NEMEA-7 / CIELO

^{235}U and ^{238}U (n,xn gamma) cross-sections

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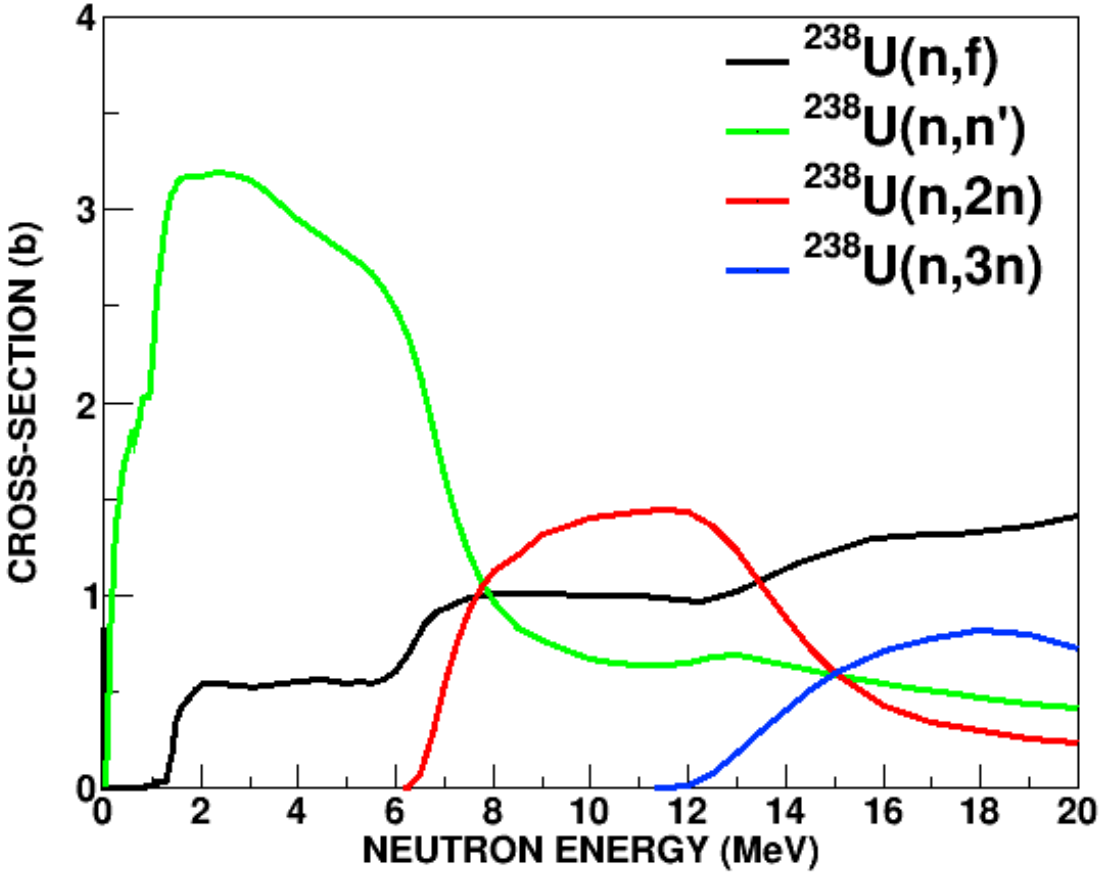
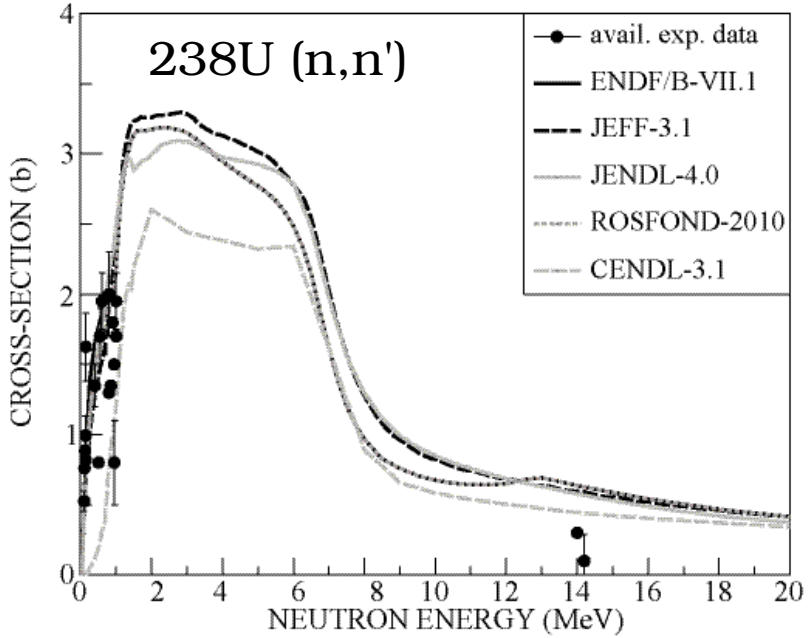
Motivations



ENDF/B-VII.1

(n,xn) reactions are important

Motivations



Entry in HPRL for (n,n') on 238U

Energy Range	Initial versus target uncertainties (%)					
	Initial	ABTR	SFR	EFR	GFR	LFR
6.07-19.6 MeV	29	12			7	
2.23-6.07 MeV	20	3	5	4	2	3
1.35-2.23 MeV	21	4	5	4	2	2
0.498-1.35 MeV	12	7	6	5	2	2
67.4-183 keV	11	7		9	7	4

Few data available (esp. between 1 and 14 MeV)
Precision requirement for data bases (OCDE/NEA – HPRL)

(n,xn gamma)

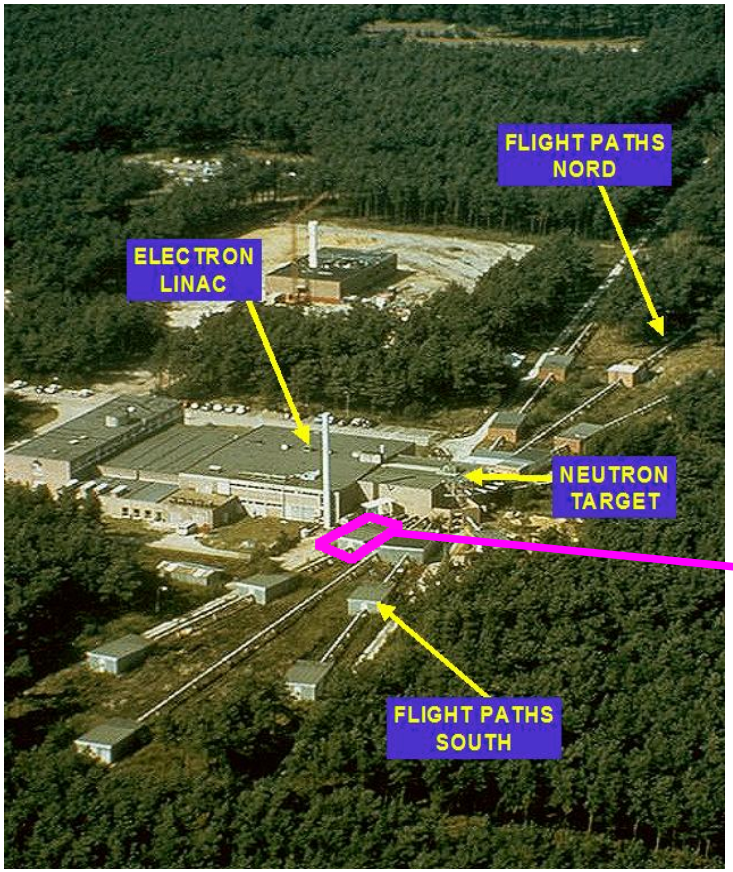
→ **Sensibility** on reactor features : k_{eff}, radial power (D. Bernard et al.)

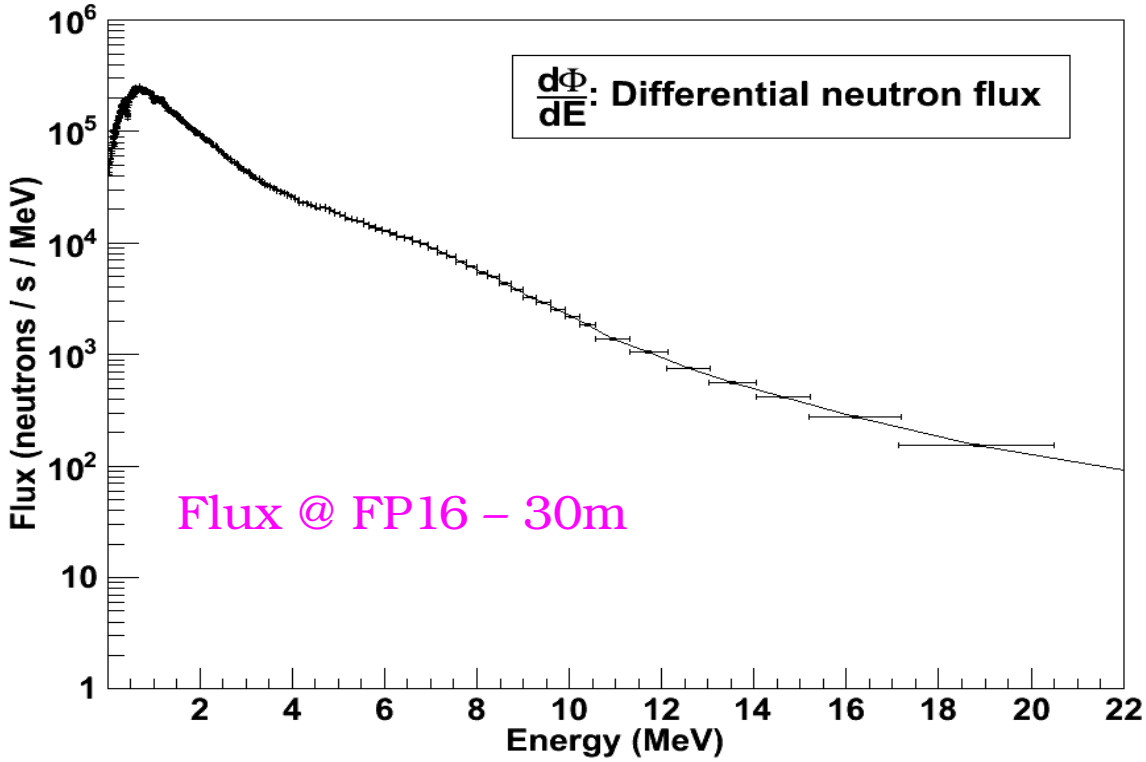
→ **Exclusive** cross-sections : **constraints** on theoretical models

Experimental area

GELINA @ IRMM, Geel, Belgium

- Pulsed electron beam on neutron production target (Uranium)
- Bremsstrahlung (photofission; gamma flash)
- Wide energy-range neutron beam (few eV to 20MeV)



