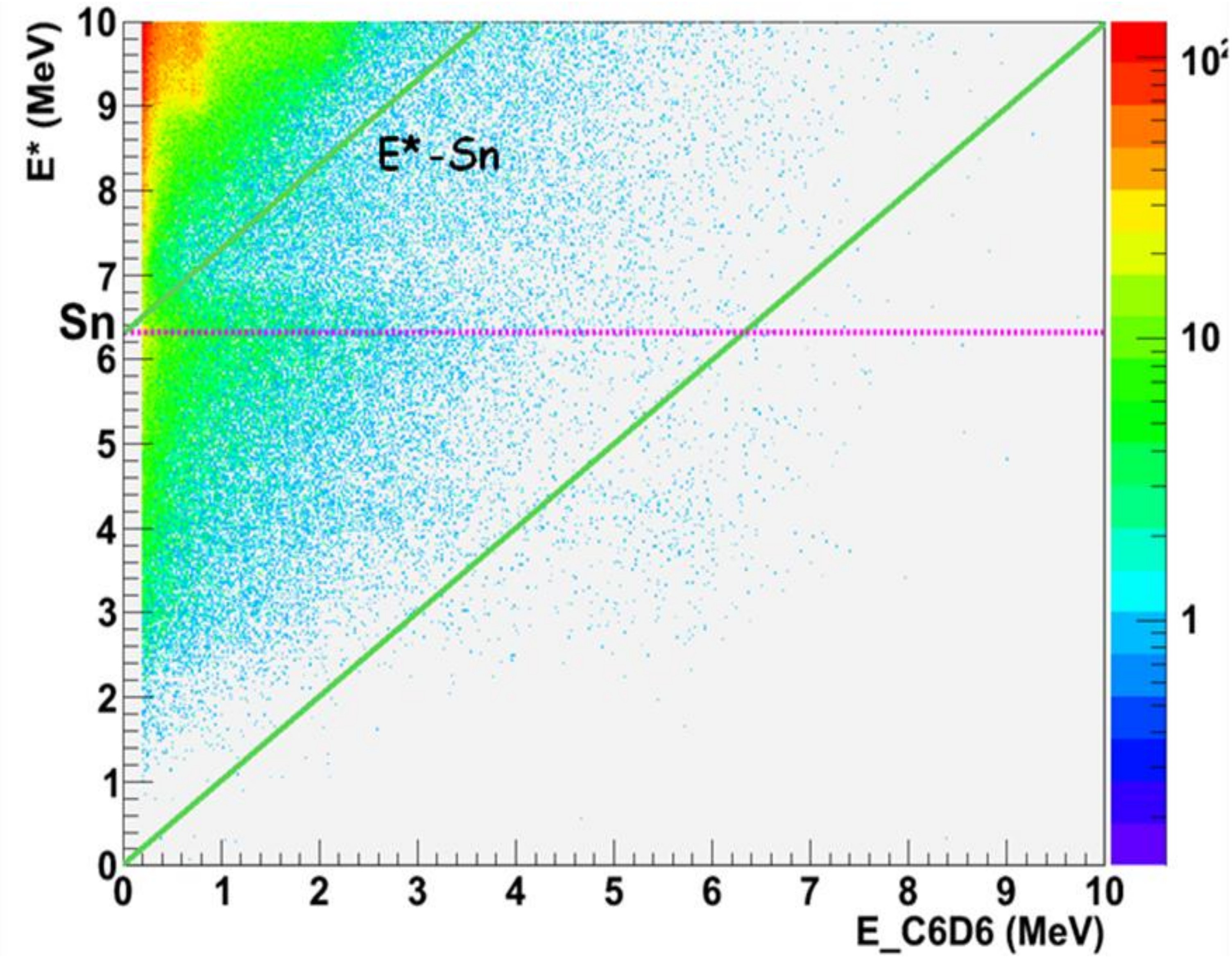
→ Neutrons thermiques:
D minimize les captures neutronique au sein même du scintillateur

Identifier la particule qui intéragit dans le scintillateur
→ **Discrimination n-γ**

