Centre d'Etudes Nucléaires de Bordeaux-Gradignan
Groupe Aval du Cycle et Energie Nucléaire

CEA-Cadarache

5TH WORKSHOP ON NUCLEAR LEVEL DENSITY AND GAMMA STRENGTH

Neutron-induced cross sections of ^{236}U, ^{238}U, ^{237}Np and ^{238}Np via the surrogate reaction method

Q. Ducasse[1,6], B. Jurado[1], M. Aiche[1], L. Mathieu[1], T.Tornyi[2], A. Goergen[2], J. N. Wilson[3], G. Boutoux [5], I. Companis[1], S. Czajkowski[1], F. Giacoppo[2], F. Gunsing[3], M. Guttormsen[2], A. C. Larsen[2], M. Lebois[4], J. Matarranz[1], V. Méot [5],T. Renstrom[2], O. Roig[5], S. Rose[2], O. Serot[6], S. Siem[2], I. Tsekhanovich[1], G. M. Tveten[2], T. Wiborg-Hagen[2], M. Wiedeking[7]

1)CENBG, Bordeaux, France
2)University of Oslo, Norway
3)IPN, Orsay, France
4)CEA/Saclay, Gif-sur-Yvette, France
5)CEA/DAM, Arpajon, France
6)CEA/Cadarache, Saint Paul lez Durance, France
7) iThemba LABS, Somerset West, South Africa

Outline of my talk

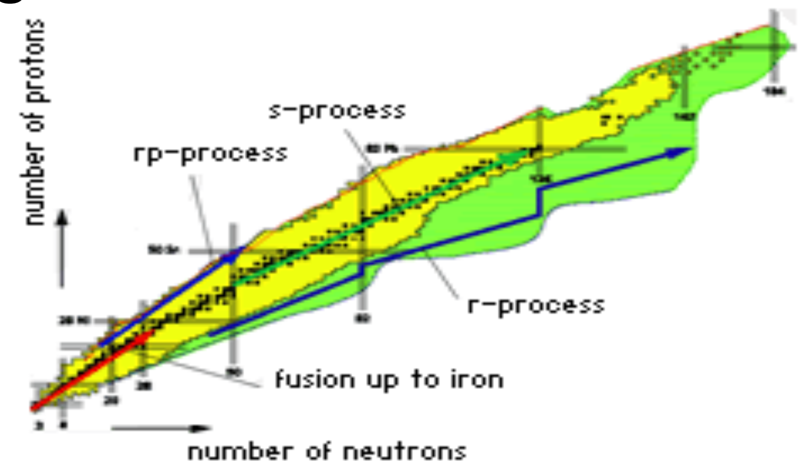
Motivation

Importance of neutron-induced cross sections of short lived nuclei:

➢Fundamental nuclear physics

➢Reactor physics

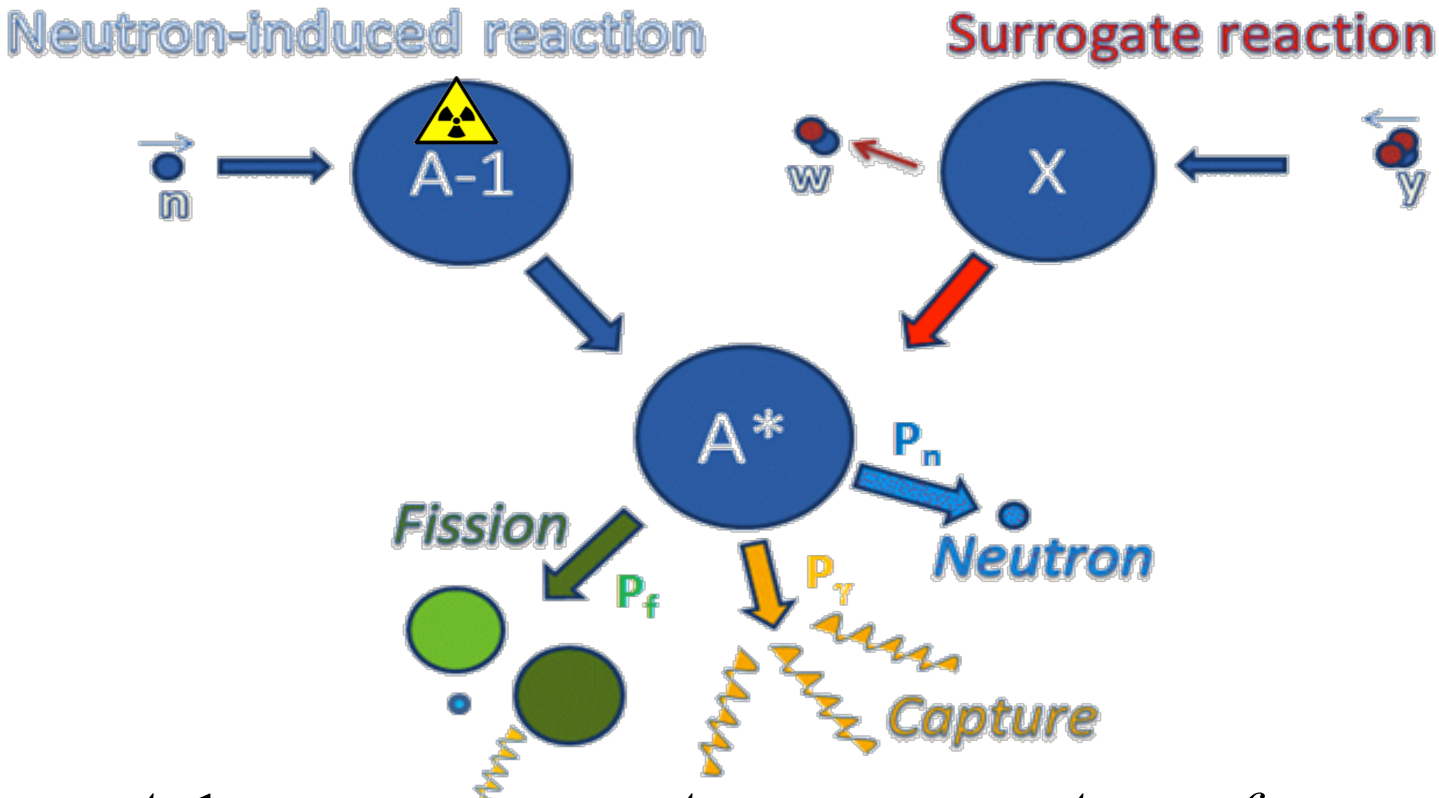
➢Stellar nucleosynthesis via r or s processes



BUT these neutron-induced cross sections of short lived nuclei extremely difficult to obtain due to the radioactivity of the targets involved.

Surrogate reaction

Surrogate Experiment : principle



$$\sigma_{decay}^{A-1}(En) \cong \sigma_{CN}^{A}(En).P_{decay}^{A,transfer}(E^*)$$

Calculated
(Optical model)

Measured

J.D. Cramer et H.C. Britt, Nucl. Sci. And Eng. 41 (1970) 177

Surrogate Experiment : validity & objective

$$\sigma_{decay}^{A-1}(En) \cong \underbrace{\sigma_{CN}^{A}(En)}_{\text{Calculated (Optical model)}} . \underbrace{P_{decay}^{A,transfer}(E^*)}_{\text{Measured}}$$

Calculated
(Optical model)

Measured

Surrogate reaction only valid if :

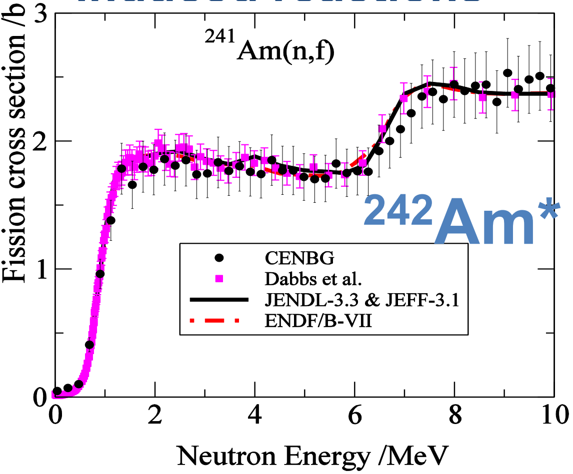
- **Compound nucleus formation**
- **$P_{decay}^{n\text{-}induced} \approx P_{decay}^{surrogate} \rightarrow$ Similar J^{π} distribution or no dependence on J^{π} (Weisskopf-Ewing limit)**

Objective :

- **Validity of surrogate method by comparing surrogate data to known n-induced data.**

Surrogate Experiment : Recent work

Comparison surrogate/neutron induced reactions



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

Examples of surrogate reactions performed since 2004

Fission

OK !

Example

Capture

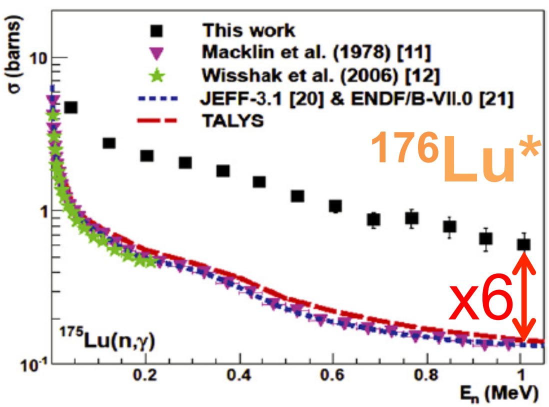
NOT OK !

