An overview of the Integral References

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The neutrón Standard Integrals

For neutron induced reactions, the principal international standards are a few constants at thermal point (the TNC table), that includes among them, fission, capture and elastic XSs for the main fissile actinides: U233, U235, Pu239 and Pu241 .

It was found useful for normalization purposes to provide integral values in standardized energy-intervals.

First was studied the (n,f) integrals in the range 20 to 60 meV, around the thermal point.

But there are many high-resolution experiments (Tof) that start measuring at energies above around 1eV, more easily reachable than the thermal point, and so, new integral data on (n,f) were proposed in the RRR, giving their ratios to the thermal point values.

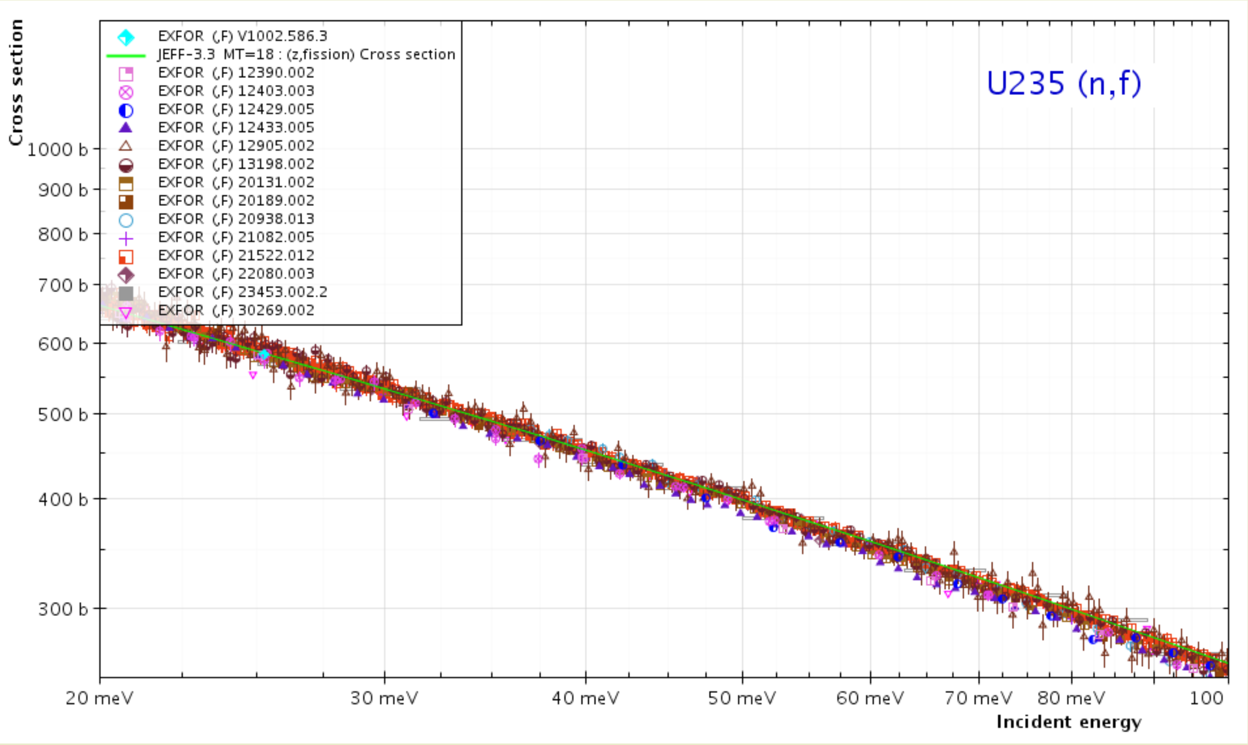
Last year, the same procedure was applied to the (n,tot) experimental data, and the corresponding (n,g) constants were deduced from the equation:

$$(n,g) = (n,tot) - (n,f) - (n,el)$$

Finally, the same procedure has been applied at energies above 1 MeV, to provide references for reactions of interest in fast-neutron reactors.

