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On the Resonance Parameters of Fissile Actinides

Summary Report of the First IAEA Consultants' Meeting on the International Nuclear Data Evaluation Network (INDEN)

IAEA Headquarters, Vienna, Austria
8 – 11 May 2018

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July 2018

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ABSTRACT

A Consultants' meeting on the Resonance Parameters of Fissile Actinides of the International Nuclear Data Evaluation Network (INDEN) was held at the IAEA headquarters in Vienna from 8 to 11 May 2018. The goal of the meeting was to identify problems in the existing evaluations of fissile actinides, to recommend new experimental programs targeted at improving the evaluations, and to define the timeline to solve the problems in the evaluations.

July 2018

Contents

1. Context

The relationship between CIELO (WPEC/SG40), the new IAEA long term evaluation program and the new working group WPEC/SG45 needs to be clarified. The work plan presented herein should help in this respect.

Discussions during the meeting were mainly focused on the ^{235}U, ^{233}U, ^{238}U, and ^{239}Pu isotopes. Connections with other important actinides, such as ^{240}Pu and ^{241}Pu, were not addressed. As these isotopes are of interest for the IAEA long term evaluation program, they will be part of future INDEN discussions.

Experimental activities and evaluation work in the resolved resonance range (RRR) were presented. The ^{235}U and ^{238}U evaluations were extensively studied in the framework of the working group SG40 (CIELO) of the Working Party on International Nuclear Data Evaluation Co-operation (WPEC) of the NEA data bank. Resonance parameters derived from new measurements are included in the latest version of the ENDF/B-VIII and JEFF-3.3 libraries. For ^{235}U, the thermal constants and the prompt-fission neutron spectrum (PFNS) with a lower average neutron energy were included. For ^{239}Pu, the resonance parameters were already revisited in the framework of the working group WPEC/SG34 completed in 2014; for ^{239}Pu, the thermal constants and the prompt fission neutron spectra (PFNS) were not updated. The data are available in ENDF/B-VIII and JEFF-3.2. Similarly, new resonance parameters of ^{233}U were established with "old" data; a new set of resonance parameters was not yet released. It will be shared among the participants of this meeting.

The report is structured as follows. After a brief review of the past and ongoing experimental programs, the status of the existing evaluations is presented. For future evaluation work, possible improvements in the analysis of the RRR are suggested. Strategies to generate evaluated neutron cross sections in the unresolved resonance range (URR) were discussed in order to correctly account for fluctuations in the experimental data, and more precisely the broad intermediate structures observed in the experimental fission cross sections. Since improved performances by updating resonance parameters cannot be addressed without improving post-observable fission quantities, past activities on Prompt Fission Neutron Spectra and neutron multiplicities were presented. A few recommendations and short-term actions are listed at the end of this report.

2. Experimental activities for improving neutron cross sections of actinides

The accuracy of the neutron capture cross section of actinides is still an open issue. Accurate measurements of the capture cross section of fissile isotopes in the RRR remains a challenging task. Over the last decade, new experimental programs were launched with the aim of improving previously measured data. The status of the experimental programs on ^{235}U performed at the nTOF-CERN and the RPI facilities were presented by D. Cano Ott and Y. Danon, respectively. The measurements carried out at the Los Alamos facilities were also discussed, including the latest ^{235}U and ^{239}Pu capture measurements. Ongoing experiments on ^{233}U and future plans for ^{239}Pu at the nTOF-CERN facility were shortly discussed during the meeting. Concerning the fertile isotopes, the need for improving the ^{238}U resonance parameters above 500 eV was presented by P. Schillebeeckx.

2.1. Status of the ^{235}U time-of-flight experiments

The main issues on ^{235}U were discussed in the framework of the CIELO project (WPEC/SG40) and within the "neutron standards" group of the IAEA. Conclusions are reported in the journal [Nuclear Data Sheets 148 (2018)]. New fission and capture cross sections used for the re-evaluation of the ^{235}U resonance parameters were measured at the DANCE, RPI and nTOF-CERN facilities. Results are included in the ENDF/B-VIII and JEFF-3.3 libraries.

