On the need for precise nuclear structure data for high quality (n, n’ γ) cross section measurements

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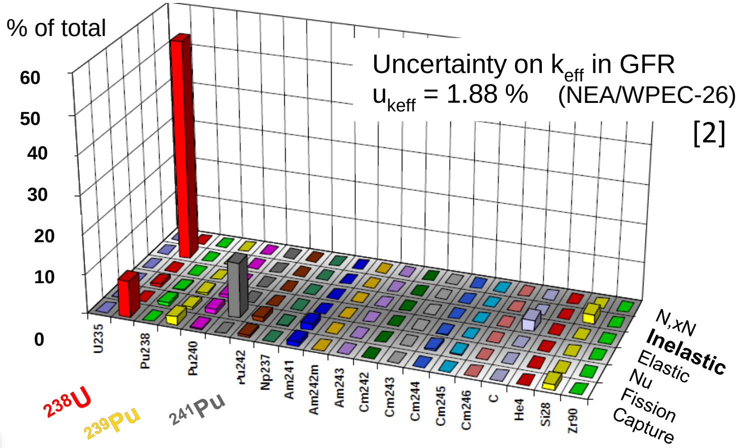
What’s at stakes with (n, n’) reactions

In the reactor, inelastic neutron scattering reactions (n, *x*n) change the number of neutrons, their energy and produce new isotopes.

Neutrons with energy around 1 MeV have a large mean free path in the reactor and contribute to non-local coupling of the power map, as they are highly affected by inelastic scattering off ^{235,238}U, there’s a high sensitivity to the $\sigma_{(n,\,n')}$. [1]

As of today, the uncertainty on $\sigma_{^{238}U}$(n, n‘) limits the accuracy of criticity and power calculation in fast neutron reactors or large core reactors.



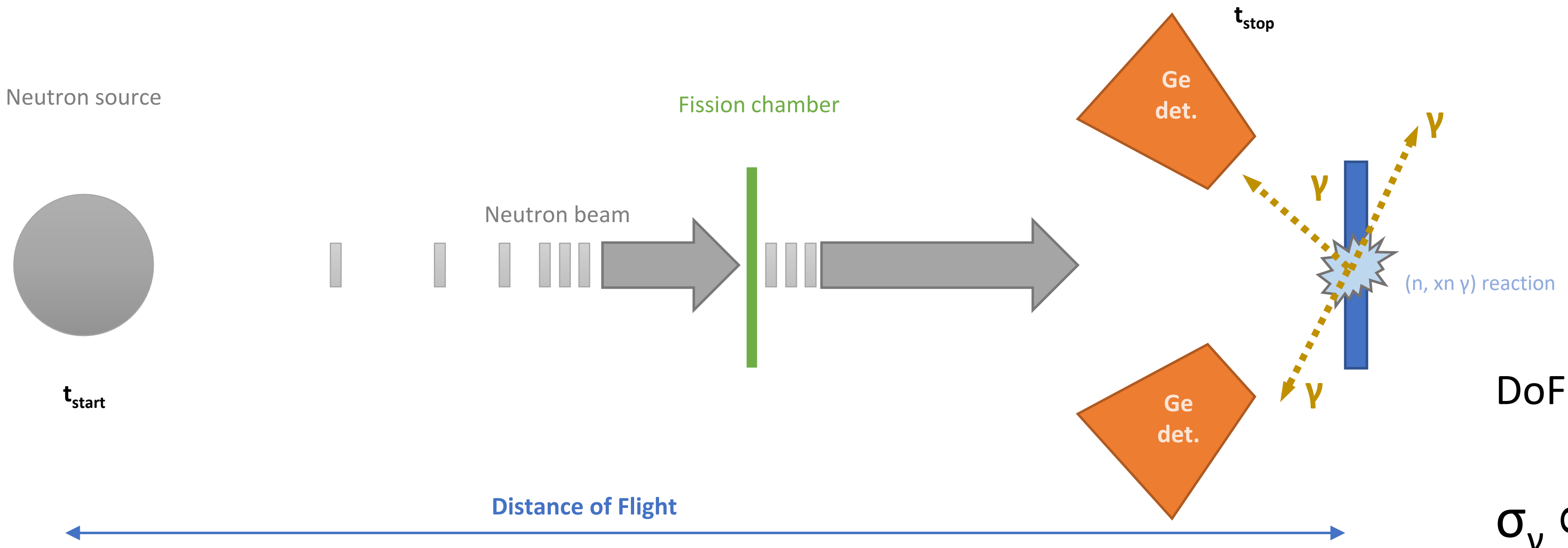
^{238}U(n, n’) cross section is found in the HPRL [3] :