Example

Desired reaction	E_n range (MeV)	Surrogate reaction	Type	Reference
		(n, f) cross sections		
^{230}Th(n, f)	0.5–10	^{232}Th(^{3}He, α))	absolute	Petit *et al.* (2004)
^{230}Th(n, f)	0.22–25	^{232}Th(^{3}He, α))	ratio	Goldblum *et al.* (2009)
^{231}Th(n, f)	0.36–25	^{232}Th(^{3}He, ^{3}He′)	ratio	Goldblum *et al.* (2009)
^{231}Pa(n, f)	0.5–10	^{232}Th(^{3}He, t)	absolute	Petit *et al.* (2004)
^{233}Pa(n, f)	0.5–10	^{232}Th(^{3}He, p)	absolute	Petit *et al.* (2004)
^{233}Pa(n, f)	11.5–16.5	^{232}Th(^{6}Li, α)	ratio	Nayak *et al.* (2008)
^{233}U(n, f)	0.4–18	^{234}U(α, α')	ratio	Lesher *et al.* (2009)
^{236}U(n, f)	0–20	^{238}U(^{3}He, α)	absolute, ratio	Lyles *et al.* (2007a)
^{237}U(n, f)	0–13	^{238}U(d, d')	ratio	Plettner *et al.* (2005)
^{237}U(n, f)	0–20	^{238}U(α, α')	ratio	Burke *et al.* (2006)
^{239}U(n, f)	0–20	^{238}U(^{18}O, ^{16}O)	ratio	Burke *et al.* (2011)
^{237}Np(n, f)	10–20	^{238}U(^{3}He, t)	absolute, ratio	Basunia *et al.* (2009)
^{238}Pu(n, f)	0–20	^{239}Pu(α, α')	ratio	Ressler *et al.* (2011)
^{241}Am(n, f)	0–10	^{243}Am(^{3}He, α)	absolute	Kessedjian *et al.* (2010)
^{242}Cm(n, f)	0–10	^{243}Am(^{3}He, t)	absolute	Kessedjian *et al.* (2010)
^{243}Cm(n, f)	0–3	^{243}Am(^{3}He, d)	absolute	Kessedjian *et al.* (2010)
		(n, γ) cross sections		
^{155}Gd(n, γ)	0.05–3.0	^{156}Gd(p, p')	absolute, ratio	Scielzo *et al.* (2010)
^{157}Gd(n, γ)	0.05–3.0	^{158}Gd(p, p')	absolute, ratio	Scielzo *et al.* (2010)
^{161}Dy(n, γ)	0.13–0.56	^{162}Dy(^{3}He, ^{3}He′)	ratio	Goldblum *et al.* (2010)
^{170}Yb(n, γ)	0.165–0.405	^{171}Yb(^{3}He, ^{3}He′)	ratio	Goldblum *et al.* (2008)
^{170}Yb(n, γ)	0.225–0.465	^{172}Yb(^{3}He, α)	ratio	Goldblum *et al.* (2008)
^{171}Yb(n, γ)	0.12–0.24	^{171}Yb(d, p)	ratio	Hatarik *et al.* (2010)
^{233}Pa(n, γ)	0–1	^{232}Th(^{3}He, p)	absolute	Boyer *et al.* (2006)
^{235}U(n, γ)	0.9–3.3	^{235}U(d, p)	ratio	Allmond *et al.* (2009)
^{237}U(n, γ)	0.2–1.0	^{238}U(α, α')	absolute, ratio	Bernstein *et al.* (2006);
^{232}Th(n,γ)	0-1.2	^{232}Th(d,p)	absolute	J. Wilson et al. (2012)
^{175}Lu(n,γ)	0-1	^{174}Yb(^{3}He,p)	absolute	G. Boutoux et al. (2012)
^{172}Yb(n ,γ)	0-1	^{174}Yb(^{3}He,α)	absolute	G. Boutoux et al. (2012)

Jutta Escher, et al., Rev. Mod. Phys. 84 (2012) 353

Rare earth nucleus



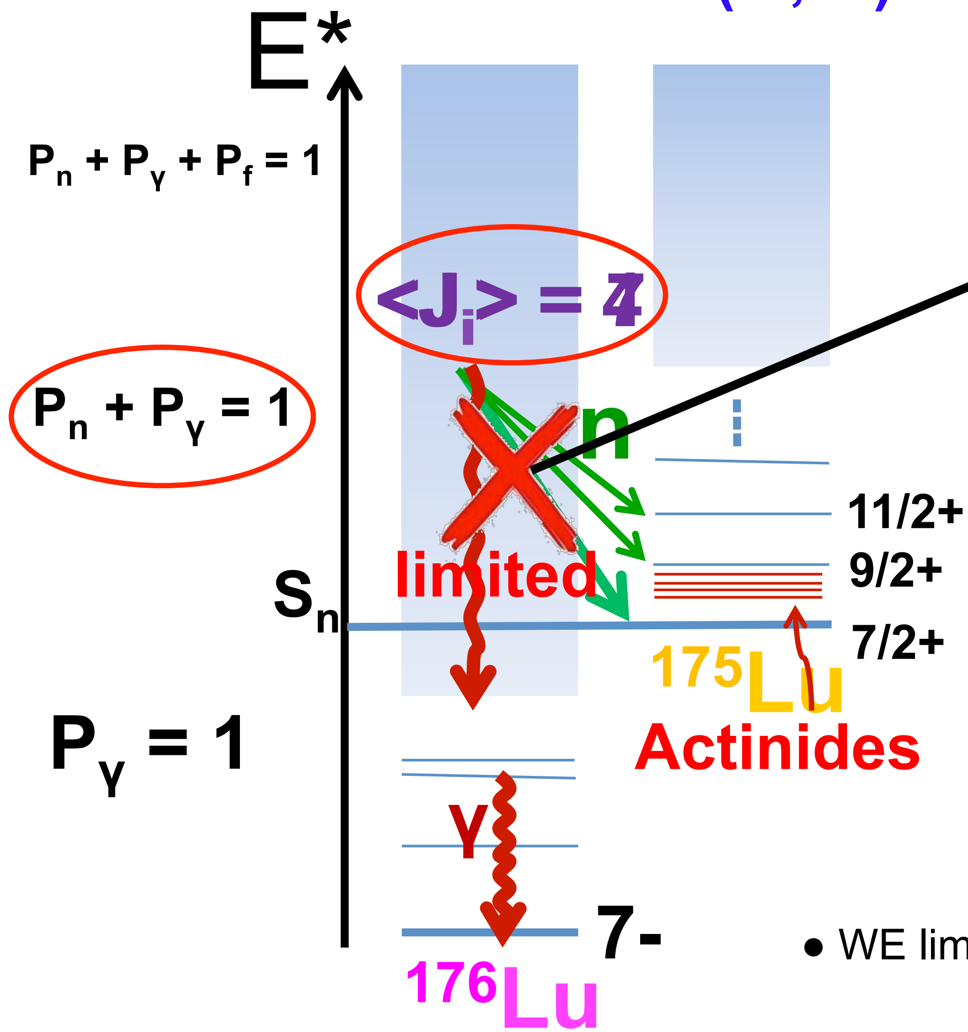
G. Boutoux, et al., Phys. Lett B 712 (2012) 319

Q.Ducasse

Surrogate Experiment : Interpretation of the results

Why σ_γ(surrogate) >> σ_γ(n-induced)

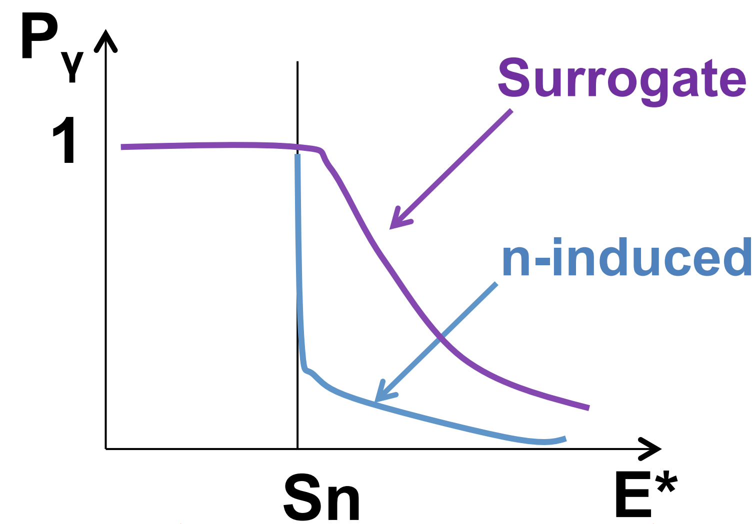
$^{174}Yb(^3He,p\gamma)^{176}Lu$ → (J',π') $^{176}Lu^*$ ← (J,π) n + ^{175}Lu



Neutron emission selection rules :

$$j_{neutron} = |J_i - J_f|$$

Dominant transitions $j_{neutron}$= 1/2 (3/2)

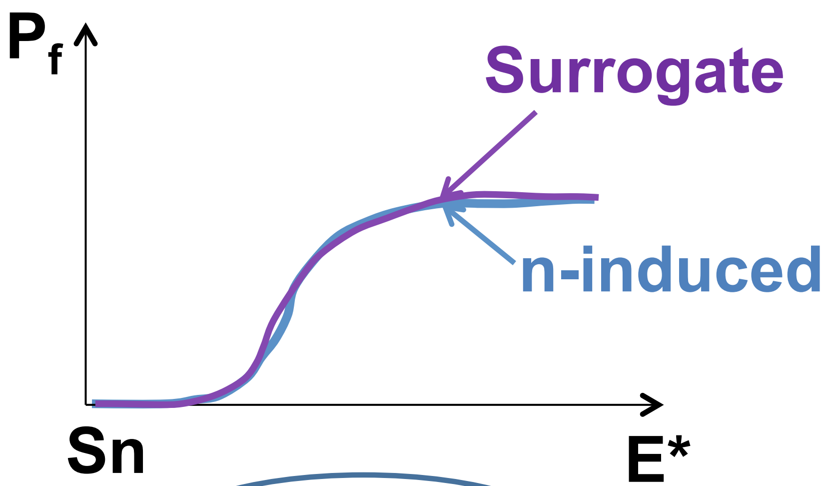


- WE limit not applicable ! ~~$\sigma_\gamma(En) \approx \sigma_{CN}(En).P_\gamma(E^*)_{J,\pi}$~~

