FIESTA 2014

Neutron-induced cross sections of actinides via the surrogate reaction method

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CEA-Cadarache

Q.Ducasse

Outline

Motivation

I) Surrogate Experiment

- a) Principle
- b) Interest & Objective
- c) Early Work
- d) Interpretation

II) Oslo measurements

- a) Experimental set-up
- b) Investigated reactions
- c) Preliminary results
- d) Statistical models

Conclusion and outlook

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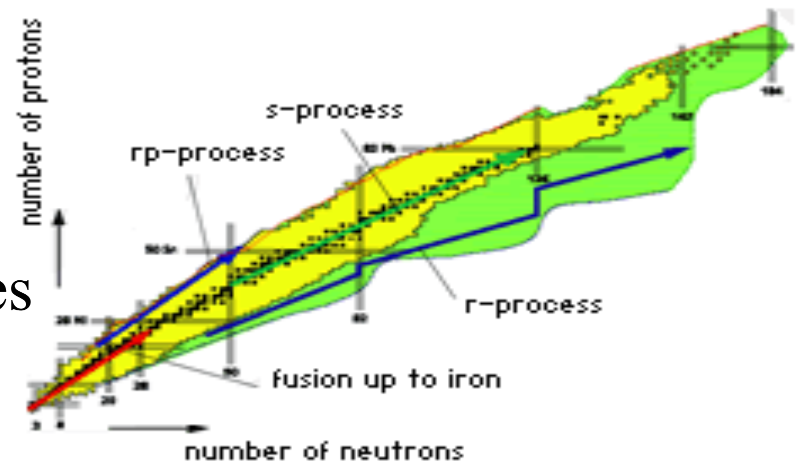
Conclusion and outlook

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 target involved.

Surrogate reaction

Outline

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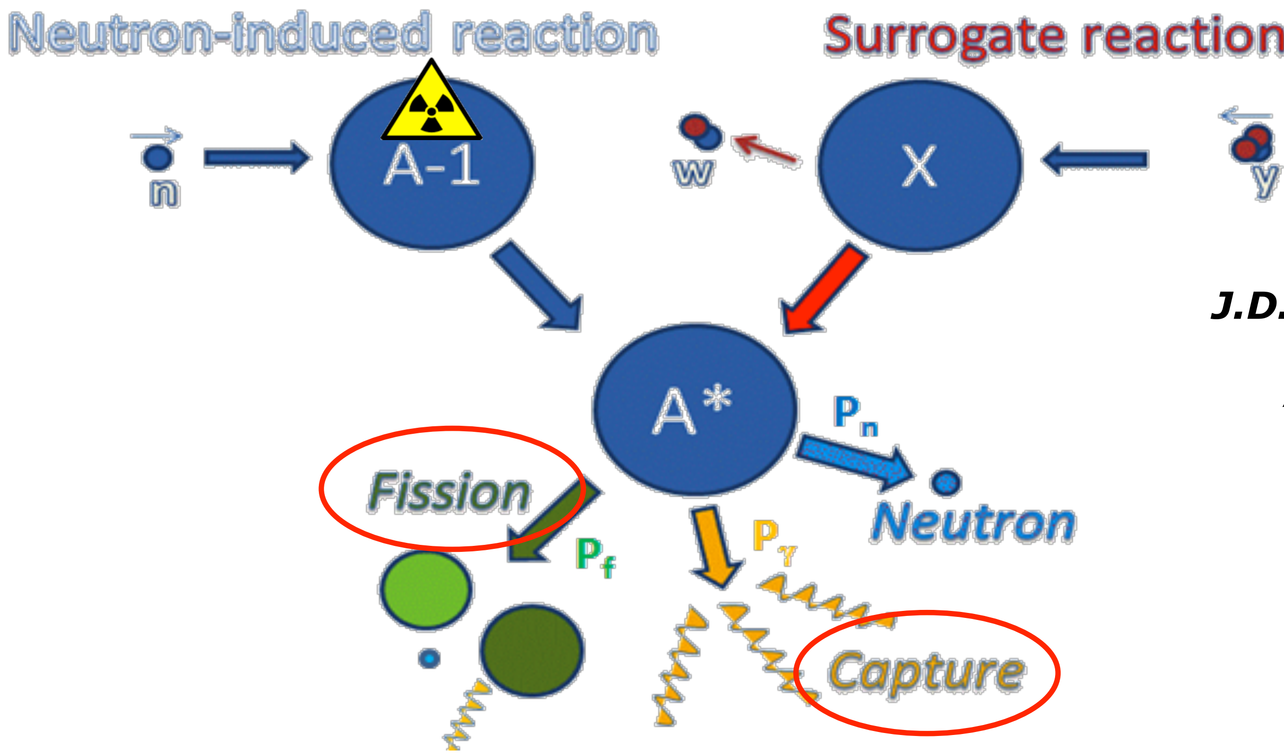
Surrogate Experiment : principle



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

$$\sigma^{A-1}_{decay}(En) \cong \sigma^{A}_{CN}(En).P^{A,transfer}_{decay}(E^*)$$

Calculated (Optical model calculations)

Measured (Surrogate experiment)

Surrogate Experiment : Interest & objective

Main interest :

- neutron-induced fission/capture cross sections extraction for nuclear reactions on short-lived (Am,Cm,Np..) nuclei in fast neutron region and to get information on nuclear structure models

Surrogate reaction only valid if :

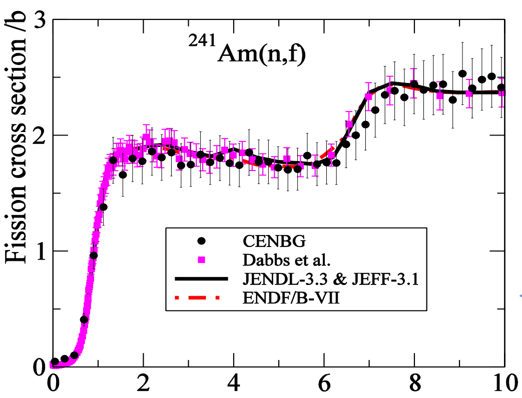
- Compound nucleus formation
- Similar spin/parity or no dependence on J^{π} of P_{decay} (Weisskopf Ewing approximation)

Objective :

- Validity of surrogate method in the actinides region by comparing surrogate data to known n-induced data.