15H	95-AM-241	(n,g),(n,tot)	SIG	Thermal-Fast
18H	92-U-238	(n,inl)	SIG	65 keV-20 MeV
19H	94-PU-238	(n,f)	SIG	9 keV-6 MeV

[1] D. Bernard, CEA/DES
[2] NEA/WPEC-26, "Uncertainty and Target Accuracy Assessment for Innovative Systems Using Recent Covariance Data Evaluations." (2008)
[3] NEA Nuclear Data High Priority Request List https://www.oecd-nea.org/dbdata/hprl/search.pl

Measuring (n, *xn*) cross sections

Indirect measurements via the exclusive (n, xn γ) channel [1,2].



DoF & ToF → En

$$\sigma_\gamma \propto N_\gamma / N_{target} \times \sigma_{n,f} / N_{FC}$$

GRAPhEME setup, at the GELINA neutron beam (JRC-Geel).

Experimentally, not all the γ are visible (intensity, electronic conversion, detection efficiency, …).

See talk « GRAPhEME: performances, achievements and future », M. Kerveno, et al. – July 26th session

[1] "How to produce accurate inelastic cross sections from an indirect measurement method?" M. Kerveno et al., EPJ Nuclear Sci. Technol. 4, 23 (2018)

[2] "GRAPhEME : a setup to measure (n, xn γ) reaction cross sections." Greg Henning, et al.. Adv. in Nuc. Instr. Meas. Met. and App., 2015.

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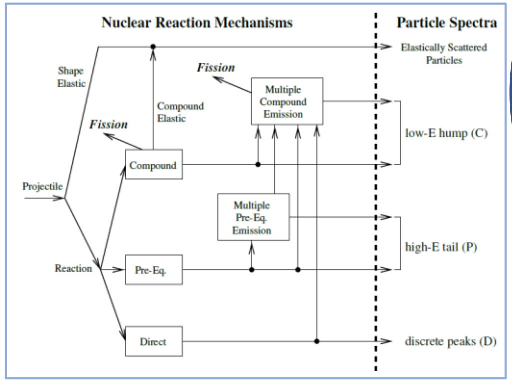
The precise σ_γ experimentally measured are compared to model predictions and used to constraint the reaction models and codes.

Reaction models
Calculation codes
(input: **structure**, optical potential, …)



Total (n, n’) cross section computed with models constrained by our measures.

Precise experimental (n, n’ γ)

This method presents a small dependency on structure data.

See talks « Measurement and evaluation of partial and total (n,xn) reaction cross-sections », F. Claeys, et al. – July 28th session and «From ^{232}Th(n,n’γ) cross sections to level production and total neutron inelastic scattering cross sections.» N. Dari Bako, et al., July 26th session

[1] "How to produce accurate inelastic cross sections from an indirect measurement method?" M. Kerveno et al., EPJ Nuclear Sci. Technol. 4, 23 (2018)
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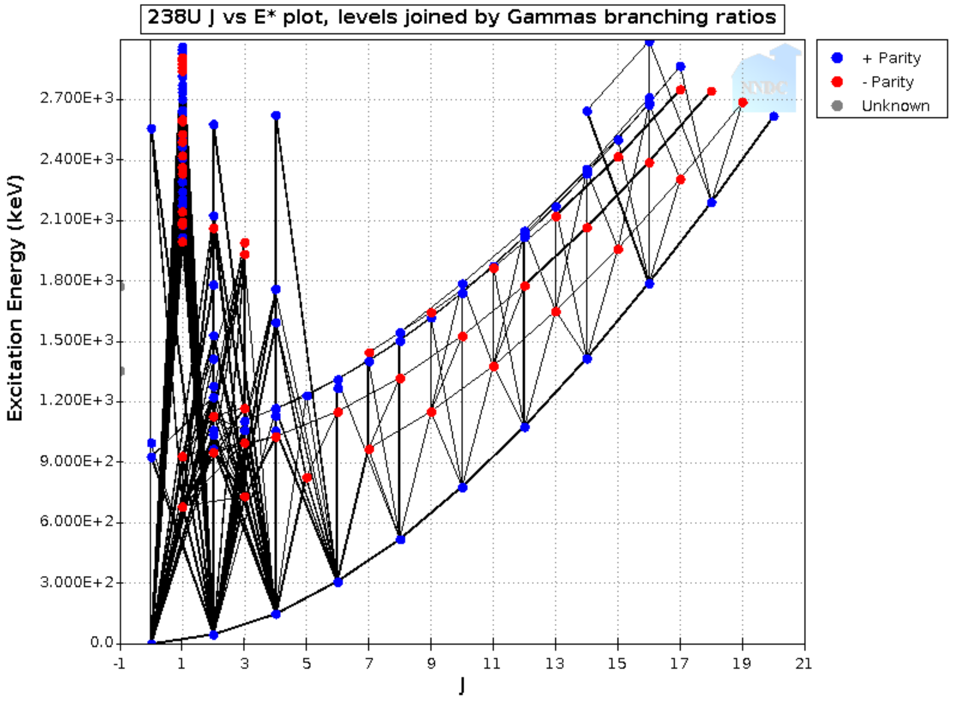
State of the Data Bases