Surrogate Experiment : Summary

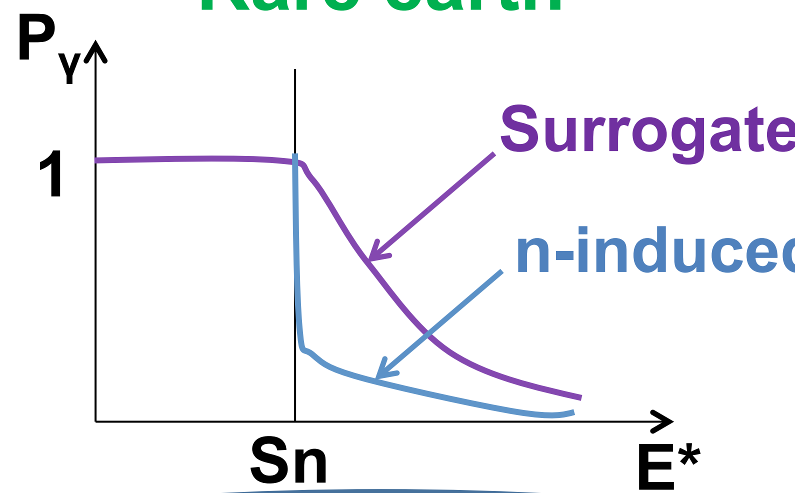
Schematical view of the results of the probabilities

Actinides



Fission OK

Rare earth



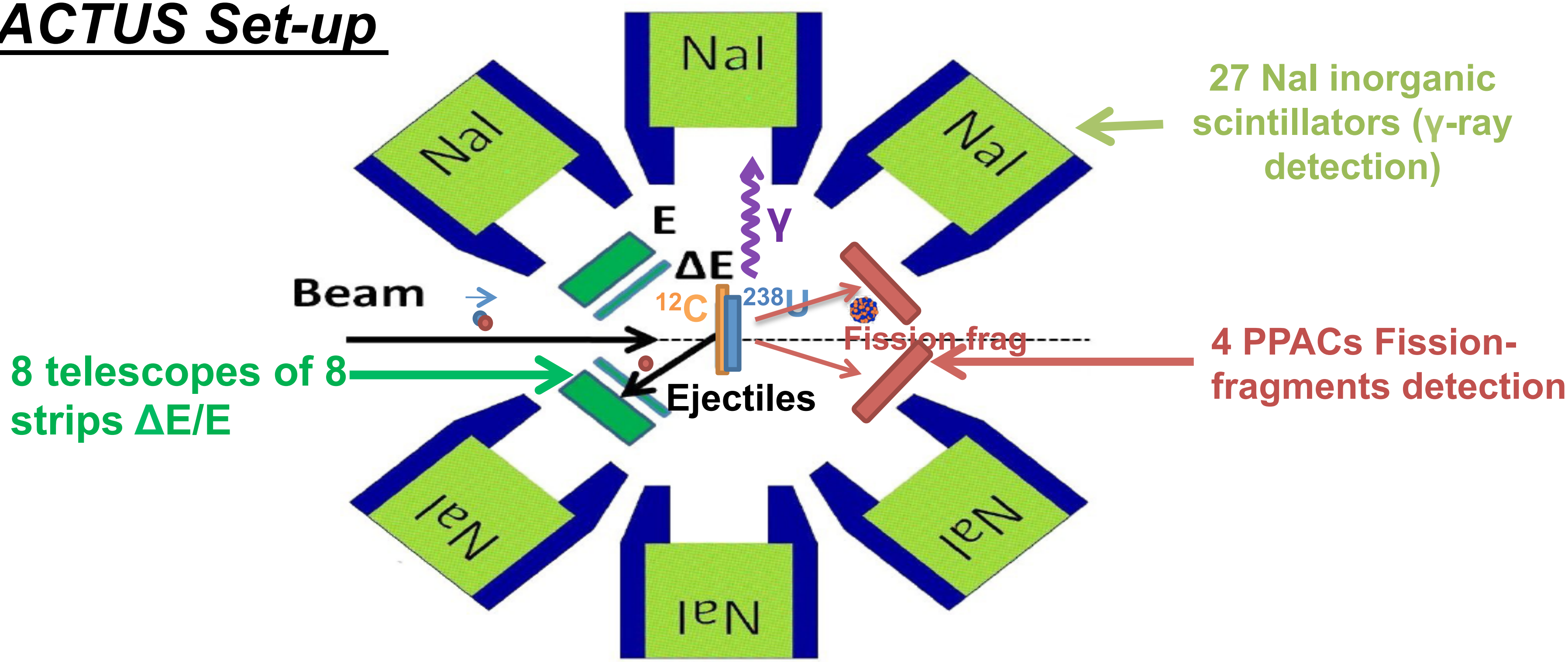
Gamma emission not OK

What about P_f AND P_γ for Actinides ?

Aim : Check if fission AND gamma decay probabilities agree with neutron data by measuring both simultaneously in the actinides region

Oslo measurements: Experimental set-up

CACTUS Set-up



$$P_{f,\gamma} = \frac{N_{f,\gamma}^{coinc}}{N_{éj} \cdot \varepsilon_{f,\gamma}}$$

❖ High detection efficiency

❖ Measurement of Fission & gamma-decay probabilities

Oslo measurements: Investigated reactions

Neutron- induced reaction	Corresponding surrogate reaction	Quantity measured
n + ^{238}U ($T_{1/2}$ = 4Gy)	^{238}U +d → ^{239}U* + p	$P_f + P_\gamma$
n + ^{236}U ($T_{1/2}$ = 23My)	^{238}U +^{3}He → ^{237}U* + ^{4}He	$P_f + P_\gamma$
n + ^{237}Np ($T_{1/2}$ = 2My)	^{238}U +^{3}He → ^{238}Np* + t	$P_f + P_\gamma$
n + ^{238}Np ($T_{1/2}$ = 2 days)	^{238}U +^{3}He → ^{239}Np* + d	$P_f + P_\gamma$

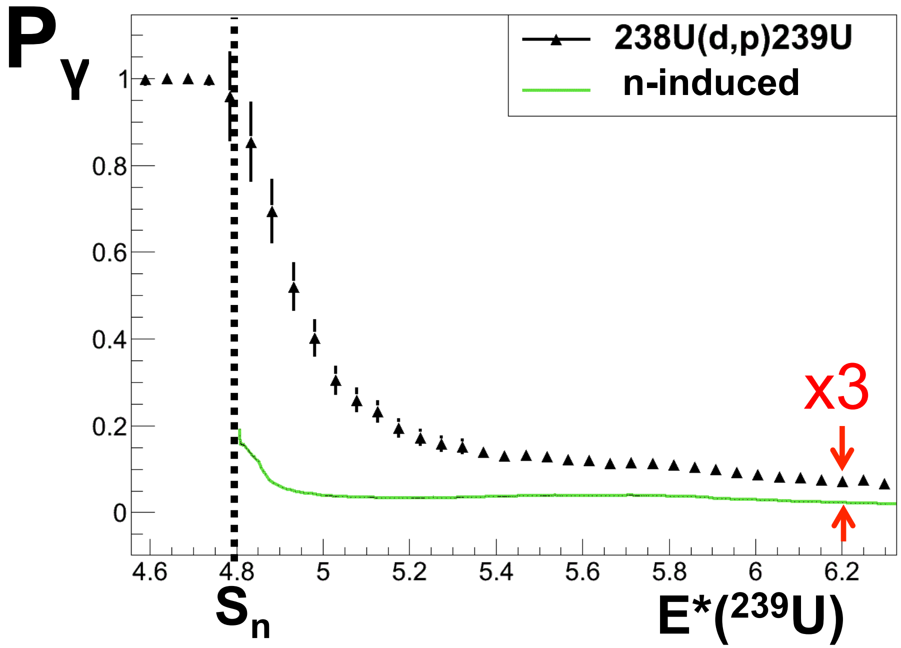
$$\sigma_{decay}^{A-1}(En) \cong \sigma_{CN}^{A}(En).P_{decay}^{A,transfer}(E^*)$$

Calculated (Optical model) — $\sigma_{CN}^{A}(En)$

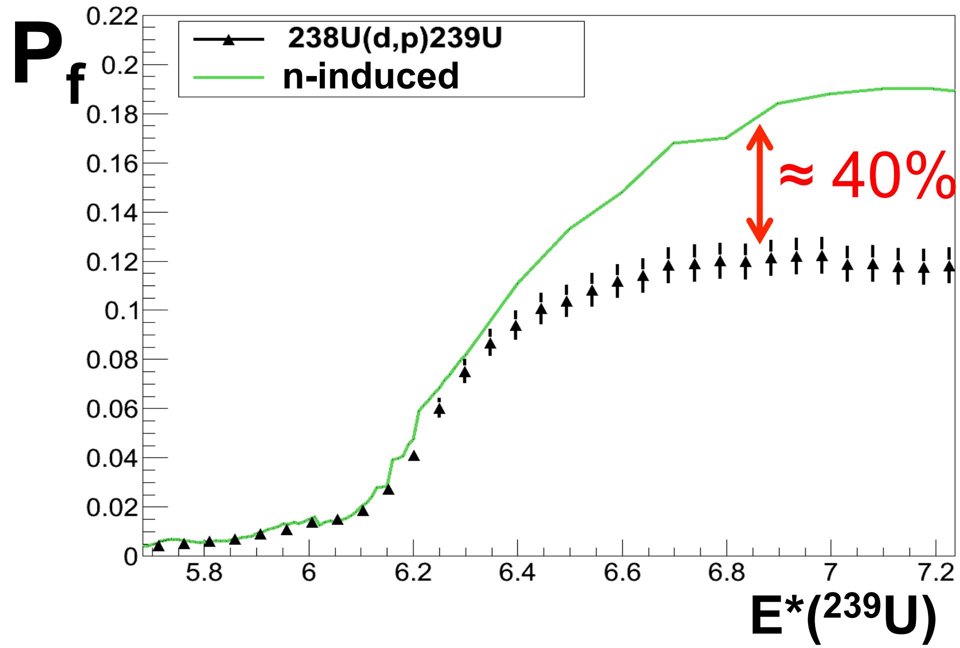
Measured — $P_{decay}^{A,transfer}(E^*)$

Oslo measurements: Results 1/3

(neutron-induced) $^{238}U + n \rightarrow {}^{239}U^* \leftarrow {}^{238}U\ (d,p)$ (surrogate)