Final results measured at the nTOF-CERN facility with the fission tagging technique were presented by D. Cano Ott and are summarized in the Appendix. Here it was shown how the problems encountered in the data analysis had been solved. The main difficulties were related to the fission tagging detection efficiency and to the detection efficiency of the (n,γ) channel. The fission cross section had to be normalized to the standard fission integral between 7.8 eV and 11 eV and the capture cross section was then given relatively to the fission cross section. The obtained results confirm the increase of the capture cross section in the low energy range between 2.2 eV and 20 eV. The increase of about 8% is lower than the one previously presented at the IAEA Consultants' Meeting in may 2016 [INDC(NDS)-0716].

Final results obtained with the RPI multiplicity detector were presented by Y. Danon and are summarized in the Appendix. This technique does not rely on fission tagging. Two capture data sets were obtained. The first one covers the thermal energy range up to 20 eV. The second one covers the energy range above 10 eV up to the keV energy range. The two data sets are shape data. They have to be normalized to the thermal capture cross section. The obtained results confirm the significant decrease of the capture cross section in the keV energy range as suggested by Japanese colleagues in the framework of the working group WPEC/SG29. One can also note that the present work offers the possibility to get quantitative information on the fission integral between 7.8 eV and 11 eV.

New ^{235}U fission experiments are planned at the GELINA facility. The data will cover the thermal and the low energy part of the RRR. Such data are of great interest for evaluators as they will be complementary to the work performed at the RPI and nTOF facilities.

Experimental works on ^{235}U at the RPI and nTOF facilities are now completed and final results are published, but not yet available in the EXFOR data base.

2.2. Status of the ^{238}U time-of-flight experiments

An extensive experimental work was performed at the GELINA facility for measuring the capture and transmission of ^{238}U samples. The resonance shape analysis of the JRC-Geel data together with ORELA data has confirmed the quality of the low energy resonance parameters available in the evaluated libraries. Negative resonances were slightly adapted in order to improve the agreement with transmission data measured at ORELA with thick ^{238}U samples. The revised resonance parameters are included in the ENDF/B-VIII and JEFF-3.3 libraries. The data are available in the EXFOR data base.

The study carried out at the JRC-Geel has also revealed sizeable deficiencies of the existing resonance parameters up to 500 eV. One of the objectives is to solve this problem in a short time scale with existing capture data from nTOF and transmission data from ORELA. A new set of resonance parameters could be provided within a year.

2.3. Status of the ^{233}U time-of-flight experiments

The data analysis of new ^{233}U capture and fission cross sections measurements is in progress at the nTOF-CERN facility. The fission tagging technique is used. Compared to the work performed on ^{235}U, analysis of the ^{233}U data will be more complicated because of the activity of the samples. Final results are not foreseen in the near future. Researchers directly involved in this experimental program should be invited to the next INDEN meeting.

2.4. Status of the ^{239}Pu time-of-flight experiments

Time-of-flight data for the $^{239}Pu(n,\gamma)$ reaction were measured at the DANCE facility [Mosby et al., Phys. Rev. C 89 (2014)] from 10 eV to 1 MeV. These data are not yet available in the EXFOR data base, but their official release is in progress. The use of these data in the evaluation procedure will significantly improve the description of the capture cross sections in the RRR, as long as correct normalization can be achieved. For the moment, uncertainties on the existing evaluation are close to 7% above 10 eV.

A long-term project on ^{239}Pu was recently proposed by CIEMAT in the framework of the 2nd CHANDA program. The main problem related to actinides is to perform experiments on samples of good quality, particularly with respect to the isotopic composition. This problem is exacerbated for ^{239}Pu. A broad sample procurement plan could be discussed between the different users in order to facilitate such types of experiment.