In the Data Base (DB) ENSDF [1], the intensity of γ rays for ^{238}U are known with an average uncertainty of 8 % (sometimes, no uncertainty given).

The level scheme starts missing levels for E^* above 1.4 MeV (45th level according RIPL [2]).
Doubts on spin-parity for levels starts at the 11th (930 keV).



RIPL-3 (Discrete Level Scheme) [2]

127-161 minutes

Discrete Levels

238U

number of levels:	285
number of gamma-rays:	587
number of levels in a complete level scheme:	45
number of levels with assigned spin and parity:	10
neutron separation energy:	6.153719 [MeV]
proton separation energy:	7.508863 [MeV]

[1] NuDat3, Evaluated Nuclear Structure Data File at National Nuclear Data Center - www.nndc.bnl.gov
[2] Reference Input Parameter Library - IAEA / Nucelar Data Service - https://www-nds.iaea.org/RIPL-3/

State of the Data Bases

Issues in data bases are found on the model/codes input files : [1]:

```
92 238   501   152                                                238U

   0  0.000000   0.0     1  0        1.410E+17                     0+
   1  0.044916   2.0     1  1        2.060E-10                     2+
                                0  1.000000 6.090E+02
   2  0.148380   4.0     1  1
4+
                                1  1.000000 1.160E+01
   3  0.307180   6.0     1  1
6+
                                2  1.000000 1.871E+00
   4  0.518100   8.0     1  1        2.300E-11                     8+
                                3  1.000000 6.260E-01
   5  0.680110   1.0    -1  2        3.500E-14                     1-
                                1  0.558700 2.000E-02
                                0  0.441300 2.000E-02
   6  0.731930   3.0    -1  3                                      3-
                                5  0.000000 1.000E+03
                                2  0.448700 1.003E-02
                                1  0.551300 1.000E-02
   7  0.775900  10.0     1  1        9.000E-12                    10+
                                4  1.000000 3.130E-01
   8  0.826640   5.0    -1  2                                      5-
                                3  0.335100 1.800E-02
                                2  0.664900 1.000E-02
   9  0.927210   0.0     1  1                                      0+
                                1  1.000000 1.412E-02
  10  0.930550   1.0    -1  3                                    (1-)
                                5  0.172400 1.000E+00
                                1  0.661100 4.650E-03
                                0  0.166500 4.260E-03
```

```
  11  0.950120   2.0    -1  3                                      2-
                                6  0.414900 1.500E+00
                                5  0.270600 8.000E-01
                                1  0.314500 4.470E-03
  12  0.966130   2.0     1  5        2.400E-12                     2+
                                6  0.065632 6.890E-02
                                5  0.037341 4.380E-02
                                2  0.449014 1.660E-02
                                1  0.326010 2.300E-01
                                0  0.122004 1.200E-02
  13  0.981770   7.0    -1  2                                      7-
                                4  0.066328 2.600E-02
                                3  0.933672 1.100E-02
  14  0.997230   0.0     1  1                                      0+
                                0  1.000000 0.000E+00
  15  1.012790   3.0    -1  5                                      3-
                               10  0.000000 2.200E+02
                                6  0.000000 8.000E-01
                                5  0.055681 1.611E-01
                                2  0.602412 5.020E-03
                                1  0.341907 4.090E-03
  16  1.028000   4.0    -1  3                                      4-
                               11  0.333333 1.000E+02
                                6  0.333333 6.000E-01
                                2  0.333333 5.900E-03
  17  1.037250   2.0     1  5        1.130E-12                     2+
                                6  0.037620 3.790E-02
                                5  0.029970 2.700E-02
                                2  0.223402 1.410E-02
                                1  0.398604 7.800E-01
                                0  0.310403 1.050E-02
```