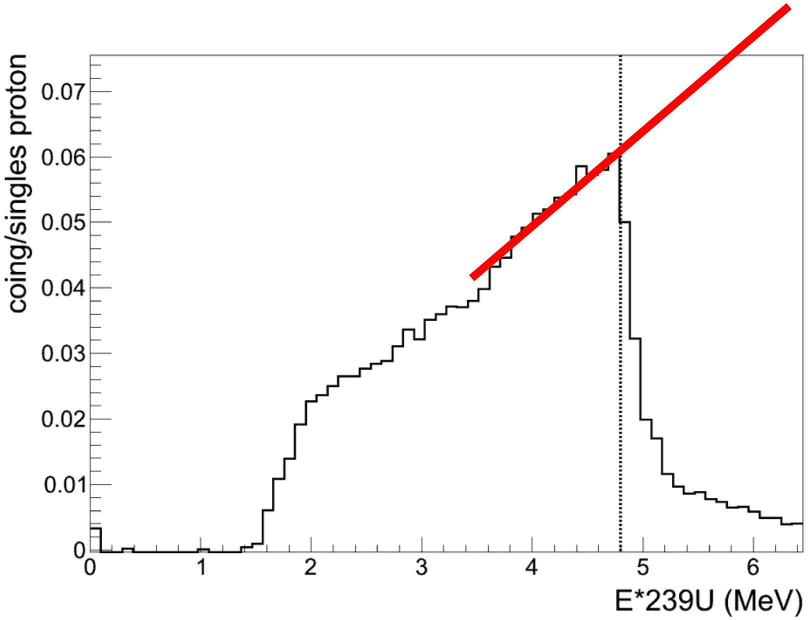


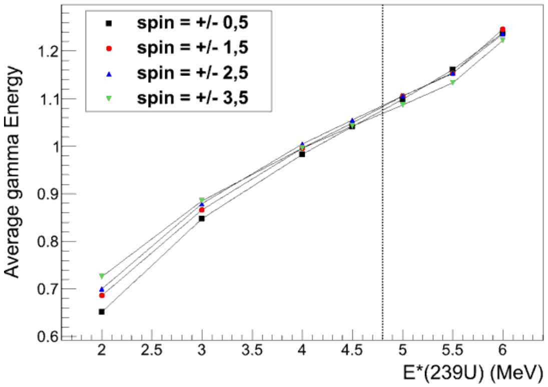
→ Neutrons rapides:
Séparation par analyse de forme (temps de relaxation du signal)

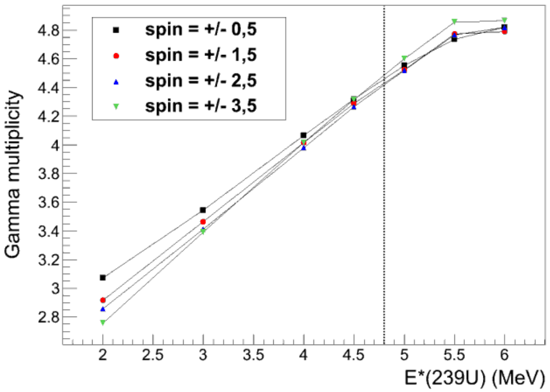



E* (MeV)
E*-Sn
Sn
E_C6D6 (MeV)
0
1
2
3
4
5
6
7
8
9
10
1
10

EXtrapolation Efficiency Method (EXEM)







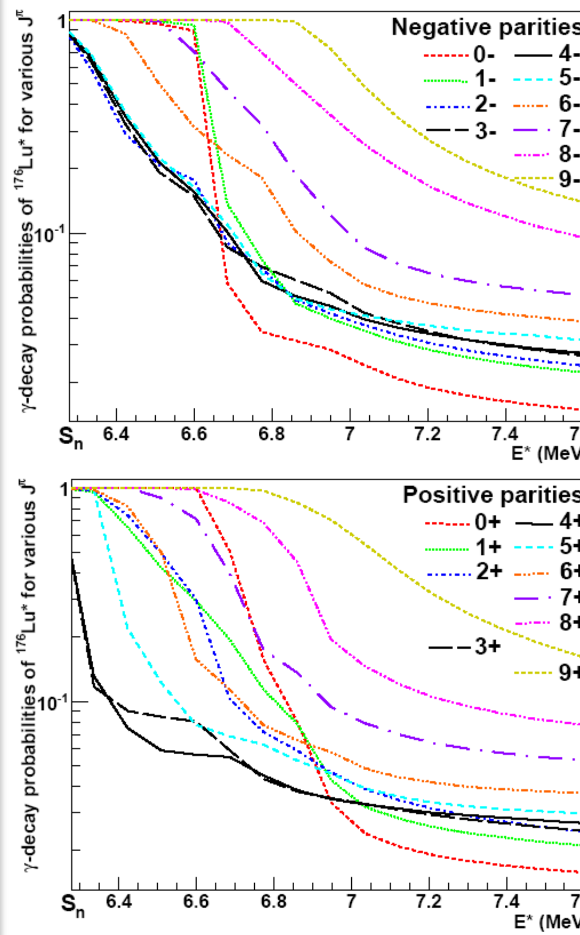
$$P_{\chi}(E^*) = \sum_{J^{\pi}} F_s^{CN}(E^*, J^{\pi}) \cdot G_{\chi}(E^*, J^{\pi})$$