3. Evaluation of the neutron cross sections of actinides

Extensive evaluation works were performed in the frame of the CIELO project in order to improve the ^{235}U and ^{238}U resonance parameters [Nuclear Data Sheets 148 (2018) 254–292]. Such improvement was achieved thanks to the experimental works briefly described in Section 1. Parallel efforts were performed within the “neutron standards group” of the IAEA, devoted to the improvement of the thermal neutron constants and standard cross sections [Nuclear Data Sheets 148 (2018) 143–188]. Similar evaluation work is intended for ^{239}Pu and ^{233}U within the INDEN program.

3.1. Status of the Thermal Neutron Constant evaluation

Table 1. Thermal fission, capture and elastic cross sections (in barns) and their absolute uncertainties [Nucl. Data Sheets 148 (2018) 143-188].

Const.	**^{233}U**	**^{235}U**	**^{239}Pu**
σ_{nf}	533.0 (2.2)	587.3 (1.4)	752.4 (2.2)
$\sigma_{n\gamma}$	44.9 (0.9)	99.5 (1.3)	269.8 (2.5)
σ_{nn}	12.2 (0.7)	14.09 (0.22)	7.8 (1.0)

New thermal neutron constants were established by using the GMA approach [Nuclear Data Sheets 148 (2018) 143–188]. Main results for the thermal capture, fission and elastic cross sections of ^{233}U, ^{235}U and$^{239}Pu$are reported in Table 1. The ^{235}U fission integral between 7.8 eV and 11 eV is 247.5 ± 3.0 b.eV. Values are quite different from the previous one, mainly because new data were included in the fitting procedure where the prior values come only from analysis of microscopic data reported by Axton [GE/PH/86, CBNM, 1986, Geel, Belgium].

For the evaluation of the ^{235}U resonance parameters available in the ENDF/B-VIII library, experimental fission and capture cross sections were normalized according to these standard values. Future ^{239}Pu and ^{233}U evaluations will follow the same strategy. However, it is important to indicate that no fission integral for ^{239}Pu and ^{233}U are recommended in the eV energy range. This missing information will be discussed within the INDEN project.

3.2. Status of the ^{235}U evaluation

The evaluation of ^{235}U available in the ENDF/B-VIII library was presented by R. Capote. The analysis of the resonance parameters was performed by M. Pigni, starting from a set of parameters established by L. Leal. They used data measured at the RPI and DANCE facilities. Final results were verified with the nTOF data presented in Section 1. The main issues were on the behavior of the capture-to-fission ratio over the full resolved resonance range. Final results confirm the slight underestimation in the eV energy range and the strong overestimation in the keV energy range of the ^{235}U capture cross section available in the previously released ENDF/B-VII.1 and JEFF-3.2 libraries. Differences between the ENDF evaluations and the RPI data were presented by Y. Danon. A few inconsistent results observed in the capture cross section below 10 eV and between 100-200 eV should be clarified.

3.3. Status of the ^{239}Pu evaluation

The status of the ^{239}Pu evaluation in the JEFF-3.2 and newly released JEFF-3.3 libraries was presented by G. Noguere. The most reliable set of resonance parameters was established in the frame of the working group WPEC/SG42. The work mainly consists in merging three independent sets of resonance parameters into a single set of parameters by keeping the performances of the evaluated data on PST benchmarks and MOX fuel calculations unchanged. Post-fission observables, such as Prompt Fission Neutron Spectrum and neutron multiplicity, remains unchanged. The merged set of resonance parameters is available in ENDF/B-VIII and JEFF-3.2.

An additional set of resonance parameters was evaluated on the basis of the merge resonance parameter file and included in the latest version of the JEFF library (JEFF-3.3). The main goal was to extend the upper energy limit of the RRR up to 4 keV in order to account for broad intermediate structures observed in the experimental fission cross sections. Such broad structures could have an impact of about 200 pcm on fast sodium-free benchmarks (SNEAK2A and SNEAK2B). In the meantime, it was intended to improve some missing interferences observed in the fission cross section. For the capture cross sections, the normalization of the Gwin's data and the behavior between the resonances (specifically between the first and second resonances) are still open issues.