Surrogate Experiment : Early work

Comparison surrogate/neutron induced reactions



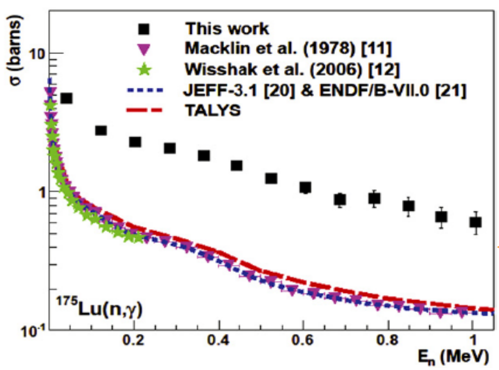
G. Kessedjian, et al., Phys. Lett B 692 (2010) 297

Fission

OK !

Example

Rare earth nucleus



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

Capture

NOT OK !

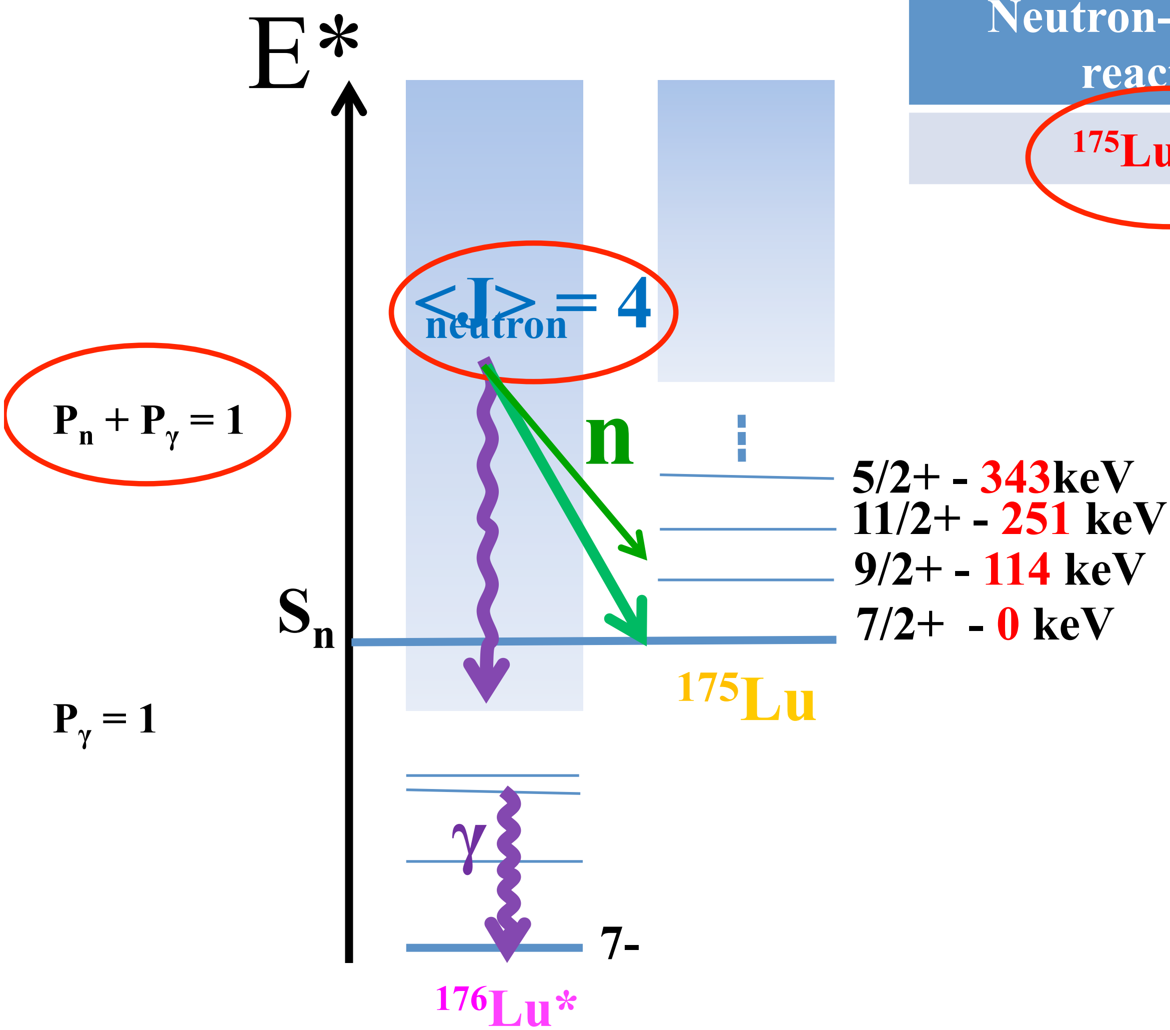
Example

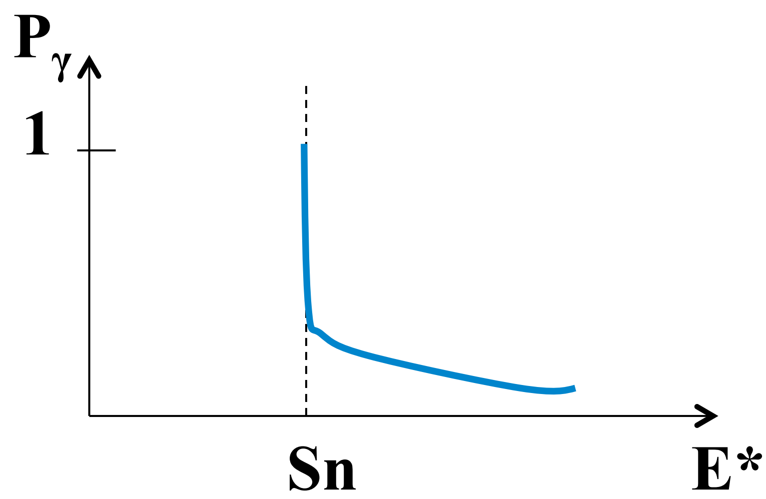
Jutta Escher, et al., Rev. Mod. Phys. 84 (2012) 353

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$, \alpha)$	absolute	Petit *et al.* (2004)
^{230}Th(n, f)	0.22–25	^{232}Th$(^3$He$, \alpha)$	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$, \alpha)$	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$, \alpha)$	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$, \alpha)$	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$, \alpha)$	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)