Integration interval in the thermal energy range

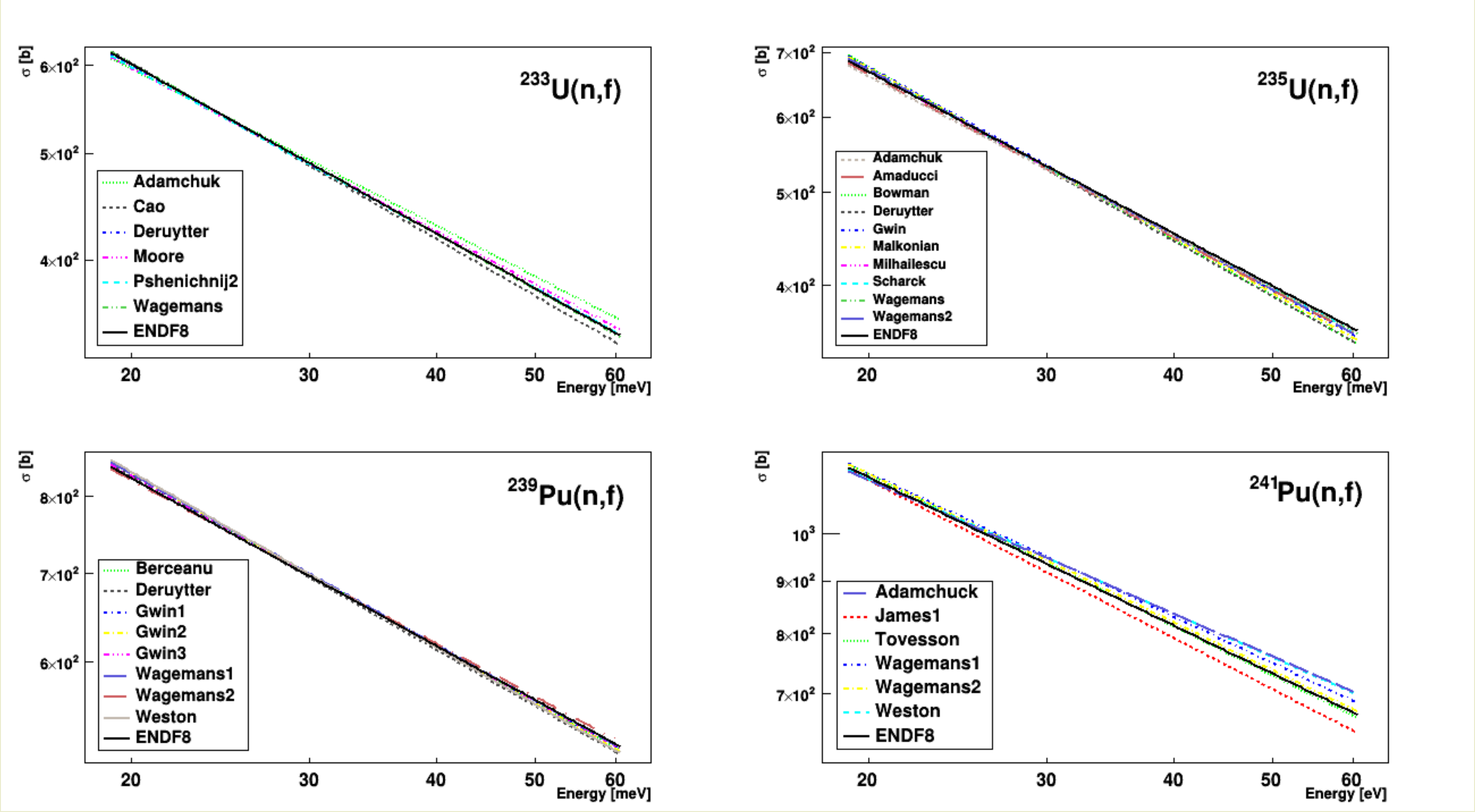
Just remembering that the analysis is based on selected experimental data, covering the energy slot of interest (20-60 eV), by fitting it to straight-lines in log-log scale. Renormalization and energy calibration was eventually needed.



Note that the actual slope in log-log scale is not 0.5 (that correspond to the 1/v law), being different for each actinide.

Anyhow, the straight-line approximation remains to be very accurate.

Fitting in the thermal range



Fits in the thermal range after renormalization (the worst case is for Pu241).

It is worth mentioning that the actual slope in log-log scale is not 0.5 (that correspond to the 1/v law) being different for each isotope.

Anyhow, the straight-line approximation remains to be very accurate.

Integration interval in the thermal energy region

In the 20-60 meV range the experimental points fits very accurately to an straight-line in log-log scale, with only two parameters:

$$\sigma(E_n) = (E_n)^b \cdot \sigma_0 / 0.0253^b$$

being σ_0 the cross section at thermal point, and b the exponent in the exponential law, that is the slope in log-log scale.

It is important to see that this fit can be done even when the experimental points don't goes down to 20 meV:

with the fitted σ_0 and b, the integral value can be analytically obtained in the whole 20 to 60 meV interval:

$$I1 = \sigma_0 \cdot (0.06^{(b+1)} - 0.02^{(b+1)}) / (0.0253^b \cdot (b+1))$$

The procedure step by step

As a matter of fact, this procedure can not be done for the (n,g) case because of the lack of good experimental data. Therefore the same procedure used for (n,f) was applied to the (n,tot) experimental data, and the corresponding (n,g) constants were deduced from the equation:

(n,g) = (n,tot) – (n,f) – (n,el)

The starting point has been to obtain these integral values for the (n,tot) reaction. As in the case of (n,f) we have proceed in a three steps way:

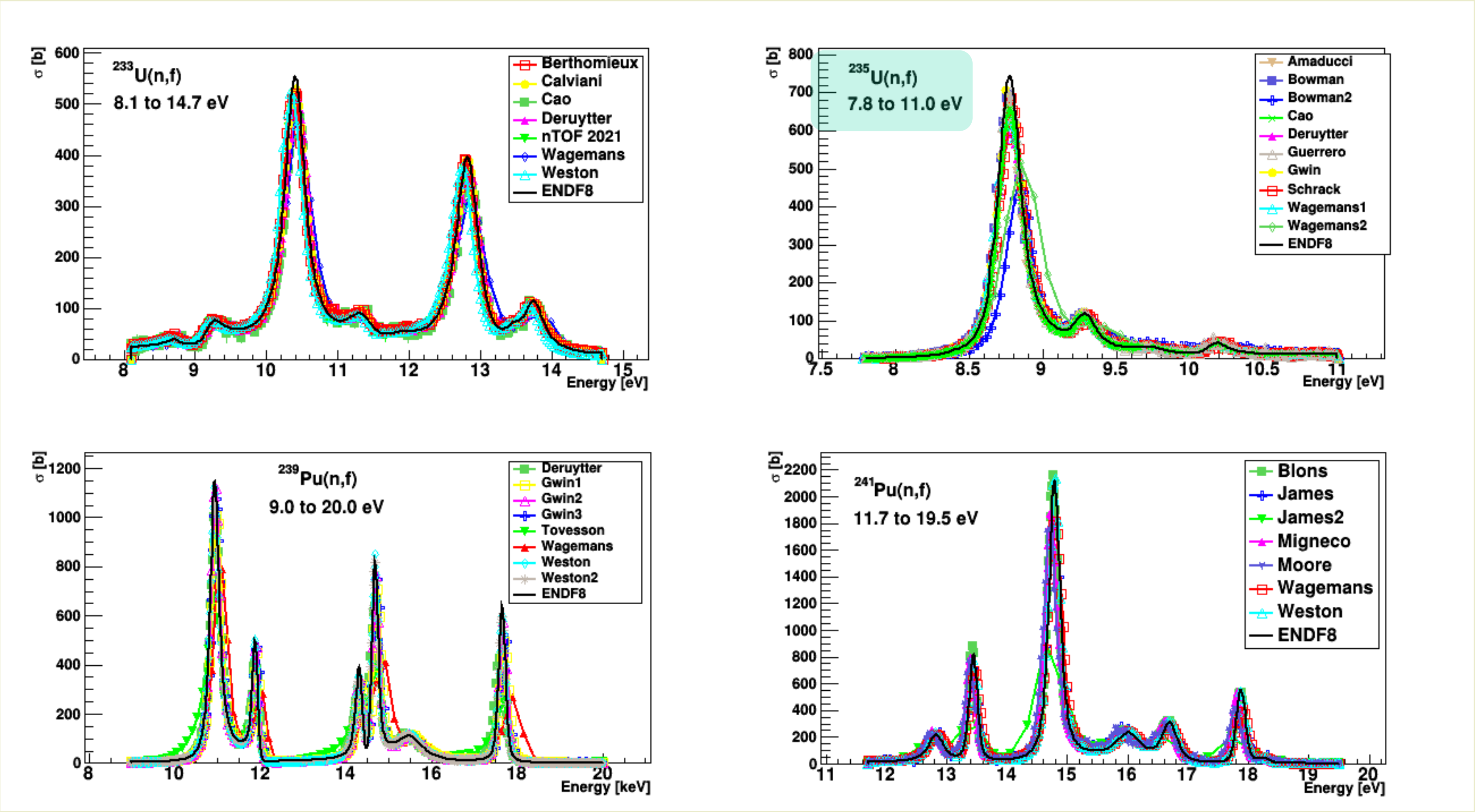
the integral values I_1 and I_3 were firstly obtained directly from the cross section data found in the selected files retrieved from EXFOR;

secondly, the integral values obtained were renormalized according to the updating of the historical values declared by authors as monitor or reference;

and thirdly, the renormalized datasets in the thermal interval were used to obtain the analytical values of b and σ_0 by fitting to straight lines in log-log scale.

Note that only those datafiles in EXFOR having point-data with high energy resolution have been selected, and few outliers has been discarded.

Integrals in the RRR



Here are shown the integration limits agreed to be used for the (n,f) analysis in the RRR.

Note that (n,f) integral for U5 has been adopted as standard in NDS2018.

These intervals have been adopted also for (n,tot), (n,el) and (n,g).

(n,tot) analysis: the case of U3

08/10/2022	U3(n,tot) integrals			Renormalized @ TNC18			*slope*	σ_{tot}	I1_anal
	I_therm	8.1-14.7	ratio	factor	I_therm	8.1-14.7	fit	fit	analytical
Block	19,36			1,005	19,46		-0,498	590,4	19,46
Bollinger	19,76			0,990	19,56		-0,496	593,5	19,57
Harvey1	19,28	863,5	44,8	1,006	19,40	868,7	-0,501	588,6	19,38
Harvey2	19,52	871,5	44,6	0,998	19,48	869,8	-0,496	590,7	19,48
Kolar		872,6		1,002		874,3			
Pattenden		854,8		1,020		871,9			
Moore	19,31			1,009	19,48		-0,500	591,3	19,47
Nikitin	19,07			1,016	19,38		-0,499	587,1	19,35
Pschenichnyj	19,46			1,002	19,50		-0,503	592,1	19,48
Safford1	19,45			1,005	19,55		-0,483	589,1	19,52
Safford2	19,34			1,008	19,49		-0,492	589,4	19,47
Mean value	**19,39**	**865,6**	**44,72**		**19,48**	**871,17**	**-0,496**	**590,2**	**19,46**
ENDF8	19,44	873,1	44,9		19,44	873,1	-0,493	588,5	19,43
JEFF 3.3	19,45	872,9	44,9		19,45	872,9	-0,492	588,7	19,44
JENDL4	19,45	872,9	44,9		19,45	872,9	-0,492	588,7	19,44
Mean value	**19,45**	**872,97**	**44,89**		**19,45**	**872,97**	**-0,492**	**588,6**	**19,44**

- The final results are highlighted in bold. They have as renormalization factor the one obtained by updating they declared beam-flux monitor at the present days, when U5(n,f) at thermal point is 587 b (NDS18). So that, every actinide result is correlated with U5.
- Note the agreement between I1 renormalized and I1 from the analytical fit, proving that the integral-reference procedure give us accurate results.

(n,tot) integral results

(n,tot)	σtot | TNC | %	I1_renorm	I3_renorm	I3 / I1	σtot / I1
U233	590.2(1.3) 590.1(2.5) 0.0	19.5(0.1) 0.3%	871.2(2.5) 0.3%	44.8	30.31(17)
U235	700.7(1.3) 700.9(1.9) 0.0	22.5(0.1) 0.3%	375.0(10) 2.7%	16.7	31.16(19)
Pu239	1028.7(1.1) 1030.8(3.5) -0.2	35.2(0.1) 0.3%	1834(38) 2.1%	52.1	29.21(18)
Pu241	1392.1(2.1) 1398(13) -0.4	45.9(0.1) 0.2%	2235(94) 4.2%	48.7	30.35(06)

Note the close agreement with TNC for the (n,tot) thermal XS

(TNC here quoted is the sum of (n,f)+(n,g)+(n,el) in the NDS-2018 table)

