https://doi.org/10.61092/iaea.xn07-jmh3

INDC(NDS)-0716
Distr. J,ST

IAEA
International Atomic Energy Agency

INDC International Nuclear Data Committee

Current Status and Open Issues of the ^{235}U Evaluation

Summary Report of an IAEA Consultants' Meeting
IAEA Headquarters, 24 – 27 May 2016

Prepared by

Gilles Noguere
CEA/DEN Cadarache
St. Paul lez Durance, France

and

Andrej Trkov
IAEA
Vienna, Austria

August 2016

IAEA Nuclear Data Section
Vienna International Centre, P.O. Box 100, 1400 Vienna, Austria

Selected INDC documents may be downloaded in electronic form from
http://www-nds.iaea.org/publications
or sent as an e-mail attachment.
Requests for hardcopy or e-mail transmittal should be directed to
NDS.Contact-Point@iaea.org
or to:
Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna
Austria

Printed by the IAEA in Austria

August 2016

INDC(NDS)-0716
Distr. J,ST

Current Status and Open Issues of the ^{235}U Evaluation

Summary Report of an IAEA Consultants' Meeting
IAEA Headquarters, 24 – 27 May 2016

Prepared by

Gilles Noguere
CEA/DEN Cadarache
St. Paul lez Durance, France

and

Andrej Trkov
IAEA
Vienna, Austria

August 2016

1. Contents

1. Introduction

The objective of this consultancy meeting was to discuss the status of the ^{235}U neutron cross sections from the thermal to MeV energy ranges, to identify the main difficulties and to propose recommendations for improving the current experimental and evaluation works.

2. Context

Since the end of the 90s, ^{235}U was the subject of several international efforts. Significant improvements were achieved in the frame of the sub-group 18 of the Working Party on International Nuclear Data Evaluation Co-operation (WPEC) of the NEA data bank. This working group provides useful recommendations for improving the "Epithermal capture cross section of ^{235}U". Ten years later, the sub-group 29, entitled "U-235 capture cross section in the keV to MeV energy region", suggested a possible overestimation of the ^{235}U capture cross section in the keV energy range. The new sub-group 40 (CIELO project, initiated in 2013) has a more ambitious goal which consists in reviewing the whole ^{235}U nuclear data from thermal to MeV energy ranges by confronting previous recommendations with new experimental results.

For ^{235}U, the revision of the capture and fission cross sections has become a necessity with the work performed on the Prompt Fission Neutron Spectra (PFNS). Results obtained by different nuclear data groups come to the same conclusion which is to decrease the average energy of the PFNS of ^{235}U at the thermal energy (2.03 MeV down to 2.0 MeV). The resulting PFNS have a sizeable impact (from few tens to several hundred of pcm) on integral benchmark calculations

At the same time, the so-called "Thermal Constants" of ^{235}U (i.e. thermal capture cross section, thermal fission cross section, neutron multiplicity …) were updated and new evaluations of the neutron cross sections over a large energy range (resonance range, unresolved resonance range and "continuum") started. The current evaluation works are performed on the basis of new experimental results which are briefly described in this report. Performances of the evaluated nuclear data files were illustrated with a large set of integral benchmarks coming from the ICSBEP data base and from the CEA facilities (EOLE, MINERVE, MASURCA, PHENIX).

The topics discussed during the meeting are summarized in the following sections.

3. Current status and open issues of the ^{235}U evaluations

The main items of interest for the current evaluation works are the new PFNS, the "Thermal Constants", the fluctuations of the neutron multiplicity in the resonance range and the shape of the capture-to-fission ratio (alpha) below 10 eV.

The "Thermal constants" are historically evaluated in the frame of the "standard neutron cross section" group of the IAEA. The latest recommendations of the "Thermal Constants" were released in 2006. New values will be released in 2016 and some of them were already included in the current evaluation works.

The PFNS of ^{235}U at thermal energy was also re-evaluated in the frame of the "standard neutron cross section" group of the IAEA. The resulting PFNS suggests decreasing the average energy by 1.5% down to 2.0 MeV.

For ^{235}U, the amplitude of the fluctuations of the neutron multiplicity can reach 1% in the resonance range. Such fluctuations exist in the JEF-2.2 evaluated library only. They were re-evaluated by V. Pronyaev on the basis of available experimental data. Trends observed in HEU-SOL-THERM benchmarks as a function of the ATLF confirm the need for reintroducing "fluctuations" of the neutron multiplicity in the evaluated libraries.

Among the selected ICSBEP benchmarks, the COMET-UH3 (HEU-COMP-INTER-003) and ZEUS (HEU-MET-INTER-006) benchmarks seem to provide contradictory trends on the keV to MeV energy ranges which are difficult to explain with the ^{235}U cross section alone. Results obtained with the COMET-UH3 seem to contradict the need for decreasing the ^{235}U capture cross section in the keV energy range as suggested in the conclusions of the sub-group 29. The capture cross section in the JEFF-3.3t1 library is as much as 30 % higher than ENDF/B-VII.1 above the resonance range and it seems to (over)compensate the reactivity gain due to the decreased capture in the resonance range, although the copper in the ZEUS benchmarks could be partly responsible for the differences.

The slope of the capture-to-fission ratio has been a longstanding issue that has already been studied by the sub-group 18. The current evaluation works suggest increasing the ^{235}U capture cross section by 15% or 20% between the 0.5 eV and 1.5 eV by following the trend imposed by the alpha values of Brooks [3]. New experimental alpha values measured at the nTOF facilities seem to confirm this trend. At energies in the keV range these new experimental results are also not in favor of a decrease of the capture cross section as suggested in the conclusions of sub-group 29. A deeper investigation of these contradictory trends is needed. Additional evidence might be obtained from the French benchmarks on the isotopic composition of irradiated fuel.

4. Thermal Constant for new standard evaluation

In the nuclear data field, the "standard evaluations" define a set of well defined "Thermal Constants", Prompt Fission Neutron Spectra, prompt gamma-ray production cross sections and neutron cross sections of interest for nuclear applications. The evaluation procedure uses the GMA (Gauss Markov Aitken) method.

For the high energy neutron cross sections, the GMA analysis is based only on microscopic data. The procedure does not rely on integral benchmarks calculations. An extensive work has been performed to recommend ^{239}Pu, ^{238}U and ^{235}U cross sections over a broader energy range by including new data. For ^{235}U, the upper energy limit will be extended up to 1 GeV by using experimental data to be measured at the nTOF facility in the near future, relative to the n,p elastic scattering.

The "Thermal Constants" are the Westcott factors, neutron multiplicities, eta values, alpha values, equivalent K1 and thermal cross sections (elastic, capture, fission). For the next release, the "Thermal Constants" will be also evaluated with microscopic data only. Maxwellian spectrum average values are not included as originally proposed by Axton (1986).

For the ^{235}U thermal capture cross section, the final value is strongly driven by the value of Wallner [1] and the alpha value of Adamchuk [2]. The ^{235}U thermal capture and fission cross sections are increased by 0.7% and by 0.5%, respectively, compared to the previous recommendation (2006). The "standard values" reported during the meeting could slightly change.

5. Review of the new measurements for alpha

In the resonance range, the existing ^{235}U evaluations are based on old data. If fission cross section seem to be well known, the evaluation of the capture cross section is based on a rather limited number of data sets measured in the 70s that cover a short energy range (E<200 eV). This could explain the conclusions of the sub-group 29 about the quality of the evaluation in the keV energy range.

The measurement of the capture cross sections of the fissile materials is a challenging work. The development of improved experimental set-up in the main time-of-flight facilities (RPI, LANL, nTOF) allowed providing new data useable up to 2 keV for the resonance analysis.

The DANCE detector (LANL) provided a relative measure of the alpha by using the gamma-ray multiplicity to separate the capture events (M=3-5) and the fission events (M=7-9). The shape of the fission cross section obtained with DANCE was verified by using PPAC detectors. For the capture cross section, the normalization has to be determined during the evaluation procedure. If the data are normalized to the ENDF\B-VII.1 evaluation [45 eV - 100 eV], the DANCE data support a decrease of the capture cross section in the keV energy range. Above 3 keV, the DANCE data suggest to increase the capture cross section. A new stilbene detector, called NEUANCE, is under study. This detector, in association with DANCE, aims to provide much information on the fission reaction (prompt neutron spectrum, improve the cross section in the high energy range, correlations between PFNS and PFGS, fission fragment spectrometry). It could also provide crucial information on the contribution of the isomeric states, which play a significant role in the capture process. The isomeric states could contribute to double counts that could lead to systematic uncertainties on the capture cross section measured with DANCE. Similar problems are expected with the TAC detector of nTOF.

At nTOF, a pilot experiment which started in 2012 provided the first measure of the $^{235}U(n,\gamma)$ reaction. A new measurement was recently performed in order to provide a measure of the alpha relative to the ^{235}U fission cross section. This was achieved by using the TAC detector with an improved association of micromegas detectors containing 10 ^{235}U samples (U_3O_8) for tagging the fission events. The obtained alpha could be used from 0.5 eV up to 200 eV. The shape of the fission cross section is in good agreement with the existing libraries. If the fission cross section is normalized between 7.8 eV to 11.0 eV with the recommended value of the standard group of IAEA (246.4 b.eV), the present alpha measurement, which are still preliminary, is in good agreement with the alpha data of Brooks [3] and suggests to increase the capture cross section by 20%. Extensive works have been performed for checking all possible sources of errors (sample inhomogeneity, detection efficiency, dead time, pile-up corrections). The TAC efficiency was well reproduced with the ^{236}U gamma-ray cascade provided by Milan Krticka using DiceBox and the DANCE data. The work of Milan Krticka accounts for the contribution of the isomers.

The RPI data were not discussed during the meeting. They are not yet officially released. They are used in the IRSN/CEA evaluation from 100 eV up to 2 keV.

6. Review of the new measurements for fission

For the first time, the ^{235}U fission cross section was measured at the nTOF facility with the PPAC detector from 1 eV to 1 GeV. The shape of the data is in excellent agreement with the Weston data (1984) even between the resonances, because of the low background. The positions of the resonance peaks are also in good agreement up to the end of the resolved resonance range, confirming the good energy calibration. The neutron flux is rather flat over a broad energy range, showing practically no "structure". The present data have been included in the current evaluation of the resonance parameters. The description of the interference between the resonances was improved and some doublets of resonances were confirmed. An excellent agreement is also observed with the ^{235}U standard fission cross section of the IAEA. Similar agreement is obtained with the ^{238}U fission cross section measured in the same conditions, confirming the good quality of the PPAC results. Few problems identified in the "standard" cross sections will be corrected in the next released (refine the energy mesh). This measurement will be used to extend the upper energy limit of the standard. New data from the n_TOF Collaboration on the ratio of the ^{235}U(n,f) vs ^{6}Li(n,t) and ^{10}B(n,a) reactions may also become available in the near future.

Another measurement performed at the nTOF facility suggests that the fission cross section in current evaluated data libraries between 10 and 30 keV could be overestimated by 4 to 6%, depending on the library. At present, discrepancies of up to 3% exist between libraries in this energy region. Furthermore, ENDF\B-VII.1 has increased the uncertainty in this region up to 4%. Data from the flux monitor of IRMM seem to confirm this trend, but further studies are needed to obtain more accurate results. A new measurement in this energy region is planned at nTOF.

7. Resonance evaluations

Two ^{235}U evaluations were discussed during the meeting. The IRSN/CEA evaluation is already available in the JEFF-3.3T2 test library. The ORNL evaluation still needs some slight improvements.

The two evaluations have the same origin. The original resonance parameters were established with the SAMMY code by Luiz Leal at ORNL. In the keV energy range, the evaluations take into account the experimental fission and capture cross section measured at the RPI facility. The low energy part started to diverge when Luiz Leal left ORNL to join the IRSN group in France.

At low energy (below 1.5 eV), the ORNL evaluation follows the alpha measurement of Brooks [3]. The shape of the alpha improved the performances on the HEU-SOL-THERM benchmarks as a function of the ATLF. The objective is to have a consistent evaluation by using the "Thermal Constants", the PFNS proposed by the "standard" group of IAEA and increased capture by up to 20% in the range below 1.5 eV. This trend is consistent with the new alpha measurements performed at nTOF with the TAC detector.

The IRSN/CEA evaluation also proposes a sizeable increase of the capture cross section up to 1.5 eV. This increase corresponds to a modification of the shape of the alpha according to more recent alpha measurements of Wartena [4] and Weigmann [5]. The modification of the alpha allows to better reproduce integral experiments carried out in the EOLE facility in cold operating conditions from 6 degC to 80 degC. A cross-check of the resonance parameters is in progress with the CONRAD code developed at CEA Cadarache.

Results obtained with the COMET-UH3 benchmarks suggest increasing the capture cross section in the keV energy range. This result does not support the conclusion of the sub-group 29.