Surrogate Experiment : Interpretation 1/2

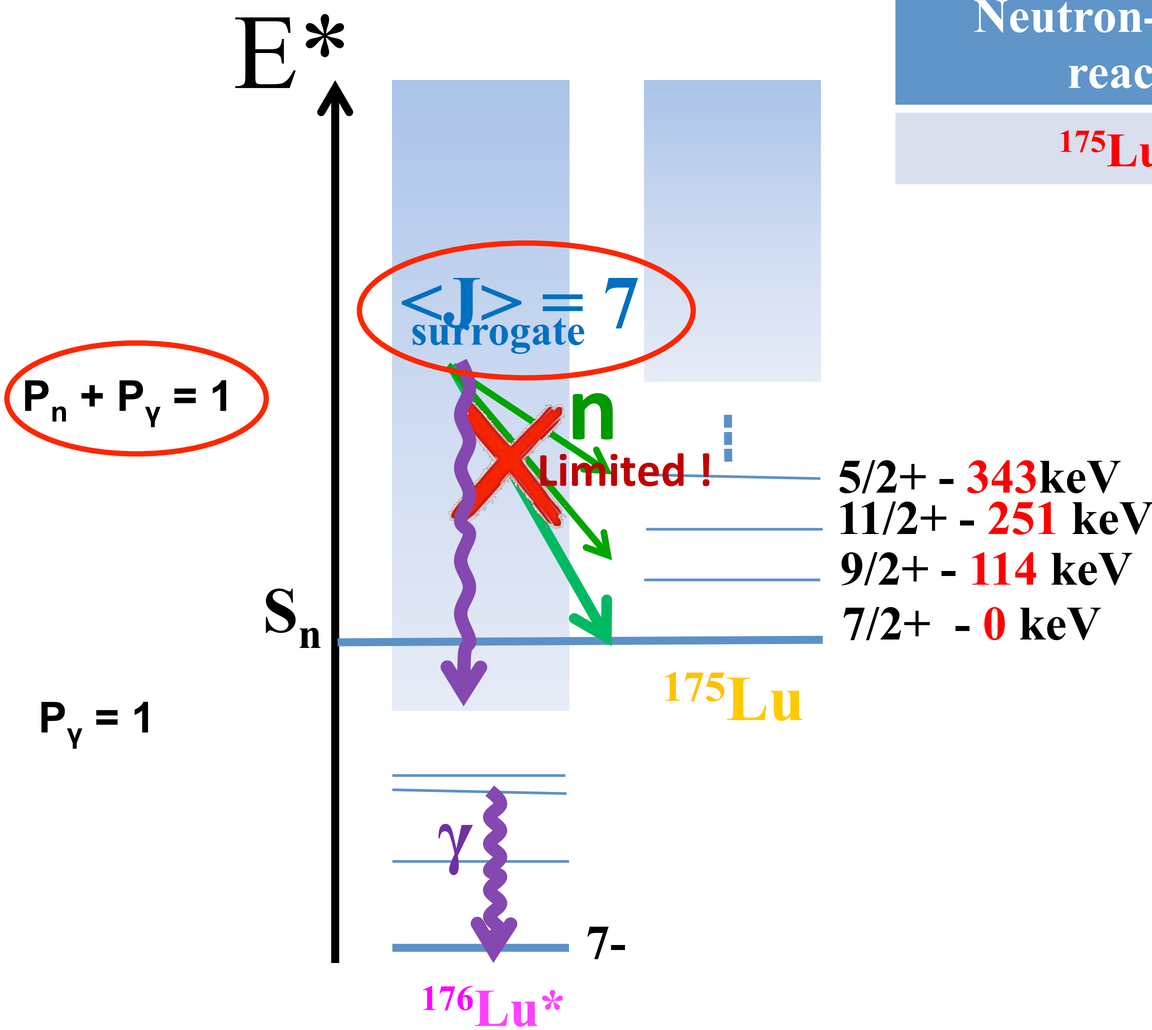
Neutron-induded reaction	Corresponding surrogate reaction
$^{175}Lu + n$	$^{174}Yb + ^{3}He \rightarrow ^{176}Lu^{*} + p$

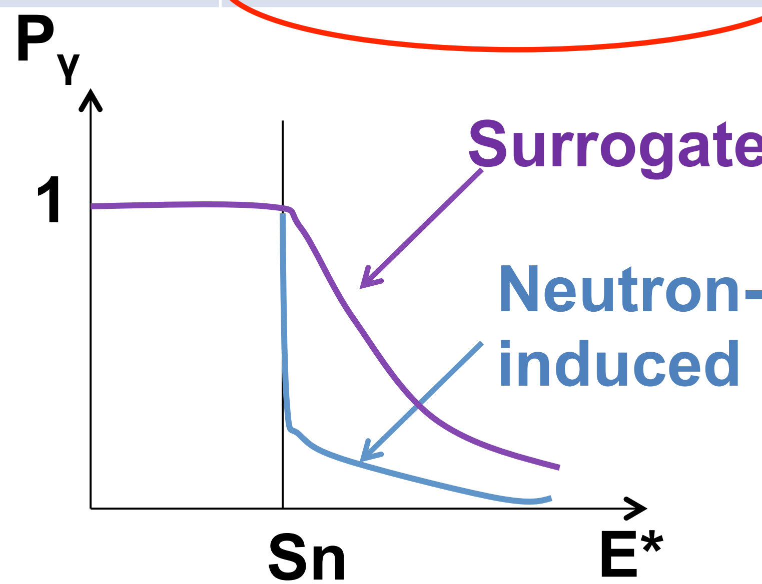




Surrogate Experiment : Interpretation 2/2

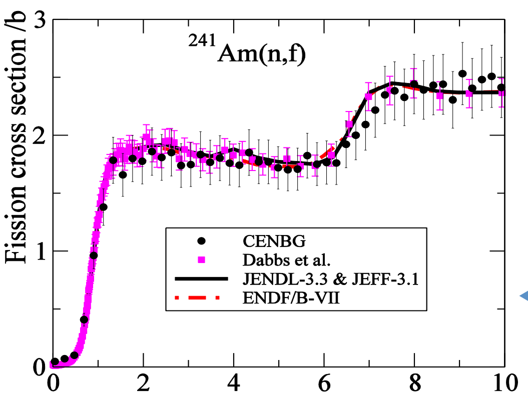
Neutron-induded reaction	Corresponding surrogate reaction
$^{175}Lu + n$	$^{174}Yb + ^{3}He \rightarrow ^{176}Lu^* + p$





Surrogate Experiment : Early work

Comparison surrogate/neutron induced reactions



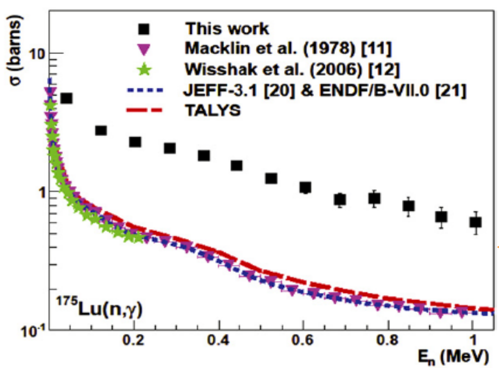
G. Kessedjian, et al., Phys. Lett B 692 (2010) 297

Fission

OK !