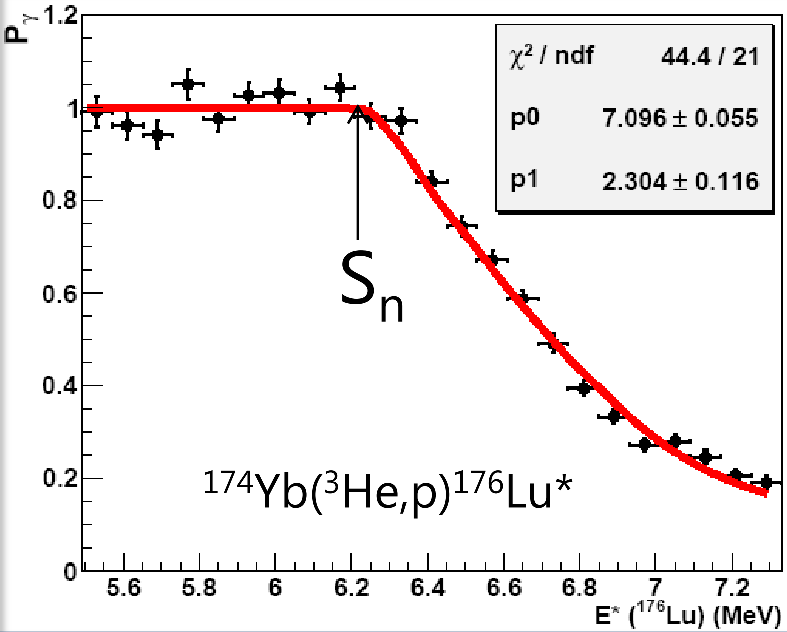
FIT

Distribution de spin modélisée par une gaussienne indépendante de l'E*

$$\frac{0.5}{\sqrt{2\pi\sigma}} e^{-\frac{(J-\bar{J})^2}{2\sigma^2}}$$

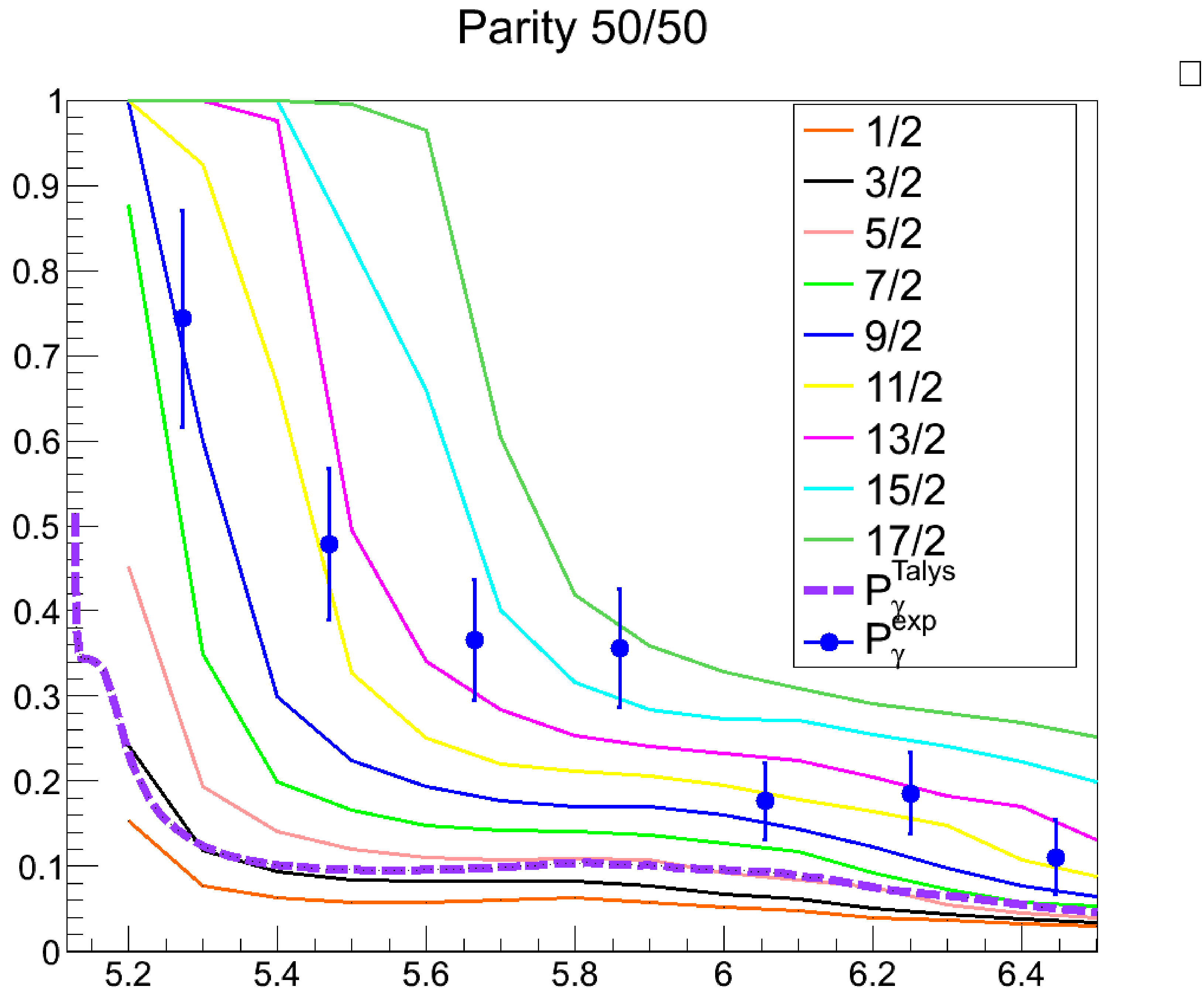
Rapport d'embranchement calculé avec TALYS





<J> = 7 ħ

σ = 2.3 ħ



Parity 50/50
1/2
3/2
5/2
7/2
9/2
11/2
13/2
15/2
17/2
P_γ^{Talys}
P_γ^{exp}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
5.2
5.4
5.6
5.8
6
6.2
6.4

Conditions T1/2>10 microsecs DE>30 keV
Possible isomers:
234Pa: GS, 4+, 6.7 h
234mPa: 74 keV, 0-, 1.1. m