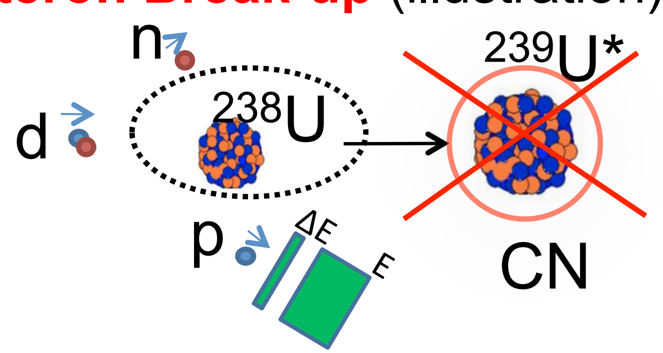


P_γ : Large discrepancies between surrogate/neutron-induced data



P_f : Discrepancies wih neutron data above fission threshold

Deuteron Break-up (illustration)

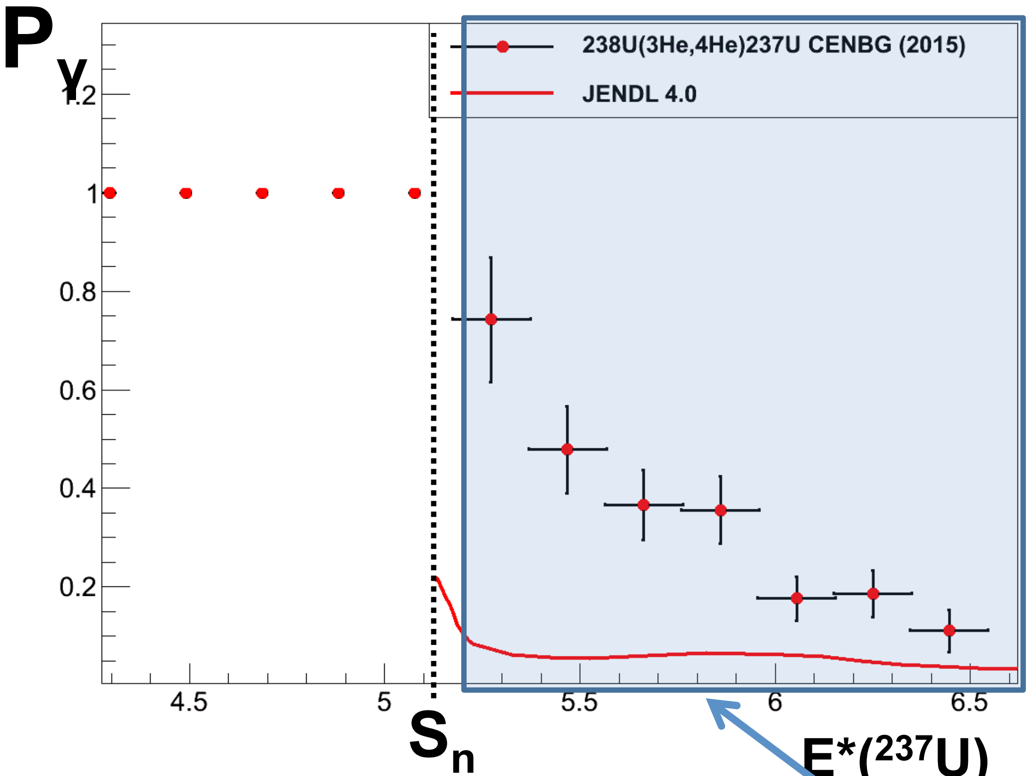


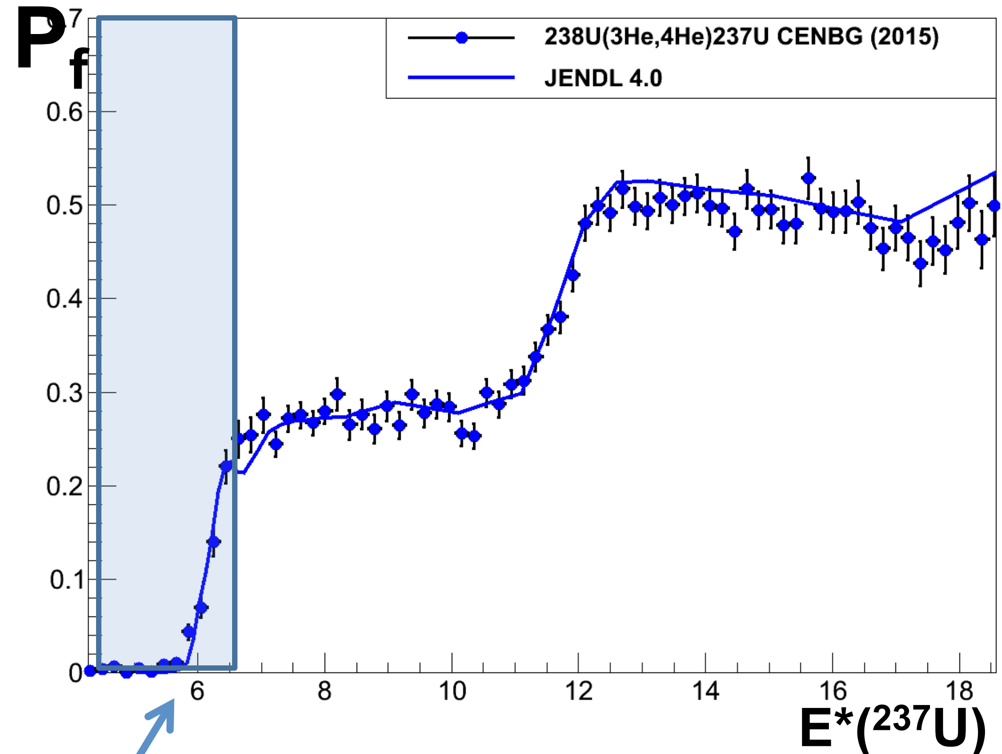
$$P_{f,\gamma} = \frac{N^{coinc}_{f,\gamma}}{N_{\acute{e}j}\,\varepsilon_{f,\gamma}}$$

Q.Ducasse

Oslo measurements: Results 2/3

(neutron-induced) $^{236}U + n \rightarrow {}^{237}U^* \leftarrow {}^{238}U(^3He,^4He)$ (surrogate)





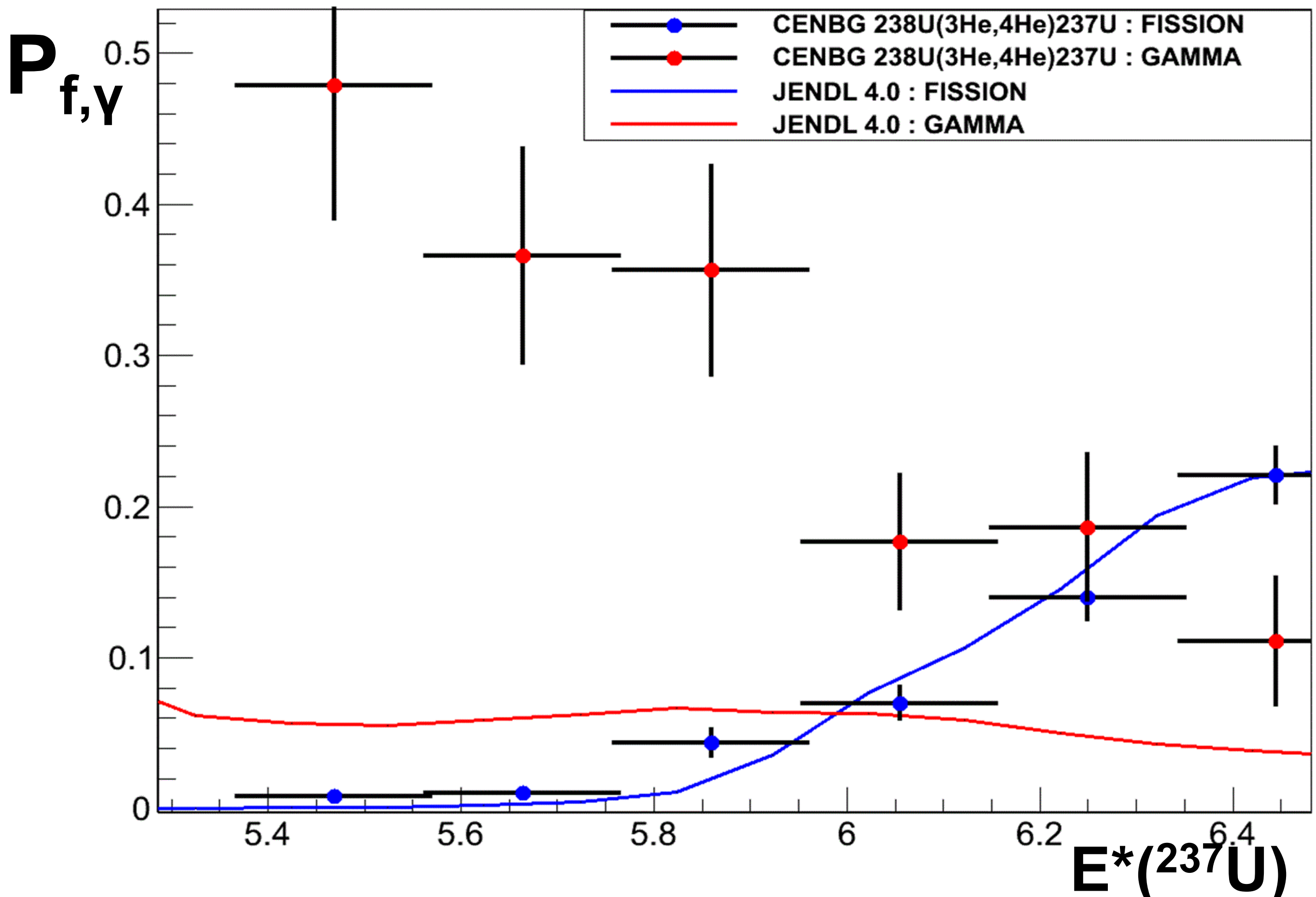
P_γ : Big discrepancies between surrogate/neutron-induced data