Example

Rare earth nucleus



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

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

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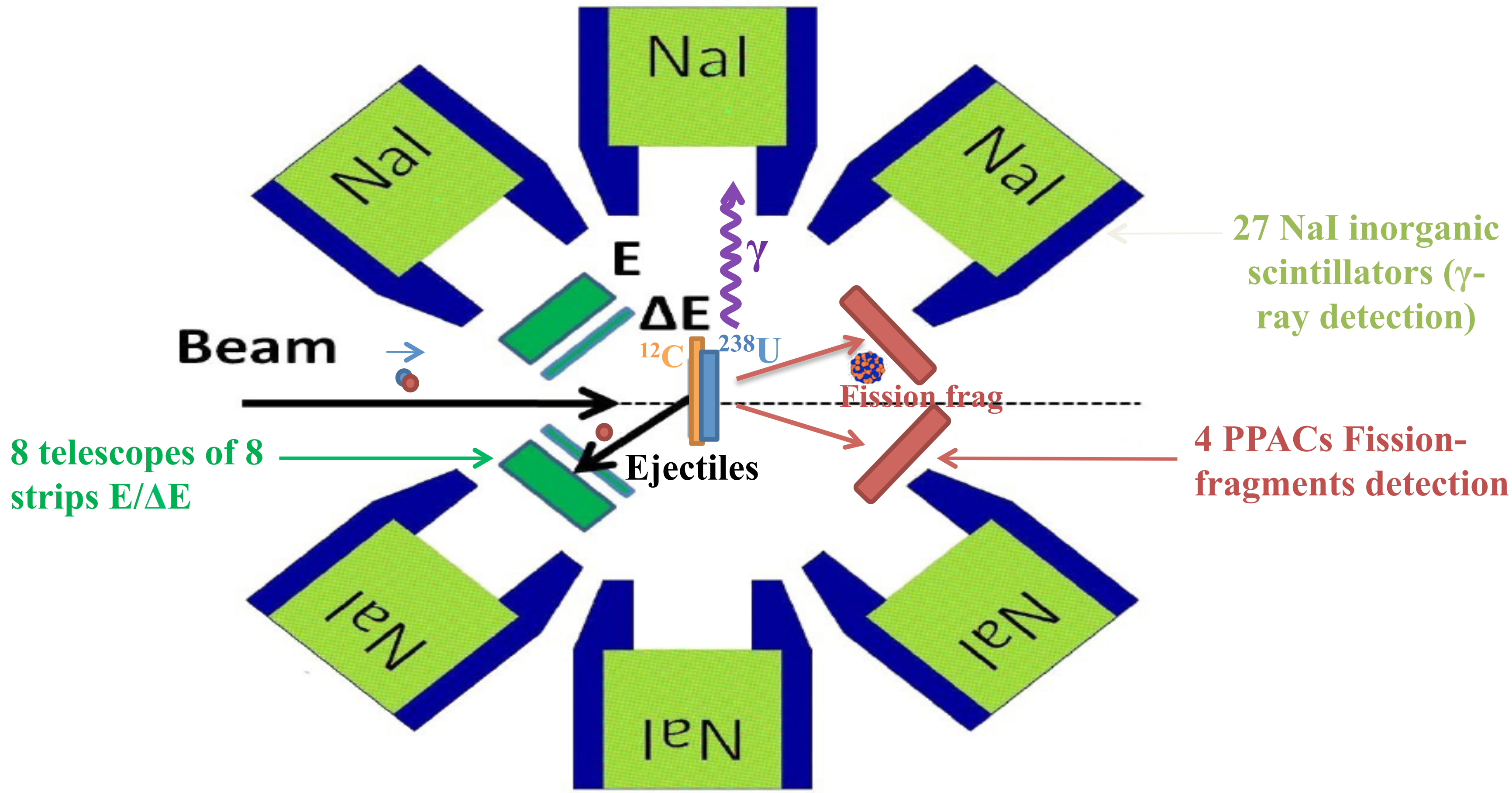
Conclusion and outlook

Oslo measurements: Experimental set-up



❖ **High detection efficiency**

❖ **Measurement of Fission & gamma-decay probabilities**

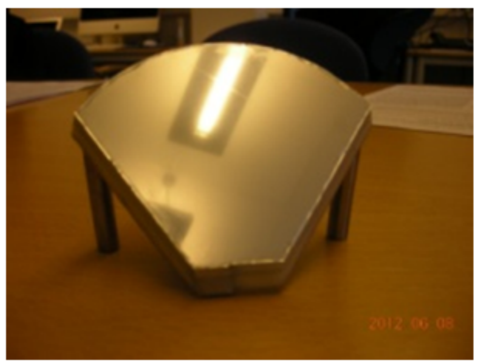
Oslo measurements: Investigated reactions

4 reactions are studied

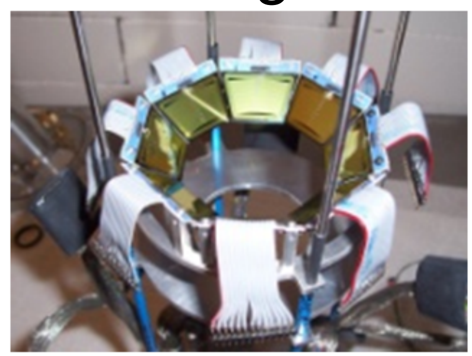
Neutron- induced reation	Corresponding surrogate reaction	Quantity measured
$^{238}U + n$	$^{238}U + d \rightarrow {}^{239}U^* + p$	$P_f + P_\gamma$
$^{236}U + n$	$^{238}U + {}^3He \rightarrow {}^{237}U^* + {}^4He$	$P_f + P_\gamma$
$^{237}Np + n$	$^{238}U + {}^3He \rightarrow {}^{238}Np^* + t$	$P_f + P_\gamma$
$^{238}Np + n$	$^{238}U + {}^3He \rightarrow {}^{239}Np^* + d$	$P_f + P_\gamma$