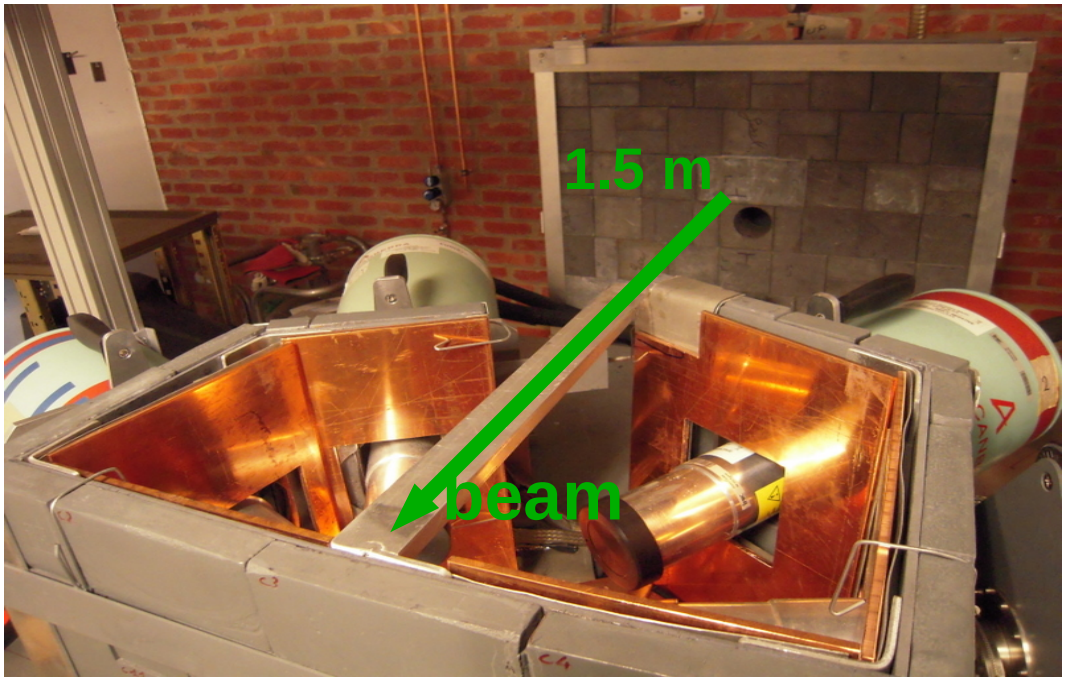


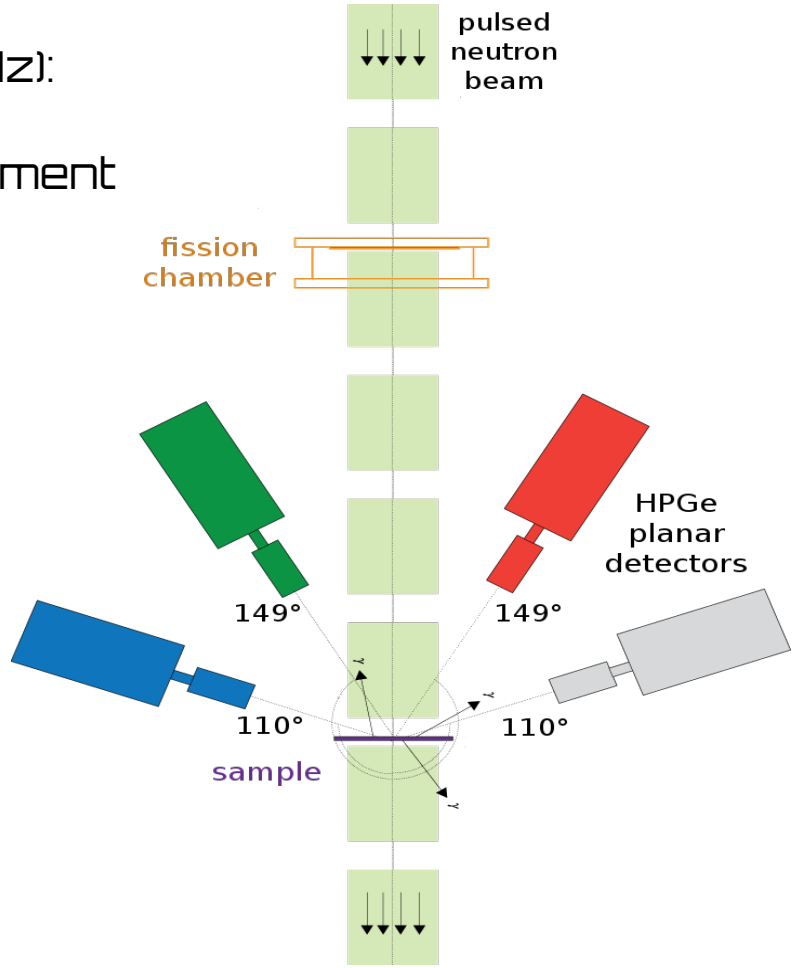
Experimental set-up

Fission chamber (neutron flux determination)
Sample (nucleus of interest)
Germanium planar detectors (**prompt gamma spectroscopy**)

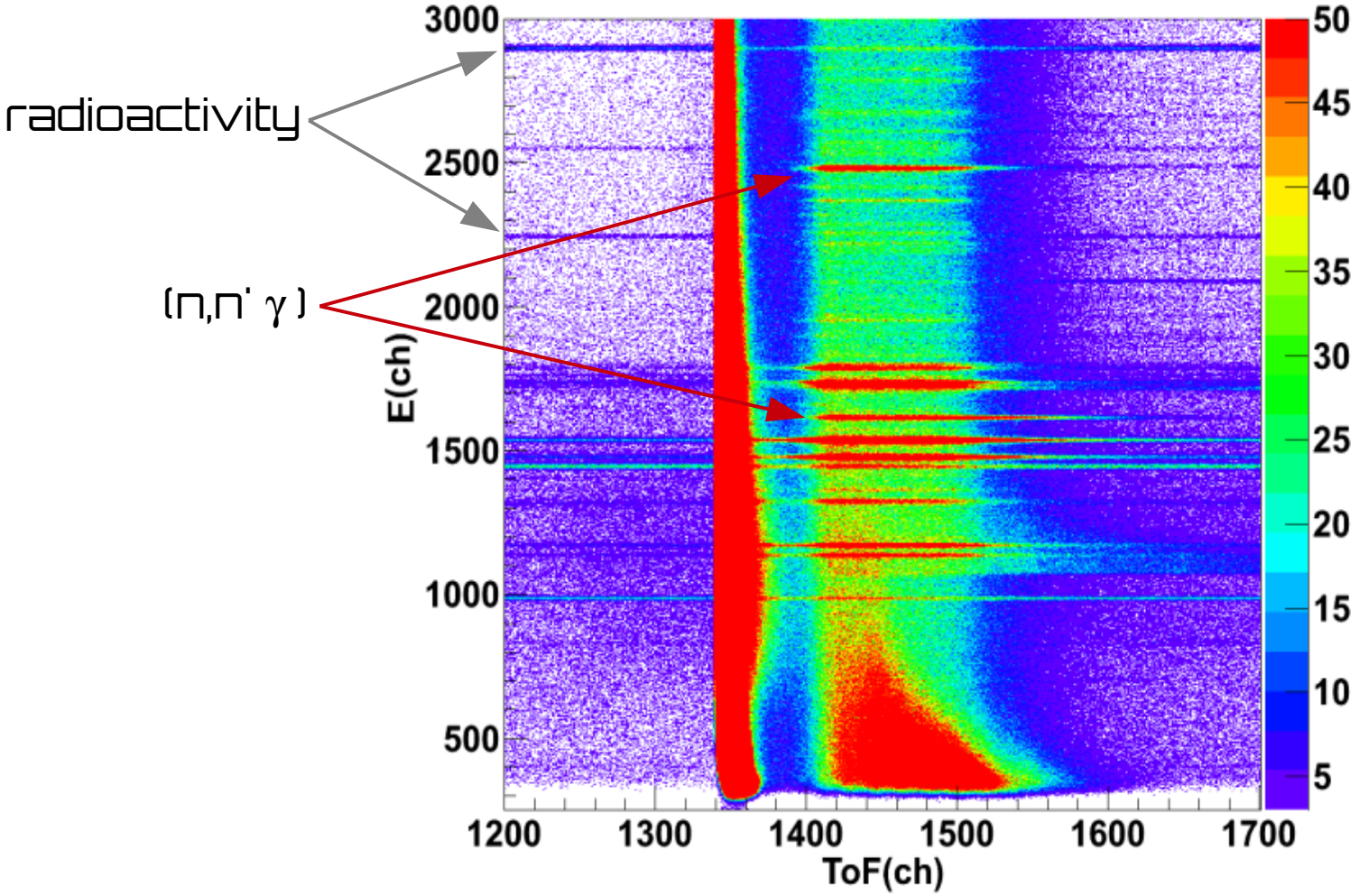
Pulsed beam (800 Hz)
Digital data acquisition (100 MHz):

- gamma energy
- Time of Flight (ToF) measurement





Data analysis



Cross-section

For one detector (at a given angle), for one gamma transition:

$$\frac{d\sigma}{d\Omega}(n,xn\gamma) = \frac{N_\gamma}{\epsilon_\gamma}\frac{\epsilon_{FC}}{N_{FP}}\sigma_{235U}(n,f)\frac{N_{235U}}{N_{sample}}$$

Uncertainty sources :

Number of counts (N_γ, N_{FP})..... ~1-20 %
Efficiencies..... ~1-2 %
Neutrons loss..... ~1 %
Dead-time & pile-up..... < 1 %
Fission cross-section..... < 1 %
N_{235U} ..... ~ 0.5 %
Samples figures :

Isotope	Purity (at.%)	Mass (g)	Diam. (cm)	Thick. (mm)
^{235}U	93.20(3)	37.43(1)	12.004(4)	0.211(6)
^{238}U	99.17(1)	10.6175(1)	7.016(3)	0.181(6)