Uncertainties of the integrals are given as the Std Dev of the experiments:

note the low values for I1 and the high ones for I3)

(n,g) analysis: thermal range

Once got both the (n,f) and (n,tot) values, then they have been used to deduce the (n,g) ones:

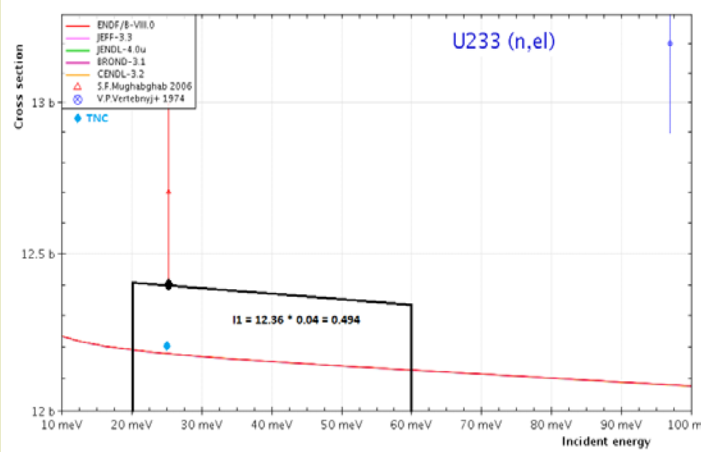
$$(n,tot) - (n,f) = (n,g) + (n,el)$$

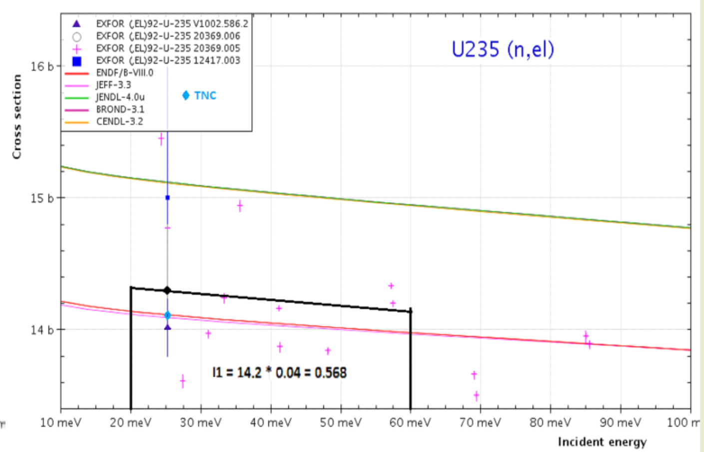
Concerning the (n,el) values, the experimental sources are very scarce in both energy ranges, introducing so an important uncertainty. Nevertheless, its effect is low because the (n,el) cross sections are much lower than the others. Moreover, the (n,el) evaluations are strongly correlated with (n,tot) and (n,f).

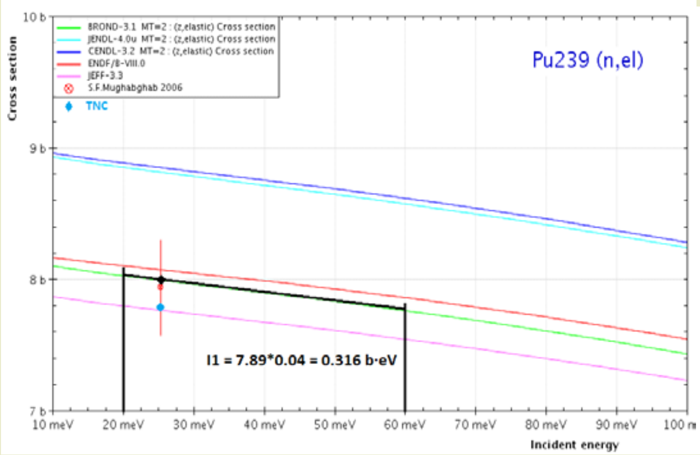
The here used (n,el) come firstly from the TNC table, but finally, was taken also into account the information given by other experimental compilations.

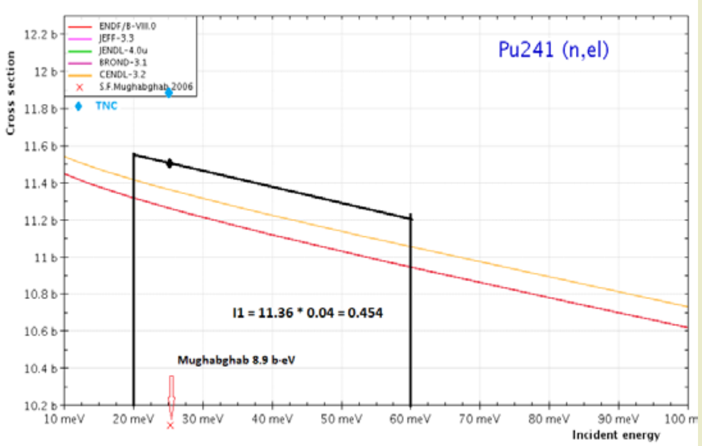
σ(n,el) [b]	U233	U235	Pu239	Pu241
This work	12.4(0.5)	14.3(0.5)	8.0(1.0)	11.5(1.5)
TNC table	12.2(0.7)	14.1(0.2)	7.8(1.0)	11.9(2.6)
Eval.Libraries	12.2	14.1-15.1	7.8-8.8	11.3
Mughabghab	12.7	14.2	7.9	8.9
Divadeenam	12.6	14.0	7.3	9.1

(n,el) analysis: thermal range









Note that experimental support is scarce.
Blue diamonds are the current TNC values