NaI scintillators

Fission detector

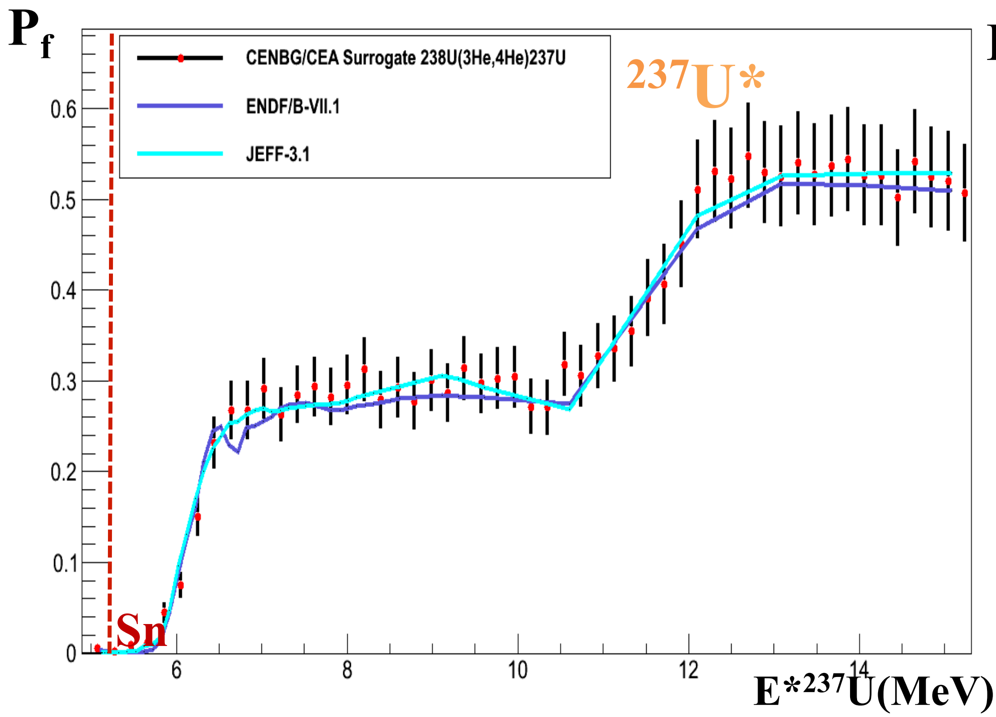


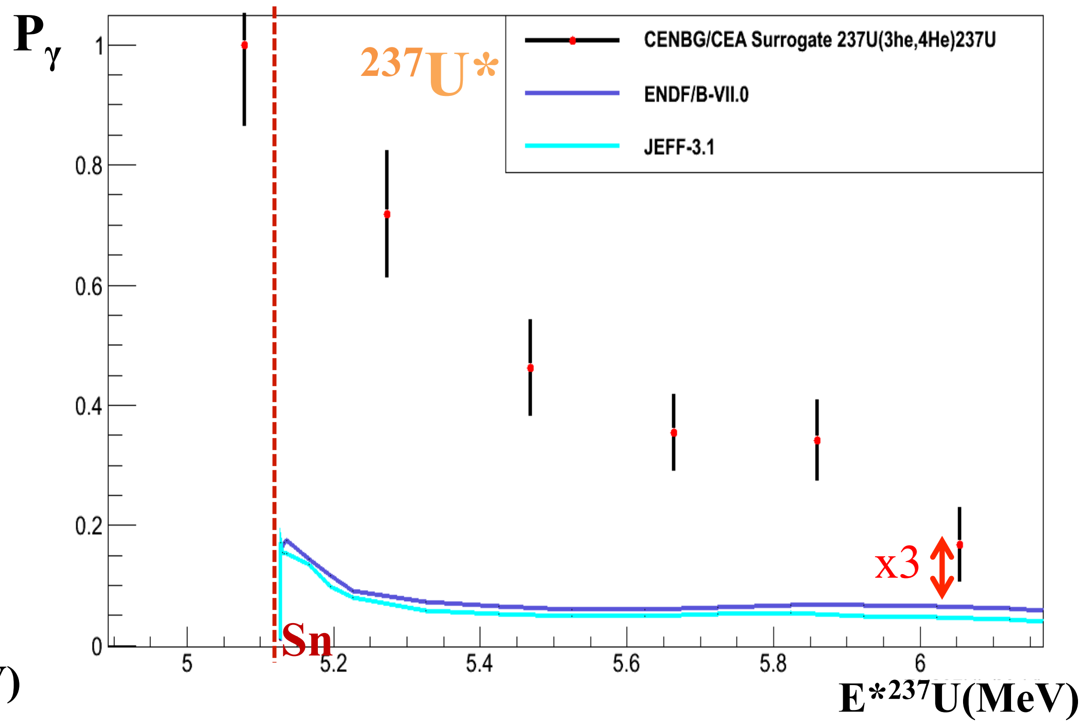
Silicon Ring detector



Oslo measurements: Preliminary results 1/2

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





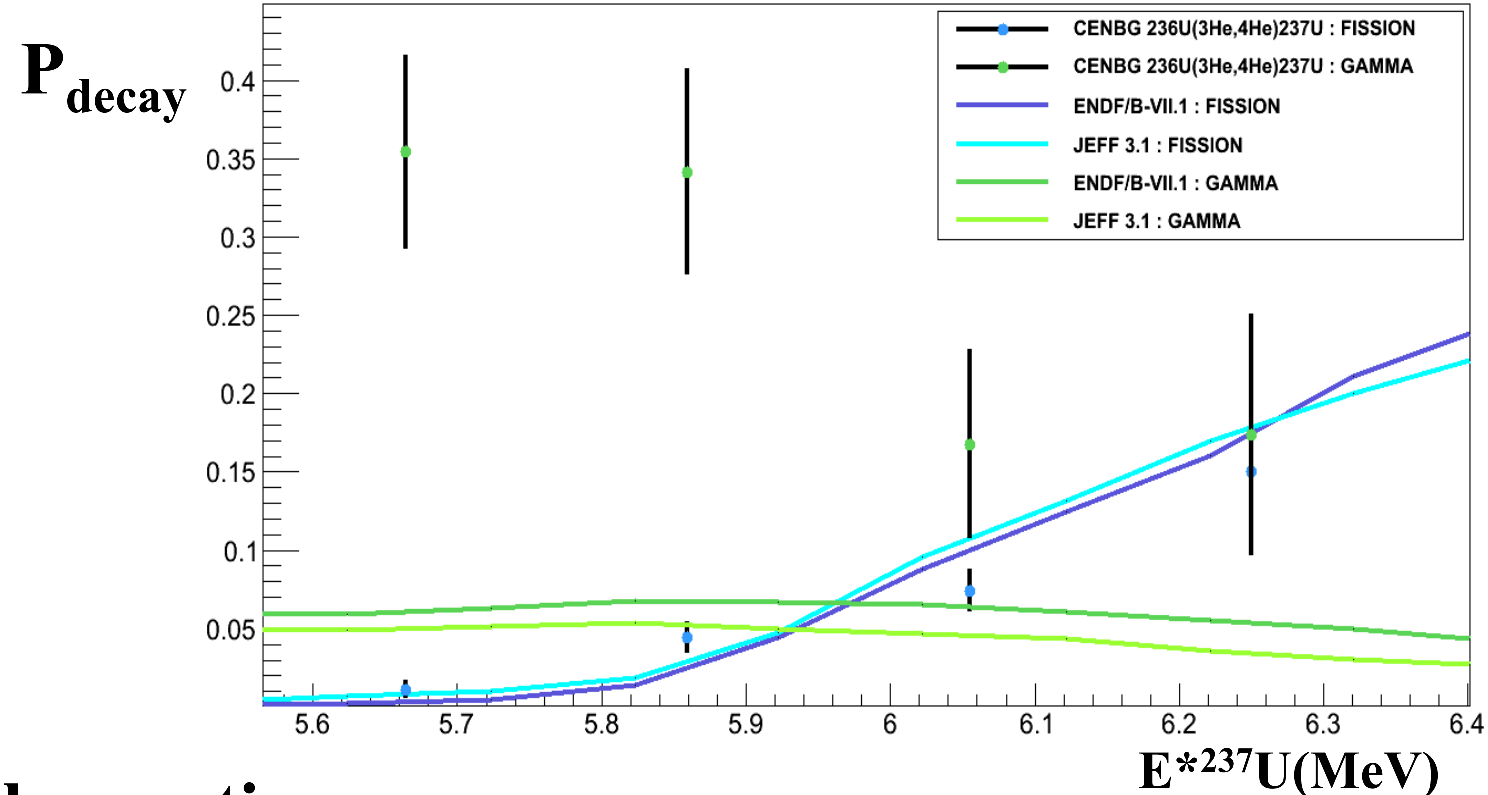
P_f : Good agreement surrogate/ neutron-induced data

P_γ : Big discrepancies between surrogate/neutron-induced data

Fission/Gamma probabilities comparison between Surrogate/neutron-induced reactions

Oslo measurements: Preliminary results 2/2

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



Observations :

- P_{γ} is much more sensitive to the spin differences that fission
- We observe the same trend for the other nuclei