Angle-integrated information using Gauss quadrature

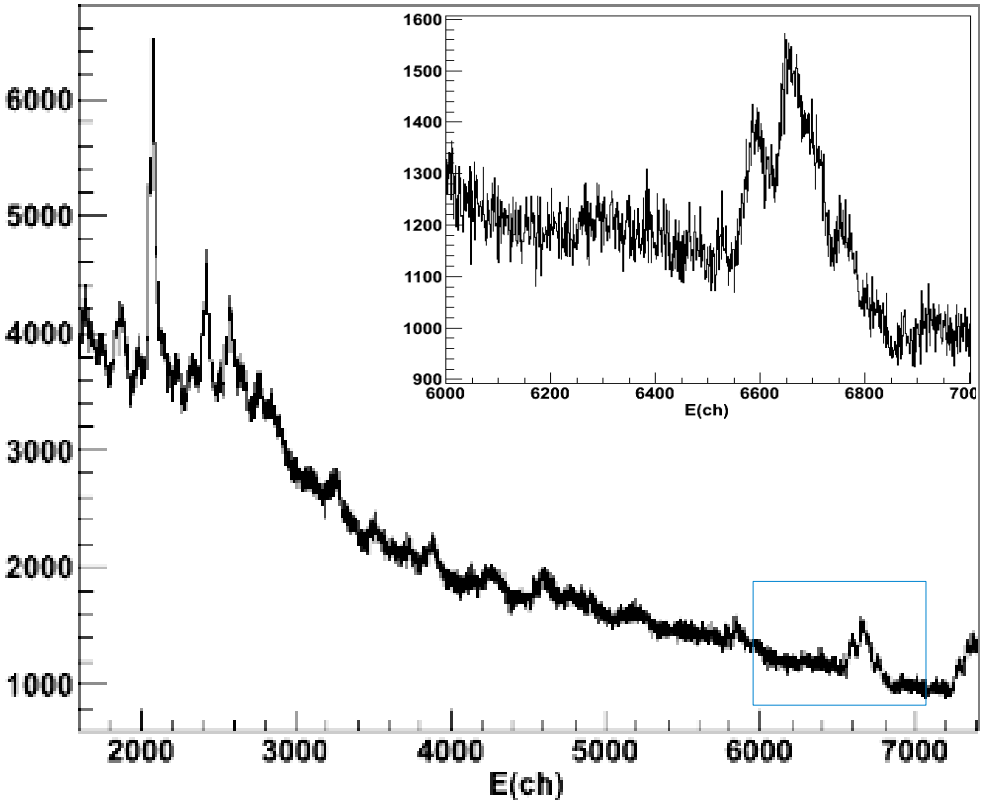
→ **Total uncertainty** budget (optimum) ~ 3 %

Challenges

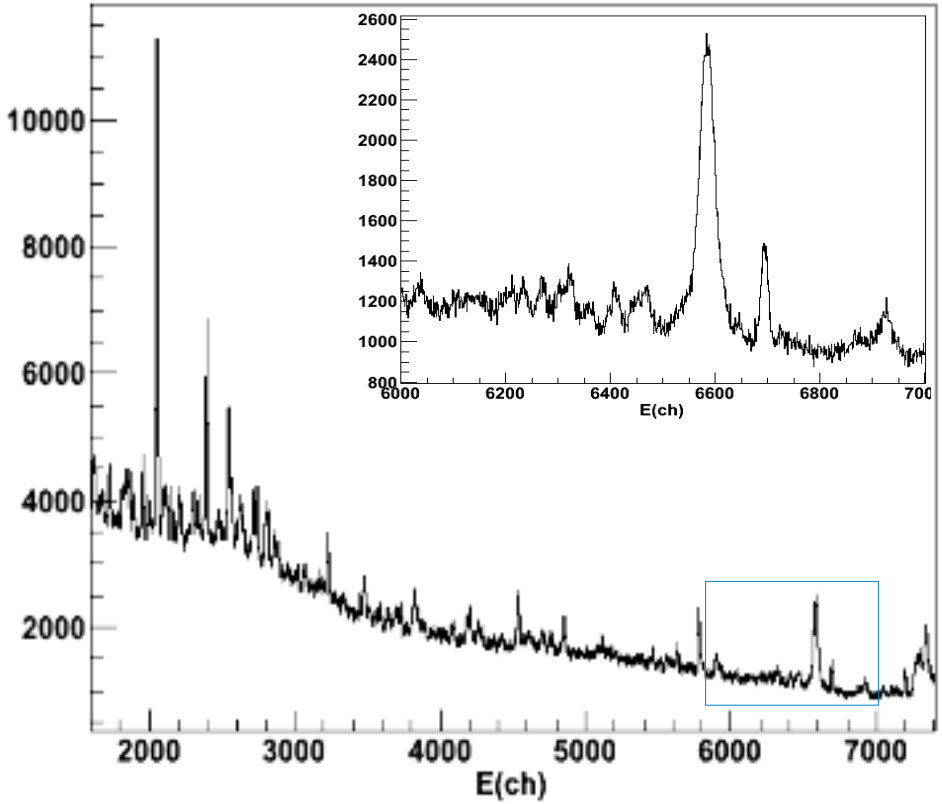
Weak transitions (low xs, high internal conversion) → high statistics

Over 1200 hours of beam time → continuous gain correction

238U "raw data"



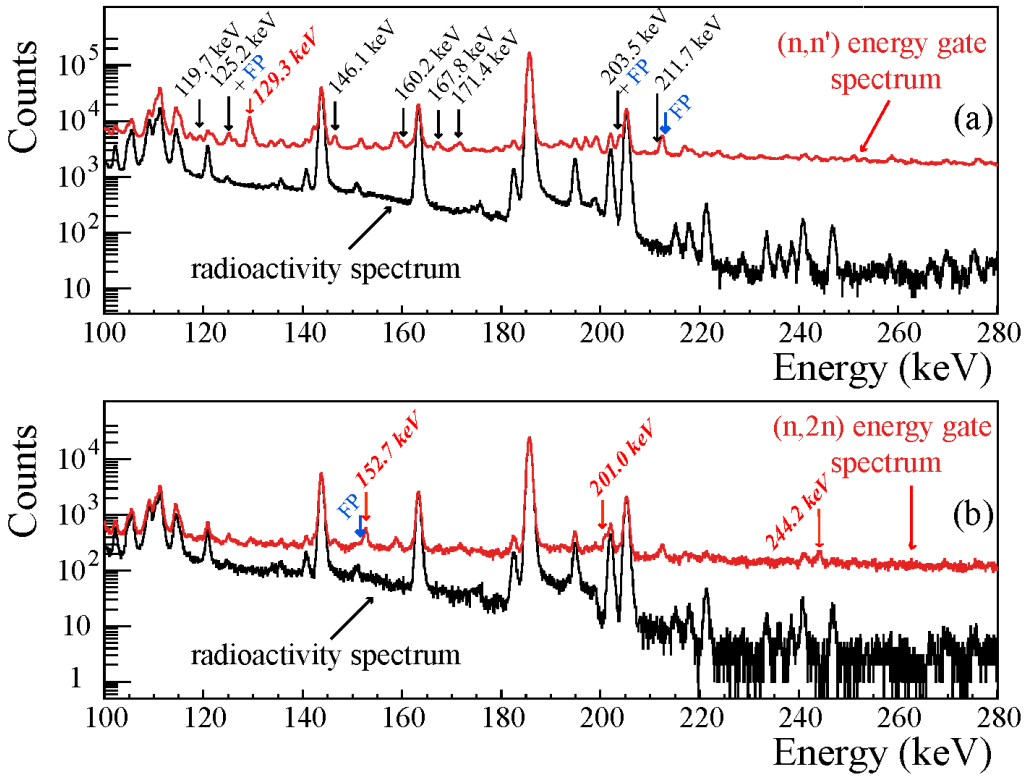
238U "corrected data"

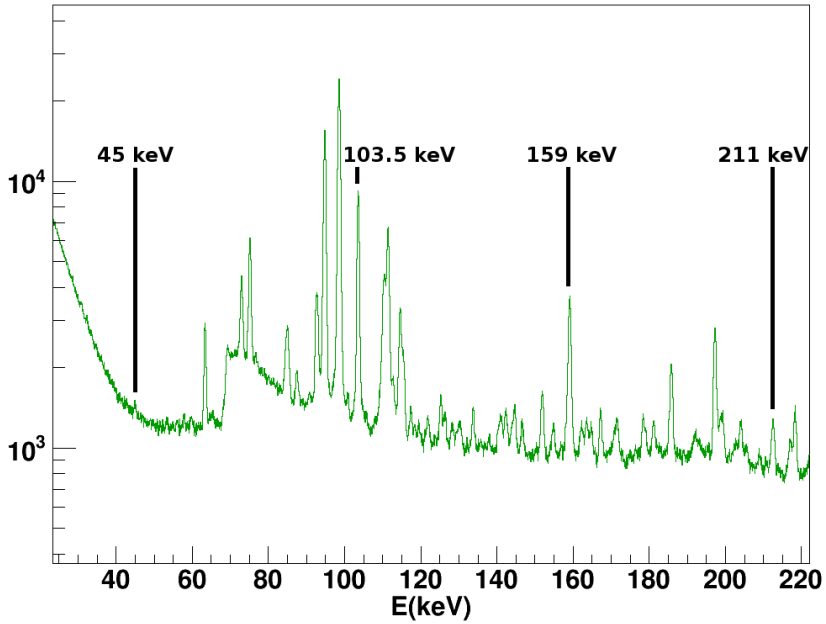


ToF determination for low amplitude signals → « shift » corrected Eg < 200keV
Sample characterization : oxydation layers? → simulation + target lab.

Challenges

235U : peaks overlap (radio + FP)