Comparing thermal XS with TNC

	σtot	σfis	σel	σcap
U3	590.4	533.0	12.3	45.07
TNC-17	590.1	533.0	12.2	44.9
E/C	0.1%	0.0%	+ 0.8%	+ 0.4%
TNC-24	590.0	533.0	12.3	45.0
E/C	0.1%	0.0%	0.0%	+ 0.2%
U5	700.4	586.4	14.2	99.8
TNC-17	700.9	587.3	14.1	99.5
E/C	0%	- 0.15%	+ 0.7%	+ 0.2%
TNC-24	699.8	586.2	14.1	99.5
E/C	+0.1%	0.0%	+ 0.7%	+ 0.2%
Pu9	1028,8	751.3	7.8	269.7
TNC-17	1030.8	752.4	7.8	269.8
E/C	-0.2%	- 0.2%	- 0.0%	- 0.0%
TNC-24	1029.0	751.0	8.0	270.0
E/C	-0.1%	+ 0.1%	- 2.0%	- 0.1%
Pu1	1392.3	1019.1	11.8	361.4
TNC-17	1397.8	1023.6	11.9	362.3
E/C	-0.4%	- 0.4%	- 0.8%	- 0.2%
TNC-24	1399.0	1024.0	11.9	363.0
E/C	-0.5%	- 0.5%	- 0.8%	- 0.4%

The values here proposed comes from the aforementioned fits, after having included recent EXFOR inputs (few files have been removed as outliers, in consequence).

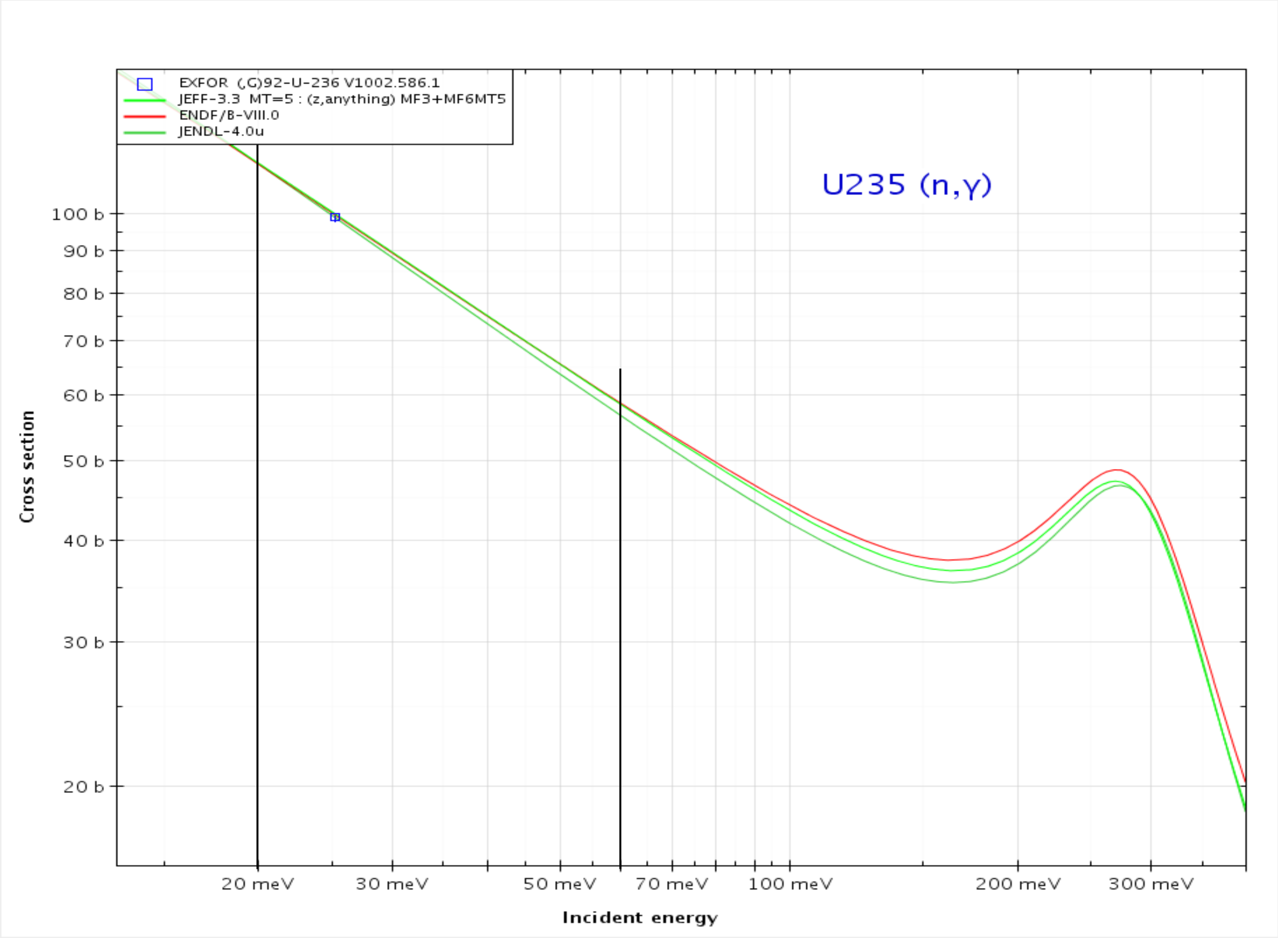
The so called “TNC-24” are the values presented by Gilles as “Target” (to be followed).