«The default choice is the RIPL-3 database(…), unknown spins, parities and branching ratios are always assigned a value, based on simple statistical spin rules.» [2]

This adds another *layer* of uncertainty when using structure data.

Even if the DB solves the issue[2], it may persists in the code package

(Corrected in RIPL3 (2020), still present in Talys-1.96 (2021))

1028	CD	4-		78.1 *4* 295.86 *6* 879.63 *11*	64 *42* <190 100 *6*

[1] excerpt from /talys/1.8/talys/structure/levels/final/z092

[2] TALYS-1.95 manual

[3] NuDat3, Evaluated Nuclear Structure Data File at National Nuclear Data Center - www.nndc.bnl.gov

State of the Data Bases

Issues of the DBs seen for many other isotopes:

- ^{232}Th [1]

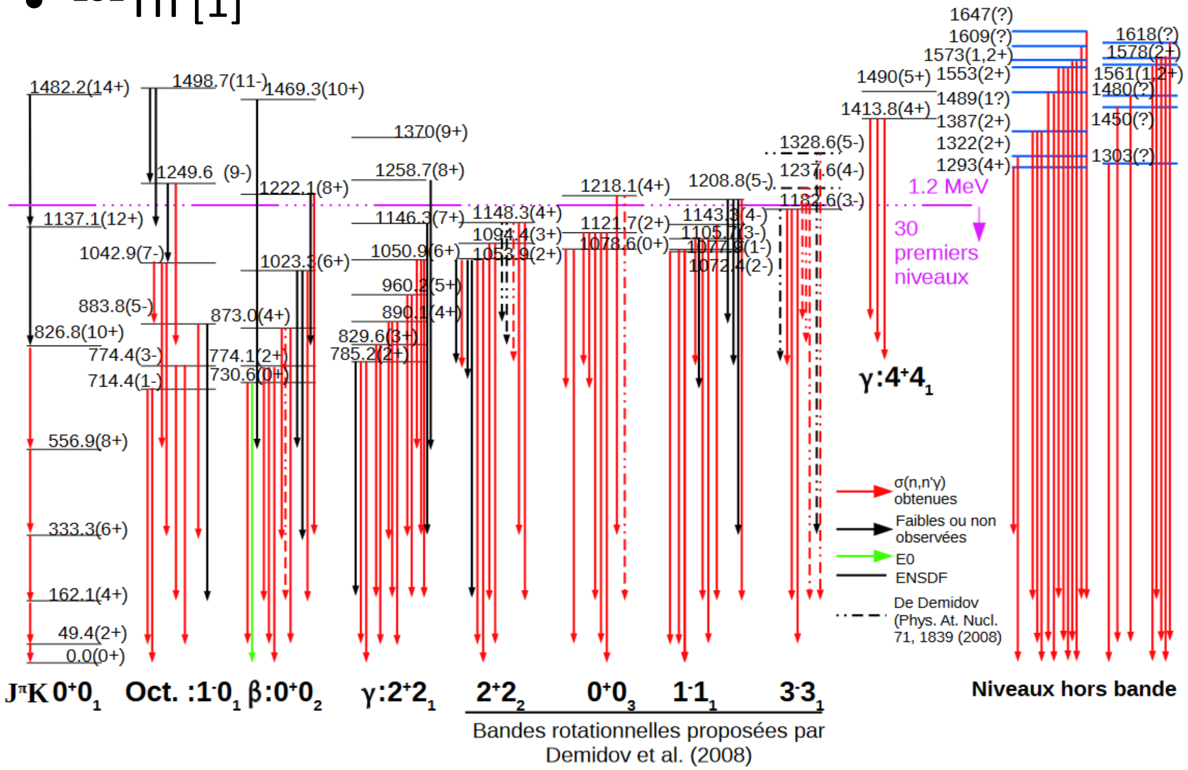


FIGURE 4.1 – Schéma de niveau du thorium-232.