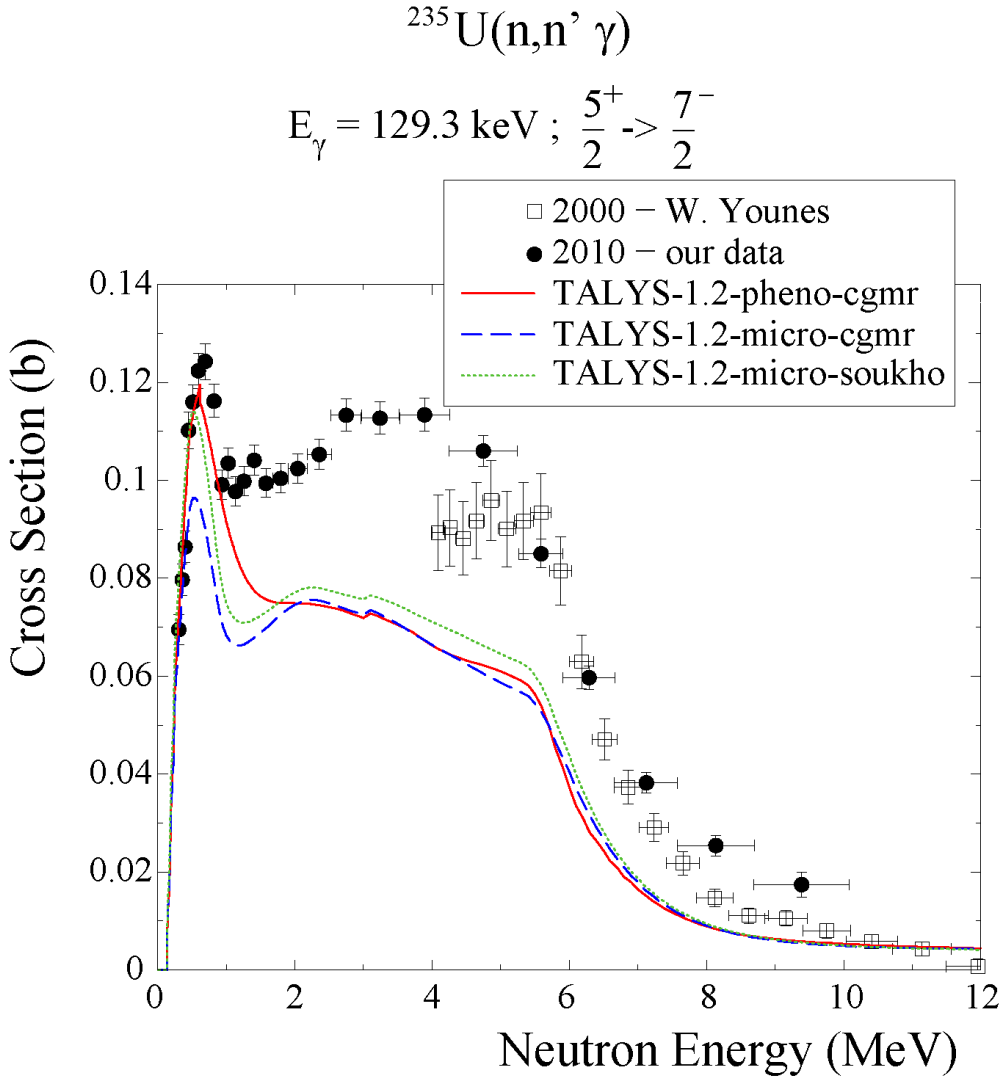


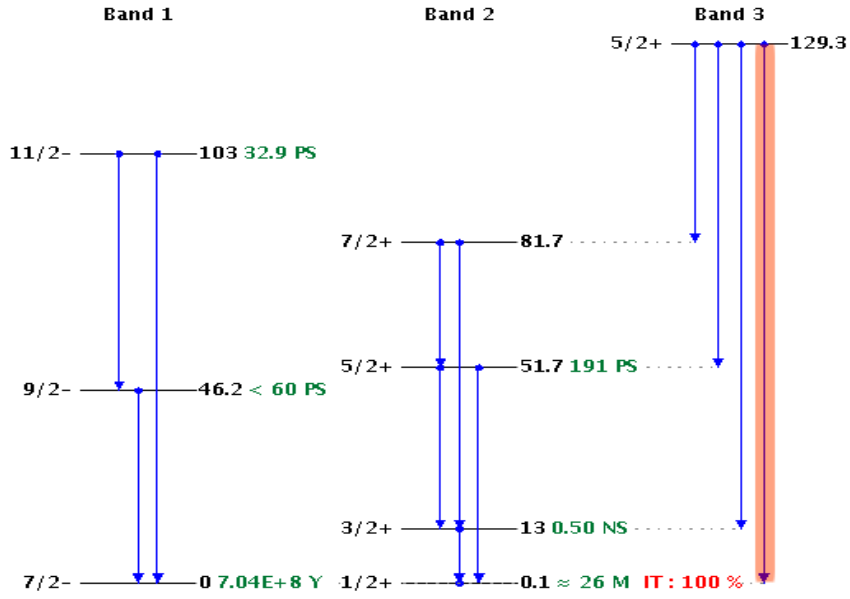


238U : first level de-excitation

Experimental results

Results for ^{235}U (n,n' gamma)





Available data:

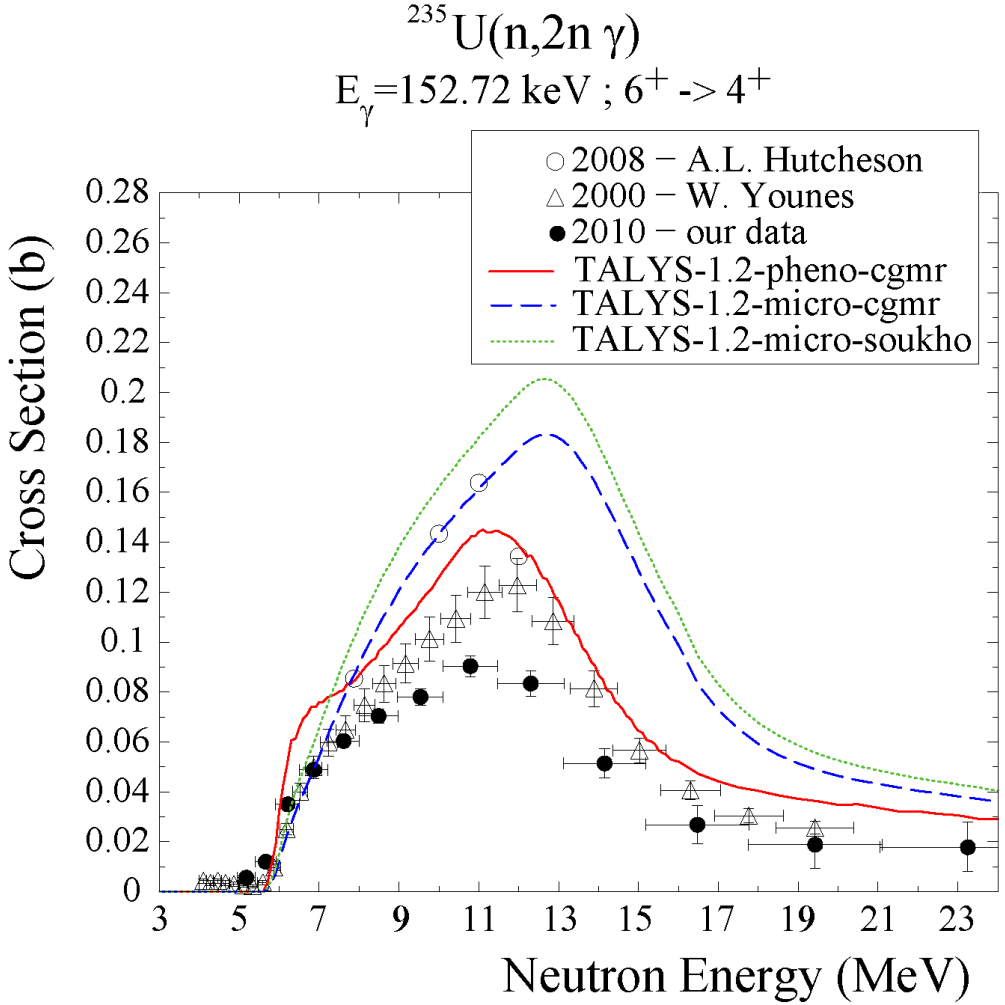
Younes et al., LLNL report UCRL-ID-140313

Model calculations :

TALYS with various inputs & optical models (P. Romain et al.)

Kerveno et al., PRC 87, 024609 (2013)

Results for ^{235}U (n,2n gamma)



3 transitions in band 1 of ^{234}U

Available data:

Younes et al., LLNL report UCRL-ID-140313

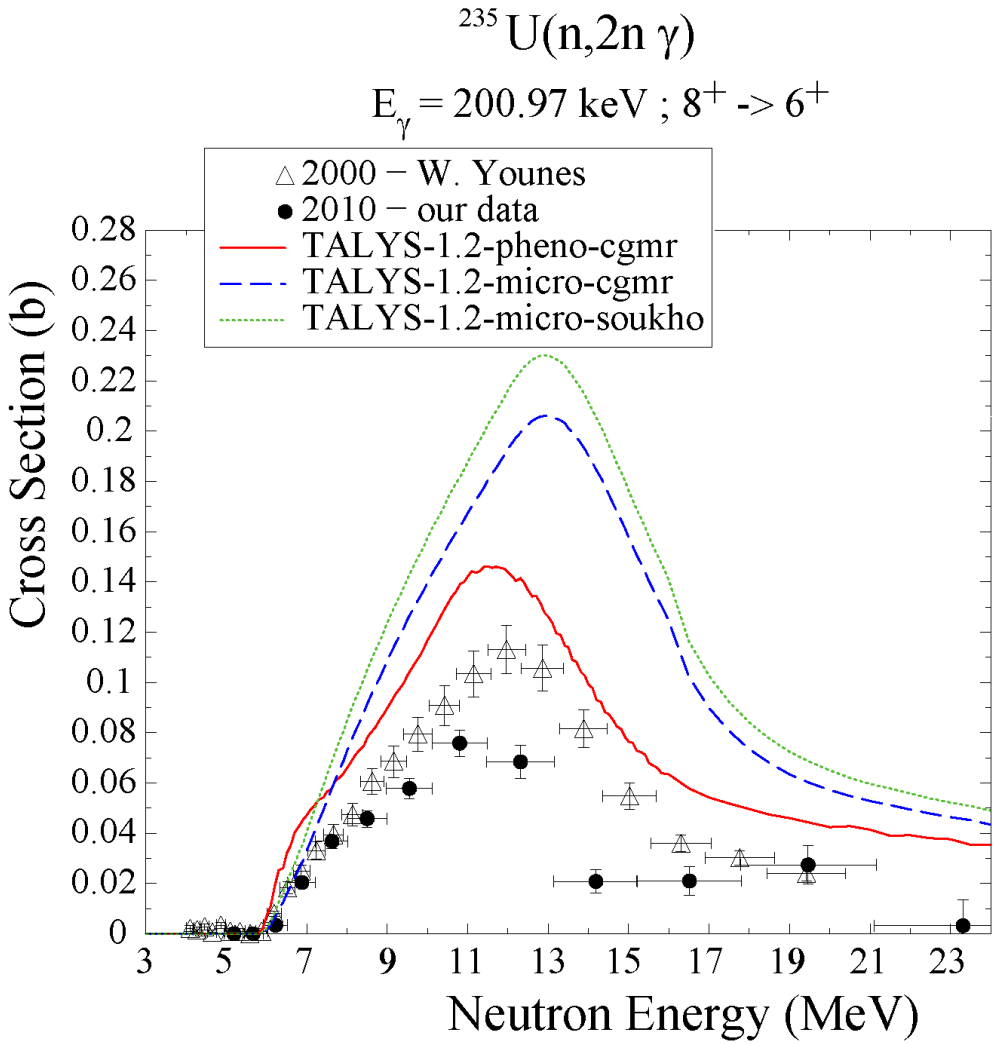
Hutcheson, PhD thesis, Duke University

Model calculations :

TALYS with various inputs & optical models

Kerveno et al., PRC 87, 024609 (2013)

Results for ^{235}U (n,2n gamma)