8. Fast neutron energy range

The ORNL/IAEA evaluation also includes the recent evaluation work performed with the OPTMAN and EMPIRE codes. The theoretical background for fission is described in a recent publication ("Extend optical model for fission", PRC 2016). For ^{235}U, the fission has to be described with a triple-humped barrier (complete-damping). The resulting fission cross section is in good agreement with the data of Wallner (at 25 keV) [1]. The main impact of this new modelisation can be seen on the decrease of the (n,n') cross section. In the final evaluation, the capture cross section was replaced by the capture cross section of ENDF\B-VII.1, the fission cross section by the "standard" values and the PFNS were those established at IAEA and by Rising-Talou at LANL.

The Fast energy range of the JEFF-3.3 T1 was not discussed. The evaluation was performed at CEA Bruyère Le Chatel with the ECIS and TALYS codes.

Contradictory integral results were obtained. Results obtained at the IAEA for the COMET-UH3 benchmarks suggest increasing the capture cross section in the keV energy range. This result does not support the conclusions of the sub-group 29. The ZEUS benchmarks calculated at IRSN are better reproduced with the JEFF-3.3 T1 library (compared to JEFF-3.2), and seem to confirm the conclusions of the sub-group 29. However, as indicated before, the capture cross section in the JEFF-3.3 T1 library is as much as 30 % higher than ENDF/B-VII.1 above the resonance range and it seems to compensate the reactivity gain due to the decreased capture in the resonance range. These ambiguous results need to be clarified.

9. Recommendations

The main result that emerges from the discussions is the possible increase of the U-235(n,γ) cross section in the Resolved Resonance Range. For the thermal capture cross section, an increase of about 0.7% (from 99.40 barn to 100.1 barns) is suggested by the work of the "neutron cross section standard" group of the IAEA on the "Thermal Constant". Above 0.5 eV, new experimental results from nTOF suggest to increase the capture cross section of ENDF/B-VII.1 and JEFF-3.1.1 by 15% to 20%, at least up to 20 eV, in agreement with the alpha data of Brooks [3]. These trends were already taken into account up to 1.5 eV in the current evaluation works (ORNL/IAEA and IRSN/CEA). The amplitude of the changes above 1.5 eV is still an open issue.

For solving the possible increase of the ^{235}U capture cross section in the resonance range, it is recommended to extend **new alpha measurements of ^{235}U down to the thermal region**, and to compare (or normalize) the data with the new standard alpha value (α_{th}=0.1705).

Similarly, **new data for the ^{235}U fission cross sections that cover the thermal energy range** up to several MeV are highly requested for checking the recommended average value of 246.4 barns.eV between 7.8 eV and 11.0 eV. Therefore new experiments based on improved detection set-ups, such as COFI (COmplete FIssion detector), are encouraged.

If the combination of the new alpha and fission data confirms the increase of the ^{235}U capture cross section, **new transmission data at room temperature** would be desired for obtaining a consistent evaluations of the resonance parameters. The current ^{235}U evaluations are strongly constrained by the transmission data of Harvey measured at nitrogen temperature (T = 77K), for which the accurate determination of the effective temperature is difficult to assess (90 K < T_{eff} < 110 K) without using crystal lattice models and an appropriate phonon spectrum.

Measurements of the neutron multiplicity from thermal to epithermal energy regions are also recommended. The existing EXFOR data seem to confirm the fluctuations of the neutron multiplicity over the low energy resonances, but they cannot provide an accurate determination of the amplitude of the fluctuations. Sizeable fluctuations close to 1% are expected around a broad structure observed in fission at 14 eV.

Sizeable impacts of the ^{236}U isomeric states are expected in the capture measurements. Such contributions were taken into account in the latest alpha measurement performed at the nTOF facility by using an improved gamma-ray cascade in the simulation of the capture detection efficiency of the TAC detectors. The impact on old measured capture cross sections and alpha values is unknown. Double counting is expected because the time window used to collect the gamma-ray events is larger than the decay time of the isomeric states.

As a consequence, experimental yields as a function of time with full experimental details have to be provided to EXFOR. A **new EXFOR template** has been established for storing time-of-flight data.

In the future releases of the recommended values by the Neutron Cross Section Standard Group of the IAEA, an average value for the capture cross section in the **energy range [4.0 eV - 7.8 eV**] should be given.

References

[1] A. Wallner, T. Belgya, M. Bichler, K. Buczak, I. Dillmann, et al., Novel Method to Study Neutron Capture of ^{235}U and ^{238}U Simultaneously at keV Energies**,** Phys. Rev. Lett. **112** (2014) 192501.

[2] Yu. V. Adamchuk, M. A. Voskanyan, G. Georgiev, , A. L. Kovtun, G. V. Muradyan, et al., Measuring the ^{235}U α values at a thermal point, Sov. J. Atomic Energy **65** (1988) 1022**.**

[3] F. D. Brooks, J. E. Jolly, M. G. Schomberg, M. G. Sowerby, η and Neutron Cross Sections of ^{235}U from 0.03 to 200 eV, AERE-M-1670, 1966.

[4] M.G. Cao, F. Migneco, J.P. Theobald, J.A. Wartena and J. Winter, Fission cross-section measurement on ^{235}U, J. Nuclear Energy **22** (1968) 211.

[5] H. Weigmann, B. Keck, J.A. Wartena, P. Geltenborta and K. Schreckenbach, Measurements of eta of ^{235}U for subthermal energies, Int. Conf. on the Physics of Reactors, Marseille, 1990.

Status of the Thermal Constants Evaluation for Standards-2016, *V. Pronyaev*

A brief overview is given of the changes in the preliminary fit of standards with 20 new data sets added to the 2004 standard database. The important changes are observed for ^{197}Au and ^{238}U capture cross sections below 100 keV due to inclusion of high-precision Geel measurements for these cross sections. For thermal cross sections, the Axton's thermal constants [E.J. Axton, Report GE/PH/01/86, 1986] evaluated with the use of experimental values at 0.0253 eV energy (labelled "micro") and thermal spectrum averaged values (labelled "macro") were used as pre-evaluated data (micro&macro fit) in the combined GMA fit for 2006 Standards. The use of only microscopic values (micro fit) as it is shown in the Axton's report leads to different evaluated thermal constants. Large difference is observed for thermal capture cross section of ^{235}U which deviates strongly from the 1/v dependence below and above thermal point. Since 1986 two accurate measurements of capture cross section for ^{235}U at 0.0253 eV were done: direct absolute measurements by Wallner [A. Wallner et al., PRL, 112, p. 192501, 2014] using accelerator mass spectrometry method and measurements of ratio of capture to fission cross section by Adamchuk (Yu.V. Adamchuck et al., Sov. J. At. En., 65, p. 1022, 1988]. The GMA fit with "micro" pre-evaluated data by Axton, and inclusion of these two new data set, increased the capture and fission cross sections at the thermal point for ^{235}U. Table below shows the comparison of GMA fits for values of the cross sections obtained with two Axton's pre-evaluated data. New data were included in the fits. As it is seen from the Table, uncertainties in the case of using "micro" fit are larger because of reduced number of experimental data. The increase of fission cross section in micro fit is compensated by decrease of nu-bar and and increase of capture. K1 paramater for constants from both fits is about the same. This means that calculations of k_{eff} for large ^{235}U assemblies with well thermalized spectrum for these two sets of constants embedded in the files will give close values. These assemblies are insensetive to the changes in the prompt fission neutron spectra (PFNS). But new constants will probably allow to make easier the compensation of changes in criticality for small high-enriched assemblies with high leakage caused by the intoduction of new evaluated PFNS in the files.

Cross section, constant	New fit with Axton's micro evaluation	New fit with Axton's micro&macro evaluation
^{235}U(n,n), b	14.09±0.22	14.09±0.22
^{235}U(n,f), b	587.17±1.37	584.34±1.03
^{235}U(n,γ), b	100.1±1.7	99.43±0.69
ν_{tot} for ^{235}U(n_{th},f)	2.4250±0.0045	2.4322±0.0036
K1, b	719.8	719.6

New ^{235}U Evaluation of the Resolved and Unresolved Resonance Range for JEFF-3.3,
G. Noguere and L. Leal

Context

Two ^{235}U evaluations (from IRSN/CEA and IAEA consortium) were discussed during the meeting. In the resonance range, the two evaluations have the same origin. The original resonance parameters were established with the SAMMY code by Luiz Leal at ORNL. They started to diverge when Luiz Leal left ORNL to join the IRSN group in France. The IRSN/CEA evaluation is already available in the JEFF-3.3T1 test library. Performances of the ENDF file on integral benchmarks were discussed during the JEFF meeting of April 2016.

The IRSN/CEA evaluation of the ^{235}U neutron cross sections is the result of three independent evaluation works. The Resolved Resonance Range (RRR) was established by Luiz Leal with the SAMMY code. Parameters of the Unresolved Resonance Range (URR) were determined with the URR option of the TALYS code at CEA of Cadarache. The "continnum" part of the ^{235}U cross sections comes from ECIS and TALYS calculations performed at CEA of Bruyère le Châtel. Only RRR and URR are presented below.

Analysis of the Resolved Resonance Range

The evaluation of RRR was performed with the SAMMY code developed at ORNL up to 2.25 keV. Results are being cross-checked with the CONRAD code developed at the CEA of Cadarache. The resonance parameters (resonance energies, partial widths and effective radius) were adjusted on transmission, capture, fission and alpha measurements. The present analysis accounts for a new high resolution fission cross section measured at the nTOF facility with the PPAC detector. Above 100 eV, the trend of the capture cross section was improved with new data measured at the RPI and LANL facilities.

The experimental fission cross sections were normalized at the thermal energy and between the energy range [7.8 eV – 11 eV] to the value of 246.4 barn.eV, as reported in 2006 by the "standard neutron cross section" group of AIEA. The fission cross section from the nTOF facility allowed a better determination of the interferences between the resonances over a wide energy range. In the keV energy range, the fission cross section remains in good agreement with the previous evaluation (ENDF\B-VII.1 and JEFF-3.2). The thermal fission cross section and the fission resonance integral obtained with JEFF-3.3T1 are summarized below:

$$\sigma_f = 584.4 \text{ barns}$$

$$I_f = 283.4 \text{ barns}$$

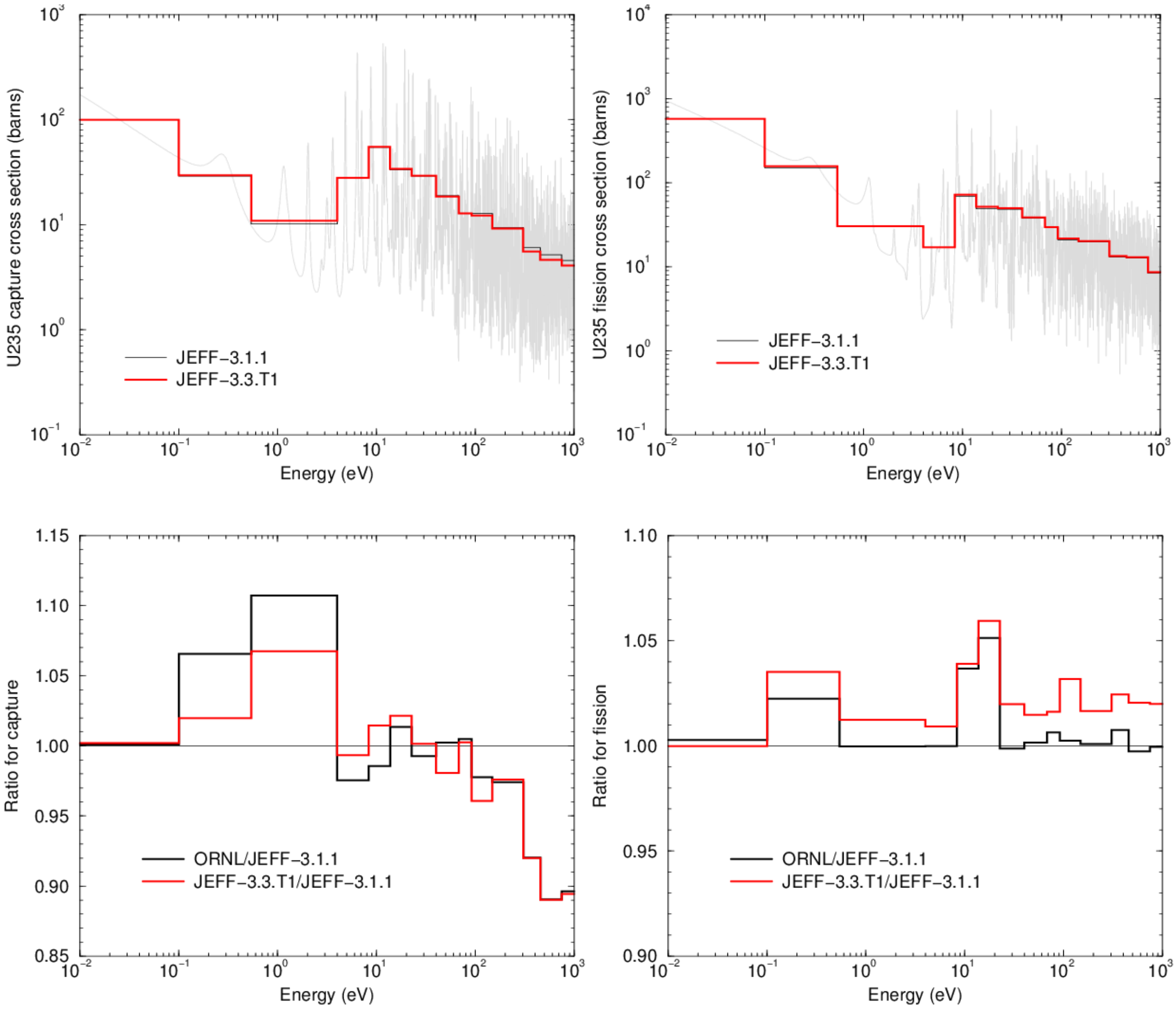

Fig. 1: *Comparison of the* $^{235}U(n,\gamma)$ *and* $^{235}U(n,f)$ *cross sections of JEFF-3.1.1and JEFF-3.3.T1. The resonance parameters from ORNL were retrieved from the AIEA webpage ("u235ib06ao17g6cnu5cf2").*

The capture cross section was increased by 1% at the thermal energy, for aproaching the "standard" value, and up to 15% below 1.5 eV. This significant increase was achieved by optimizing the parameters of few negative resonances, adequately chosen for reproducing alpha measurements of Wartena (1987) and Weigman (1990). Older alpha data from Brooks (1966) were not considered in the analysis. Above 100 eV, the ^{235}U capture cross section is mainly based on the capture data measured at the RPI facility. As a result, the current evaluation follows the conclusions of the sub-group WPEC/SG-29 that suggests decreasing the capture cross section in the keV energy range. "Thermal constants" associated to the capture reaction are listed below:

$$\sigma_\gamma = 99.6 \text{ barns}$$

$$I_\gamma = 141.8 \text{ barns}$$

Table 1: MCNP results obtained for the ZEUS benchmark (HMI-006) with JEFF-3.3.T1.