- Can we explain these results with statistical model calculations ?

Oslo measurements: Statistical models 1/3

Statistical model (Hauser-Feshbach) approach :

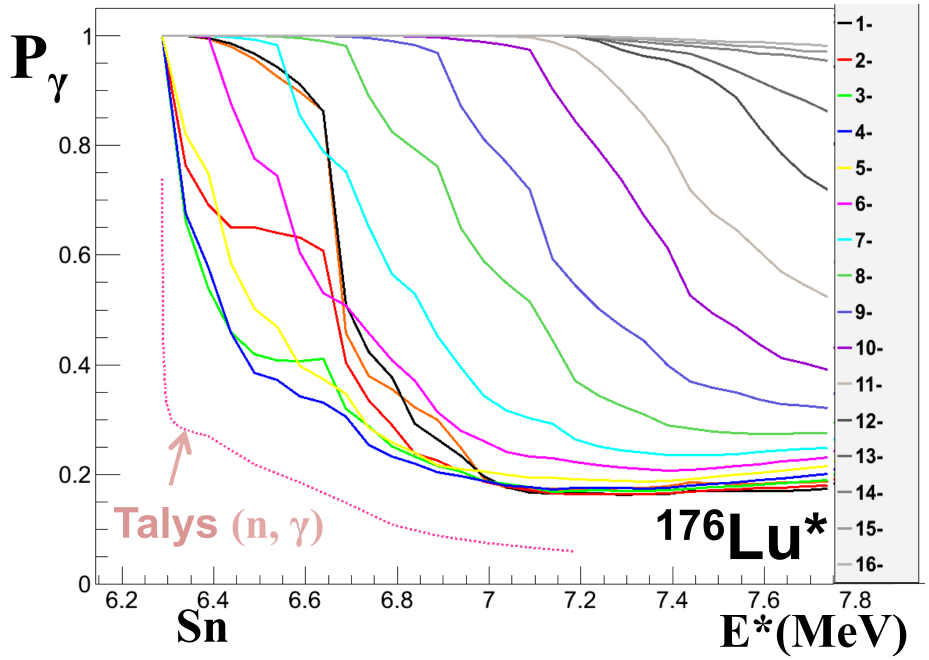
FIFRELIN Code : Fission Fragment Evaporation Leading to an Investigation of Nuclear data (developed in CEA Cadarache)

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

1/3) Selection of the model that reproduce Pγ from (n, γ) reactions

Level density model : CTM

- **Can NOT reproduce P_γ from (n, γ) reactions**



Oslo measurements: Statistical models 2/3

Statistical model (Hauser-Feshbach) approach :

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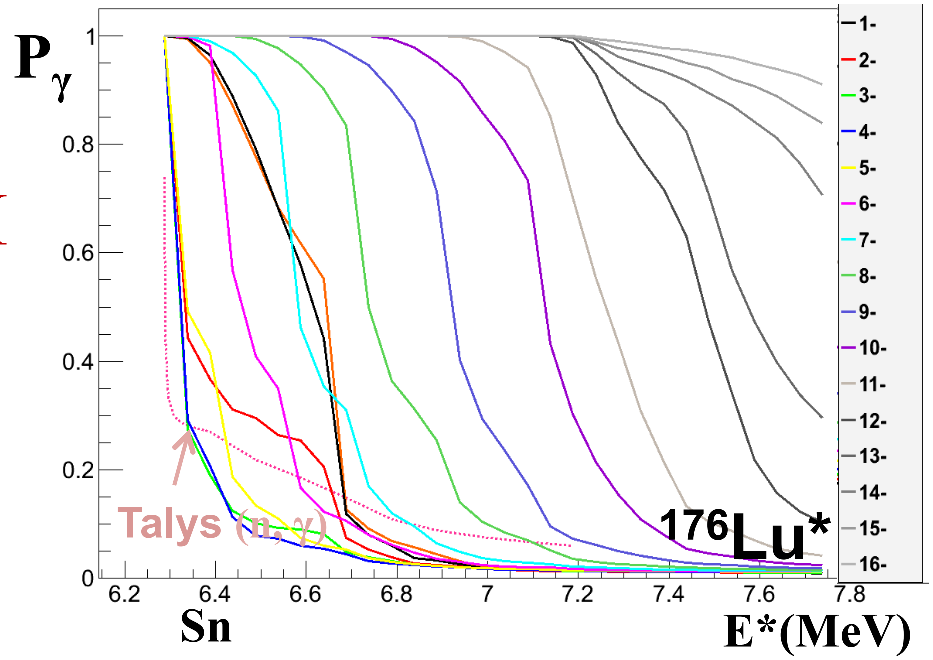
1/3) Selection of the model that reproduce Pγ from (n, γ) reactions