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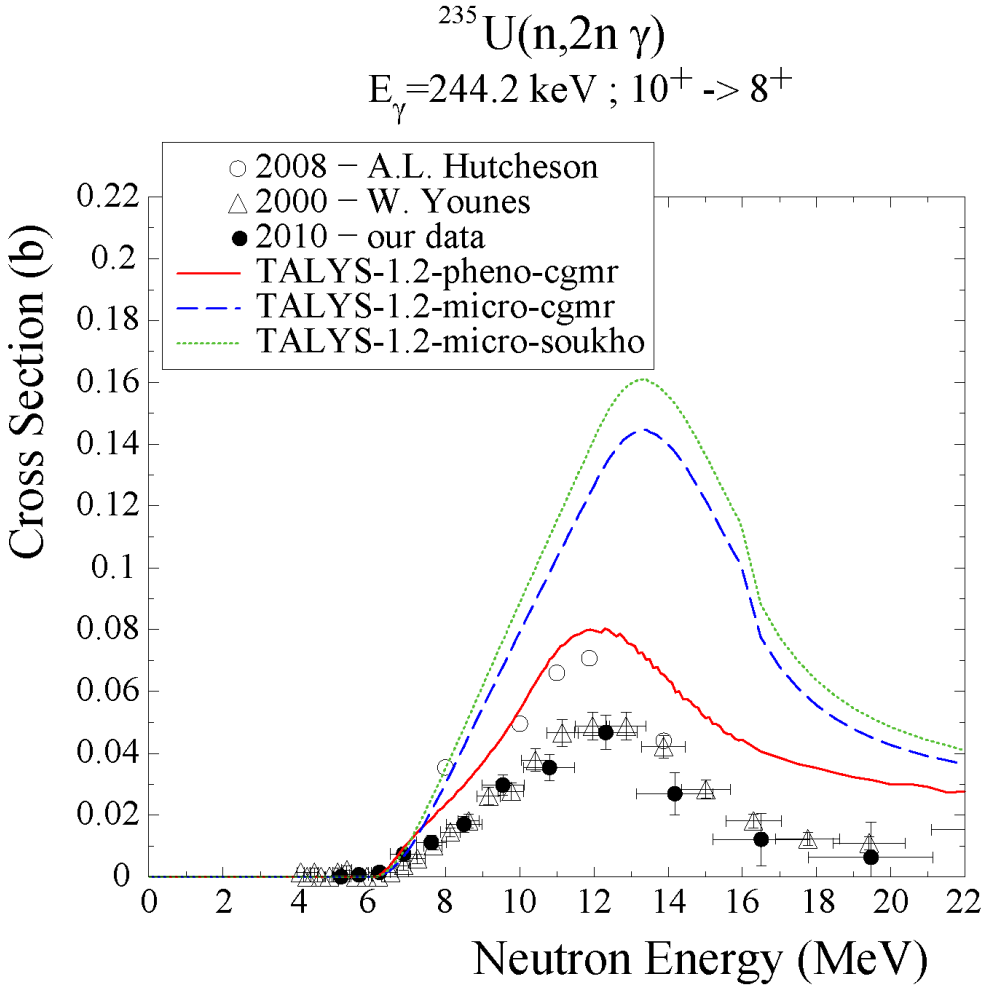
Results for ^{235}U (n,2n gamma)



3 transitions in band 1 of ^{234}U

Available data:
Younes et al., LLNL report UCRL-ID-140313
Hutcheson, PhD thesis, Duke University

Model calculations :
TALYS with various inputs & optical models

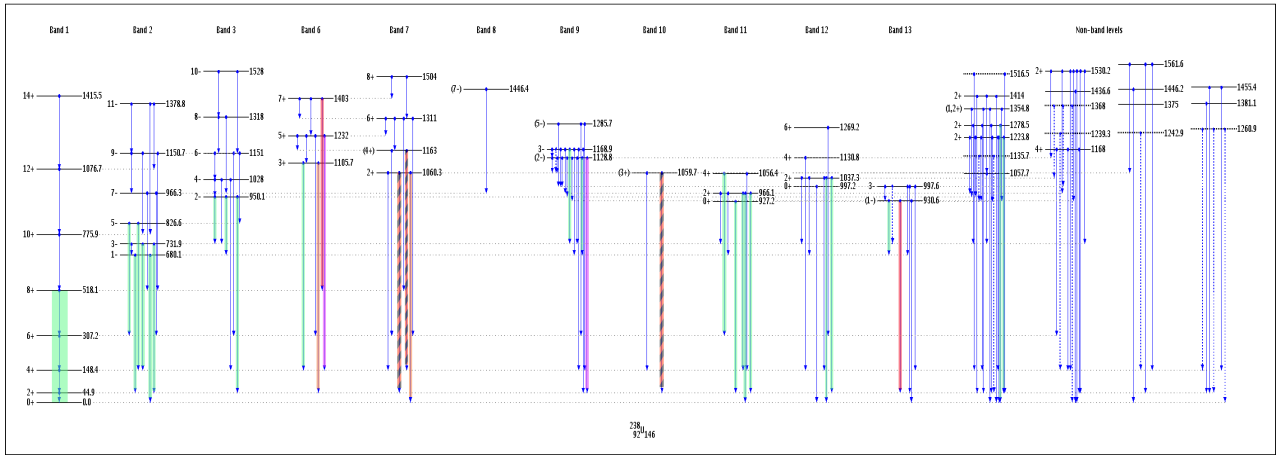
Kerveno et al., PRC 87, 024609 (2013)

→ phenomenological approach works best
→ Not many xs, but pointing out description problems

A more comfortable case, with more constraining power : ^{238}U.

Results for ^{238}U(n,xn gamma)

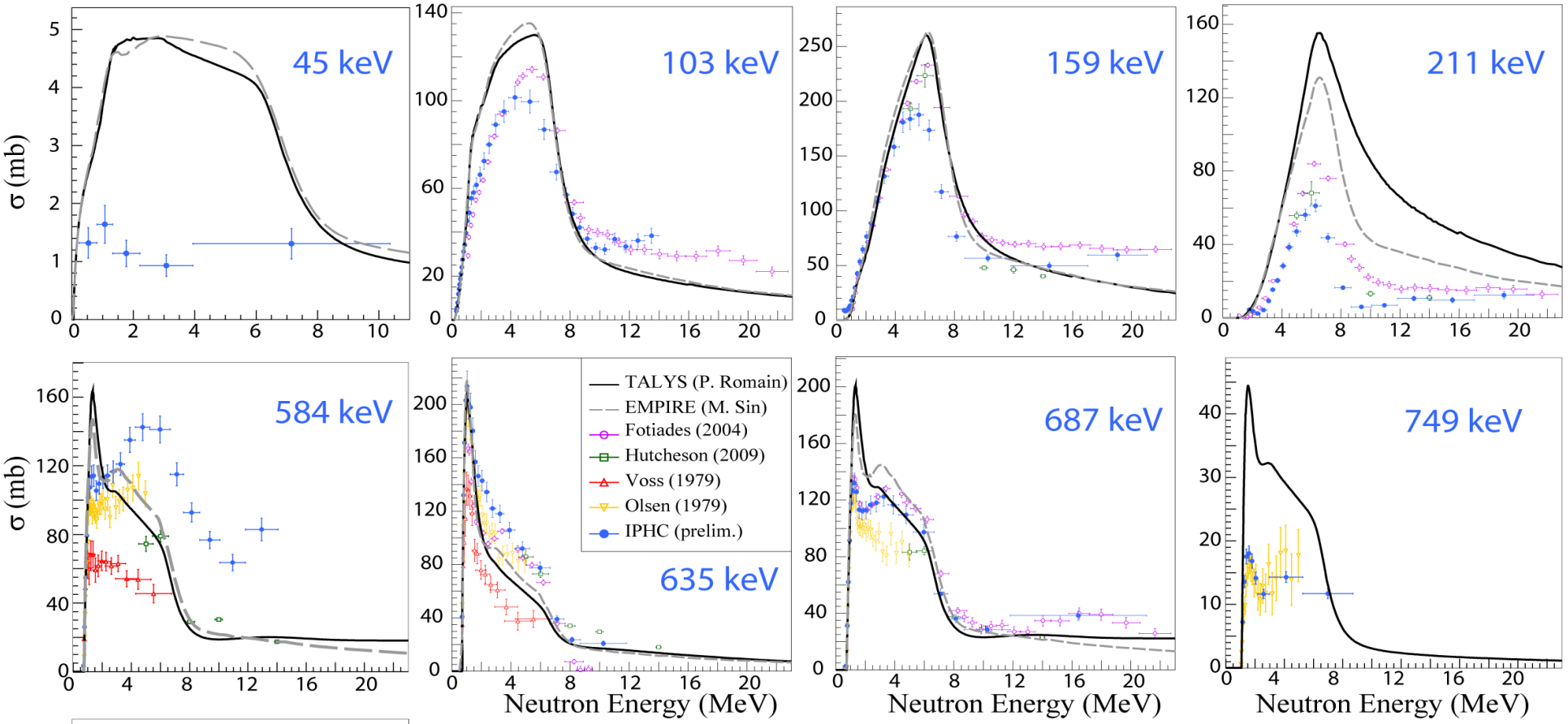
→ 3 (n,2n γ) transitions
→ 4 (n,3n γ) transitions
→ 35 (n,n'γ) transitions, among which :
4 within Band 1
6 going to G.S.