			ZEUS1	**ZEUS2**	**ZEUS3**	**ZEUS4**
keff		**(exp.)**	0.9977 ±0.0008	1.0001 ±0.0008	1.0015 ±0.0009	1.0016 ±0.0008
C-E	**KAERI**	**(pcm)**	-427	-398	-430	-144
	NEA	**(pcm)**	-429	-445	-565	-253
	AIEA	**(pcm)**	-498	-431	-574	-253

The impact of the modifications of the low energy cross sections (Fig. 1) was studied on integral benchmarks carried out at the EOLE reactor of CEA Cadarache and on a set of Post Irradiated Experiments performed in power reactors. Compared to JEFF-3.1.1, the JEFF-3.3T1 evaluation improves the C-E results of the MISTRAL-1 program, given as a function of the temperature (from 10°C to 80°C). In the meantime, calculations of the isotopic ratio U236/U238 in irradiated UOX fuels provide C/E-1 values close to -0.5% on average. The ZEUS benchmarks (HMI-006) was used to test the consistent description of the cross sections above 100 eV. It is composed of four configurations characterized by an increasing hardness of the neutron flux. The EALF varies from 4 keV, 9 keV, 22 keV to 81 keV. The C-E results obtained with the full JEFF-3.3T1 library are given in Table 1.

As discussed during the meeting, the ZEUS results depend on the Copper evaluation. In addition, results for the 3rd and 4th configurations of the ZEUS benchmark strongly depend on the description of the cross sections in the "continuum" part

Analysis of the Unresolved Resonance Range

The analysis of the URR was performed with the ECIS and TALYS codes up to 150 eV. A new option was included in the TALYS code for automatically generated average parameters compatible with the processing system NJOY.

Prior average parameters were established from the statistical analysis of the resonance parameters. The s-wave neutron strength function and mean level spacing were deduced from an ESTIMA analysis. The average radiation width was simply deduced from the mean value of the individual radiation widths. Since the results obtained from the resonance parameters of JEFF-3.3T1 are in good agreement with the values compiled by Mughaghab in the Atlas of Neutron Resonances (Edition 2006), we decided to use them as prior information for the URR analysis:

$$10^4 S_0 = 0.98 \pm 0.07$$

$$D_0 = 0.49 \pm 0.02 \text{ eV}$$

$$\langle \Gamma_\gamma \rangle = 38.1 \pm 1.7 \text{ meV}$$

The URR parameters were determined by using the Integral Data Assimilation procedure of the CONRAD code. We included in the evaluation procedure integral trends provided by the PROFIL and PROFIL-2 sample irradiation experiments carried out in the fast reactor PHENIX of the CEA Marcoule. They were designed to collect integral information for improving the neutron-induced cross sections of interest for fast reactor applications. These experiments consisted in pins containing a large number of samples (~ 130 samples) of almost pure separated actinides and fission products isotopes. Each pin was irradiated during several months in the PHENIX reactor and then analysed by ICPMS.

Table 2: ^{235}U average capture and fission cross sections (in barns) calculated with the TALYS code in the unresolved resonance range from 0.5 keV to 150 keV, and compared with the ^{235}U evaluation “u235ib06ao17g6cnu5cf2” retrieved from the IAEA webpage.

Energy groups	This work		u235ib06ao17g6cnu5cf2	
	^{235}U(n,γ)	^{235}U(n,f)	^{235}U(n,γ)	^{235}U(n,f)
0.5 – 1.0	4.41	10.53	4.40	10.44
1.0 – 1.5	3.31	8.05	3.28	7.88
1.5 – 2.0	2.74	6.78	2.48	6.40
2.0 – 3.0	2.27	5.69	2.00	5.28
3.0 – 5.0	1.77	4.53	1.50	4.49
5.0 – 9.0	1.32	3.50	1.23	3.32
9.0 – 15.0	1.01	2.78	0.98	2.80
15.0 – 25.0	0.80	2.31	0.79	2.33
25.0 – 40.0	0.67	2.01	0.66	2.03
40.0 – 67.0	0.55	1.78	0.56	1.81
67.0 – 100.0	0.46	1.62	0.47	1.63
100.0 – 150.0	0.39	1.49	0.38	1.49

The PROFIL experiments were simulated with the ERANOS-2.2 code. The obtained results show that the alpha ratio of ^{235}U can be derived from the (^{235}U / ^{238}U) and (^{236}U / ^{235}U) individual isotopic ratios, which characterize the ^{235}U fission and capture cross sections respectively.

The simultaneous adjustment of the PROFIL results with the AIEA recommendation for the fission cross section lead to a set of optical and statistical model parameters able to provide a capture cross section in good agreement with the existing EXFOR data up to 150 keV. The obtained capture and fission cross sections averaged over a broad energy mesh are reported in Table 2.

The comparison of the average capture cross sections calculated in the URR and in the RRR seems to confirm the conclusions of the working group WPEC/SG-29, i.e. the ^{235}U capture cross section in ENDF\B-VII.1 and JEFF-3.1.1 libraries are overestimated in the keV energy range.

High accuracy ^{235}U(n,f) cross-section data in the resonance energy region, *I. Duran*

The ^{235}U neutron-induced fission cross-section is widely used as reference for measuring other fission cross sections, but in the resonance region it is not considered as an international standard [1] but as an IAEA neutron cross-section reference [2]. In the U5 data file in this IAEA webpage, the second row corresponds to the integral of the ^{235}U fission cross section in the energy range 7.8 – 11 eV having a value of 246.4 with an uncertainty of 0.5%, that can be used as a good reference for normalization of the cross sections experimentally obtained.

In this exercise, we deal with a new analysis of the experimental data obtained with a detection setup based on parallel plate ionization chambers (PPACs) at the CERN-nTOF facility. Comparing it with the ENDF/B-VII evaluation in the range from 1 eV to 10 keV , the IAEA reference file from 100 eV to 10 keV , and the SAMMY fit performed by Luiz Leal et al. [3] there is a general good agreement but it suggest some minor adjustments in the IAEA file.

The result of a recent nTOF work on the U8/U5 cross section ratio in the threshold energy region is included as well as an evaluation of the U5(n,f) cross section at intermediate energies.

The ^{235}U(n,f) cross section measured by PPACs at CERN-nTOF

The experimental setup at CERN-nTOF [4] included a reaction chamber with ten PPAC detectors allowing the simultaneous measurement of nine targets. Two targets of ^{235}U and ^{238}U were used as reference and so the primary results of most measurements are the ratios between different fission cross-sections. Targets in the PPAC setup used in 2003 were perpendicular to the neutron beam whereas in the 2012 setup they were tilted at 45° relative to the neutron beam to improve the geometrical acceptance of the detector, decreasing so the efficiency corrections.

The neutron flux from thermal energy to 150 keV is typically extracted on the basis of the ^{6}Li(n,t) and ^{10}B(n, α) reactions, normalized to each other at thermal energy. Thanks to the combination of these different standard reactions, the neutron flux at nTOF in the first experimental area is evaluated with an accuracy of 1-2% from thermal neutron energy up to 10 keV. Details on the procedure used for the neutron flux determination at nTOF can be found in [5]. Two different spallation target setups were used in 2003 and 2012, using different moderators, and also de collimators were refurbished, producing so different neutron-flux functions, as can be seen in Fig. 1. The data acquisition system in 2012, with respect to 2003, was upgraded and the analysis software redone in such a way that the 2003 and 2012 datasets can be taken as two independent experiments.

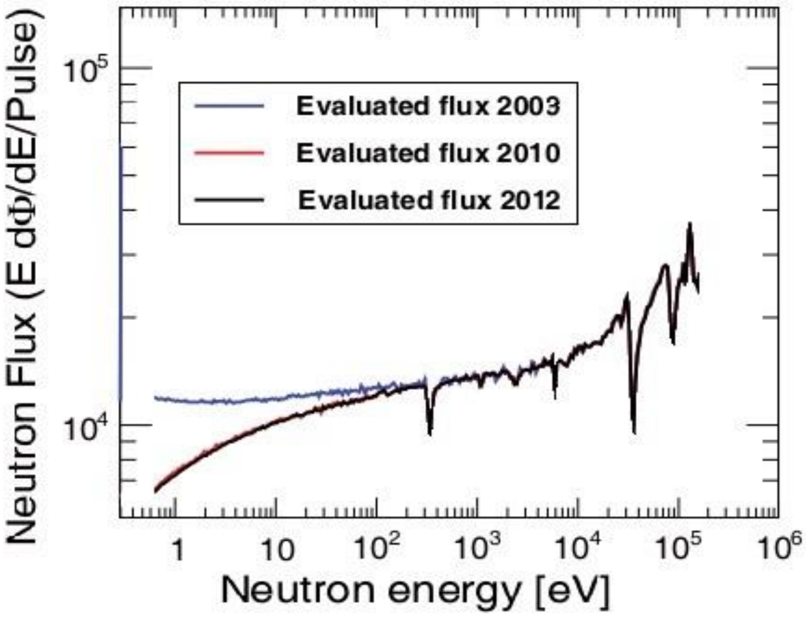

Fig 1. *Neutron flux at nTOF for different campaigns.*

From 2010 Boron was added to the water used as moderator.

The time-of-flight to energy calibration and its resolution function was done at nTOF and details can be found in [6]. The datasets has been produced with a resolution of 2000 bins/decade with an energy uncertainty lower than 0.05% (in eV) over the energy range 1 eV to 10 keV This accuracy has been checked looking at the Al(n,g) deep at 5.9 keV and to the U5(n,f) big resonance at 9.4 eV. The nTOF U5(n,f) cross sections has been obtained directly multiplying the neutron flux function by the selected events, assuming that the efficiency for selecting fission events from the coincidence of both fission fragments is constant within less than 1%, in this reduced energy range. The datasets were normalised according to the recommended standard of the fission integral in the energy range 7.8 eV to 11 eV.

A resonance re-evaluation of the ^{235}U(n,f) reaction has been recently carried to address the issues regarding standard values in the energy range from 10^{-5} eV to 2250 eV [3]. In this ^{235}U resonance analysis performed with the code SAMMY, the nTOF data [5], normalized to the recommended IAEA value in the energy range 7.8 eV to 11.0 eV, were included in addition to the average standard values related to the fission cross section and the standard thermal values for fission and capture, as well as the elastic cross sections. The fission cross-section measurement carried out by Paradela et al. at the nTOF facility also reinforced the standard set of averaged fission cross-section values [1] in the resonance region from 100 eV up to 2 keV. These data were also replicated with calculations using the revised resonance parameters as shown in Table 1.

Table 1. U5(n,f) cross sections [barn] measured at CERN-nTOF compared with different evaluations.