P_f : Good agreement surrogate/ neutron-induced data

ZOOM

Oslo measurements: Results 2/3

(neutron-induced) $^{236}U + n \rightarrow {}^{237}U^* \leftarrow {}^{238}U({}^{3}He, {}^{4}He)$ (surrogate)

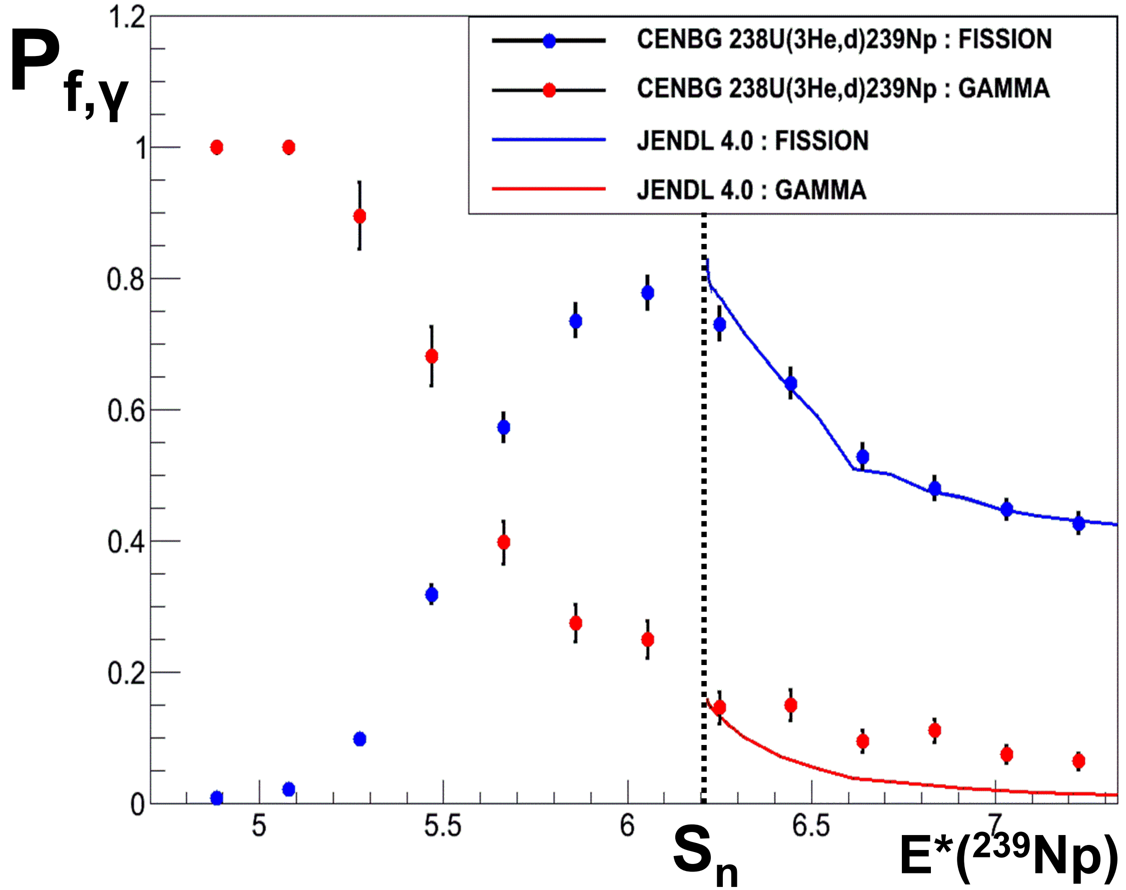


Observations :

- ➢ P_γ is much more sensitive to the spin differences than fission

Oslo measurements: Results 3/3

(neutron-induced) ^{238}Np + n → ^{239}Np* ← ^{238}U(^{3}He,d) (surrogate)



Observations :

- P_γ is much more sensitive to the spin differences than fission
- Can we explain these results with statistical model calculations ?

Oslo measurements: Comparison with statistical models 1/2

Statistical model (Hauser-Feshbach) approach :

EVITA code (CEA France)

Aim : Use of statistical model to see if it reproduces/can explain the different sensibilities to the spin parities distribution for the gamma/fission decay

STEP 1 : Fix the parameters of the model that reproduce the neutron data (LD, γSF…)

$$P_{decay} = f(LD, \gamma SF, \ldots)$$

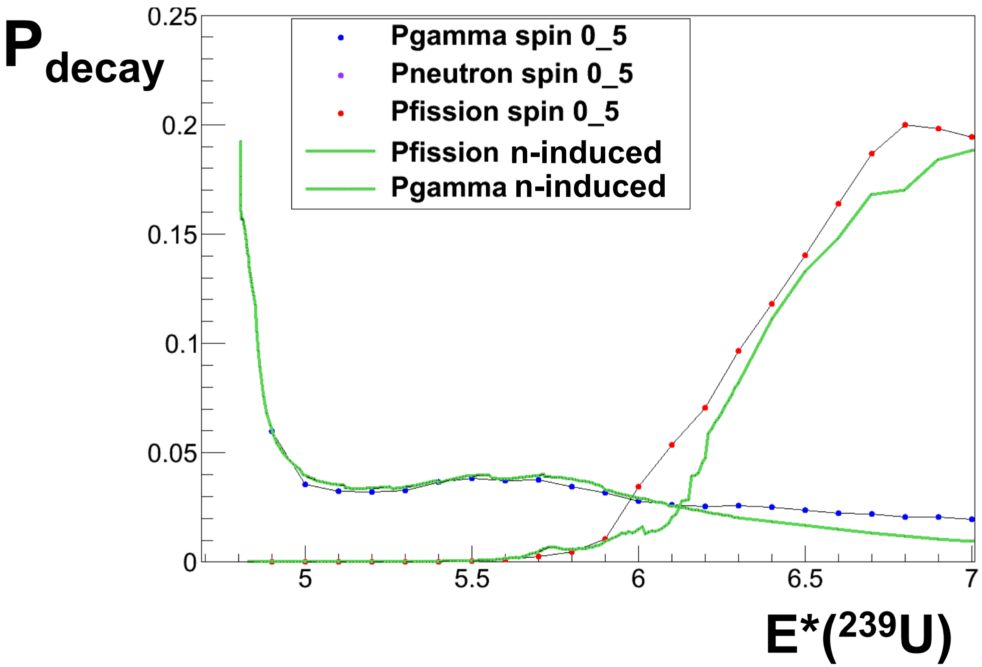
STEP 2 : Use the sensibility to spin of P_γ to extract information on the populated spin distribution $\langle J^{surrogate} \rangle$ of the transfer reaction

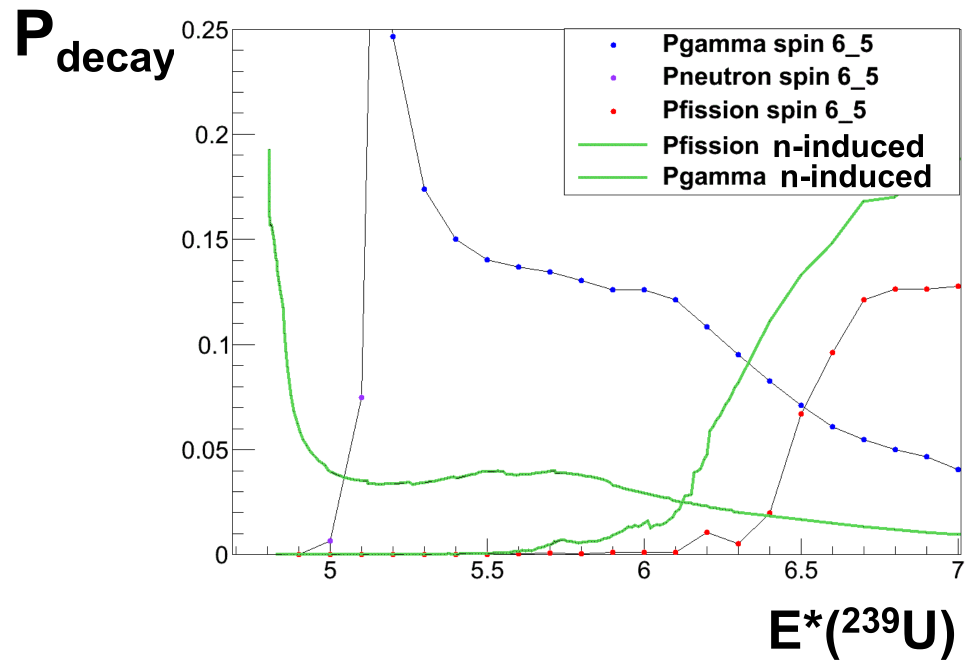
STEP 3 : Implementation of $\langle J^{surrogate} \rangle$ in the code to extract the calculated fission probability P_f^{EVITA} and compare it with the experimental one.

Oslo measurements: Comparison with statistical models 2/2

STEP 1 : Fix the parameters of the model that reproduce the neutron data (LD, γSF…)

(neutron-induced) ^{238}U + n → $^{239}U^*$ ← ^{238}U + d (surrogate)





Observations :

- P_γ and P_f are both very sensitive to the Jπ

➡ In contradiction with what we observe → can not reproduce surrogate data ?