From an experimental point of view, new transmission data of the first resonances (0.3 eV) is required. The only existing experimental total cross sections in the low energy range were measured in 1958 by Bollinger. High resolution fission measurements in the keV energy range are also needed in order to extend the upper energy limit of the RRR, at least up to 5 keV in order to take into account part of the broad intermediate structures observed up to 30 keV.

3.4. Status of the ^{233}U evaluation

The evaluation of the ^{233}U resonance parameters was presented by L. Leal. The evaluation is based on "old" data. His resonance parameters agree with the capture cross section measured by E. Berthoumieux et al. at the nTOF facility [see proc. of ND2007]. He extends the resolved resonance range from 1 keV up to 2 keV. The obtained evaluation significantly improved integral trends of a selected set of ICBEP benchmarks. However, post-fission quantities (PFNS and neutron multiplicity) should be improved.

The present set of resonance parameters has not yet been released in an international evaluated nuclear data library. It will be shared within the INDEN program for further benchmarking tests.

4. Analysis of the resolved resonance range

The INDEN program aims to coordinate new evaluation work, specifically on ^{239}Pu and ^{233}U by using an evaluation strategy similar to the one used for ^{235}U and ^{238}U (CIELO project). This program also provides the opportunity to introduce improved physical ingredients into the evaluation procedure.

4.1. Resonance shape analysis codes

Evaluation of the neutron cross sections of actinides in the RRR is routinely performed by R-Matrix codes such as SAMMY and REFIT. The CONRAD code (developed at CEA Cadarache) is used for internal CEA evaluation activities. At JAEA, new functionalities were introduced in the AMUR code (originally designed for light element evaluations) to handle evaluations of heavier nuclei.

The presentation of the AMUR code by S. Kunieda has provided the opportunity to recall the experimental constraints related to the analysis of the time-of-flight data (Experimental resolution function, Doppler broadening, multiple scattering corrections, use time-of-flight instead of neutron energy, etc). A few IAEA meetings addressed these issues and a new EXFOR template was designed to provide all the required information [INDC(NDS)-0647].

4.2. Inelastic contribution in the ^{235}U resolved resonance range

For ^{235}U, the threshold of the inelastic cross section is in the RRR. The inelastic contribution was never included in the evaluation of the resonance parameters. Due to improved capabilities in processing codes like NJOX and AMPX, one of the improvements could be the introduction of inelastic widths in order to correctly reconstruct the inelastic cross section in the resonance region. This implies the need of introducing higher partial waves in the calculations. Up to now, the ^{235}U evaluation only contains s-wave resonances. An addition of p- and d-waves will allow to correctly describe the inelastic cross section and, to a lesser extent, the weak anisotropy in angular distributions.

4.3. "Direct" fission process

"Direct" fission usually defines the fission reaction without taking into account the two-step (n,γf) process. In the evaluation procedure, the description of the interference effects observed in the "direct" fission reaction is rather difficult. Some missing interferences can be observed in the ^{239}Pu evaluation. The addition of more than two fission widths could provide a better description of the experimental data between the resonances. However, this approach is phenomenological and is intended to add an additional degree of freedom in the fitting procedure.

Another proposition concerns the use of an energy dependent penetration factor for the fission channel. This approach aims to account for cross section enhancements due to intermediate structures in fission. It was recently applied to analyze the ^{234}U(n,f) reaction measured at the nTOF facility [Leal Cidoncha, JEFDOC-1915, 2018] and never used for fissile systems. Broad structures observed in the fission cross sections of ^{239}Pu and in ^{235}U could be reproduced by using this phenomenological approach.

