High-resolution evaluation of the U5(n,f) cross section from 3 keV to 30 keV

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Abstract. 235U neutron-induced fission cross-section is commonly used as reference for determining other isotope fission cross-section. However, below 150 keV this cross section is only included as Standard at the thermal point and recently its integral value between 7.8 eV and 11 eV [1]. The resolved resonance region, spanning up to 2.25 keV, has been re-evaluated with high resolution in the last ENDF/B-VIII release [2] and a SAMMY resonance analysis was done by L. Leal et al. [3] including the CERN-nTOF experimental work of Paradela el al. [4] up to 10 keV, taken into account the IAEA Reference file. In this work the 235U(n,f) low-background and high-resolution experimental data obtained at the CERN-nTOF facility is combined with previous high-resolution experimental data, in order to produce a very fine grid dataset with normalisation to the IAEA Reference file. The extremely-high energy calibration required to reproduce the resonance sharp profiles is based on the nTOF DAQ system with a resolution below 0.1% with reference to the 8.78 eV resonance and to the sharp Al(n,g) capture dip at 5.904 keV. The comparison of the so-evaluated profile with the experimental data and with the evaluated ones will be discussed.

1 Introduction

Accurate data on the fission of heavy nuclei at energies beyond the resolved resonance region (RRR) are of a renewed interest for both fundamental and applied nuclear physics. Most neutron cross section measurements are made relative to the neutron cross section standards, being so the basis for measurements and evaluations. Very few cross sections can be measured absolutely and in most cases cross sections are measured relative to the standards or to the data files retrieved from the evaluated libraries. An important point is that the accuracy of a cross section is limited by the uncertainty in the reference cross section relative to which it is measured. There is so a need for additional data related to standard isotopes used as reference and the extension in energy range of certain cross sections, as remarked in Ref [1].

Concerning the 235U neutron-induced fission cross-section, below 150 keV this cross section is only included as Standard at the thermal point and recently its integral value between 7.8 eV and 11 eV [1]. The resolved resonance region, spanning up to 2.25 keV, has been re-evaluated in this energy range with high resolution in the last ENDF/B-VIII release [2] and a SAMMY resonance analysis was done by L. Leal et al. [3] after including the work of Paradela el al., presented at WONDER-2015 [4], and taken into account the IAEA Reference file. This result of L. Leal has been included in the last up-dating version
of JEFF (JEFF-3.3). Above 2.25 keV the current ENDF/B-VIII shows a coarse energy resolution, notwithstanding its integral mean values are in fine agreement with the point-wise dataset in the IAEA Reference file. JEFF-3.3 and JENDL-4.0, on the other hand, are giving only a smooth line.

\( ^{235}\text{U}(n,f) \) reaction has been amply measured and a bunch of entries can be retrieved at the EXFOR library, many of them consisting on single points, mean cross-section values in a broad energy interval or low energy resolution cross-section spectra. The aim of this work is to determine the shape of the \( ^{235}\text{U}(n,f) \) cross section with an improved energy resolution, in the energy region of the Unresolved Resonance Region (URR) up to 30 keV. So that, after inspection of the EXFOR library some selected datasets have been retained arriving to the conclusion that, besides the CERN-nTOF-PPAC results, the dataset of Weston and Todd [5] is the one having the best compromise between statistics and energy resolution, even though its bad energy calibration.

In the RRR, below 2.25 keV, most of the resonances found are of Class I, having so its energy intervals increasingly closer. On the other hand, in the transition from the RRR to the URR, the resonance structures due to the coupling of Class II states to Class I ones become more and more probable, resulting in a too high density of barrier transition states that make it almost impossible to resolve (for a detailed explanation see Ref. [6] and references therein). Above 3 keV, nevertheless, the cross-section spectrum is dominated by the grouping of the observed cross section peaks, pointing to the existence of resonance structures that have been so far not well resolved.

### 2 Evaluation procedure

When looking for the best energy achievable from the experimental data sets, only a few can be retrieved having both high statistics and an energy resolution high enough, as otherwise is difficult discerning statistical artifacts from real resonances. To overcome these difficulties different datasets must be compared between them, but only after a careful energy re-calibration and a suited re-normalisation. In Fig 1 can be seen some results from EXFOR [5] and [7-12] for two energy ranges. In both panels can be perceived that an evident correlation exists, even though the scatter of the points due to not having a correct calibration. It is worth of mention the coarse miscalibration of the Bowman’s dataset [7] shown in the left panel (light blue).