216Th: GS, 0+, 26.0 ms
216mTh: 2.0400 MeV, 8+, 134 µS

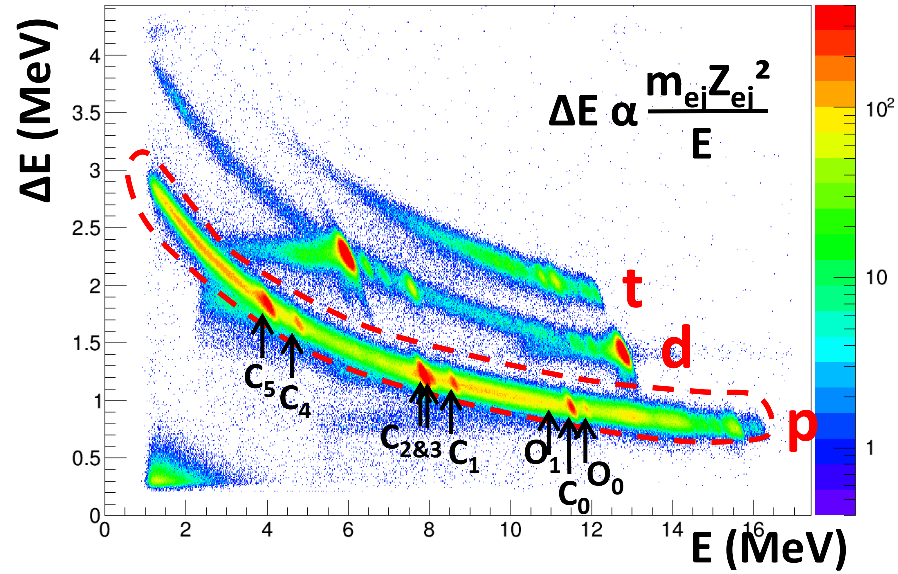
213Ra : GS, 1/2- ,2.73 m
213mRa : 1.7700 MeV, 17/2-, 2.20 ms

III) Mesures des probabilités d'émission gamma et de fission

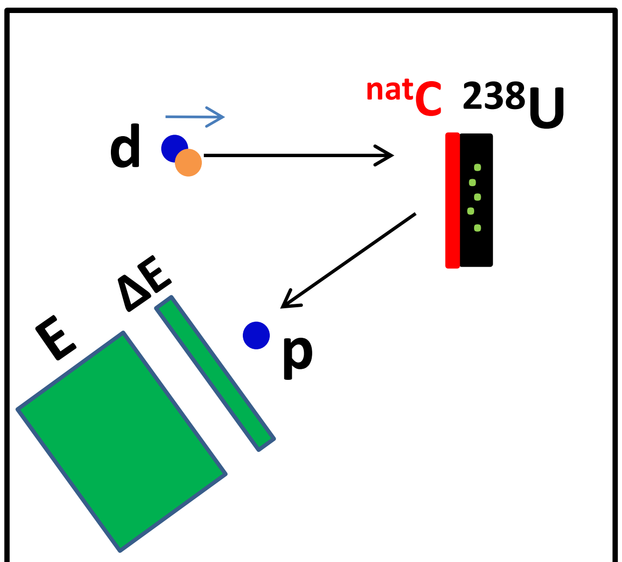
Analyse des données : détermination de $P_{s,\chi}(E^*) = N_{\chi}^{coinc}(E^*) / N_{éj}(E^*).\varepsilon_{\chi}(E^*)$

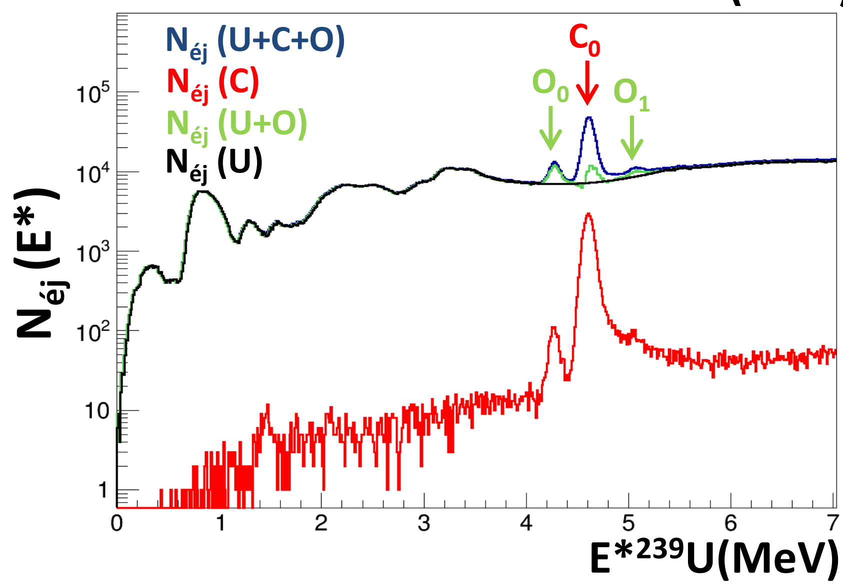
- Identification du noyau composé associé à la voie de substitution grâce à la matrice d'identification des éjectiles
- Cinématique des réactions de transfert :