Comparing integrals with evaluations

	$I1_{tot}$	$\sigma_0/I1$	$I1_{fis}$	$\sigma_0/I1$	$I1_{el}$	$\sigma_0/I1$	$I1_{cap}$	$\sigma_0/I1$	$I3_{tot}$	$I3_{fis}$	$I3_{el}$	$I3_{cap}$
U3	19.47	30.33	17.50	30.40	0.487	25.26	1.45	31.08	872.0	685.0	84	103.0
I3/I1									44.8	49.8	172.5	71.0
Old EVs	19.47	30.26	17.50	30.45			1.49	29.93	873.0	686.7	85	101.3
E/C	0.0%	+0.2%	0.0%	-0.16%			-2.8%	+3.8%	-0.1%	-0.2%	-1.2%	+1.7%
New EVs			17.50	30.46						684.8		
E/C			0.0%	-0.2%						-0.5%		
U5	22.48	31.15	18.77	31.24	0.56	25.54	3.15	31.67	374.5	246.7	36	92.3
I3/I1									16.6	13.2	64.3	29.3
Old EVs	22.50	30.97	18.86	31.0			3.16	31.42	374.4	246.9	36	91.3
E/C	-0.1%	+0.6%	-0.5%	+0.8%			-0.3%	+0.8%	+0.0%	-0.1%	0.0%	+1.1%
New EVs			18.86	31.24						246.9		
E/C			-0.5%	+0.8%						-0.1%		
Pu9	35.21	29.21	25.41	29.56	0.31	25.81	9.49	28.44	1850	1061	110	679.5
I3/I1									52.5	41.7	355	71.9
Old EVs	35.27	29.11	25.37	29.52			9.67	27.99	1865	1062.3	110	692.3
E/C	-0.2%	+0.3%	+0.16%	+0.1%			-1.9%	-1.6%	-0.8%	-0.1%	0.0%	-1.9%
New EVs												
E/C												
Pu1	45.87	30.35	34.03	29.93	0.46	25.55	11.37	31.78	2256	1351	147	758
I3/I1									49.2	39.7	319	66.6
Old EVs	45.47	30.47	33.88	29.90			11.40	31.84	2276	1324	168	784
E/C	+0.9%	-0.4%	+0.4%	+0.1%			-0.3%	-0.2%	-0.9%	+2.0%	-14.3%	-3.4%
New EVs												
E/C												

The values here proposed comes from the aforementioned fits, after having included recent EXFOR inputs (and few files have been removed as outliers, in consequence).

Discrepancies are mostly below 1% but for few values highlighted in green, pointing to bad evaluations for capture.

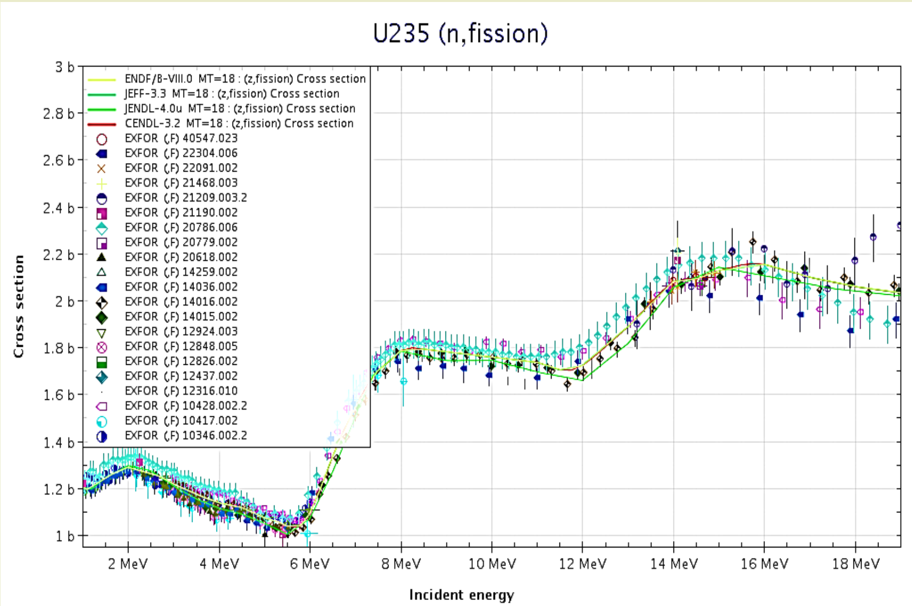

EXFOR (,G)92-U-236 V1002.586.1
JEFF-3.3 MT=5 : (z,anything) MF3+MF6MT5
ENDF/B-VIII.0
JENDL-4.0u
U235 (n,γ)
100 b
90 b
80 b
70 b
60 b
50 b
40 b
30 b
20 b
Cross section
20 meV
30 meV
50 meV
70 meV
100 meV
200 meV
300 meV
Incident energy

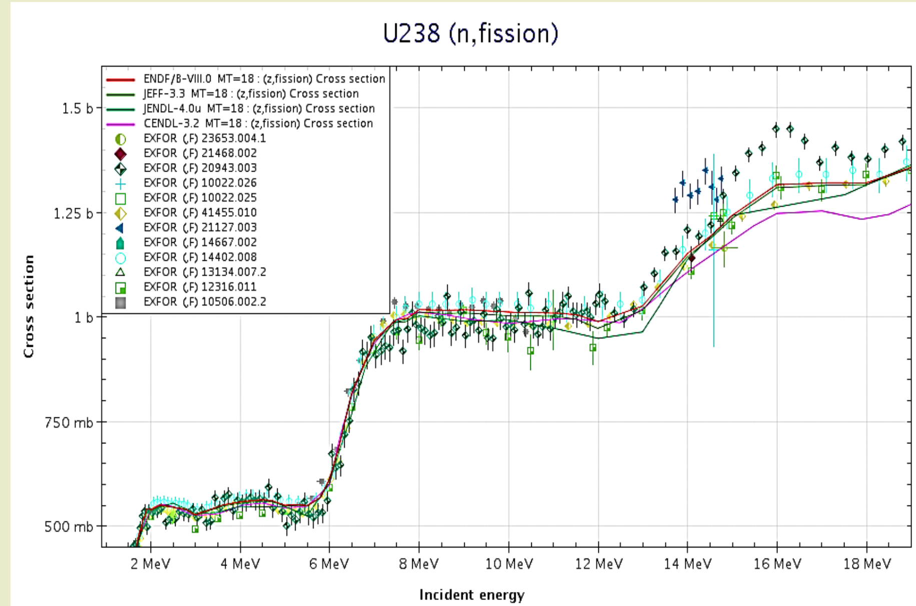
The integration procedure applied above 1 MeV

The question now is to look for high quality references for fission above 1 MeV, to improve the present standards and so the evaluation of those actinides involved in the fast-reactors cycle.