En (eV)	<2012>	<2003>	SAMMY	IAEA	ENDF	<2012>/iaea
100-200	21,00	21,05	21,02	21,17	20,32	0,992
200-300	20,64	20,73	20,77	20,69	20,60	0,997
300-400	13,21	12,89	13,22	13,13	12,81	1,006
400-500	13,57	13,57	13,49	13,78	13,29	0,985
500-600	15,12	15,05	15,20	15,17	14,87	0,997
600-700	11,36	11,46	11,53	11,51	11,24	0,987
700-800	10,87	10,91	11,10	11,10	10,88	0,979
800-900	8,129	8,137	8,150	8,213	7,977	0,990
900-1000	7,290	7,356	7,370	7,502	7,240	0,972
1000-2000	7,257	7,291	7,286	7,303	7,138	0,994
2000-3000	5,313	5,211	5,332	5,386	5,290	0,986
3000-4000	4,740	4,721	4,794	4,784	4,778	0,991
4000-5000	4,206	4,193	4,273	4,261	4,207	0,987
5000-6000	3,810	3,766	3,823	3,838	3,905	0,993
6000-7000	3,286	3,185	3,353	3,291	3,287	0,999
7000-8000	3,299	3,115	3,215	3,236	3,158	1,019
8000-9000	2,927	2,906	3,094	3,009	2,940	0,973
9000-10k	3,009	3,058	3,064	3,120	3,043	0,964

In Fig. 2 the ratios of these datasets are shown. The ratio of the nTOF experimental results obtained in 2003 over those of 2012, is shown in the first strip; after normalized in the 7.8 to 11 eV energy slot, its ratio keeps a systematic flat behavior up to 6 keV, where the statistical spread becomes bigger than 2%. In the second strip the last result of Leal [3] are compared with the IAEA reference values [2]; there is not a systematic deviation observed, being all the points but two below 2%. In the third strip is shown the ratio of the mean value of both nTOF datasets over the mean value of IAEA and Leal datasets. Here the agreement endorses the goodness of the four datasets, even though a small systematic difference is found and the agreement is improved when an offset of 0.05 b is applied.

Such an offset of 50 mb represents less than 0.5 % for energies below 700 eV, rising over 1.5% above 7 keV, and over 2.5% above 20 keV. As a consequence, the uncertainties reported in the IAEA reference file above 700 eV are not consistent with our experimental data.

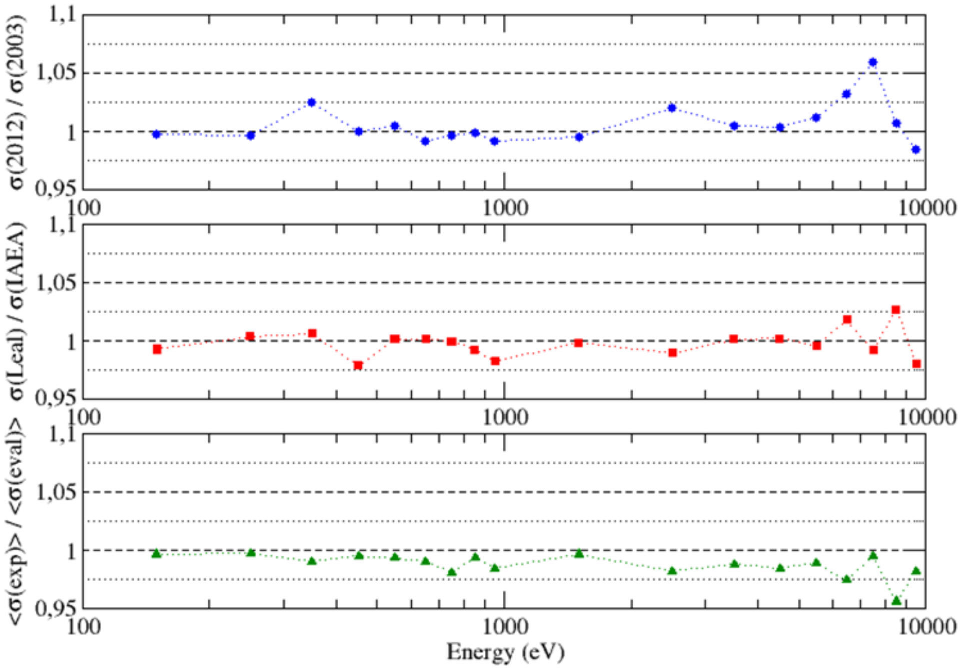

Fig. 2. *Comparison between experimental and evaluated datasets.*

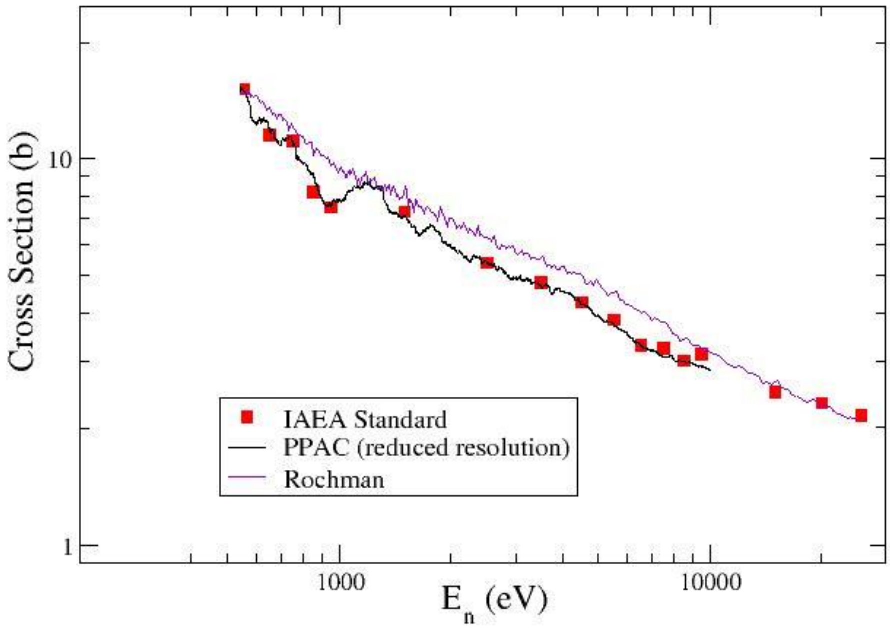

Fig. 3. *IAEA points compared with the Rochman 2005 dataset (in EXFOR).*

In Fig. 3 can be seen how the shape of the Rochman dataset is straight in the double-log plot, whereas the IAEA points do not follow this trend above 700 eV. The black line represent the nTOF(2003) data after being rebined and smoothed.

Going back to the Table 1 it is worth to mention that the ENDF/B-VII integral values, besides a 2% difference in the normalization value at 7.8 to 11eV, show a sharp step at 2.25 keV [7], corresponding with the transition from the RRR to the URR; this step is not confirmed by the experimental datasets.

The ratio U8/U5 measured at the threshold region at CERN-nTOF.

The fission cross-sections of ^{235}U and ^{238}U are of fundamental importance in the field of nuclear technology. In particular, accurate fission cross-sections up to hundreds-of-keV region are needed for the development of innovative fast reactors. The $^{235}U(n,f)$ cross section is an international standard at 0.0253 eV and above 0.15 MeV, and $^{238}U(n,f)$ is standard beyond 2 MeV [1]. While the $^{235}U(n,f)$ standard is commonly used for neutron flux measurements from thermal to high energy, the $^{238}U(n,f)$ threshold cross section can be more conveniently used in the presence of a high neutron background at low energy.

To address the need of new and accurate data for future improvements of these standards a series of measurements of the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio were performed at the CERN nTOF facility up to 1 GeV. Some of these measurements are described in detail in Ref. [8]. The ^{238}U fission cross section has been measured relative to the ^{235}U fission cross section at CERN – nTOF with different detection systems. These datasets have been collected and suitably combined to provide a very high counting statistics in the energy region around the threshold from about 500 keV up to 3 MeV in Ref. [9]. The systematic uncertainty of the weighted average ratio, taking into account the normalisation to the IAEA standards, were calculated from the energy-dependent uncertainties given by different experiments and is roughly estimated to be less than 1.5% (1 σ).

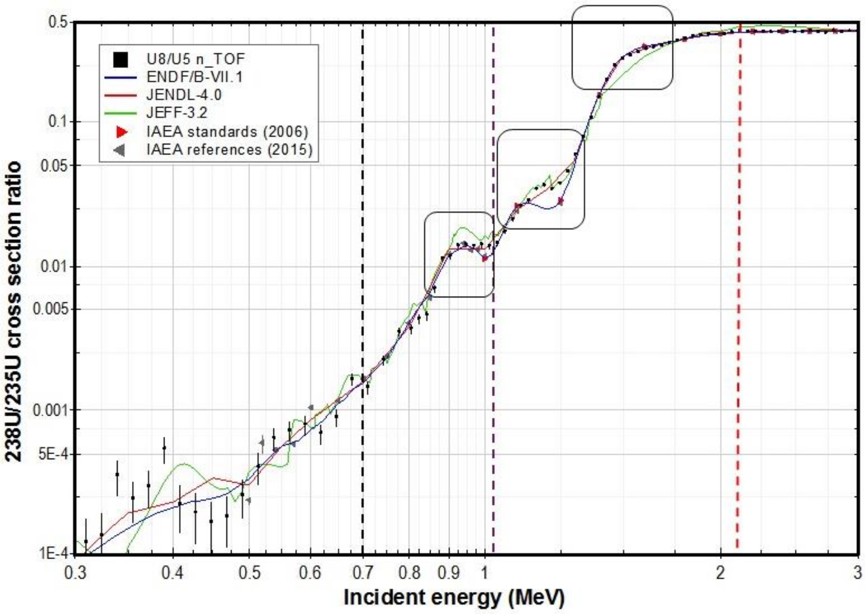

Fig. 4. *The $^{238}U/^{235}U(n,f)$ cross-section ratio from the weighted average of the nTOF datasets compared with the IAEA standard (2006) and reference (2015) and major evaluations.*

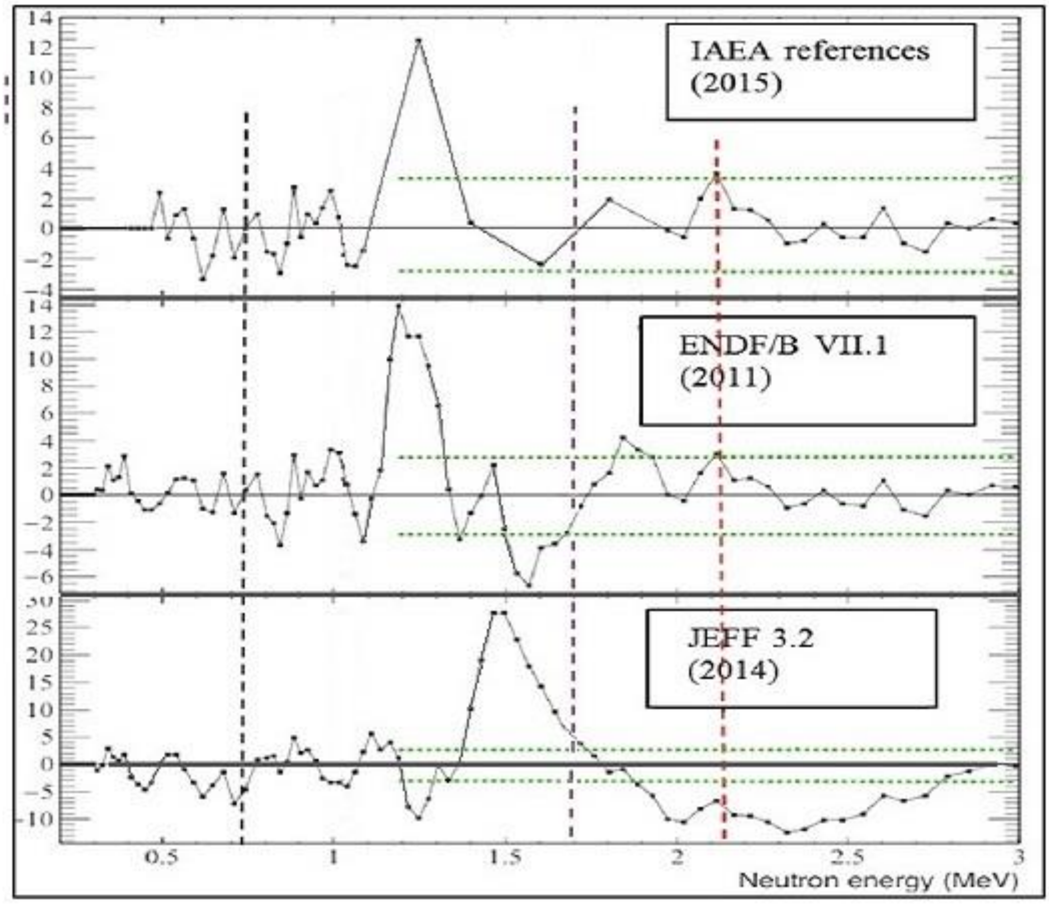

Fig. 5. *The residual of the nTOF data with selected references and evaluations, divided by 1σ of the nTOF dataset.*

From Figs. 4 and 5 It can be noted differences >5σ from the nTOF averaged values at the threshold region, while above 2 MeV the nTOF data agree with both IAEA and ENDF. The big difference with IAEA and ENDF around 1.2 MeV is due to the bad evaluation of the vibrational resonance at this point. It must be noted too the big energy jump adopted by IAEA at the beginning of each decade. It is worth to mention the disagreement with JEFF around 1.5 MeV and even worst above 2 MeV where both U5(n,f) and U8(n,f) cross sections are assumed to be standards.