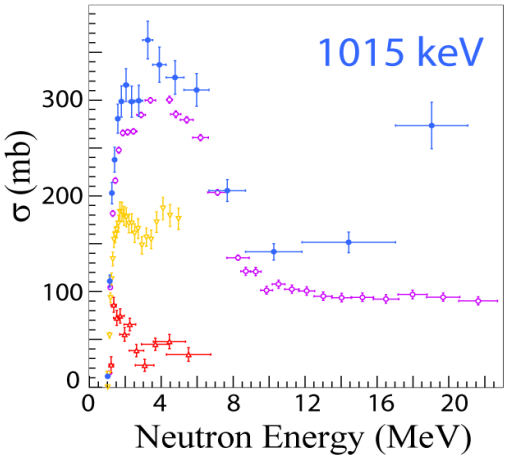


List of treated (n,xnγ) on ^{238}U

E_γ (keV)	Reaction	Ei (Jπ)	Ef (Jπ)
44.915	(n,n')	44.915 (2+)	0 (0+)
103.5	(n,n')	148.38 (4+)	44.915 (2+)
104.2	(n,3n)^{236}U	149.5 (4+)	45.2 (2+)
106.3[a]	(n,2n)^{237}U[a]	162.3 (9/2+)	56.3 (5/2+)
148.567	(n,2n)^{237}U	159.962 (5/2+)	11.393 (3/2+)
155	(n,2n)^{237}U	317.3 (13/2+)	162.3 (9/2+)
158.8	(n,n')	307.18 (6+)	148.38 (4+)
160.3	(n,3n)^{236}U	309.8 (6+)	149.5 (4+)
211	(n,n')	518.1 (8+)	307.18 (6+)
212.46	(n,3n)^{236}U	522.3 (8+)	309.8 (6+)
218.1	(n,n')	950.1 (2-)	731.93 (3-)
251.2	(n,n')	930.6 (1-)	680.11 (1-)
270.1	(n,n')	950.1 (2-)	680.11 (1-)
436.9	(n,n')	1168.88 (3-)	731.93 (3-)
448.1	(n,n')	1128.8 (2-)	680.11 (1-)
519.46	(n,n')	826.64 (5-)	307.18 (6+)
583.55	(n,n')	731.93 (3-)	148.38 (4+)
635.19	(n,n')	680.11 (1-)	44.915 (2+)
642.3	(n,3n)^{236}U	687.6 (1-)	45.2 (2+)
678.3	(n,n')	826.64 (5-)	148.38 (4+)
679.96	(n,n')	680.11 (1-)	0 (0+)
686.99	(n,n')	731.93 (3-)	44.915 (2+)
749.2	(n,n')	1056.38 (4+)	307.18 (6+)
818.06	(n,n')	966.13 (2+)	148.38 (4+)
849.4	(n,n')	997.58 (3-)	148.38 (4+)
882.3	(n,n')	927.21 (0+)	44.915 (2+)
885.46	(n,n')	930.6 (1-)	44.915 (2+)
888.9	(n,n')	1037.25 (2+)	143.38 (4+)
905.5	(n,n')	950.1 (2-)	44.915 (2+)
921.19	(n,n')	966.13 (2+)	44.915 (2+)
952.65	(n,n')	997.58 (3-)	44.915 (2+)
957.3	(n,n')	1105.71 (3+)	148.38 (4+)
966.9	(n,n')	966.13 (2+)	0 (0+)
992.32	(n,n')	1037.25 (2+)	44.915 (2+)
1015	(n,n')sum	1060.27 (2+)	44.915 (2+)
		1059.66 (3+)	44.915 (2+)
		1163 (?)	148.38 (4+)
		... and 1014.5 in ^{27}Al	
1020	(n,n')sum	1167.99 (4+)	148.39 (4+)
		1168.88 (3-)	148.39 (4+)
1037.3	(n,n')	1037.25 (2+)	0 (0+)
1060.3	(n,n')sum	1060.27 (2+)	0 (0+)
		1105.71 (3+)	44.915 (2+)
1084.08	(n,n')sum	1128.84 (2-)	44.915 (2+)
		1232 (5+)	148.38 (4+)
1123	(n,n')	1168.88 (3-)	44.915 (2+)
1179.3	(n,n')	1223.78 (2+)	44.915 (2+)
1278.8	(n,n')	1278.54 (2+)	0 (0+)

[a] Observed, but not referenced in NNDC website.





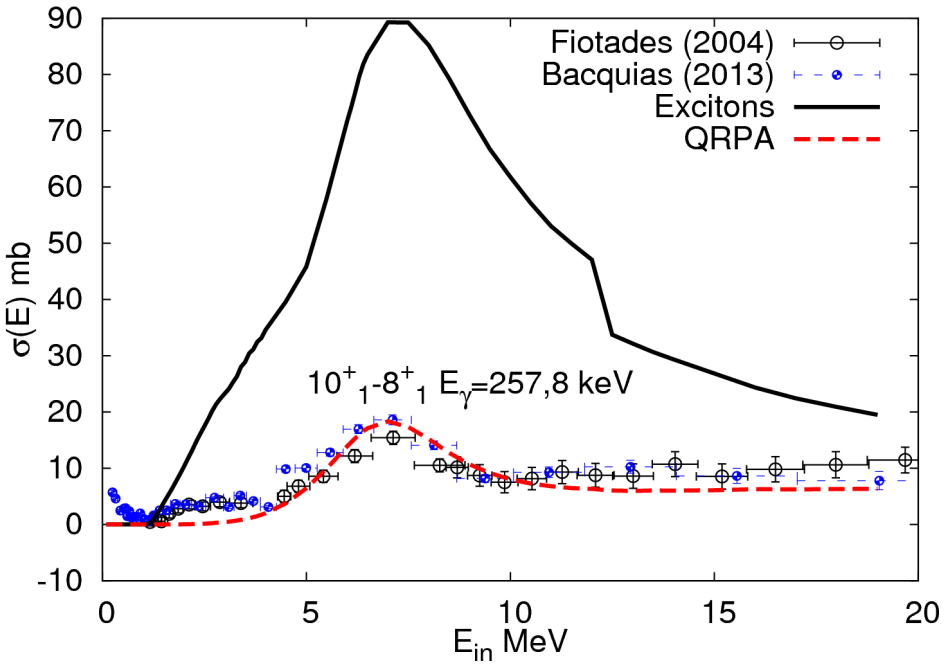
Available data:

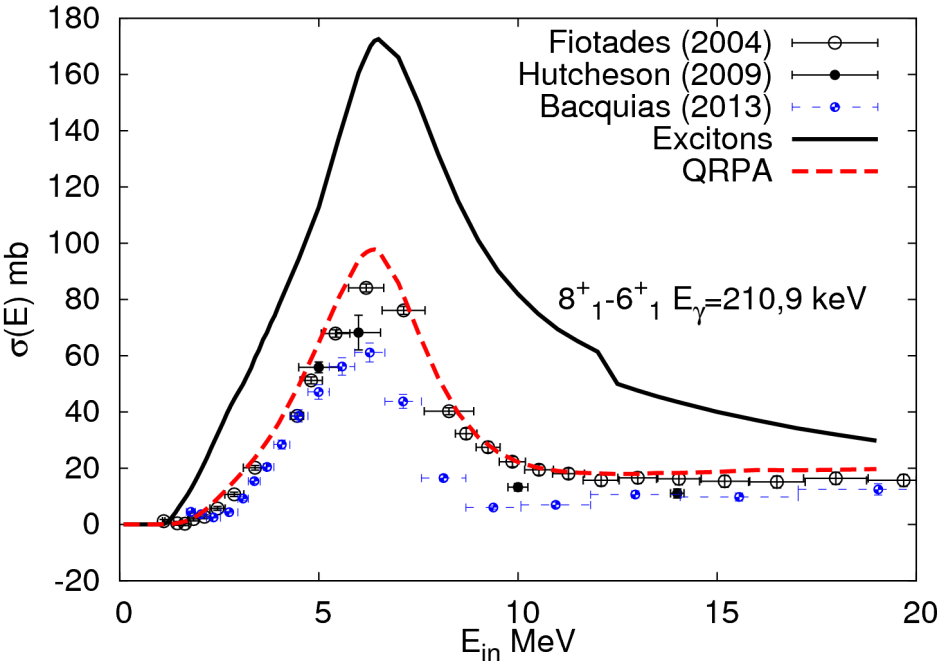
- 29 (n,xn γ) by Fotiades et al., PRC 69, 024601 (2004)
- 9 (n,xn γ) by Hutcheson et al., PRC 80, 014603 (2009)
- 6 (n,n' γ) by Voss et al., Kern. Karlsruhe reports, 2379 (1979)
- 28 (n,n' γ) by Olsen et al., Knoxville proc., p.677 (1979)

→ 42 (n,xn γ) in our data set, **comprehensive & coherent**

Theoretical models : TALYS & EMPIRE **No general agreement !**

M. Dupuis et al. (CEA) – TALYS calc.
QRPA inelastic scattering model





Outlook

^{235}U : TALYS calc. OK for fission & total inelastic but not for partial inelastic
^{238}U : Large & coherent data set
Good precision (~3% when optimum stat.)

Impulse collaboration with theoreticians:
→ experimental: branching ratios (CHANDA)
→ theoretical: collective effects, spin distributions, level densities...

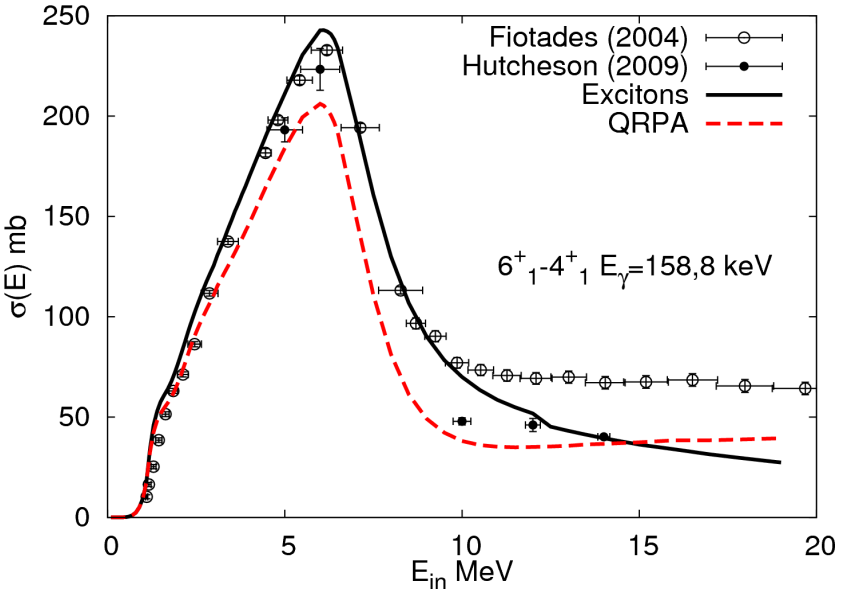
Next results :