Niveau Ex(J^π)	Énergie gamma (keV)	Intensité relative mesurée	Intensité relative ENSDF
873,0 (4^+)	539,9	17(3)	100
	710,5	22(4)	Transition absente
	823,6	100(2)	Non mentionnée
1042,9 (7^-)	159	19(4)	100
	486	100(2)	65
1121,7 (2^+)	347,2	11(1)	30
	407,3	12(1)	37
	959,3	37(2)	100
	1072,6	100(2)	Non mentionnée
	1121,7	5(1)	Non mentionnée

TABLE 4.1 – Intensités relatives mesurées et issues de ENSDF.

- Also for ^{233}U, ^{239}Pu (it's even worse).

[1] Eliot Party. Etude des réactions (n, xn) pour les noyaux fertiles / fissiles du cycle du combustible innovant au Thorium. Thèse Uni. Strasbourg (2019)

Sensitivity of (n, n'γ) result to structure data

A Monte-Carlo study can show the sensitivity of cross section to *Branching Ratios* (BR) [1].

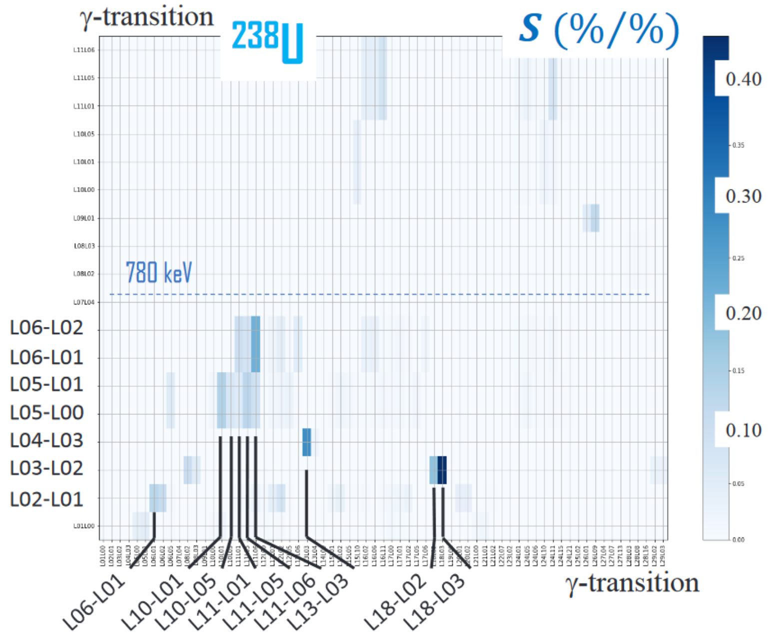


Figure 7. (color online) Sensitivity matrix for γ-production cross sections to Branching Ratios in ^{238}U. L_i is the number of the level in TALYS.

With the average uncertainty on BR in databases, that means that calculated cross section can come with up to 4% uncertainty from structure data alone.

Our experimental $\sigma_{(n,\, n'\gamma)}$ data have uncertainties from 3 to 20 %.

With ~ 5 % experimental uncertainty and 4 % calculated uncertainty, the constrains on models are not enough to reach the 2-5 % target uncertainty for the evaluated total (n ,n') cross section.

See poster « Using Monte-Carlo method to analyze experimental data and produce uncertainties and covariances », G. Henning et al. – July 26th session

[1] M. Kerveno et al, "What can we learn from (n,xnγ) cross sections about reaction mechanism and nuclear structure?", EPJ Web of Conferences 239, 01023 (2020)

Conclusions & Perspectives

Importance of (n, *x*n) reactions for reactors.

Need new data, improved models to reach the precision level required for evaluations.

Indirect measurement via (n, *x*n γ) to constrains the models.

But the uncertainty on structure data limit the relevance of exp. vs. calculations comparisons.

Not yet enough for an uncertainty on (n, n') cross section at 5 %.

Need new structure data, better BR, verify some levels and transitions existence in ^{238}U, but also ^{232}Th, ^{233}U, ^{239}Pu.

Let people doing structure measurement know about the issue and the importance of improved structure data.

Publish our data and their interpretation with the used structure data to allow future re-evaluations.

Acquire new structure data (ourselves or motivate others to do so).

Evaluation *bottleneck* : It takes time and people to move from a new experimental value to integration into evaluated DB and later reaction models.