The ^{235}U(n,f) cross section at intermediate energies

Accurate data on the fission of heavy nuclei at intermediate energies are of a renewed interest for both fundamental and applied nuclear physics. While for the energy range from 20 to 200 MeV there are experimental data good enough to get accurate evaluations, in the energy range from 200 MeV to 1 GeV there are not. The only evaluated information coming from the JENDL/HE-2007 nuclear data library has been seriously criticised by the work of Lo Meo et al. [10]. On the other hand, the IAEA has recently issued a document [11] on the recommended references to be used in nuclear-fission applications in the intermediate energy region. The case of ^{235}U, ^{238}U, ^{209}Bi and ^{nat}Pb are there studied, being clearly stated the lack of an accurate enough experimental reference-point, to calibrate the experimental apparatuses used at different laboratories.

In this work we will discuss on the (n,f) cross-section proposed as references by the IAEA for ^{235}U, ^{238}U and ^{209}Bi, comparing it with a new analysis combining the measurements performed at CERN-nTOF of their cross-section ratios [12] and [8] with new calculations done by A. Ventura using MC codes based on phenomenological models INCL++, GEMINI++, and ABLA07. The calculations are cross-checked with those calculated for the (p,f) reactions, where experimental values are available.

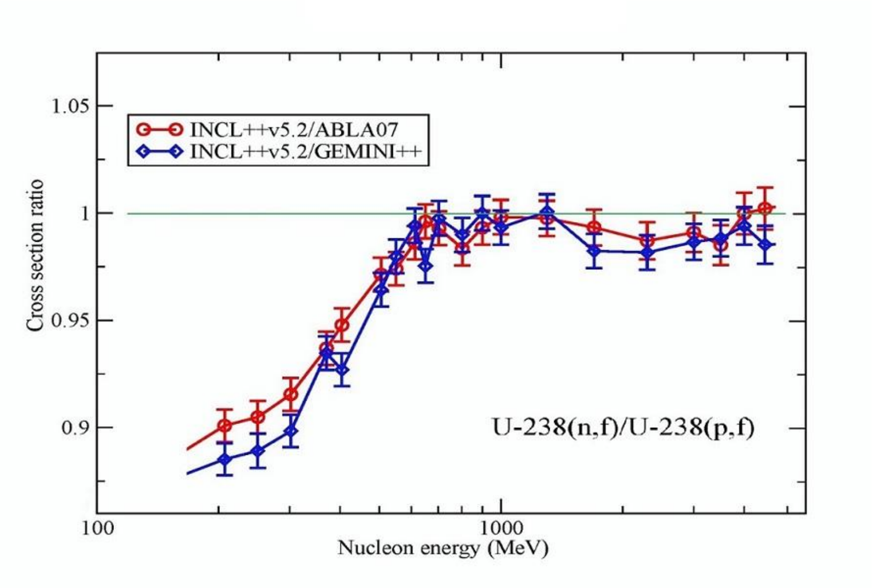

Fig. 6. *Ratio of the U8 fission cross-sections induced by neutrons and by protons, as calculated by A. Ventura (2016)*

As shown in Fig. 6, the U5 fission cross-sections induced by neutrons is higher than by protons up to around 600 MeV, being almost equals from here on. This fact allow us to determine the U5(n,f) cross section at around 1 GeV, where its maximum value is expected. The same applies for the U5(n,f) and U5(p,f) cross sections. In Fig. 7 are plotted some available experimental data on U5(p,f) cross section as well as the Ventura fits based on both GEMINI and ABLA07 on INCL++. As can be seen the model-based calculations agrees well with the Kotov data [13] from 500 to 1000 MeV but it show a shape having a maximum at 900 MeV and a smooth minimum around 300 MeV. This smooth shape with a minimum and a maximum is repeated also for the (n,f) calculations and for every actinide studied in [12] (Th, U, Np and Pu) and is consistent with the calculations reported by Kotov in [13] using a two-step cascade/evaporation model.

We have so evaluated the (n,f) cross sections for ^{238}U, ^{235}U and ^{209}Bi, in the intermediate energy region going from 200 MeV to 3 GeV. For the Uraniums, our points definitively discard the JENDL/HE evaluations above 300 MeV, falling inside the confidence corridor proposed by IAEA but for the points around 300 – 400 MeV where a discrepancy is found. It is worth to be noticed that this discrepancy comes from the Kotov (n,p) data as can be seen in Fig. 7.

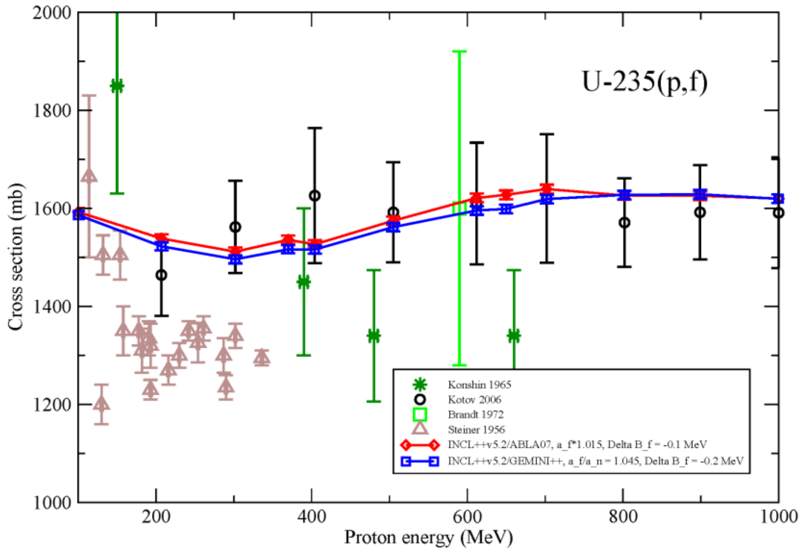

Fig. 7. *Ventura's fit to the U5(p,f) cross-section experimental data.*

Starting from the respective ratios between U5, U8 and Bi, that were measured at CERN-nTOF, having as reference the (p,f) values around 1 GeV and the minimum-maximum smooth shape behaviour from the models calculation, we have performed an evaluation of the U5, U8 and Bi (n,f) cross sections that will be presented at ND2016.

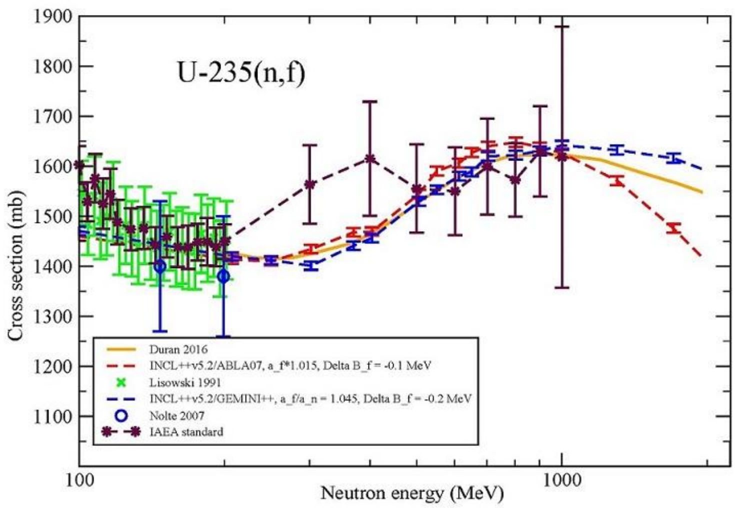

Fig. 8. *New evaluation of the U5(n,f) cross section at intermediate energies*

Our evaluation falls inside the uncertainties associated to the IAEA recommended values in [11] but for the values at 300 and 400 MeV, were the IAEA evaluation is clearly over-estimated.

References

[1] A.D. Carlson, et al., International Evaluation of Neutron Cross Section Standards, Nuclear Data Sheets **110/**12 (2009) 3215-3324 (pg 3291).

[2] See https://www-nds.iaea.org/standards/

[3] L. Leal, et al., Evaluation of the ^{235}U Resonance Parameters to fit the standard recommended values. To be presented at ND2016.

[4] C. Paradela, et al. Neutron-induced fission cross-sections measured at CERN-nTOF facility, Phys. Rev. C **82,** (2010) 034601.

[5] M. Barbagallo et al., High-accuracy determination of the neutron flux at CERN-nTOF, Eur. Phys. J. A **49** (2013) 156.

[6] C. Guerreo, et al., Performance of the neutron time-of-flight at CERN-nTOF, Eur. Phys. J. A **49** (2013) 27.

[7] C. Paradela, et al., High accuracy U8(n,f) data in the resonance energy region. EPJ Web of Conferences **111** (2016)02003

[8] C. Paradela, et al., High-accuracy determination of the U8/U5 fission cross-section ratio up to 1 GeV at CERN-nTOF, Phys. Rev. C **91** (2015) 024602.

[9] M. Diakaki, et al., Towards the high-accuracy determination of the ^{238}U fission cross section at the threshold region at CERN – n_TOF, EPJ Web of Conferences **111** (2016) 02002.

[10] Lo Meo, et al., Fission induced by nucleons at intermediate energies, Nucl. Physics A **933** (2015) 43-67.

[11] B. Marcinkevicius, et al., ^{209}Bi(n,f) and ^{nat}Pb(n,f) Cross Sections as a New Reference and Extension of the ^{235}U, ^{238}U and ^{239}Pu(n,f) Standards up to 1 GeV, IAEA report INDC(NDS)-0681, 2015.

[12] D. Tarrio, et al., Neutron-induced fission cross-section of ^{nat}Pb and ^{209}Bi from threshold to 1 GeV at CERN-nTOF. Phys. Rev. C **83** (2011) 044620.

[13] A.A. Kotov, et al., Energy dependence of proton induced fission cross sections for heavy nuclei in the energy range 200–1000 MeV, Phys. Rev. C **83** (2011) 034605.

The ^{235}U(n,f) cross section between 10 and 30 keV neutron energy and above 200 MeV: collecting new, high accuracy data at n_TOF, *N. Colonna*

The ^{235}U(n,f) cross section in the tens of keV range

Since its start of operation, the n_TOF Collaboration has invested a large effort in the accurate determination of the neutron flux in the full energy range of the beam, i.e. from thermal to approximately 1 GeV. To this aim, three neutron-conversion reactions have been used: the ^{6}Li(n,t)^{4}He, the ^{10}B(n,α)^{7}Li, and the ^{235}U(n,f). The various reactions are cross section standards in different neutron energy regions, and therefore their combination ensure a complete coverage of the wide neutron spectrum of the n_TOF beam. To minimize the uncertainties related to the experimental setups (such as detector efficiency, dead-time corrections, self-shielding corrections, etc…) several different detection systems have been developed and used over the years: the SiMon array, based on Silicon detectors, the MicroMegas chamber, a high performance gas detector, a calibrated fission ionization chamber from PTB, and Parallel Plate Avalanche Counters. To minimize effects related to the targets, ^{6}Li, ^{10}B and ^{235}U deposits of different thickness and transverse dimensions have been used, prepared in different laboratories.

The neutron flux from thermal energy to 150 keV is typically extracted on the basis of the ^{6}Li(n,t) and ^{10}B(n,α) reactions, while from 150 keV to to 1 MeV the ^{235}U(n,f) reaction is also included in the flux determination. All three reactions are normalized to each other at thermal energy. Above 1 MeV the flux is extracted only on the basis of the ^{235}U(n,f) reaction. Thanks to the combination of the different standard reaction, the neutron flux at n_TOF in the first experimental area is typically extracted with an accuracy of 1-2% from thermal neutron energy up to a few keV, and 2-4% for neutron energies from 10 keV to 200 MeV, while above this energy an uncertainty of 5% is assumed, mostly due to the uncertainty on the ^{235}U(n,f) cross section. More details on the procedure used for the neutron flux determination at n_TOF can be found in [1]. In that paper, the measured flux is compared with the one obtained from FLUKA simulations of the spallation target, while in [2] it is compared with GEANT4 simulations. In both cases, a remarkable agreement is observed in the shape (i.e. the energy dependence) of the neutron flux, at all neutron energies.

The comparison of the flux extracted with different detection systems and based on different neutron-converting reactions has revealed a discrepancy in the 10-30 keV neutron energy range. In particular, while the flux obtained on the basis of the ^{6}Li(n,t) and ^{10}B(n,α) reactions show a consistent behavior and are in agreement with the simulated flux, the results based on the ^{235}U(n,f) cross section are systematically lower. This is shown in Fig. 1, where the black symbols represent the flux obtained from a combination of the ^{6}Li and ^{10}B data (the so-called “evaluated flux”), the red curve the results of FLUKA simulations, while the colored symbols represent the flux based on the ^{235}U(n,f) reaction, measured with two different detectors, one of which (the “PTB”) is a well calibrated fission chamber. The discrepancy is between 4 and 8 % depending on the energy. It is important to remark that below and above this energy, no systematic difference is observed between the various results. Therefore, the only plausible explanation of the observed discrepancy seem to be related to an overestimate of the ^{235}U(n,f) cross section in this energy region. In the plot, the ENDF/B-VII.0 cross section was used. The discrepancy persist, to a different degree, when other libraries or the IAEA reference file are used for the ^{235}U(n,f) cross section. In particular, the difference is maximum when JEFF3.1 is used, being in average of 8%, and minimal for JENDL4, being around 5% in average.