The low-background and high-resolution \( ^{235}\text{U}(n,f) \) experimental data obtained at the CERN-nTOF facility can not be taken alone because of its limited statistics. We started so by combining different data sets from measurements done with different detector setups but having the same time-to-energy calibration. The CERN-nTOF facility is described in detail.
in Refs. [13] and [14], and the data analysis is described in Refs [4] and [15 - 17]. We take advantage of the very high stability of both the neutron flux and the DAQ system timing that having a clock frequency of 2 GHz gets an energy resolution well below 0.1%, all along this energy range.

2.1 Data reduction and conditioning

As above mentioned, there is in EXFOR many entries for the $^{235}\text{U}(n,f)$ reaction measurements, but only a few having both high statistic and fine energy resolution. So that, this work is based in only those susceptible of passing a suited filter without loss of the required information. Every dataset was managed to have around 2000 bin/decade in order to cope with the extremely-high energy calibration required to reproduce the resonance sharp profiles. Then a triangular Barlett filter was applied in order to reduce the statistical scatter without reducing the binning. The nTOF energy calibration has been taken as reference with reference to the $^{235}\text{U}(n,f)$ 8.775(3) eV resonance and to the sharp Al(n,g) capture dip at 5.904(5) keV. In Fig 2 (left) is shown the nTOF data (in blue) matching the ENDF/B-VIII evaluation and in the right plot is the dip produced by the capture and by the scattering of neutrons produced in the windows of the neutron-beam vacuum pipe. In this way we know that the accuracy of the energy calibration is below 0.1% in all the energy range. The cross section of the nTOF datasets has been normalised in order to match the IAEA standard value of the cross section integral in the energy interval 7.8 to 11 eV (247.5 b · eV), as recommended in [1]. Then, both the energy calibration and the cross section normalisation of the nTOF datasets were kept untouched along the rest of the procedure.

Once the nTOF dataset was accurately calibrated, different resonance peaks along the energy range were used to re-calibrate and re-normalise the datasets of Weston and Bowman. It is worth to mention that whereas the Weston data were quite fine calibrated (a few percent both in energy and in cross section) the Bowman data required severe shifts (the original energy calibration was found to be non-linear) and the cross section normalisation do not match correctly all along the energy range, as it will be shown later. The thereafter called USC-Eval file was then built starting by introducing points (energy-cross section) at those resonances having maxima and minima clearly seen in both the PPACs nTOF dataset and the Weston dataset, because these data files are the most reliable. Plotting the USC-Eval together with the experimental profiles, more points were added in an iterative process, in order to reproduce as close as possible both experimental datasets.

At this point, we realised that number of resonance peaks were composed of two or even few peaks not being resolved in one or other data files. This ambiguity required the comparison with other experiments and so the Bowman data [7], and sometimes also the Lemley data [8], were used to cross-check the assignment of the peaks. Moreover, the data

![Fig. 2. $^{235}\text{U}(n,f)$ peak at 8.773 eV and Al(n,tot) dip at 5.904 keV used as time references in this work.](image-url)
from an experiment performed at CERN-nTOF using a FIC detector has been used too, as it can be taken as an independent experiment. The analysis of this experiment [18] is not yet finished but it shows a very high energy resolution and has been useful to prove the existence of some doubtful peaks. So that, every peak introduced in the USC-Eval file required to be present in at least two different experiments and having some trace in others. It is worth to mention that, after the correct calibration of all the datasets, the grade of coincidence has been surprisingly high, as it will be shown in the next section. Finally, the whole USC-Eval dataset was normalised in order to fit with the point-wise values recommended by the IAEA Reference file [19]. This result is shown in Table 2, at the end of the text, compared with the recent evaluations.

Fig. 3. Comparison of the USC-Eval with experimental datasets at different energy intervals.