Level density model : CGCM

- **CAN reproduce P_γ from (n, γ) reactions**

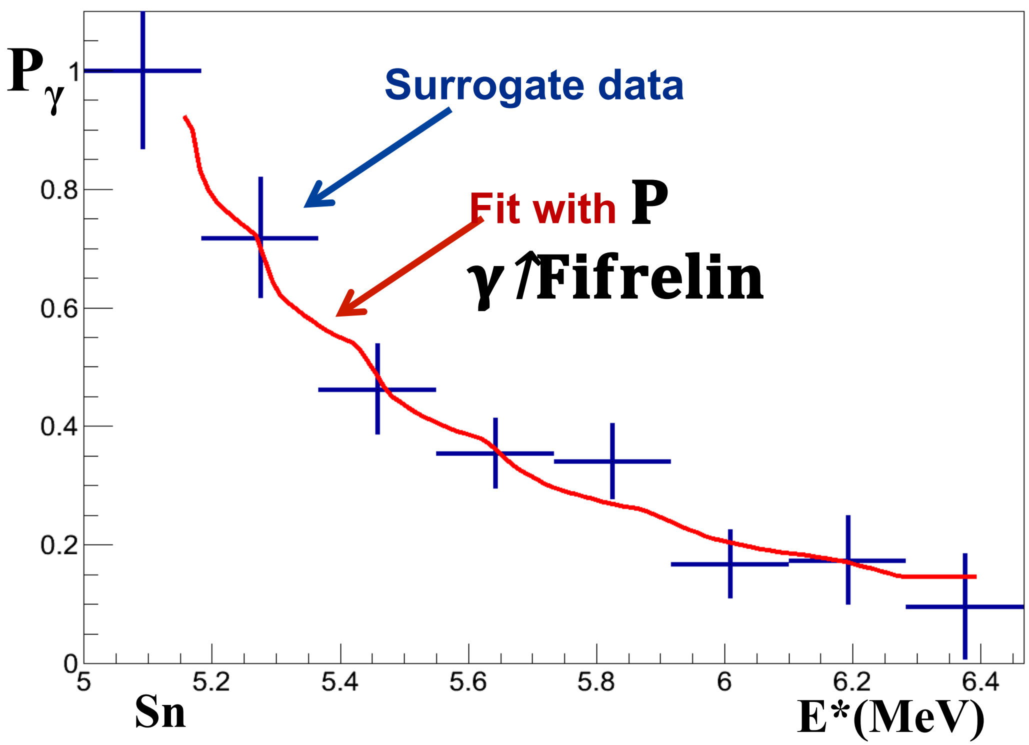


Oslo measurements: Statistical models 3/3

2/3) Use the sensibility to spin of P_γ to extract information on the populated spin distribution of the transfer reaction

- **Fit of the surrogate data for ^{237}U (^{236}U + n) assuming a gaussian distribution**

$$P_\gamma^{Surrogate}(E^*) \approx \sum_{J\pi} \left[\frac{1}{2\sigma\sqrt{2\pi}} e^{-(J-\bar{J})^2/2\sigma^2}\right] \times P_\gamma^{Fifrelin}(E^*,J,\pi)$$



Q.Ducasse

Models used
Strength function : **EGLO**
Level Density : **CGCM**

<J,surrogate> = 4,1

TO DO:

3/3) Implement the populated spin distribution in the code to extract the calculated fission probability to compare it with the experimental one.

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Conclusion and outlook

Conclusion

- The surrogate method is the only way to obtain information of very radioactive nuclei ($T_{1/2}$ < few days) such as :
  - Fission : Cross section measurements (reliable to neutron data)
  - Gamma emission : Constrain parameters of the level density and the strenght function
- Fission much less sensitive to the spin distribution than gamma emission
  - Need help of statistical model to conclude
- Theoretical challenge: Spin distribution of the compound nucleus determination in a surrogate experiment

Experimental outlook

- April 2015 : Expected surrogate experiment at IPN Orsay
  - Beam time : 2 weeks
  - Same target : ^{238}U , same beam (^{3}He)
  - Complementary measurements : fission fragments anisotropy and increase counting rate