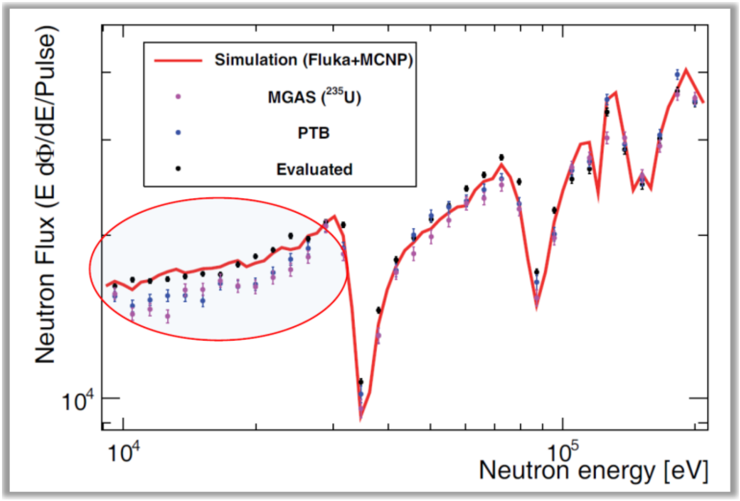

Fig. 1: *Comparison of the n_TOF neutron flux determined at n_TOF on the basis of different neutron-converting reactions and different detectors, and with FLUKA simulations (from Ref. [1]).*

A close inspection of the cross section and declared uncertainties in this energy region reveals some interesting behavior. As just mentioned, the average cross section in the 10-30 keV neutron energy region shows a larger than expected variation from one library to the other. Relative to the IAEA reference cross section, JEFF3.1 is 0.5% higher, ENDF/B-VII.1 0.5% lower, while JENDL4 is 2.4% lower. Most importantly, the uncertainty in ENDF/B-VII.1 has been raised to 4%, as compared to ~1% of VII.0, only in this energy region, probably due to a larger scattering of experimental data. It should be noted that at this energy both ^{6}Li(n,t) and ^{10}B(n,α) reactions start to be affected by an anisotropy in the angular distribution of emitted products, which in the past was not well characterized (and may still be affected by a sizable uncertainty). Angular distribution effect could therefore affect previous (as well as the n_TOF) results when extracting the ^{235}U(n,f) cross section relative to the ^{6}Li(n,t) and ^{10}B(n,α) standard cross section, if the experimental apparatus is sensitive to the angular distribution of products emitted in these reactions. Another potential problem is the presence, in this energy region, of resonant structures in the ^{235}U(n,f) cross section, observed only in high resolution measurements, which may complicate the combination and fitting of all available dataset.

Triggered by the observation in [1] of a possible systematic effect in the ^{235}U(n,f) cross section between 10 and 30 keV, a check was performed at IRMM on the ratio of this cross section relative to the ^{10}B(n,α) reaction used for the monitoring of the GELINA neutron beam. At present the results are not available, as only a very preliminary analysis has been performed to date. According to a private communication a systematic difference relative to various libraries has also been observed in the GELINA data, although not at a conclusive level.

A final remark regards the measurement of the capture-to-fission cross section ratio for ^{235}U measured at Los Alamos. As reported in [3], the capture cross section, determined from the α-ratio shows an deviation, of 8 to 10%, relative to the evaluations. This observation could in fact be compatible with the deviation of the fission cross section described above, rather than a problem in the capture cross section.

The observations reported above are mostly qualitative and only hint to the existence of a possible discrepancy, at the level of a few percent, in the ^{235}U(n,f) cross section in the 10-30 keV neutron energy range. As a consequence, it is not possible at present to reach a conclusion, and new, accurate measurements are needed to verify and eventually quantify the discrepancy. To this regard, a new, dedicated measurement is foreseen at n_TOF. Furthermore, new data on the ^{235}U(n,f)/^{10}B(n,α) cross section should become available from IRMM in the near future.

References

[1] M. Barbagallo, et al., High-accuracy determination of the neutron flux at n TOF, Eur. Phys. J. A **49** (2013) 156.

[2] S. LoMeo, et al., GEANT4 simulations of the n TOF spallation source and their Benchmarking, Eur. Phys. J A **51** (2015) 160.

[3] M. Jandel, et al., New Precision Measurements of the ^{235}U(n,γ) Cross Section, Phys. Rev. Lett. **109** (2012) 202506.

Measurements at the DANCE facility, *M. Jandel*

The experimental program focused on ^{235}U neutron-induced reaction studies using the DANCE facility at Los Alamos National Laboratory was presented. The current emphasis of the program is to improve the alpha measurements for ^{235}U and ^{239}Pu. In case of ^{235}U, an increased population of the isomeric states was observed during the measurements of capture cross section in 2007-2011 years [1a, b]. With the new experimental program, we are addressing the issue of unexpectedly large population (possibly up to 30 %) of U-236 isomeric states in ^{235}U capture reaction. This peculiar feature is of interest to fundamental nuclear structure but will have an impact on the precise determination of the capture cross section, consequently, the alpha values for ^{235}U, from DANCE experimental data.

Significant updates have been made to the DANCE facility in the last few years. Firstly, a new detector array – NEUtron detector Array at DANCE (NEUANCE), shown in Fig. 1, was designed and built to improve our understanding of the prompt fission and capture gamma-ray emission [3]. Secondly, a new data acquisition system (DAQ) has been implemented at the DANCE facility early in the 2015/2016 beam cycle. The new DAQ allows for acquiring the data continuously in a wide neutron-incident energy region from thermal energy up to 1 MeV [2].

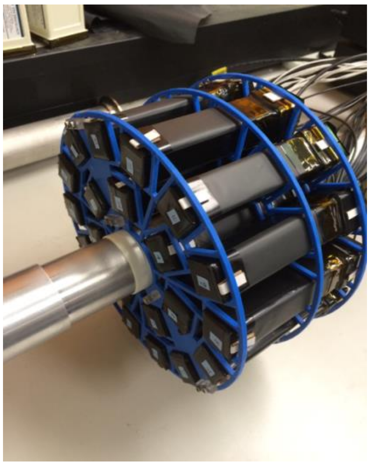

Fig. 1. The NEUANCE detector array consists of 21 stilbene detectors. It's designed to fit the central cavity of the DANCE array.

The production data was taken in January-February 2016 beam cycle. The NEUANCE detector was placed in the center of the DANCE array and measurements with gamma-ray calibration sources, Cf-252 and n+^{235}U were carried out.

A data analysis is underway and with the new dataset we will be able to address several important issues raised at this meeting. We will have a shape measurement of alpha for a wide neutron incident energy interval, from thermal energy up to 1 MeV. We will provide new data on prompt fission neutron spectra as a function of incident neutron energy. In addition, we will extract correlations between the prompt-fission neutrons and prompt fission gamma rays and if the counting rate permits we will determine the neutron-incident energy dependence of these correlations. Detailed description of the experimental programs that are underway and planned at DANCE can be found in [3].

New data on capture cross section and alpha values will be also obtained from the datasets acquired in original DANCE configuration, in 2007-2011. This follow up of the PRL article [Jan2012b] would include improved treatment of the systematic errors originating from the offline data analysis and precise corrections for scattering effects in the 26 mg/cm^2 target used in the measurements. However, the data won't be able to address the neutron-incident energies below 8 eV.

References

[1a] M. Jandel, T. A. Bredeweg, E. M. Bond, M. B. Chadwick, A. Couture, et al., New Precision Measurements of the $^{235}U(n,g)$ Cross Section, Phys. Rev. Lett. 109 (2012) 202506.

[1b] M. Jandel et al., Neutron-induced fission measurements at the DANCE and LSDS facilities at LANL, 5th Int. Conf. on Fission and properties of neutron-rich nuclei (ICFN5), 4-10 November 2012, Conference proceedings (J.H. Hamilton, A.V. Ramayya, Eds) World Scientific, 2014, p. 416, Los Alamos Report #LA-UR-13-20355

[2] A. Couture, et al., Enhancing the Detector for Advanced Neutron Capture Experiments, EPJ Web of Conferences **93** (2015) 07003.

[3] M. Jandel, B. Baramsai, E. Bond, G. Rusev, C. Walker, et al., Capture and fission with DANCE and NEUANCE, Eur. Phys. Jour. A **51** (2015) 179.

Measurement of the neutron capture cross section of the fissile isotope 235U with the CERN n_TOF Total Absorption Calorimeter and fission tagging based on micromegas detectors, ***J. Balibrea, E. Mendoza, D. Cano Ott***

The neutron capture cross section of ^{235}U has been measured at the CERN n_TOF facility [1] with a BaF_2 Total Absorption Calorimeter – for obtaining the (n,γ) yield – and two different fission tagging configurations based on 2 and 10 micromegas detectors (FTMGAS) shown in Fig. 1. A 5 cm thick spherical neutron absorber shell made of borated polyethylene was used between the FTMGAS chamber and the TAC for reducing the background of scattered neutrons.

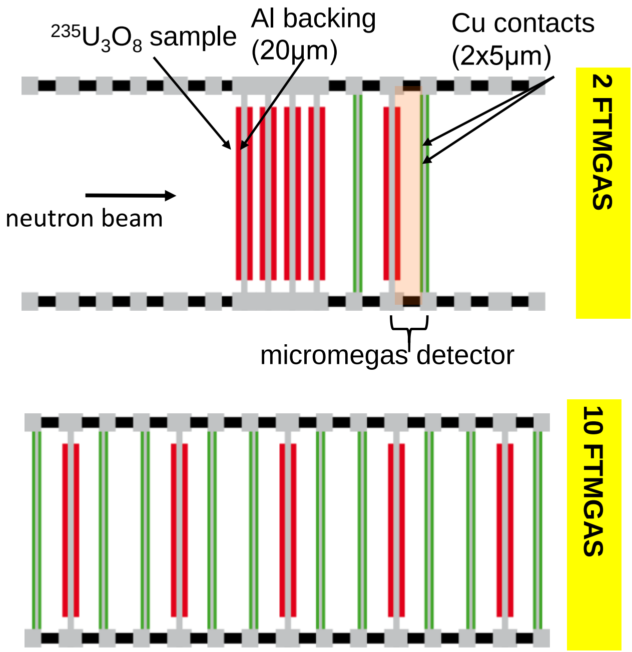

Fig. 1. *Top: configuration of 2 FTMGAS and a stack of 8 samples for the 235U(n,γ) cross section measurement. Bottom: configuration of 10 FTMGAS, each one encapsulating a sample, for the measurement of the* $^{235}U(n,\gamma)$ $^{235}U(n,f)$ *ratio.*

Ten isotopically enriched samples of $^{235}U_3O_8$ produced at IRMM Geel were used in the measurements. The samples have a surface density of 300 µ/cm^2, are deposited on a 20 µm thick aluminum backing and have diameter of 42 mm, thus covering the entire neutron beam. The uranium isotopic content is as follows: ^{233}U<0.001%, ^{234}U=0.036%, ^{235}U=99.94%, ^{236}U=0.011%, ^{238}U=0.013%.

The configuration with the 2 FTMGAS was dedicated to the $^{235}U(n,\gamma)$ cross section measurement. A stack of 8 bare ^{235}U samples and two samples encapsulated inside the FTMGAS were placed in the beam for improving the signal to background ratio (i.e. to minimize the amount of dead material from the fission tagging setup in the neutron beam). A low fission tagging efficiency of ~20% was achieved.

As it has been demonstrated by Guerrero et al. [2], it is possible to remove accurately the gated fission γ-ray background at low tagging efficiencies by selecting events with a high γ-ray multiplicity which correspond only to (n,f) γ-rays and for which the TAC has a nearly 100% detection efficiency. Indeed, a simplified version of this technique, without any fission tagging, has been used as well at LANL in the ^{235}U cross section measurement by Jandel et al. [3]. The option of having fission tagging capabilities at a low efficiency has been preferred for the measurement at n_TOF for deducing the normalization of the data strictly from experimental parameters, without the need for using evaluated cross section data as an external reference.

The configuration with the 10 FTMGAS was dedicated to the ^{235}U(n,f)/^{235}U(n,γ) ratio (α-ratio) for well resolved resonances, as a cross check for the 2 FTMGAS data and for the measurement of γ-ray energy distributions from the lowest lying resonances. Each sample was inserted into a FTMGAS for measuring the fission cross section with a high efficiency (~90%) at the price of having a much larger dead material (i.e. background) than with the 2 FTMGAS configuration.