  $E^*(^{239}U) = E_{faisceau} + Q - E_{recul}(m_{ej}, \Theta_{ej}) - E_{ej}$



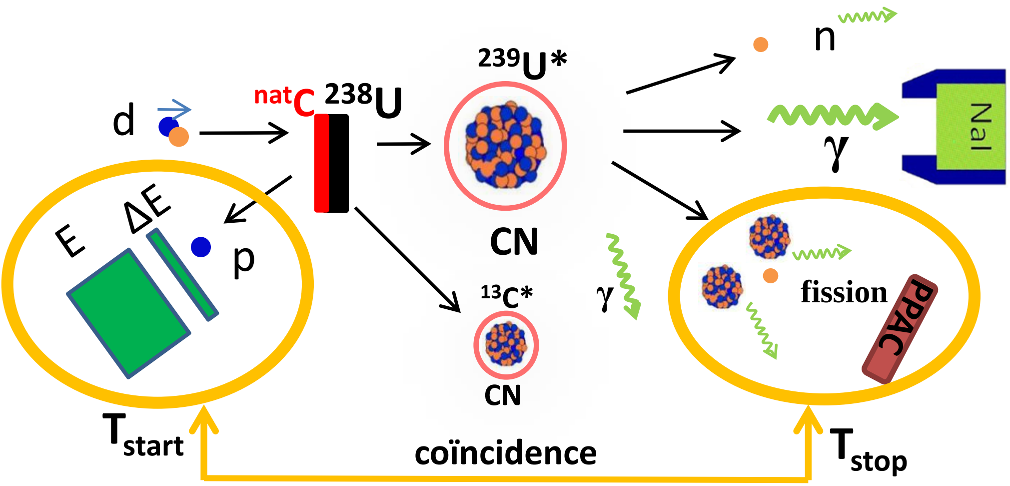
Soustraction du fond Carbone et de la contamination à l'oxygène

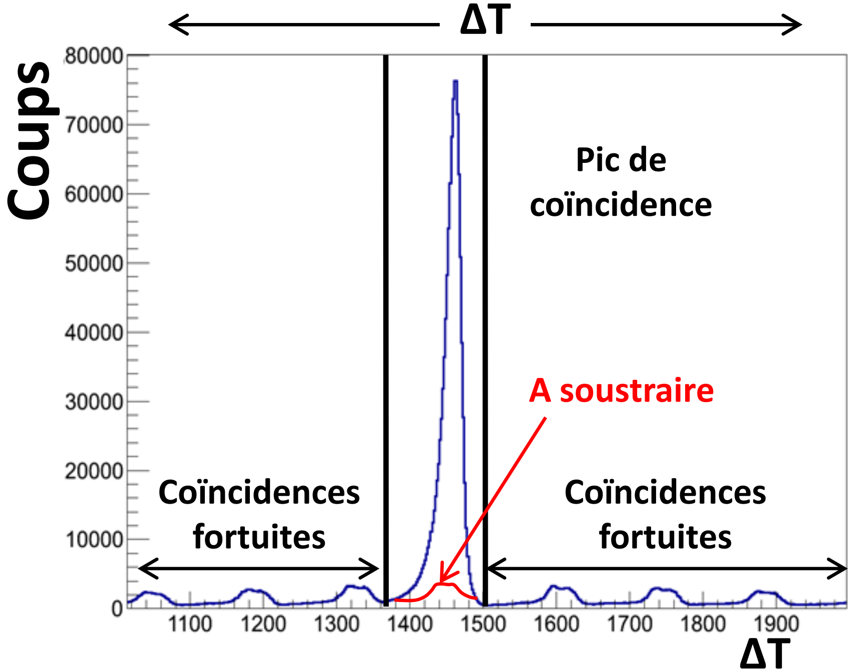


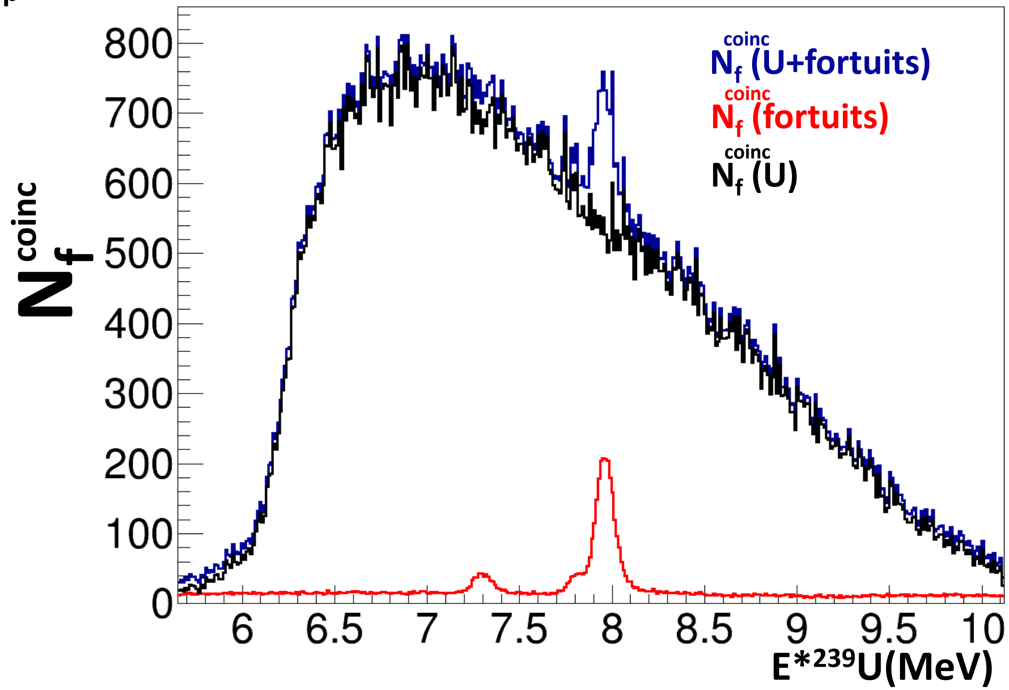


III) Mesures des probabilités d'émission gamma et de fission

Analyse des données : détermination de $P_{s,f}(E^*) = N_f^{coinc}(E^*) / N_{éj}(E^*).\varepsilon_f(E^*)$