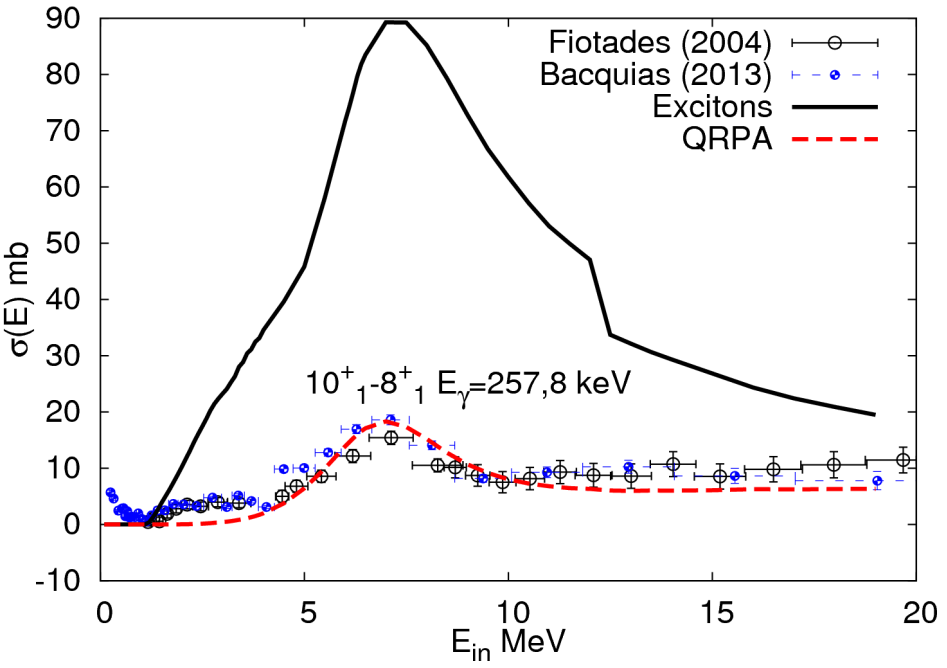
- ^{232}Th
- ^{182,183,184,186}W

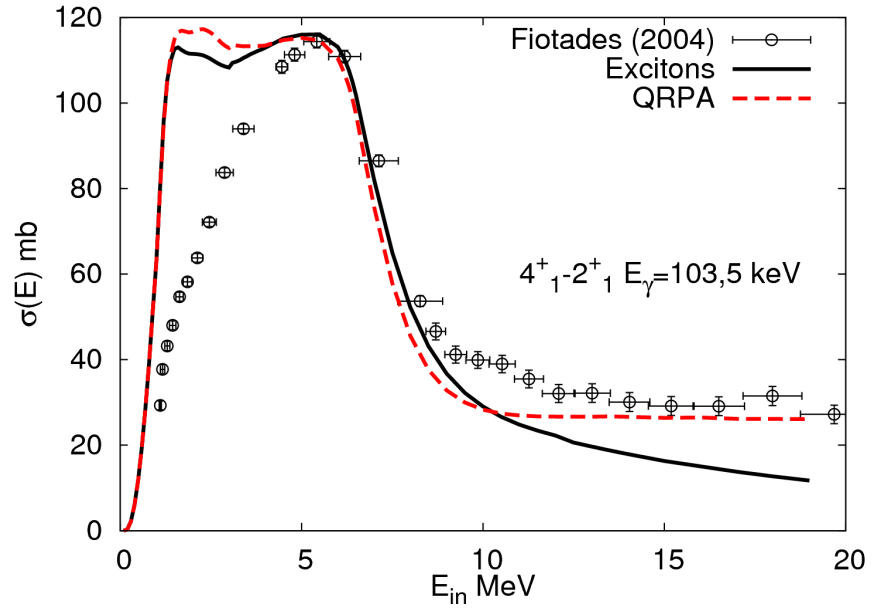
Next measurements :

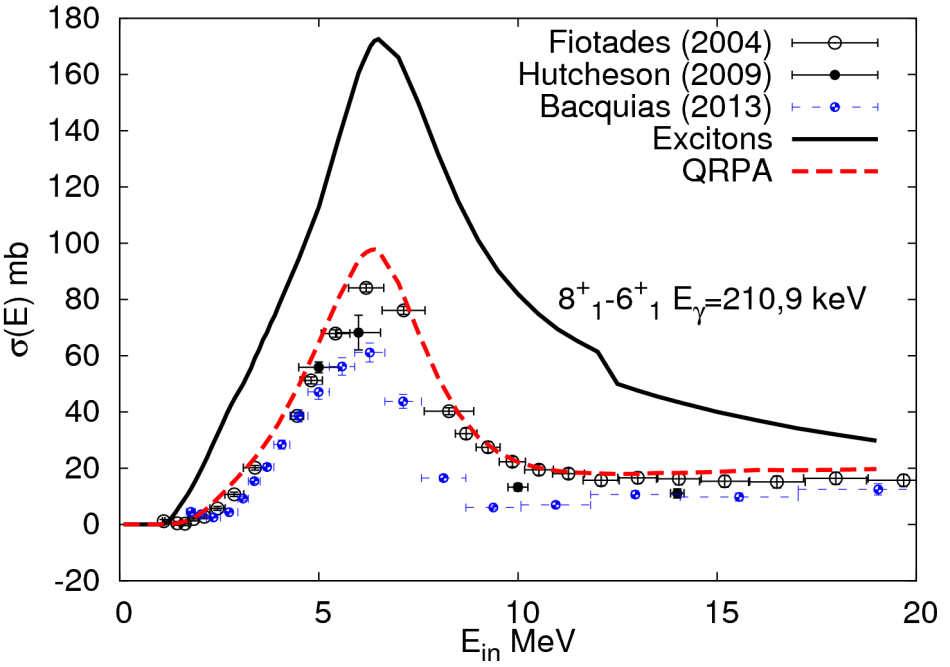
- ^{233}U (challenge, because high activity, very dense levels...)
- ^{239}Pu ?

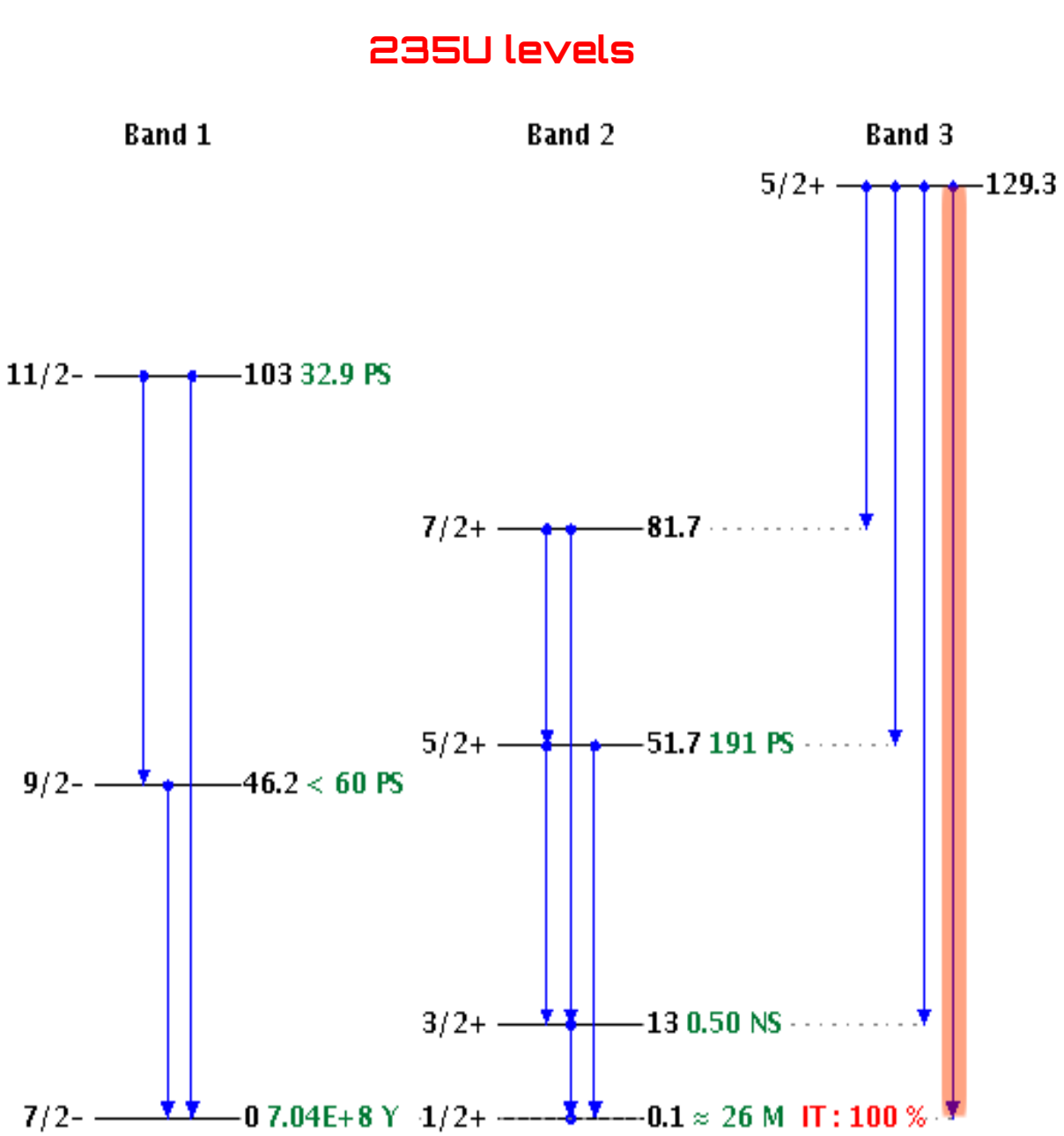
M. Dupuis et al. (CEA) – TALYS calc.
QRPA inelastic scattering model