3 Results
In this section are shown the results of the $^{235}\text{U}(n,f)$ evaluation based on the CERN-nTOF PPACs experiments, combined with the Weston data and compared to the ones of Bowman, Lemley and Furman. In this way we can said that the shape of the cross section spectrum reproduce well the experimental datasets and, on the other hand, its integral mean values
are in a fair agreement with the GMA nodes used by the IAEA for the Reference files. In Fig. 3 are shown some plots comparing the result of our evaluation with the experimental data at different energy intervals. In Fig 4 are summarised the statistics of such a comparison for the four experimental datasets: namely: nTOF-PPACs, nTOF-FIC, Weston and Bowman. In the left panel is the histogram of the energy residuals, showing that after the energy re-calibration the dispersion of the energy at the resonance peaks is 0.11% which is compatible with the energy resolution of each individual setup. In the right is the histogram with the residual of the cross-section values at the peaks with a RMS dispersion of 5.2% with maximum values of 20%. As the evaluated values are a compromise between the experimental ones, the differences from experiments to evaluation are lower than the differences between experiments. It must be noted that this differences arose because most resonances have a very narrow peak, depending so its apparent height on the energy binning.

Fig. 4. Statistics of the energy and cross section values of the resonance peaks, taken as the differences between evaluation and experiments in percent.

3.1 Main findings
The high degree of coincidence found between the Paradela data at CERN-nTOF and those of Weston at ORNL is confirmed by other high-resolution datasets. More than 280 peaks have been unambiguously identified, distributed as follows: 70 from 3 to 5 keV; 73 from 5 to 8 keV; 56 from 8 to 13 keV; and 82 from 13 to 30 keV. The position in energy of these points is statistically distributed with a RMS of 1.1 % (Fig. 3-left).

In a recent paper of G.F. Bertsch et al. [20] the authors examine the autocorrelation function of the 235U(n,f) reaction with a view to quantify the presence of intermediate structures in the cross section. Finally they claim that the apparent fluctuations due to compound nucleus resonances, on the order of the eV energy scale, do not present structure but in the region around 20 keV. They based the study mainly in the Perez data from ORNL [21], discarding among others the Weston data, with the argument that the Perez dataset has a superior energy resolution, what it is false in the range below 30 keV (from the information available in EXFOR). This bad choice is leading us to criticize the Bersch assertion. In Fig. 5 is presented the smoothed USC-Eval which suggests the existence of correlated peaks on the scale of 1 keV, that have the same profile as the 22 keV structure analysed in [20]. That structure shape can be suspected around 9 keV, 15 keV, and 19 keV, for instance. The existence of narrowest structures is also suggested below 9 keV in the plots presented in Fig. 3.
3.2 Numerical results
The numerical values of the USC-Eval data file are at the end, in Table 1. The uncertainty in energy is 0.1 % and in the cross section it can be estimated to be 2.6 %, assuming that the evaluated values are the mean of the experimental data with an energy binning of 2000 bin / decade. In Table 2 are the integral mean values compared with last evaluated libraries

4 Conclusions
An evaluation of the $^{235}$U(n,f) reaction has been made in the energy range from 3 keV to 30 keV, comparing datasets from different experiments having high statistics and a fine energy resolution. The very high coincidence between those experimental datasets allow us to unambiguously assign the energy and cross section value at the identified peaks with the resolution equivalent to 2000 bin/decade, with an uncertainty in energy below 0.1% and in cross section of 2.6%.

The shape of the cross section suggest the existence of resonance structures paving the way to a further understanding of the compound nucleus fission barriers.

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Table 1. USC-Eval [Energy in eV – Cross section in barn]