Let us start by looking for the best suited integration interval above 1 MeV.

Two plateaus above 1 MeV

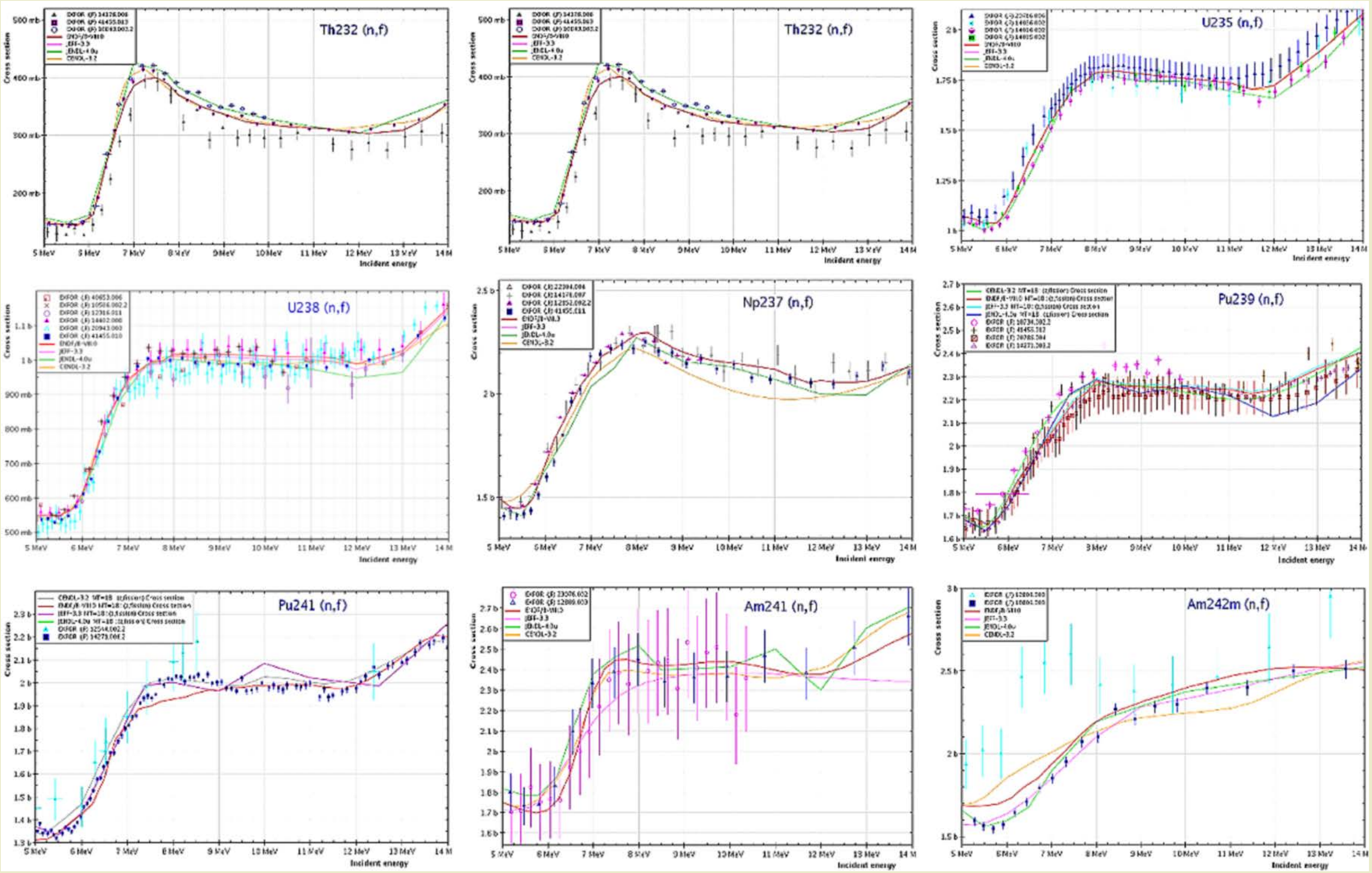




The first plateau has been more widely measured and it is always very useful for absolute measurements using the well known self-fission neutron spectrum of Cf252 sources.

On the other hand, the second plateau is more useful for ToF experiments because the XS values are higher and flatter, and without sharp changes in the FF anisotropy, for the whole set of actinides.

Plateau at 9 MeV



This general trend around 9MeV for the whole group of actinides makes useful to define as unique interval of integration, from 8 to 10 MeV.

Selecting the EXFOR sample

The second step after adopting the integration limits is to select those high-resolution datafiles to be used to obtain the integral reference value.

All the selected datafiles have been retrieved from EXFOR rejecting as outliers, eventually, those showing either anomalous dispersion or an integral value statistically not compatible with the mean value of the others.

Every experimental datafile has been, eventually, renormalized using as factor the ratio of its declared monitor/reference to the present Standards.

Finally, the points in every dataset falling in the selected interval have been fitted to straight-lines, giving so the fitted value at 9 MeV and the integral value.