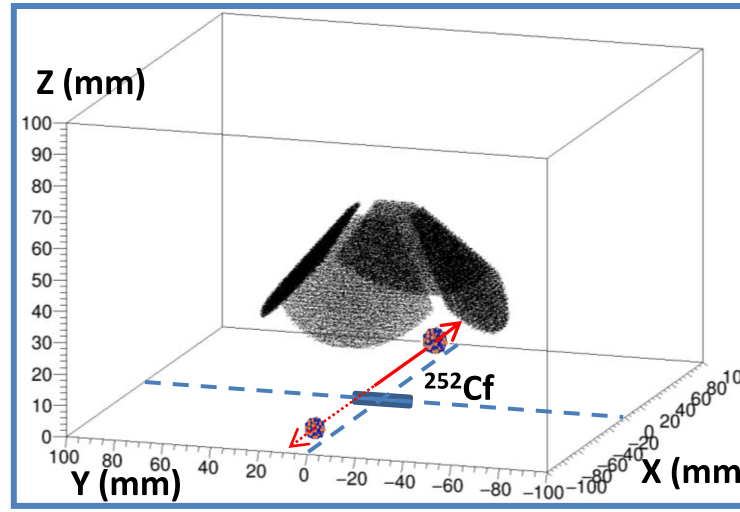
III) Mesures des probabilités d'émission gamma et de fission

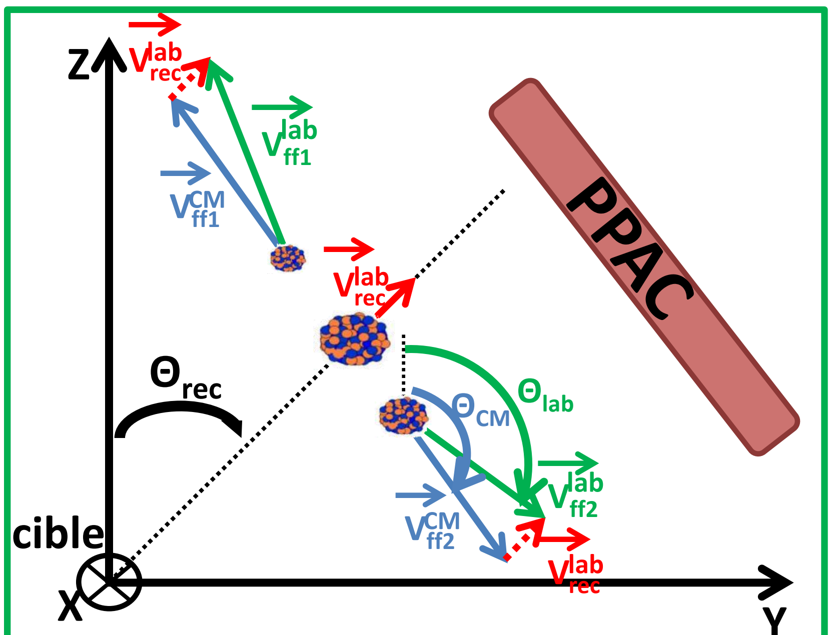
Analyse des données : détermination de $P_{s,f}(E^*) = N_f^{coinc}(E^*) / N_{éj}(E^*).\varepsilon_f(E^*)$

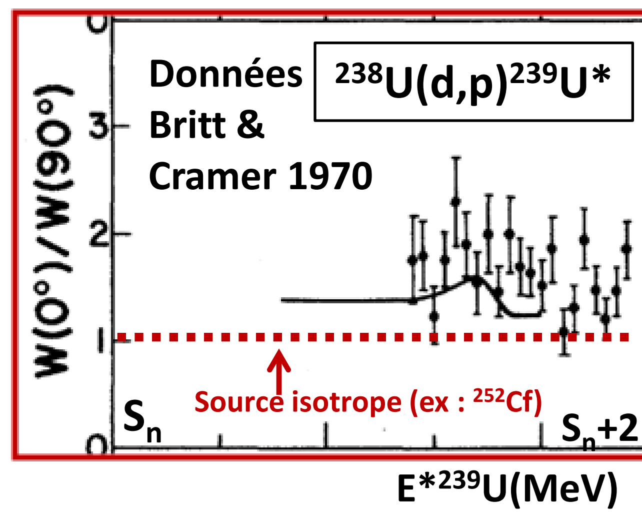
$$\varepsilon_f^{tot} = f(\varepsilon_f^{géo}, \varepsilon_f^{anisotropie}, \varepsilon_f^{entrainement})$$