➡ Surrogate data represent an important test to statistical models

Conclusion

The surrogate method

➢The surrogate method is the only way to obtain information of very radioactive nuclei ($T_{1/2}$ < few days)

Results

- Fission : Cross section measurements are comparable to neutron data
- Gamma emission : Cross section measurements are NOT comparable to neutron data → use it for fixing statistical model parameters

Observations

➢Fission much less sensitive to the spin distribution than gamma emission

Statistical model calculations

➢ Seem not to be able to reproduce experimental surrogate data

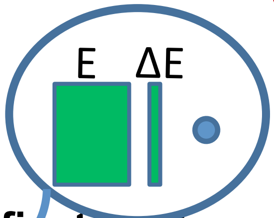
THANK YOU FOR YOUR ATTENTION

1) Analyse de la voie $^{238}U(d,p)^{239}U \leftrightarrow n + {}^{238}U$

Equation conservation en énergie

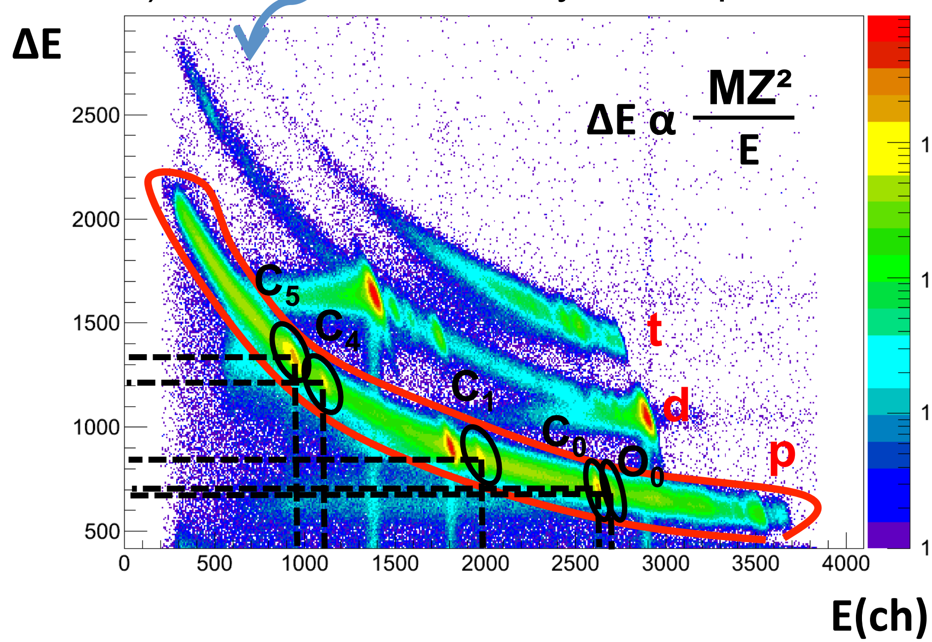
E*(CN) = E_{pro} + $Q_{reaction}$ – $E_{ejectile}$ – E_{recul}(CN) - Erecul

Connues — Calibration — Se calcule

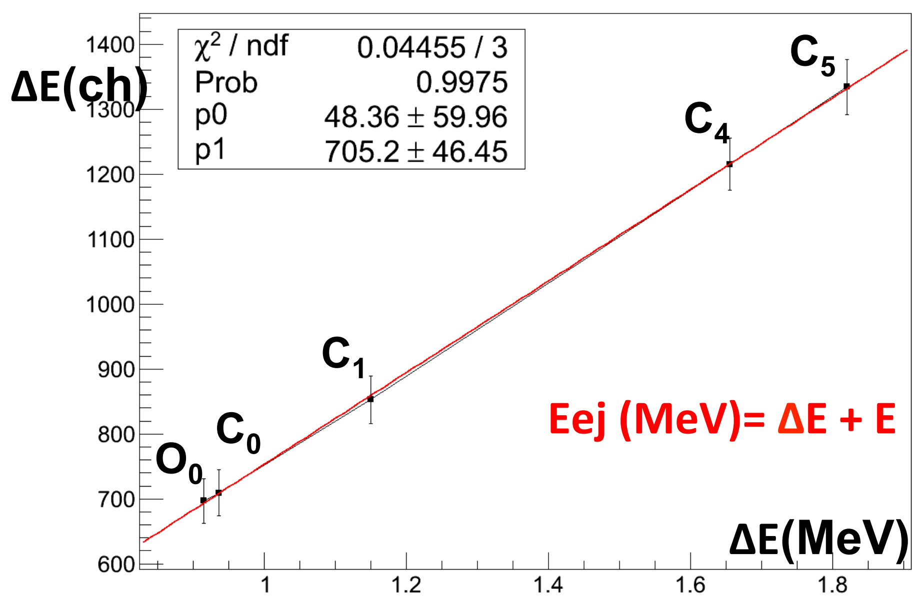


***E*(CN)** = Energie d'excitation du CN formé*
***E_{pro}** = Energie du faisceau (15 MeV)*
***$Q_{reaction}$** = Δmc² = 2.582 MeV*
***$E_{ejectile}$** = ΔE + E*
***E_{recul}** (CN) = Energie de recul du CN*

A) **Identification** du noyau composé formé



B) **Calibration** en énergie de la réaction

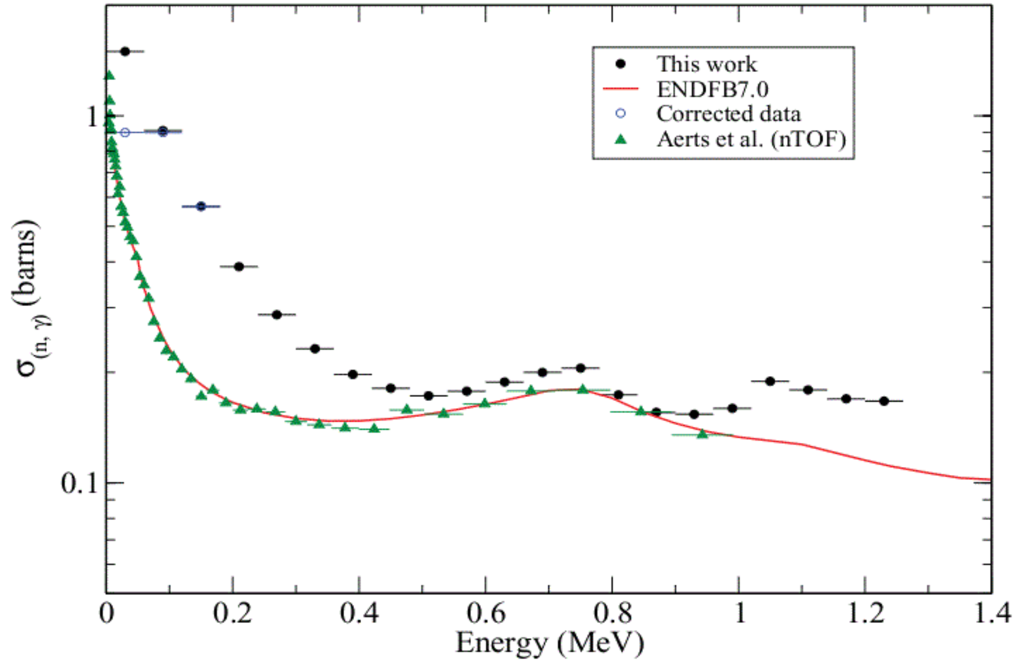


Neutron induced reaction

n + ^{232}Th (stable)

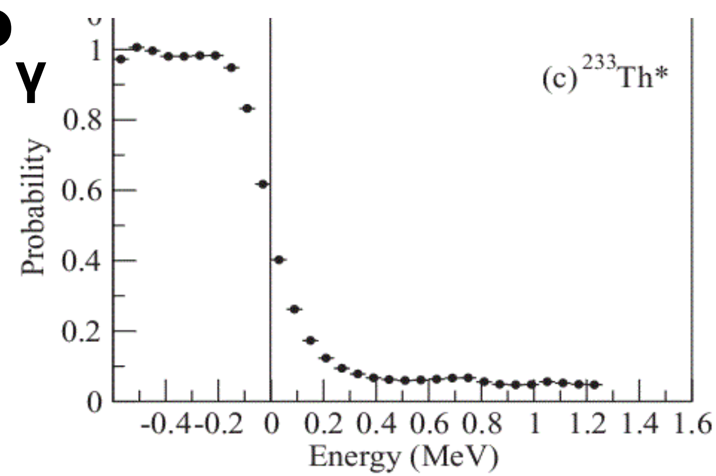
Surrogate reaction

^{232}Th +d → ^{233}Th* + p



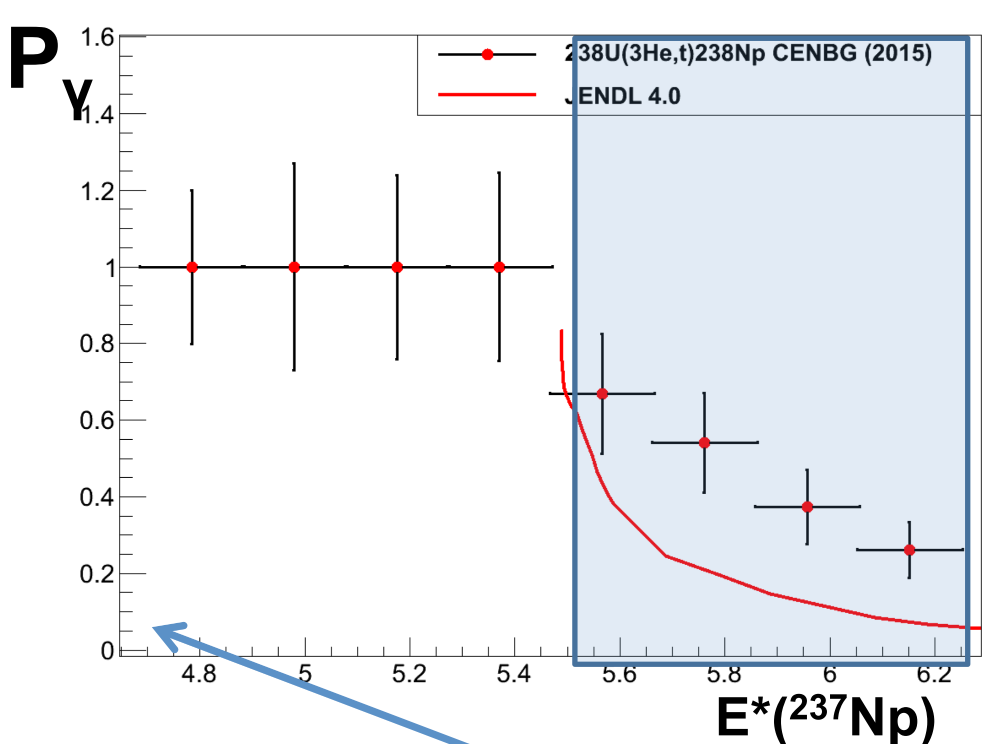
J. N. Wilson et al, Phys. Ev C 85, 034607 (2012)