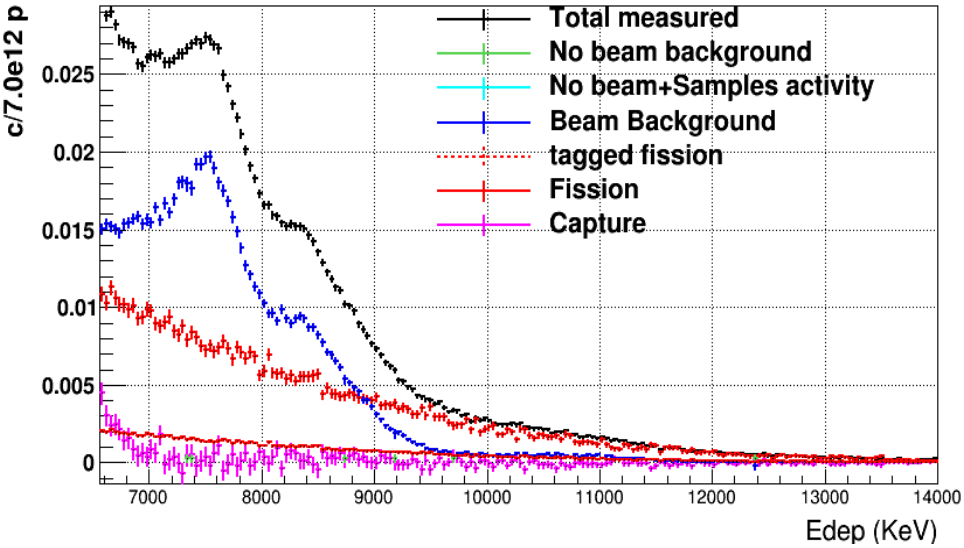

Fig. 2. *Different components of the total energy deposition spectrum (black curve) in the TAC above the Sn(^{236}U): beam related background (blue curve), fission γ-rays (red curves, total and in coincidence with the FTMGAS), neutron capture yield (magenta curve) and decay γ-rays (green curve).*

The neutron-induced fission cross section has been normalized to the integral value from 7.8 to 11.0 eV, which is accurately well known (< 0.5%). Then, in the thin target approximation, the normalization of the neutron-induced capture cross section is given by the following expression:

$$\int \sigma_\gamma(E_n)dE_n = \int \sigma_f(E_n)dE_n \frac{\varepsilon_f}{\varepsilon_\gamma} \frac{\int \frac{C_T(E_n) - C_B(E_n)}{\phi(E_n)} dE_n}{\int \frac{C_f(E_n)}{\phi(E_n)} dE_n}$$

Where

C_T are the total counts in the TAC.
C_B background counts in the TAC.
C_f are the counts due to fission in the FTMG.
ε_γ is the TAC detection efficiency.

ε_F is the FTMG detection efficiency.
Φ is the neutron fluence.

The normalization doesn't depend on the mass samples neither on the beam interception factor or the integral neutron fluence. A very small dependence on the neutron fluence shape is also obtained.

The fission detection efficiency ε_f has been calculated using cuts in the total energy deposited in the TAC (E_{sum}) above the neutron separation energy, where no counts due to the (n,γ) electromagnetic cascades are detected (except for pileup or summing). The methodology applied is a combination of the one developed by Carrapiço et al.[4] and C. Guerrero et al. [2]. The different components in the E_{sum} spectra are shown in Fig. 2 and the ε_f was computed from:

$$\varepsilon_f = \frac{c_{tagged}}{c_T - c_B}$$

Where the number of tagged counts is $c_{tagged} = \varepsilon_f \varepsilon_{TAC} N_{fiss}$ and the number of counts in the TAC due to fission events is $c_f = c_T - c_B = \varepsilon_{TAC} N_{fiss}$. A value of $\varepsilon_f = 0.1894 \pm 0.0013$ was obtained for the 2 FTMGAS configuration and $\varepsilon_f = 0.851 \pm 0.009$ for the 10 FTMGAS configuration.

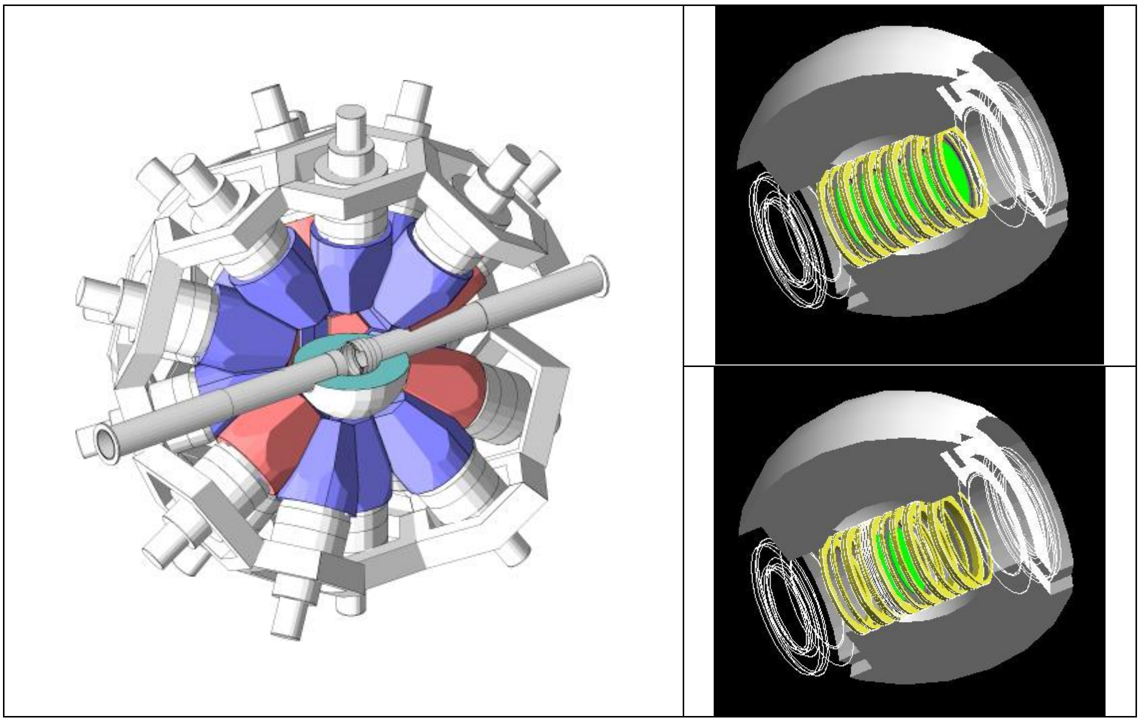

Fig. 3. *Geometric models of the TAC (left) and the 2 FTMGAS (top right) and 10 FTMGAS (bottom right) detectors surrounded by the neutron absorber.*

The efficiency for detecting capture events has been obtained from very detailed Monte Carlo simulations of the response of the TAC to realistic capture cascades. The geometry modelled in GEANT4 can be seen in Fig. 3.

Two experimental effects observed in the data had to be included in the statistical model applied for the generation of the ^{236}U γ-ray cascades:

- An unexpectedly high population of the long-lived isomeric state in ^{236}U at ~1MeV of excitation energy with $T_{1/2}$=100ns.
- The effect of the short-lived state in ^{236}U at 645 keV with $T_{1/2}$=4ns.

The capture γ-ray cascades have been provided by Milan Kritcka [5] using DICEBOX code [6]. The parameters of the EM cascades have been adjusted from DANCE [3] experimental data. These cascades include the long-lived isomeric state at 1 MeV of excitation energy. The cascades have been simulated in the detailed TAC + FTMGAS geometry already implemented in GEANT4 for two different configurations: 2FTMGAS with the neutron absorber and 2 FTMGAS without neutron absorber.

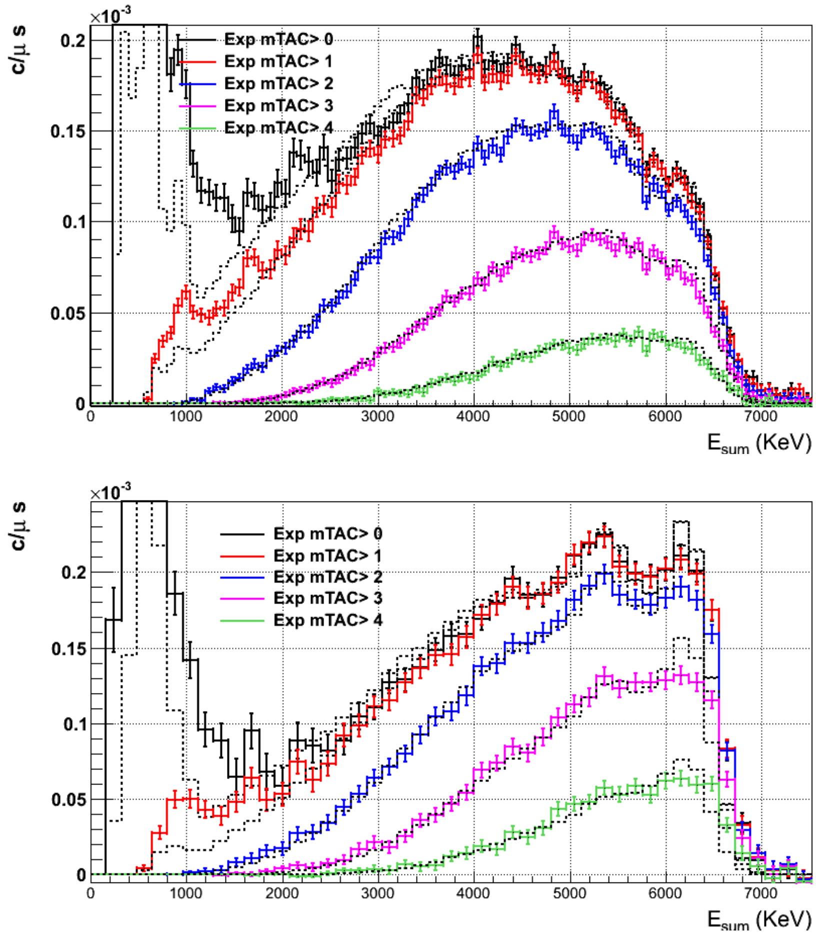

Fig. 4. *Top: energy deposition spectra in the TAC due to capture events with neutron absorber. Bottom: energy deposition spectra in the TAC without neutron absorber.*

Fig. 4 shows the excellent agreement between the MC simulations and the experimental data obtained for various conditions on the multiplicities in the TAC. In this way, it is possible to determine the efficiency of detecting the capture γ-ray cascades as a function of the conditions in the E_{sum} and the crystal multiplicity (m_γ) with an accuracy better than 2% [7].

The preliminary analysis performed has revealed a $^{235}U(n,\gamma)$ cross section about 20% larger than the one reported in ENDF-B/VII.1 and JEFF-3.2 in the range between 1 eV and 40 eV. Figs 5, 6 and 7 show the comparison of the n_TOF data (with 2 FTMGAS) and JEFF-3.2 $^{235}U(n,\gamma)$ cross sections in various energy ranges. The broadening due to the sample temperature and the resolution function has been included in the evaluated cross section for an appropriate comparison. As it can be observed, the experimental data are systematically above the evaluated cross section in the entire energy range.

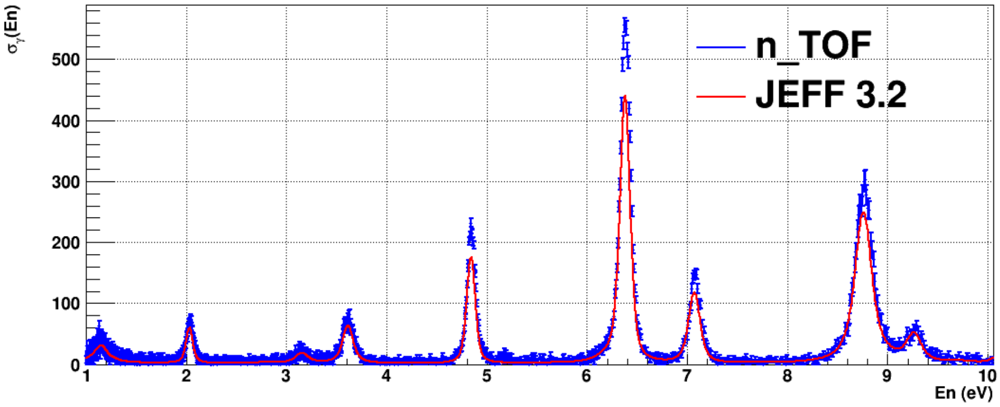

Fig. 5. *Comparison of the experimental (blue points) and evaluated JEFF-3.2 (red curve)* $^{235}U(n,\gamma)$ *cross section.*

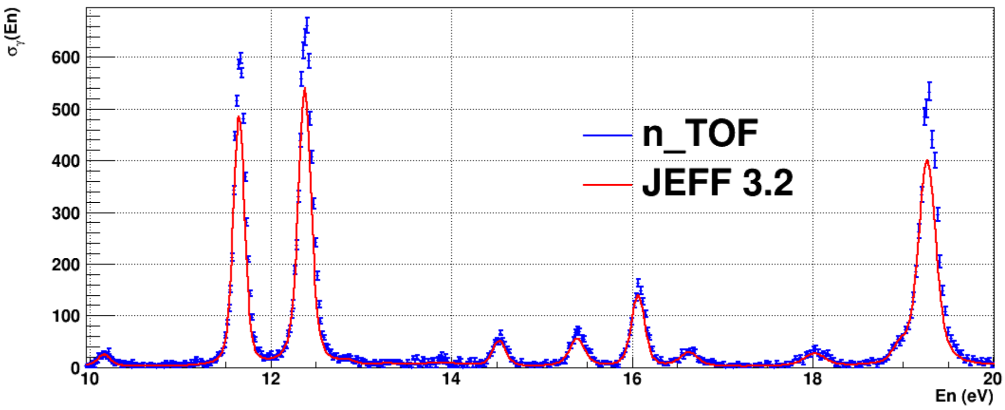

Fig. 6. *Comparison of the experimental (blue points) and evaluated JEFF-3.2 (red curve)* $^{235}U(n,\gamma)$ *cross section.*