| Energy (eV) | Cross Section (barn) |
|------------|----------------------|
| 3000       | 5.167                |
| 3005       | 6.420                |
| 3009       | 6.802                |
| 3013       | 6.144                |
| 3019       | 5.288                |
| 3023       | 4.650                |
| 3028       | 5.192                |
| 3036       | 4.226                |
| 3040       | 5.144                |
| 3045       | 4.683                |
| 3049       | 6.432                |
| 3051       | 5.288                |
| 3053       | 4.610                |
| 3058       | 4.883                |
| 3061       | 4.198                |
| 3062       | 3.201                |
| 3065       | 6.432                |
| 3069       | 5.288                |
| 3071       | 5.144                |
| 3075       | 4.683                |
| 3079       | 3.201                |
| 3083       | 4.610                |
| 3084       | 4.883                |
| 3088       | 4.198                |
| 3089       | 3.201                |
| 3092       | 4.610                |
| 3093       | 4.883                |
| 3096       | 4.198                |
| 3097       | 3.201                |
| 3098       | 4.610                |
| 3099       | 4.883                |
| 3101       | 4.198                |
| 3102       | 3.201                |
| 3103       | 4.610                |
| 3104       | 4.883                |
| 3105       | 4.198                |
| 3106       | 3.201                |
| 3109       | 4.610                |
| 3109       | 4.883                |
| 3110       | 4.198                |
| 3111       | 3.201                |
| 3112       | 4.610                |
| 3113       | 4.883                |
| 3114       | 4.198                |
| 3115       | 3.201                |
| 3116       | 4.610                |
| 3117       | 4.883                |
| 3118       | 4.198                |
| 3119       | 3.201                |
| 3120       | 4.610                |
| 3121       | 4.883                |
| 3122       | 4.198                |
| 3123       | 3.201                |
| 3124       | 4.610                |
| 3125       | 4.883                |
| 3126       | 4.198                |
| 3127       | 3.201                |
| 3128       | 4.610                |
| 3129       | 4.883                |
| 3130       | 4.198                |
| 3131       | 3.201                |
| 3132       | 4.610                |
| 3133       | 4.883                |
| 3134       | 4.198                |
| 3135       | 3.201                |
| 3136       | 4.610                |
| 3137       | 4.883                |
| 3138       | 4.198                |
| 3139       | 3.201                |
| 3140       | 4.610                |
| 3141       | 4.883                |
| 3142       | 4.198                |
| 3143       | 3.201                |
| 3144       | 4.610                |
| 3145       | 4.883                |
| 3146       | 4.198                |
| 3147       | 3.201                |
| 3148       | 4.610                |
| 3149       | 4.883                |
| 3150       | 4.198                |
| 3151       | 3.201                |
| 3152       | 4.610                |
| 3153       | 4.883                |
| 3154       | 4.198                |
| 3155       | 3.201                |
| 3156       | 4.610                |
| 3157       | 4.883                |
| 3158       | 4.198                |
| 3159       | 3.201                |
| 3160       | 4.610                |
| 3161       | 4.883                |
| 3162       | 4.198                |
| 3163       | 3.201                |
| 3164       | 4.610                |
| 3165       | 4.883                |
| 3166       | 4.198                |
| 3167       | 3.201                |
| 3168       | 4.610                |
| 3169       | 4.883                |
| 3170       | 4.198                |
| 3171       | 3.201                |
| 3172       | 4.610                |
| 3173       | 4.883                |
| 3174       | 4.198                |
| 3175       | 3.201                |