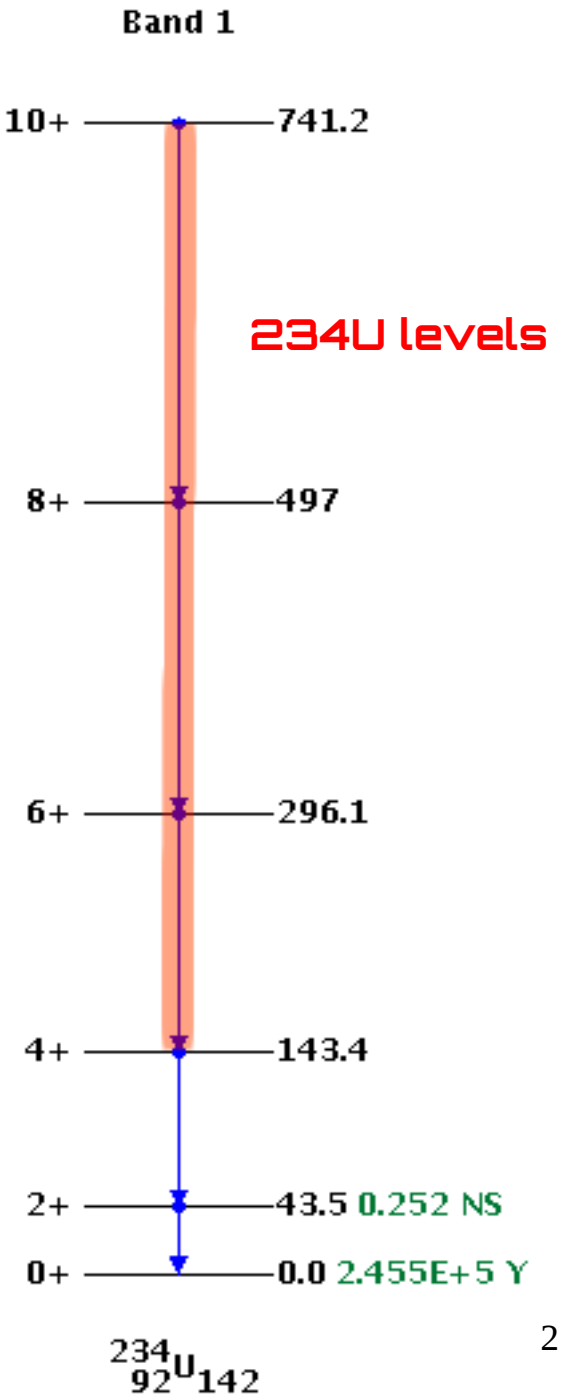




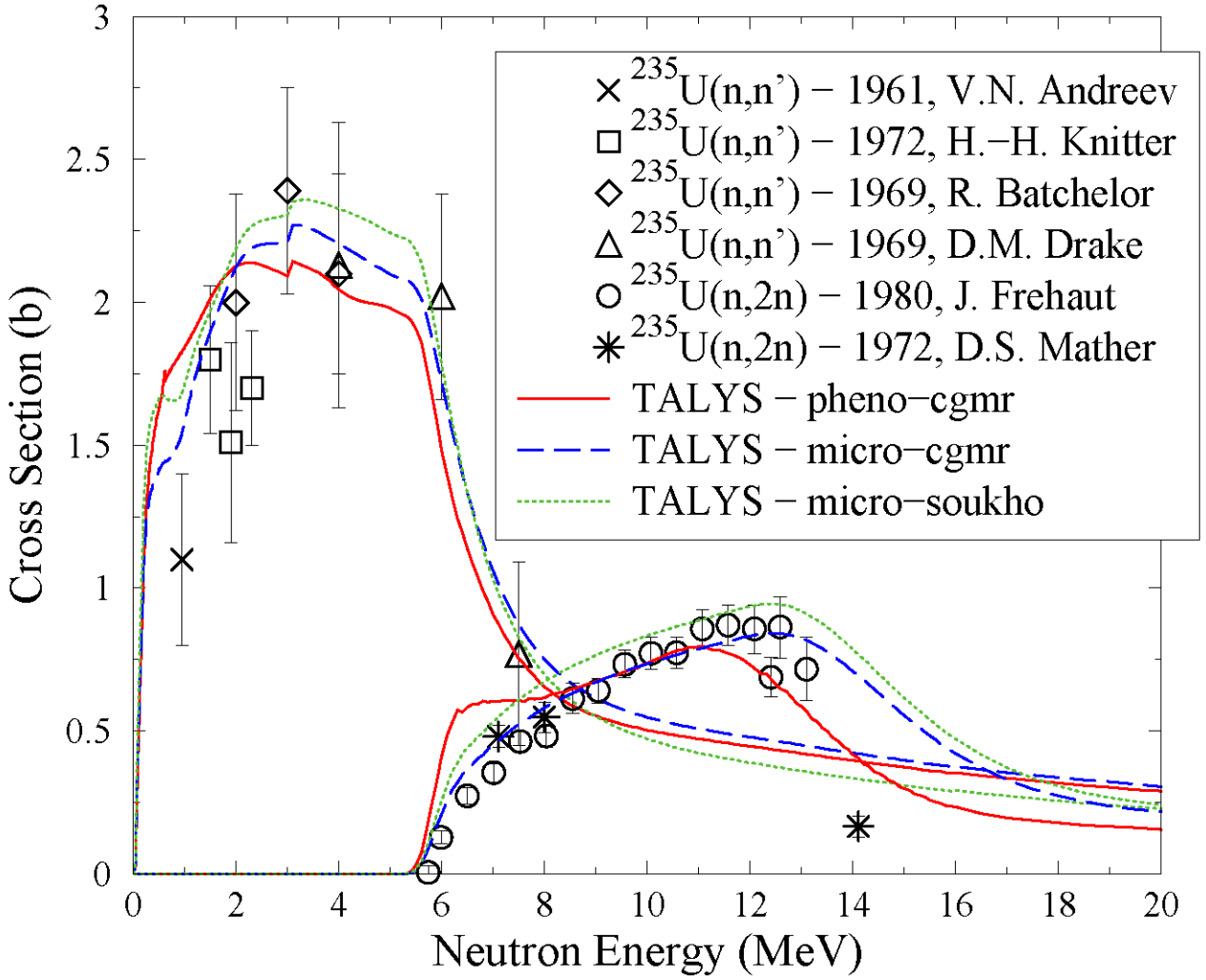


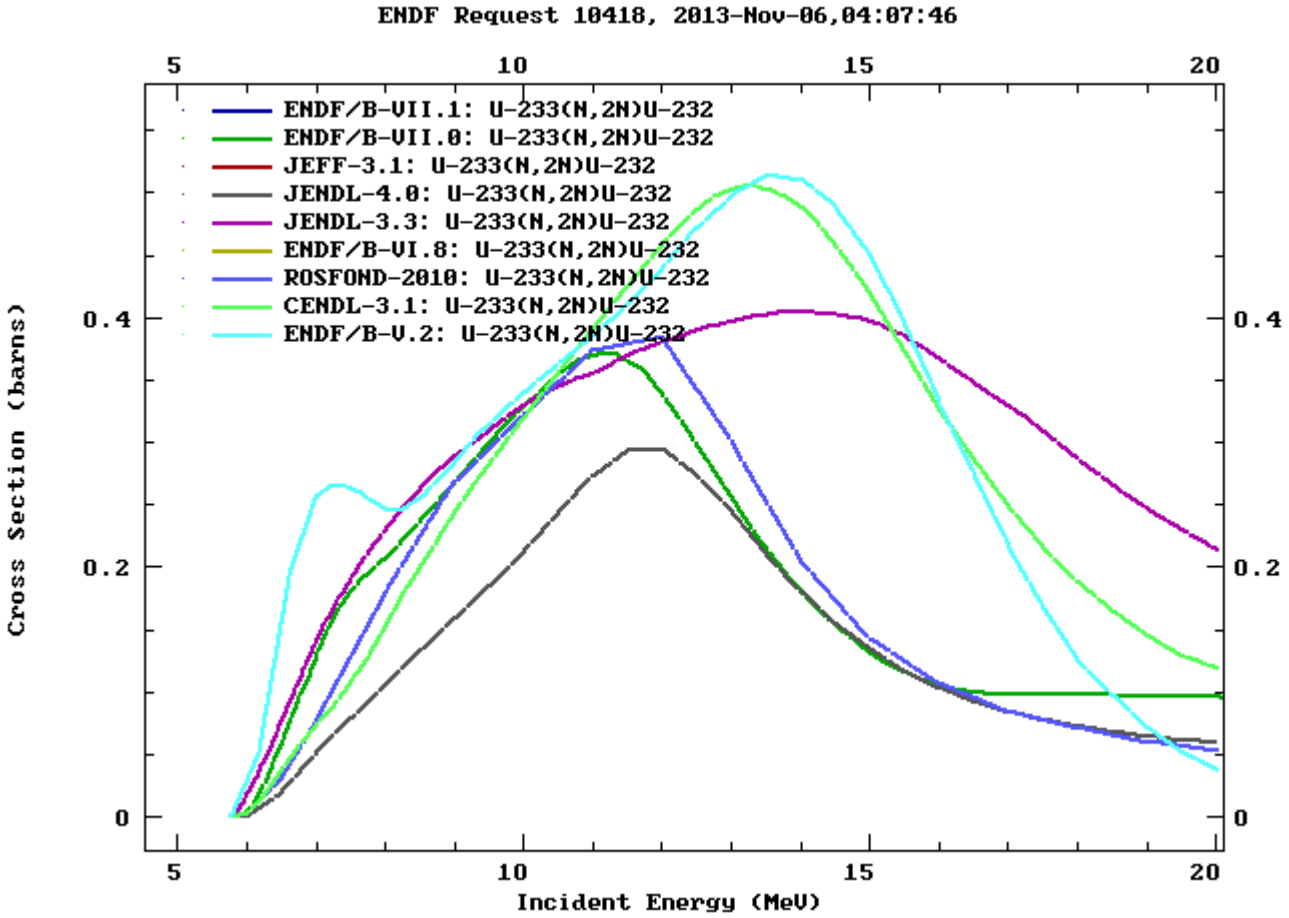



235U levels
Band 1
Band 2
Band 3
11/2-
103 32.9 PS
9/2-
46.2 < 60 PS
7/2-
0 7.04E+8 Y
7/2+
81.7
5/2+
51.7 191 PS
3/2+
13 0.50 NS
1/2+
0.1 ≈ 26 M IT : 100 %
5/2+
129.3

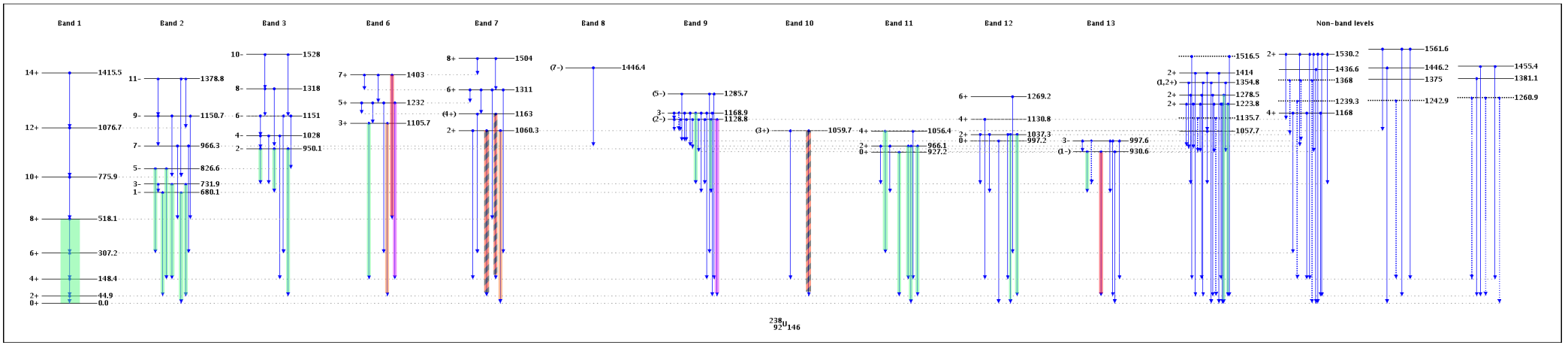

Band 1
234U levels
10+
741.2
8+
497
6+
296.1
4+
143.4
2+
43.5 0.252 NS
0+
0.0 2.455E+5 Y
234 92U142

235U total (n,n') & (n,2n) cross-sections




ENDF Request 10418, 2013-Nov-06,04:07:46
ENDF/B-VII.1: U-233(N,2N)U-232
ENDF/B-VII.0: U-233(N,2N)U-232
JEFF-3.1: U-233(N,2N)U-232
JENDL-4.0: U-233(N,2N)U-232
JENDL-3.3: U-233(N,2N)U-232
ENDF/B-VI.8: U-233(N,2N)U-232
ROSFOND-2010: U-233(N,2N)U-232
CENDL-3.1: U-233(N,2N)U-232
ENDF/B-V.2: U-233(N,2N)U-232
Cross Section (barns)
Incident Energy (MeV)
0
0.2
0.4
5
10
15
20

238U levels



See html interactive version