48 % = 41 % + 4 % (1-7%) + 3 %

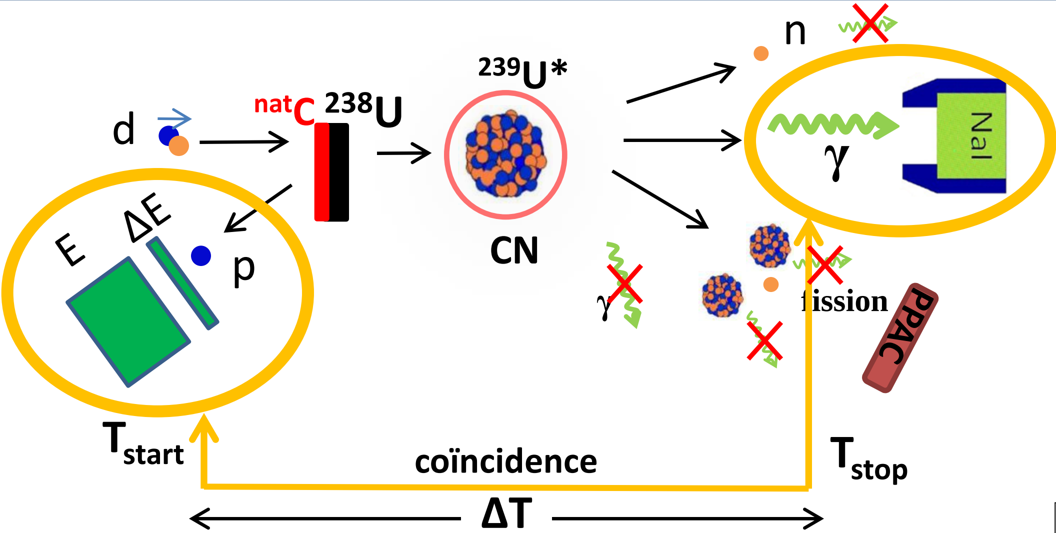
- Mesure de $\varepsilon_f^{géo}$ avec une source isotrope d'émission de fragments de fission de ^{252}Cf d'activité connue → Simulation
- Inclusion de $\varepsilon_f^{anisotropie}$ dans le Centre de Masse (CM) dans la simulation avec les données de Britt et Cramer
- Inclusion de $\varepsilon_f^{entrainement}$ dans la simulation en prenant en compte l'effet d'entrainement du noyau de recul







Analyse des données : détermination de $P_{s,\gamma}(E^*) = N_\gamma^{coinc}(E^*) / N_{éj}(E^*).\varepsilon_\gamma(E^*)$



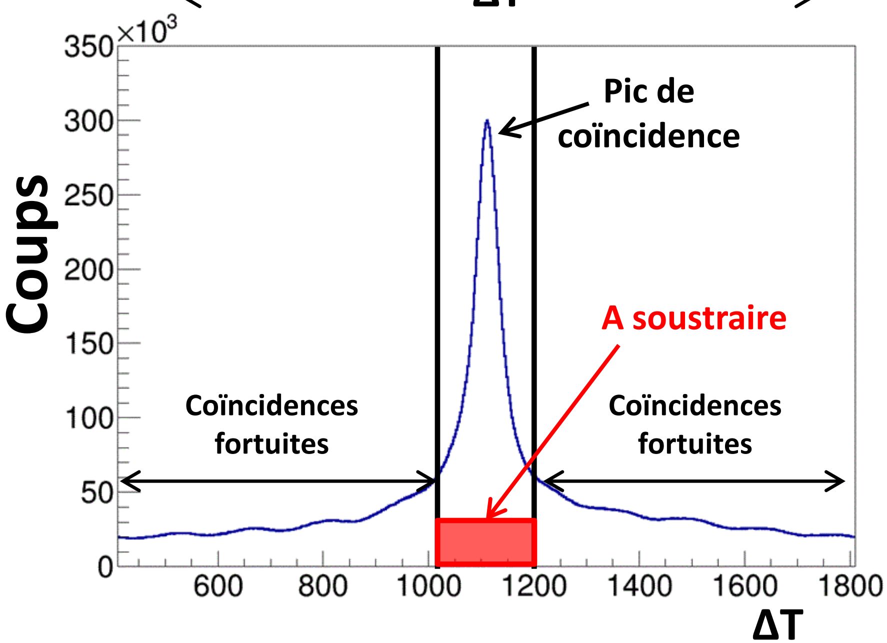
Suppression des gammas « **post-neutron** »