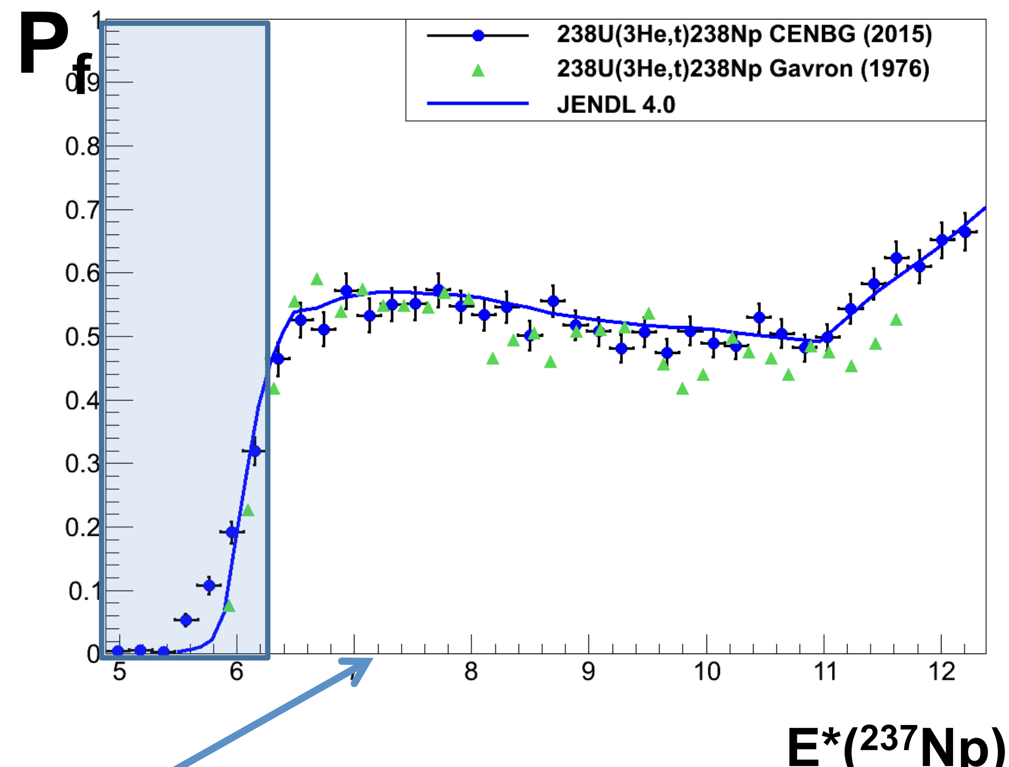
P_γ



Oslo measurements: Results 1/2

(neutron-induced) $^{238}U + n \rightarrow {}^{238}Np^* \leftarrow {}^{237}Np + t$ (surrogate)





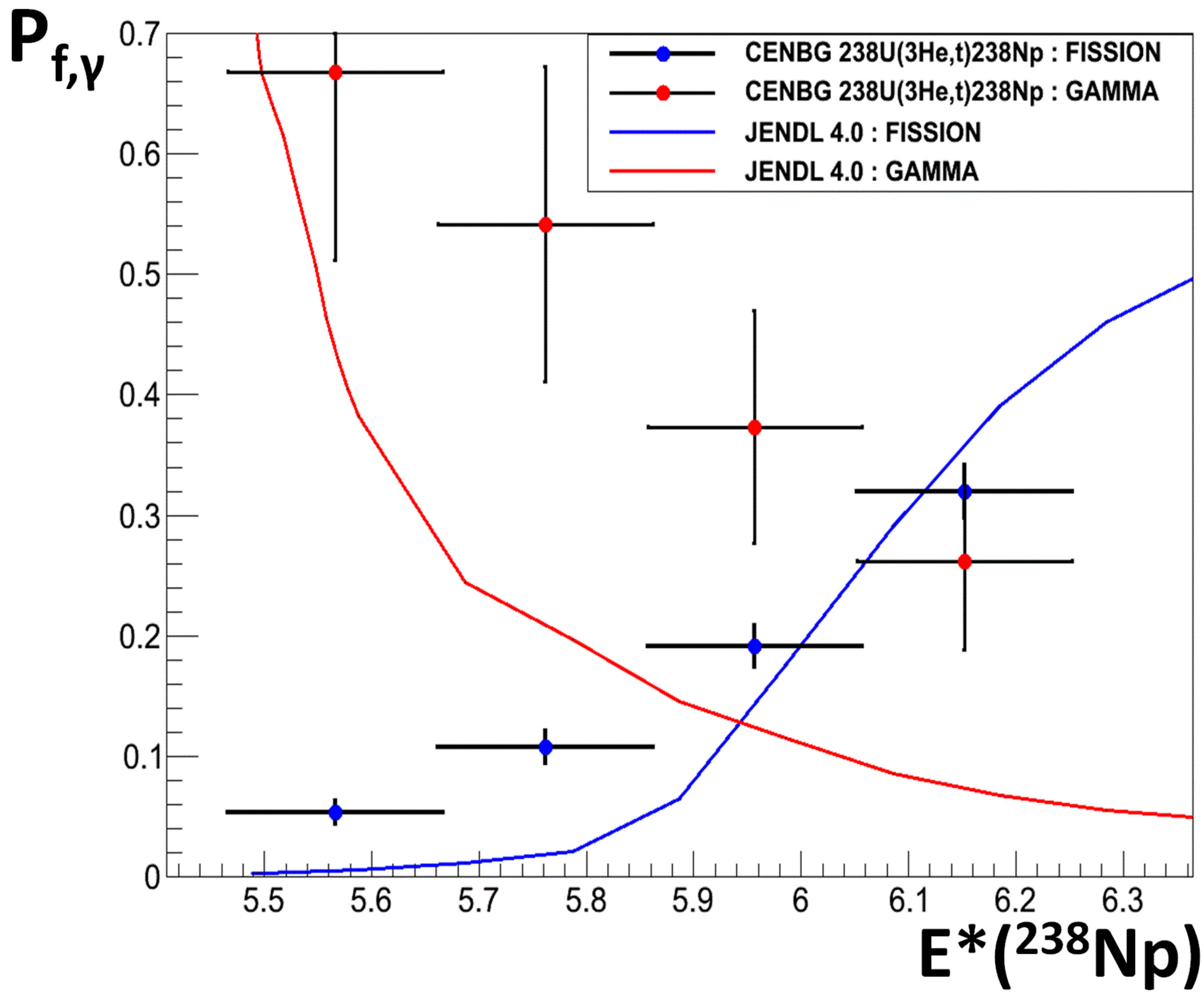
P_f : Good agreement surrogate/ neutron-induced data

P_γ : Big discrepancies between surrogate/neutron-induced data

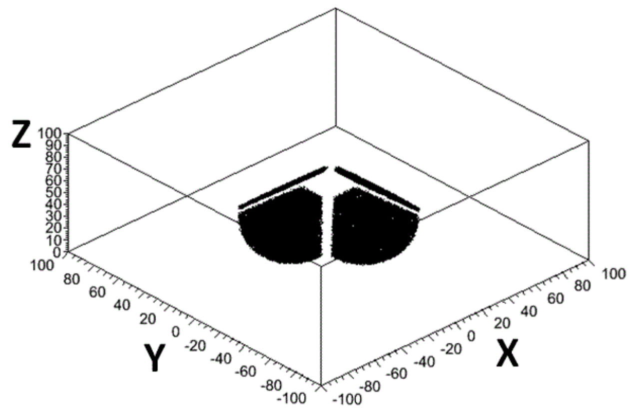
ZOOM

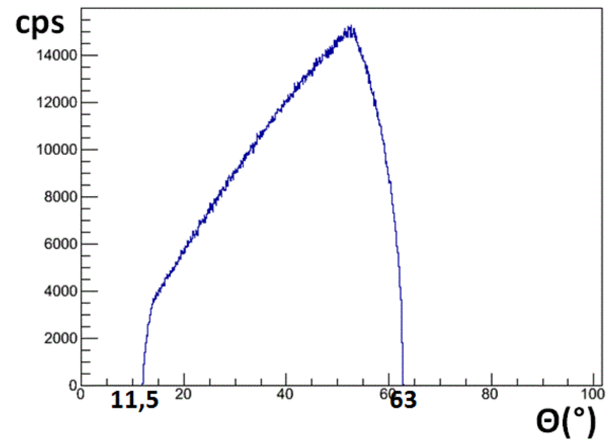
Oslo measurements: results

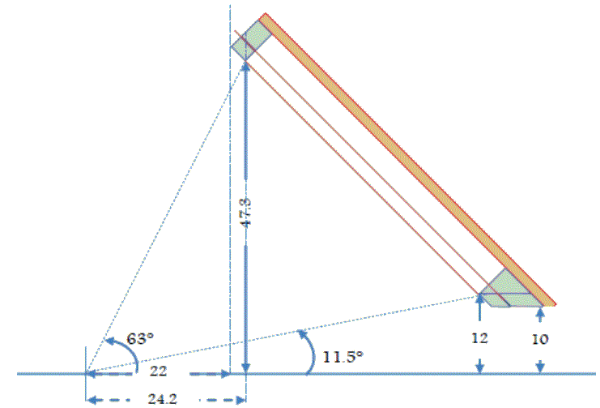
(neutron-induced) $^{237}Np + n \rightarrow {}^{238}Np^* \leftarrow {}^{238}U({}^{3}He,t)$ (surrogate)