| 3176       | 4.610                |
| 3177       | 4.883                |
| 3178       | 4.198                |
| 3179       | 3.201                |
| 3180       | 4.610                |
| 3181       | 4.883                |
| 3182       | 4.198                |
| 3183       | 3.201                |
| 3184       | 4.610                |
| 3185       | 4.883                |
| 3186       | 4.198                |
| 3187       | 3.201                |
| 3188       | 4.610                |
| 3189       | 4.883                |
| 3190       | 4.198                |
| 3191       | 3.201                |
| 3192       | 4.610                |
| 3193       | 4.883                |
| 3194       | 4.198                |
| 3195       | 3.201                |
| 3196       | 4.610                |
| 3197       | 4.883                |
| 3198       | 4.198                |
| 3199       | 3.201                |
| W        | E        | PJ  | e      |
|---------|---------|-----|--------|
| 4986    | 3.508   | 5000| 4.415  |
| 5055    | 4.172   | 5061| 4.517  |
| 5127    | 4.344   | 5148| 3.187  |
| 5215    | 3.278   | 5235| 3.706  |
| 5282    | 4.314   | 5301| 3.542  |
| 5366    | 3.400   | 5383| 4.507  |
| 5455    | 3.532   | 5470| 2.944  |
| 5542    | 4.689   | 5552| 4.375  |
| 5664    | 3.055   | 5666| 3.816  |
| 5772    | 4.796   | 5796| 3.715  |
| 5852    | 4.111   | 5872| 4.892  |
| 5975    | 3.918   | 5992| 3.217  |
| 6055    | 3.827   | 6066| 3.252  |
| 6106    | 2.994   | 6120| 3.258  |
| 6191    | 2.964   | 6199| 2.933  |
| 6299    | 2.830   | 6336| 3.735  |
| 6396    | 3.380   | 6411| 3.998  |
| 6464    | 3.725   | 6488| 2.852  |
| 6557    | 2.750   | 6581| 3.705  |
| 6647    | 3.441   | 6661| 2.700  |
| 6728    | 2.558   | 6745| 3.073  |
| 6810    | 3.938   | 6825| 3.563  |
| 6884    | 2.954   | 6899| 3.471  |
| 6986    | 3.745   | 7000| 3.502  |
| 7060    | 3.918   | 7076| 4.111  |
| 7158    | 2.598   | 7200| 3.647  |
| 7270    | 2.685   | 7285| 3.107  |
| 7351    | 3.593   | 7369| 3.644  |
| 7438    | 2.548   | 7461| 2.923  |
| 7540    | 3.705   | 7570| 2.497  |
| 7645    | 3.461   | 7661| 3.177  |
| 7741    | 2.252   | 7770| 3.157  |
| 7875    | 3.461   | 7904| 2.619  |
| 8018    | 2.870   | 8032| 2.710  |
| 8115    | 3.207   | 8138| 2.513  |
| 8260    | 2.311   | 8290| 2.954  |
| 8400    | 3.278   | 8429| 3.146  |
| 8520    | 2.827   | 8548| 2.750  |
| 8655    | 3.623   | 8685| 3.146  |
| 8795    | 2.943   | 8817| 2.883  |
| 8935    | 2.492   | 8930| 2.334  |
| 9010    | 2.385   | 9047| 3.018  |
| 9144    | 3.859   | 9170| 3.654  |
| 9312    | 2.994   | 9340| 3.009  |
| 9466    | 3.323   | 9501| 3.319  |
| 9620    | 2.944   | 9650| 2.842  |
| 9783    | 3.197   | 9802| 3.329  |
| 9951    | 3.345   | 9970| 3.197  |
| 10090   | 2.740   | 10120|2.730  |
| 10275   | 2.538   | 10300|2.771  |
| 10474   | 2.750   | 10533|2.603  |
| 10744   | 2.952   | 10764|2.599  |
| 10997   | 2.386   | 11080|2.374  |
| 11244   | 2.690   | 11252|2.791  |
| 11415   | 2.559   | 11460|3.004  |
| 11711   | 2.456   | 11782|2.416  |
| 11990   | 2.499   | 12010|2.700  |
| 12170   | 2.548   | 12220|2.619  |
| 12405   | 2.416   | 12460|2.213  |
| 12620   | 2.355   | 12682|2.492  |
| 12819   | 2.512   | 12882|2.264  |
| 13164   | 2.853   | 13210|2.898  |
Table 2. Integral mean values compared with last evaluated libraries. $E_n$ is in keV and the cross section in barn.

In brackets are the ratios of the USC-Eval to the evaluated libraries.

| $E_{ini}$ | $E_{fin}$ | EvalUSC | ENDF-VIII | JEFF-3.3 | IAEA[Ref 19] |
|----------|----------|---------|-----------|----------|--------------|
| 3.00     | 4.00     | 4.802   | 4.804 (1.00) | 4.653 (1.03) | 4.792 (1.00) |
| 4.00     | 6.00     | 4.286   | 4.294 (1.00) | 4.273 (1.00) | 4.268 (1.00) |
| 5.00     | 8.00     | 3.850   | 3.842 (1.00) | 3.823 (1.01) | 3.847 (1.00) |
| 6.00     | 8.00     | 3.270   | 3.368 (0.97) | 3.352 (0.98) | 3.298 (0.99) |
| 8.00     | 10.00    | 2.720   | 2.729 (0.97) | 2.709 (0.97) | 2.714 (1.01) |
| 10.00    | 12.00    | 2.153   | 2.155 (1.01) | 2.135 (1.03) | 2.121 (1.03) |