  → More accuracy for the surrogate probabilities determination

THANK YOU FOR YOUR ATTENTION

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

P_f et P_γ du ^{237}Np

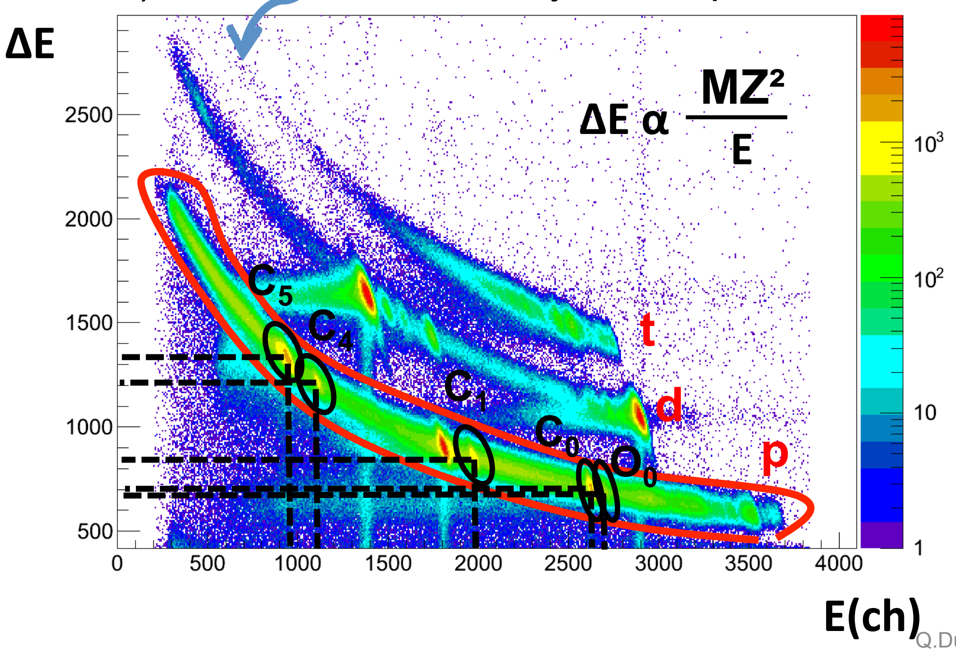
Equation conservation en énergie

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

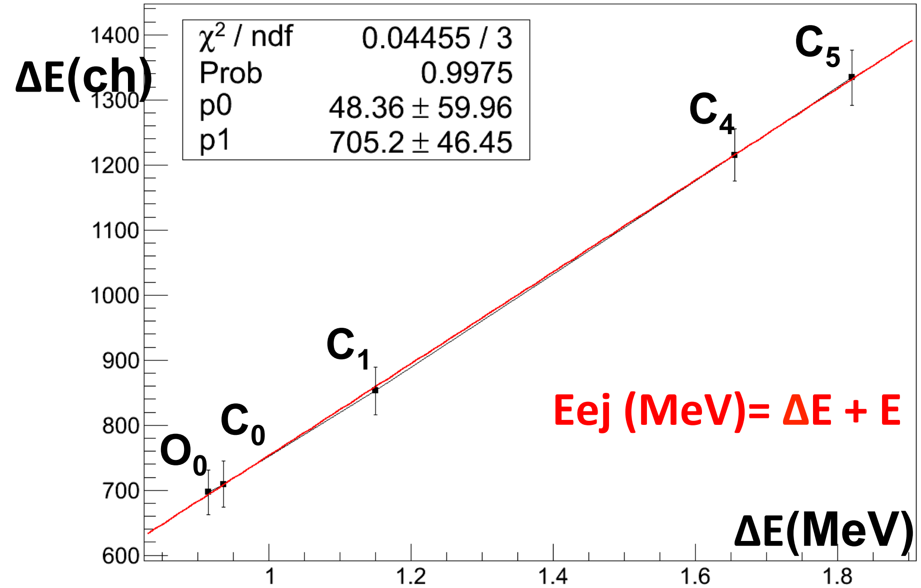
Connues ($E_{pro} + Q_{reaction}$) — **Calibration** ($E_{ejectile}$) — Se calcule ($E_{recul}(CN)$)

- ***E*(CN)*** *= Energie d'excitation du CN formé*
- E_{pro} *= Energie du faisceau (15 MeV)*
- $Q_{reaction}$ *= Δmc^2 = 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



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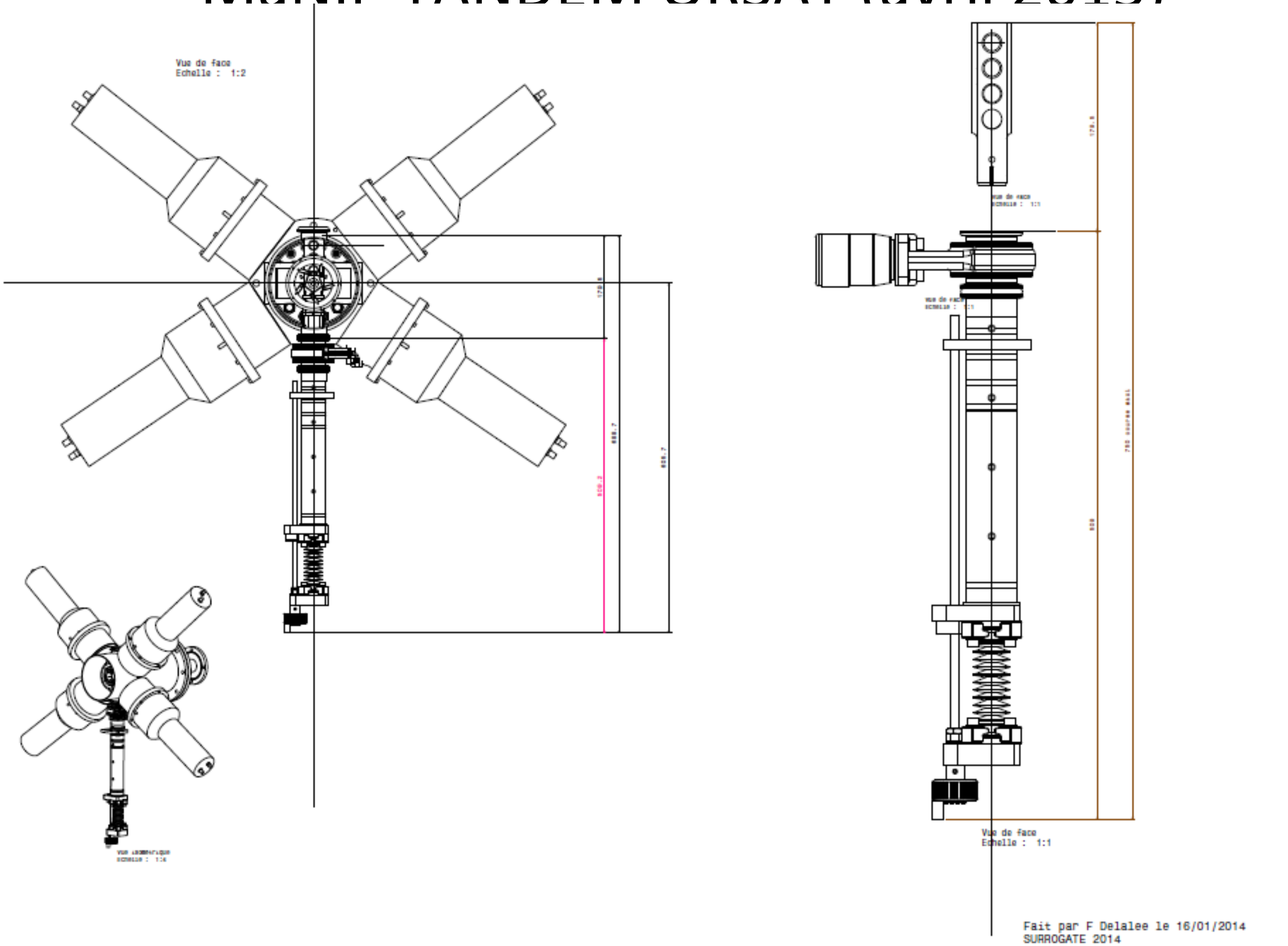
MaNIP TANDEM ORSAY (avril 2015)



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