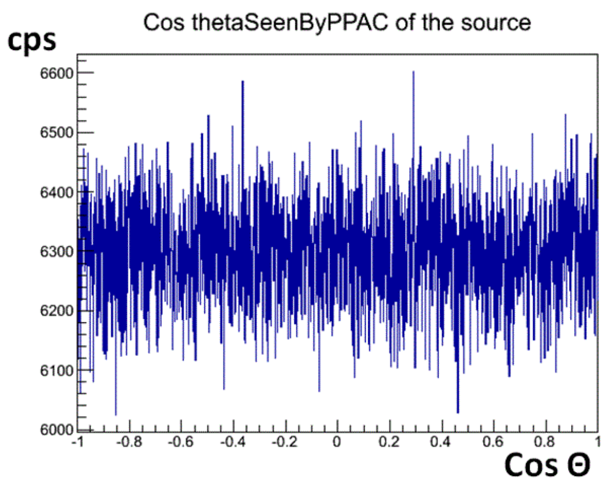


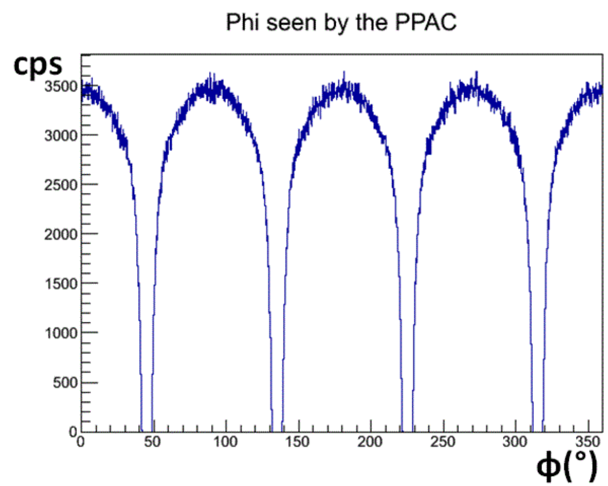
Fission detection efficiency







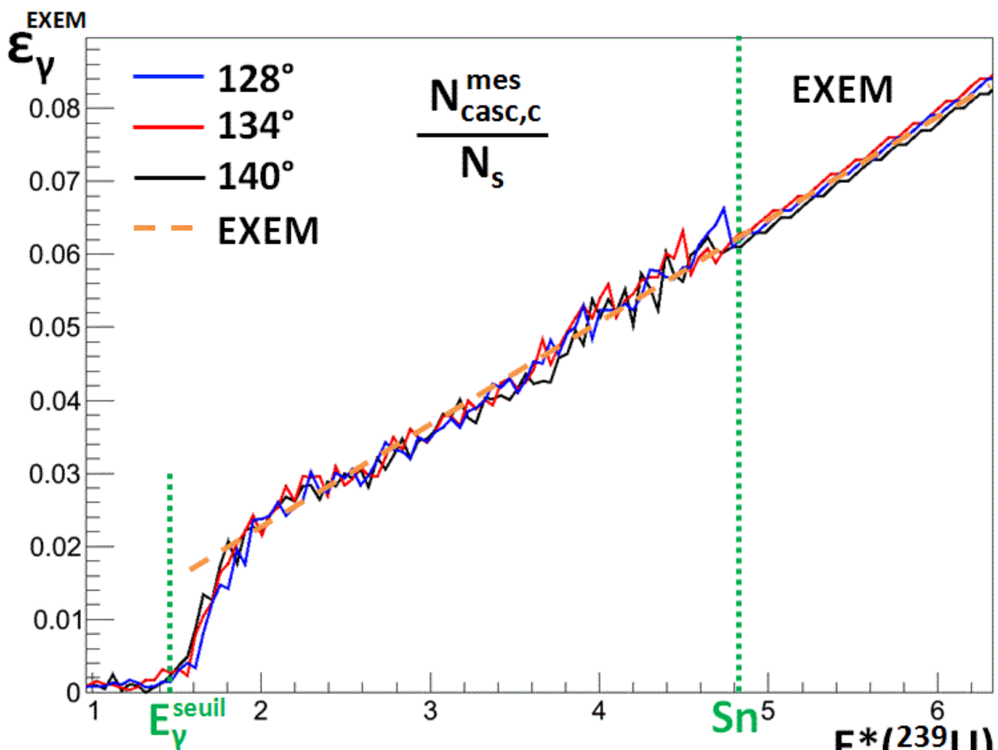


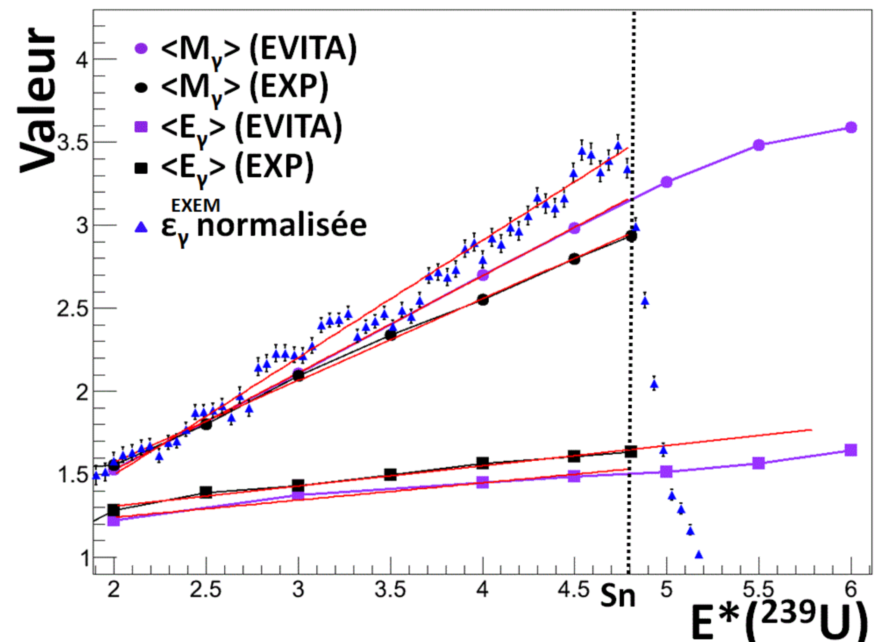


Gamma detection efficiency

$$P_\gamma(E^*) = \frac{N_\gamma(E^*)}{N_{éj}(E^*) \times \varepsilon_\gamma(E^*)}$$

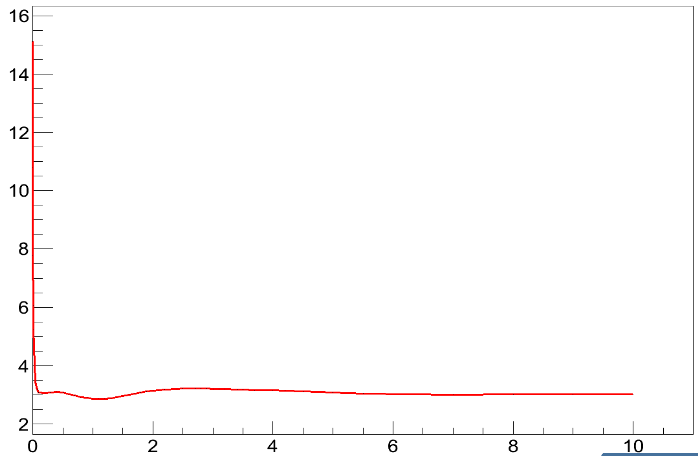
For $E^* < S_n$, $P_\gamma = 1$ ⟹ $\varepsilon_\gamma = \frac{N_{\gamma coinc}(E^*)}{N_p(E^*)}$



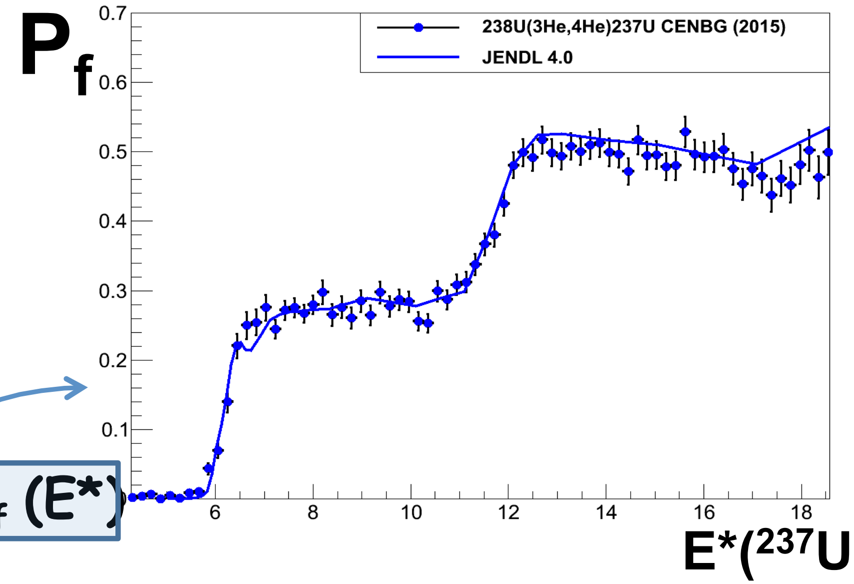


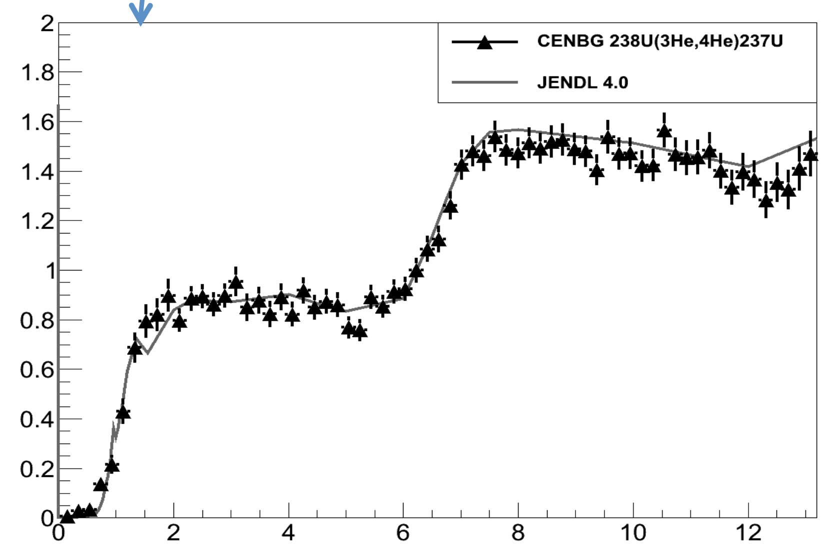
$\varepsilon_\gamma = f(M_\gamma, E_\gamma) \approx k.\ M_\gamma$ (k = constant)

Cross section-probability equivalence



$$\sigma_f(En) \approx \sigma_{CN}(En).P_f\ (E^*)$$





Calibration ^{3}He