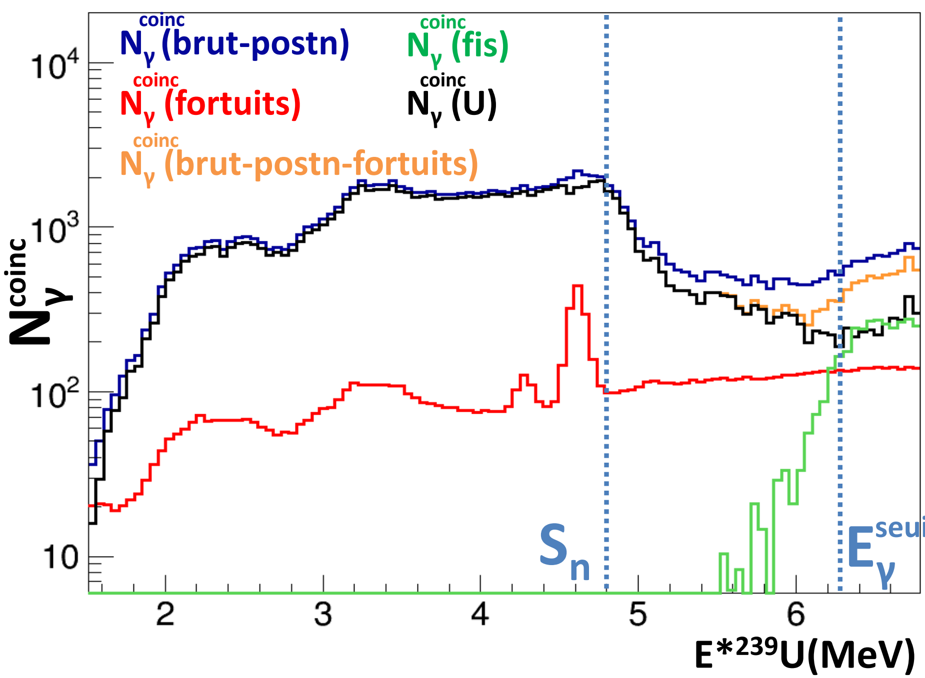
$E_{\gamma,post-n}^{max} = E^*-S_n$

$\Rightarrow E_\gamma^{seuil} = E_{\gamma,post-n}^{max} = 1,5$ MeV

Suppression des coïncidences **fortuites**

Suppression des gammas de **fission**





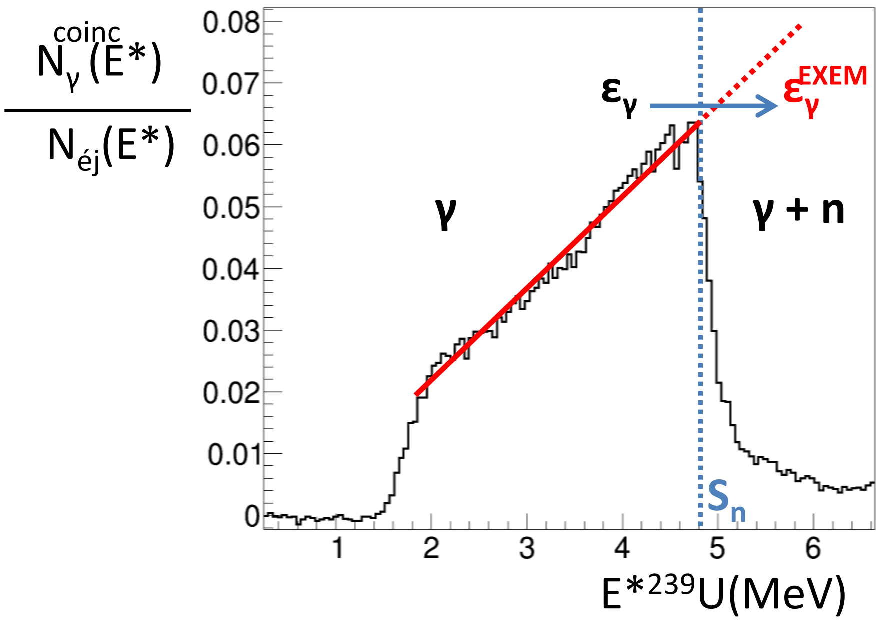
III) Mesures des probabilités d'émission gamma et de fission

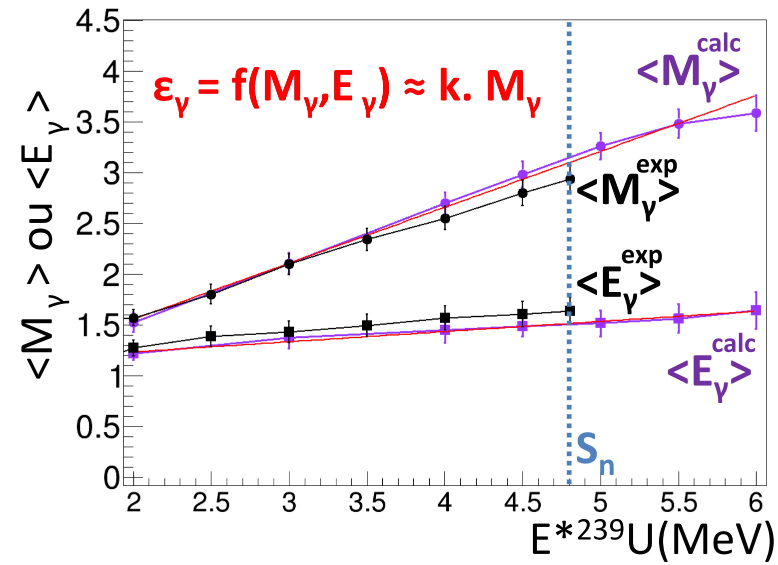
Analyse des données : détermination de $P_{s,\gamma}(E^*) = N_\gamma^{coinc}(E^*) / N_{éj}(E^*).\varepsilon_\gamma(E^*)$

Méthode EXEM (EXtrapolated Efficiency Method) :

$$P_\gamma(E^*) = \frac{N_\gamma^{coinc}(E^*)}{N_{éj}(E^*) \times \varepsilon_\gamma(E^*)} = 1 \text{ (pour } E^* < S_n) \Rightarrow \varepsilon_\gamma(E^*) = \frac{N_\gamma^{coinc}(E^*)}{N_{éj}(E^*)}$$

Hypothèse de la méthode : la tendance de $\varepsilon_\gamma(E^*)$ se poursuit à plus haute E*





- **Les calculs EVITA basés sur le modèle statistique confortent l'hypothèse de la méthode**
- **Méthode EXEM validée par le calcul de $\varepsilon_\gamma(E^*)$ par la méthode des fonctions de poids**