First conclusions

- The values obtained by integrating in wide energy ranges are consistent, proving the usefulness of the procedure.

- Concerning (n,f), the integral values I1 and I3, and its ratios to the thermal constant, are worth of being accepted as IAEA References.

- Concerning (n,g), the high-resolution experimental datasets are not of good quality.

Therefore, the procedure has been applied to (n,tot) showing consistency of the final data, with low uncertainties, both in the thermal region and in the RRR. So, the (n,tot) integral values can be adopted too as Reference.

- Concerning (n,el), there is a lack of accurate data, pointing to the need of good experiments all along the thermal and low enegy ranges.

On the ratios of integrals

Once adopted the same integration interval for the whole set, their ratios become important constraints at the evaluation time.

It is worth noting that both U5(n,f) and U8(n,f) are Standards and, as a matter of fact, <u>the best-known quantity is the ratio of both XS</u>.

This ratio was analyzed in detail in the paper on the USU. Different statistical models were used, giving finally a value at 9 MeV of 0.572, with an uncertainty of 0.3%.

If the ratio at 9 MeV is taken from the Standards (NDS18) is 0.571.

In the recent paper on the evaluation of Cf SACS in the 1 to 5 MeV interval, a renormalization is proposed, leading to a ratio of 0.573

In the present work we evaluate the mean value of the ratios at 9 MeV as obtained by fitting to straight-lines the 18 datasets retrieved from EXFOR. This gives us a value of 0.570(2), 0.4% statistical uncertainty.

This is showing that the method of fitting to straight lines (as it was done in the thermal energy range) is reliable enough.

<u>The value of 0.572 can be hold as Reference</u>

The case of U8(n,f)

24/05/2023	U8(n,f) 8-10 MeV integrals					
	year	EXFOR	XS@9MeV	factor	XS Renorm.	Integral 8-10
Meadows	1975	10506 002 2	0,991	1,010	1,001	2,002
Smith	1957	12316 011	0,975	1,020	0,995	1,989
Tovesson	2014	14402 008	1,031	1,005	1,036	2,072
Leugers	1976	20943 003	0,987	1,020	1,007	2,013
Scherbakov	2002	41455 009	0,990	1,005	0,995	1,990
Pankratov	1963	40653 006	0,994	0,990	0,984	1,968
Mean value			**0,995(10)**		**1,003(9)**	**2,006(18)**
ENDF8			1,017		1,014	2,028
JEFF 3.3			1,009		1,007	2,014
CENDL 3.2			0,999		0,998	1,996
JENDL4			0,989		0,994	1,988
Mean value			**1,004(9)**		**1,003(6)**	**2,007(13)**

Integrals from ratio U8(n,f) / U5(n,f) [mean value of XS U5 = 1,768 b]					
	year	EXFOR	Mean	*(1)	*(2)
Meadows	1975	10906 002	0,577	1,020	2,040
Difilippo	1978	10635 002	0,568	1,004	2,008
Behrens	1977	10653 004	0,564	0,997	1,994
Lisowski	1991	14016 003	0,577	1,020	2,040
Tovesson	2014	14402 009	0,579	1,024	2,047
Casperson	2018	14498 002	0,562	0,994	1,987
Cierjaks	1976	20409 002	0,560	0,990	1,980
Coates	1975	20414 002	0,573	1,013	2,025
Paradela	2015	23269 002	0,573	1,013	2,026
Jie Wen	2020	32798 002	0,580	1,025	2,051
Goverdovski	1983	40831 003	0,565	0,999	1,997
Scherbakov	2002	41455 002	0,562	0,994	1,987
Mean value			**0,570(2)**	**1,008(4)**	**2,015(8)**

Six XS datafiles retrieved from EXFOR:
The fitted values at 9 MeV are renormalized;
The uncertainties have been calculated from the standard deviation to the non-weighted **mean values.**

The first column shows the point-values **at 9 MeV in** the evaluated libraries, and in the **second one are the values after fitting in the** same way that for the experimental datasets.

The same procedure is applied to the 12 ratio **datasets retrieved from EXFOR.**

In column (1) are the XS values obtained after
multiplying by **1.766 b** and in column (2) are **their corresponding integrals.**

Why 1.766 b?

Wich is the best STANDARD?

Actually, we have three values derived from different experiments (not fully uncorrelated): the XS of U5, the XS of U8 and their ratio.

Let's take as reference the U5(n,f) @ 9 MeV because there are many ratios to them of the whole set of actinides measurements.

Let's take the U5(n,f) XS @ 1 MeV = 1.766 b,
derived from the renormalized fits of the U5(n,f) experimental datasets, following the present method.

It is worth mentioning that no matter this number is, what it is important is to have a main reference (to be changed, eventually).

So, if the ratio U8/U5 is 0.572, the U8(n,f) XS @ 9 MeV becomes 1.010 b,
to be compared with the point-wise value given by GMA for the NDS of 1.017(14) b, and with the mean value 1.003 b given by both the integrals procedure and the evaluated libraries.

CONCLUSIONS

-Integral references in both the thermal energy range and in the RRR were defined, probing to be very useful for evaluators.

They are easy to be used for normalizing both old and new experimental datasets.

- Both (n,f) and (n,tot) integral references at low energies are based on consistent experimental datasets, and can be taken as Standards for both U5 and U8.

- An integrating interval above 1 MeV is defined from 8 to 10 MeV, in order to better normalize the evaluated datafiles, first for those in the TNC table and then for those being of interest for new nuclear technology.

Fitting to straight-lines in the 8 to 10 MeV range provide good enough values for most of the actinides involved in the fast-neutron reactors (to be used for re-normalization purposes).

For the U5/U8 (n,f) ratio the value of 0.572 @ 9 MeV can be hold as Standard (?)