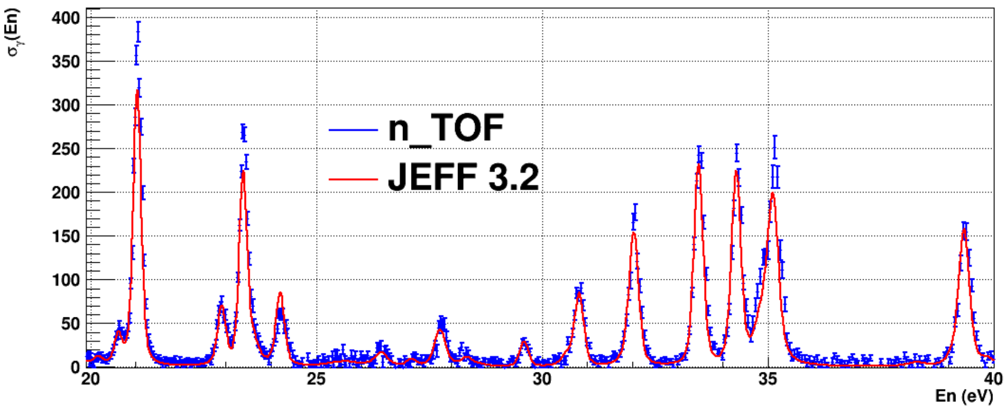

Fig. 7. *Comparison of the experimental (blue points) and evaluated JEFF-3.2 (red curve)* $^{235}U(n,\gamma)$ *cross section.*

The results obtained with the 10 FTMGAS are equivalent.

Figs 8, 9 and 10 show the comparison of the α-ratios (α_R) obtained from the n_TOF data and the comparison to the data by Brooks et al. [8]. As it can be seen, the preliminary n_TOF data are compatible within uncertainties with the data by Brooks. Similar results have been obtained with the 10 FTMGAS configuration.

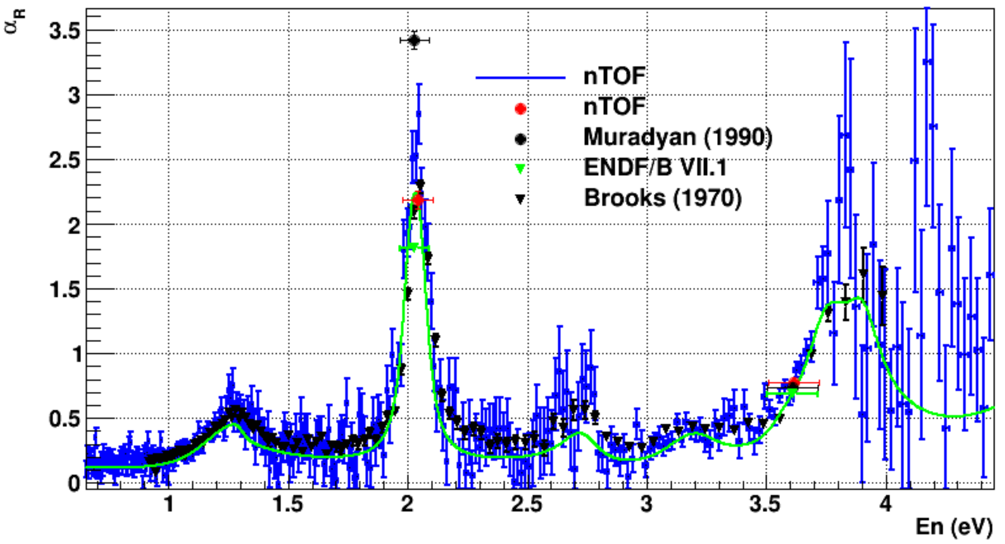

Fig. 8. *Comparison between the experimental α-ratios from the n_TOF measurement and the data by Brooks et al.*

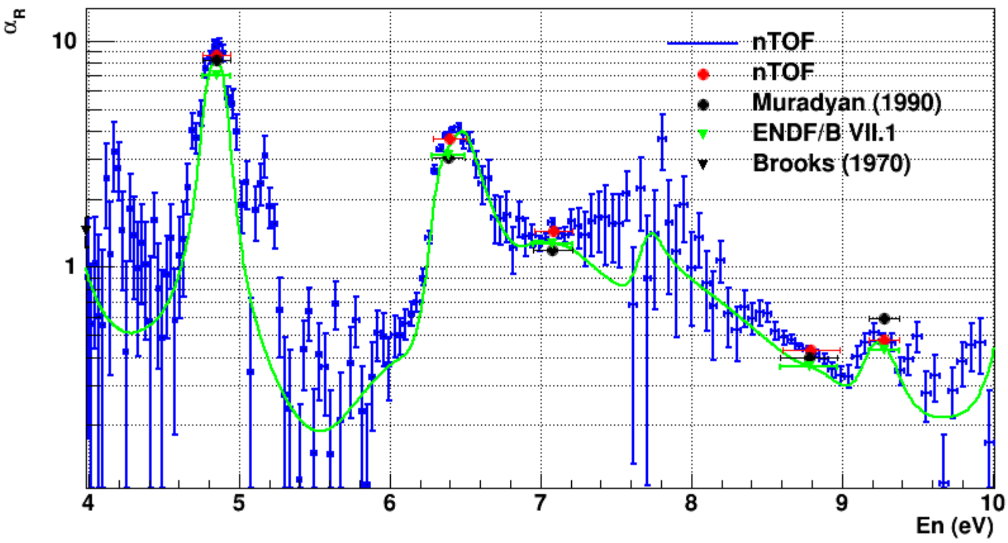

Fig. 9. *Comparison between the experimental α-ratios from the n_TOF measurement and the data by Brooks et al.*

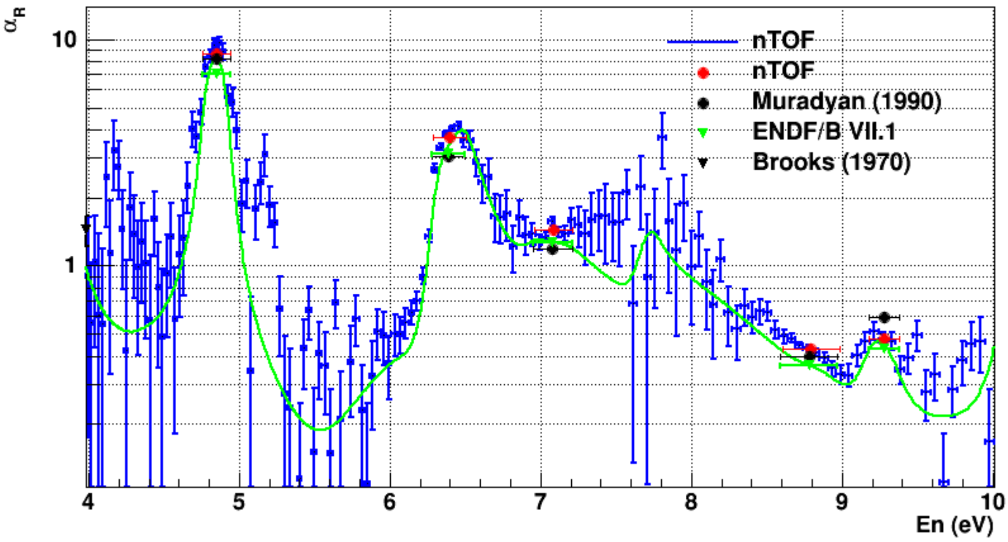

Fig. 10. *Comparison between the experimental α-ratios from the n_TOF measurement and the data by Brooks et al.*

Summary and conclusions

The preliminary analysis of the ^{235}U(n,γ) cross section measurement performed at n_TOF with the Total Absorption Calorimeter and fission tagging micromegas detectors show a 20% larger (n,γ) cross section than reported in JEFF-3.2 and ENDF-B/VII.1 in the range between 1 eV and 40 eV. The α-ratios derived from the n_TOF data are compatible with those reported by Brooks et al [8]. We are aware that this is a striking result and thus are still revising in detail all possible instrumental effects that could introduce such a significant bias.

References

[1] F. Gunsing et al., Nucl. Instrum. Methods Phys. Res. B **261** (2007) 925.

[2] C. Guerrero et al., Eur. Phys. J. A (2012) 48:29.

[3] M. Jandel et al., Phys. Rev. Lett. **109** (2012) 202506.

[4] C. Carrapiço et al. Nucl. Instr. Methods Phys. Res. A **704** (2013) 60.

[6] F. Becvar, Nucl. Instr. Methods Phys. Res. A **417** (1998) 434.

[7] C. Guerrero et al., Nucl. Instr. Methods Phys. Res. A **671** (2012) 108.

[8] F.D Brooks, et al., "Eta and neutron cross sections of ^{235}U from 0.03 to 200 eV", AERE-M (1670).

APPENDIX 2

Consultants' Meeting on
"Current Status and Open Issues of the U-235 Evaluation"

IAEA, Vienna, Austria
24-27 May 2016
Meeting Room VIC C0234

PROVISIONAL AGENDA

Tuesday, 24 May

08:30 – 09:30 **Registration (IAEA Registration Desk, Gate 1)**

09:30 – 10:00 **Opening Session**
Welcoming address (Arjan Koning, NDS Section Head)
Administrative matters
Election of Chairman and Rapporteur
Adoption of the Agenda

10:00 – 17:30

Introduction (A. Trkov): Current Evaluation Work

- Thermal constants
- Resonance range
- Fast energy range
- New measurements

Thermal Constants (V. Proniaev)

- Status of the evaluation for Standards

New Measurements

- LANL (M. Jandel)
- n-TOF (D. Cano)
- n_TOF fission (I. Duran)

Coffee break(s) as needed
12:30 – 14:00 Lunch break

Wednesday, 25 May

09:00 – 17:30

Resonance Evaluations

- ORNL (M. Pigni)
- CEA (G. Noguere)

Fast Neutron Energy Range

- IAEA (R. Capote)

Coffee break(s) as needed
12:30 – 14:00 Lunch break

19:00 Dinner at a restaurant down town (see separate information in folder)

Thursday, 26 May

09:00 – 17:30

Verification and Validation

- Comparison with differential measurements
- Normalisation and fluctuations in nu-bar
- Alpha
- Trends of HST benchmarks with ATLF
- Testing on a broad set of benchmarks
    - compensating effects
    - remaining outliers (discussion)

Actions

Coffee break as needed
12:30 – 14:00 Lunch break

Friday, 27 May

09:00 – 13:00

Drafting of the Summary Report

Closing of the Meeting

Coffee break as needed

Consultants' Meeting on
"Current Status and Open Issues of the U-235 Evaluation"
IAEA, Vienna, Austria
24 – 27 May 2016

LIST OF PARTICIPANTS

FRANCE
Gilles NOGUERE
CEA/DEN Cadarache
St. Paul lez Durance 13108
E-mail: Gilles.noguere@cea.fr

ITALY
Nicola COLONNA
Istituto Nazionale Fisica Nucleare –
Sezione di Bari
V. Orabona 4
Bari 70125
E-mail: Nicola.colonna@ba.infn.it

SPAIN
Daniel CANO
CIEMAT
Avenida Complutense 22
Madrid 28040
E-mail: Daniel.cano@ciemat.es .

Ignacio DURAN
Universidad de Santiago de Compostela
Facultad de Fisica
Departamento de Fisica de Pariculas
Santiago de Compostela
La Coruñña 15782
E-mail: Ignacio.duran@usc.es

RUSSIA
Vladimir PRONIAEV
ATOMSTANDART
Rosatom State Corporation
Bolshaya Orynka str. 24
Moscow
E-mail: vgpronyaev@yandex.ru

USA
Marco PIGNI
Oak Ridge Natinal Laboratory
P.O. Box 2008, Bldg 5700
Oak Ridge TN
E-mail: pignimt@ornl.gov

Marian JANDEL
Los Alamos National Laboratory
PO Box 1663
Los Alamos NM
E-mail: mjandel@lanl.gov

IAEA
Andrej TRKOV
Tel. +43-1-2600 21712
E-mail: A.trkov@iaea.org

Roberto CAPOTE NOY
Tel. +43-1-2600 21713
E-mail: Roberto.capotenoy@iaea.org

Both:
International Atomic Energy Agency (IAEA)
NAPC / Nuclear Data Section
Vienna International Centre, P.O. Box 100
A-1400 Vienna

Nuclear Data Section
International Atomic Energy Agency
Vienna International Centre, P.O. Box 100
A-1400 Vienna, Austria

E-mail: nds.contact-point@iaea.org
Fax: (43-1) 26007
Telephone: (43-1) 2600 21725
Web: http://www-nds.iaea.org