4.4. Two-step (n,γf) process

The latest proposed improvement concerns the treatment of the (n,γf) process which is always present in fissile systems. The addition of partial widths related to this two-step process is needed to reproduce fluctuations in the prompt neutron multiplicity. The (n,γf) process was introduced in CONRAD calculations by using the model proposed by Fort [Nucl. Sci. Eng. 99 (1988)] on the basis of the original work of Lynn [Phys. Lett. 18 (1965)].

The (n,γf) reaction is calculated as a fraction of the capture cross section and then added to the “direct” fission reaction. As a consequence, the calculated fission cross section increases between the resonances. Partial fission widths and signs of the reduced amplitude widths should be adapted for reproducing the data. Consequences on the radiation widths were not yet clearly quantified.

4.5. Resonance Parameter Covariance Matrix

Despite numerous works published in the last ten years, the propagation of the systematic uncertainties during the evaluation procedure is still an open question. The INDEN program provides the opportunity to clarify the different evaluation procedures of the Resonance Parameter Covariance Matrix.

5. Analysis of the unresolved resonance range

The definition of the upper energy limits of the RRR and the description of the unresolved resonance range were discussed during the meeting. The main issue concerns the missing levels and the accurate description of the fluctuations observed in the experimental data, such as the broad intermediate structures in the fission cross section of ^{235}U and ^{239}Pu. The evaluation strategy chosen by the evaluator could have a strong impact on the calculations of the self-shielding corrections.

In order to solve this problem, one needs to distinguish between the treatment of the “statistical” fine resonance structures and the treatment of broader structures, such as the intermediate structures observed in the fission channel. From this distinction, the fine structures can be interpreted via the Probability Tables formalism. For the broader structures, we need to increase the upper energy limit of the RRR as high as reasonably achievable considering the availability of data with sufficient resolution. No consensus was found on the appropriate evaluation strategy to be applied for the structures still present in the unresolved resonance range.

In order to investigate the performances of different strategies, it was proposed to define simple benchmarks based on transmission measurements of thick samples. Existing data on

Tantalum, Gold and ^{238}U are good candidates for this exercise. The definition of the benchmarks will be prepared by P. Schillebeeckx and shared among the participants of this meeting.

6. Post-fission observables

Evaluation works performed in the frame of the CIELO project have clearly demonstrated that performances of a given set of resonance parameters cannot be achieved without improved description of the Prompt Fission Neutron Spectrum and neutron multiplicity. Experimental and theoretical projects at LANL (Chi-nu project) and CEA of Bruyère Le Chatel will provide valuable information for the INDEN project.

6.1. Prompt fission neutron spectrum (PFNS)

PFNS were extensively studied on a dedicated CRP and also in the frame of the neutron standard group of IAEA. PFNS of ^{235}U at thermal energy is now considered as a second standard after the ^{252}Cf spontaneous fission spectrum.

One of the remarkable results is that all recent studies converge through the same conclusion. They all propose to decrease the mean energy of the PFNS of ^{235}U, ^{239}Pu and ^{233}U by at least by 1.5%. The presentation of R. Capote also indicates the excellent agreement obtained between the different mean energies reported in Ref. [Nucl. Data Sheets 131 (2016)]. As a consequence, the reactivity of the Integral benchmarks increases and a very large impact can be observed for benchmarks characterized by a high leakage fraction.

6.2. Neutron multiplicity

In the RRR, prompt neutron multiplicity has an energy-dependent fluctuating behavior. Its origin is due to the spin of the resonances and to the (n,γf) process. This effect is correlated to the capture cross section. Larger fluctuations are then expected for large capture-to-fission ratios or alpha.

The phenomenological model originally proposed by Lynn and used by Fort for the ^{239}Pu evaluation in the JEFF libraries can only explain the dips observed in the measurements. The increase of the experimental multiplicity is not well understood. Moreover, according to this model, fluctuations due to the (n,γf) process can only be observed in ^{239}Pu, because of one of the fission channel is partially open. Therefore, for ^{235}U, fluctuations higher than those involved by the spin effect cannot be explained via this model alone. The introduction of the penetration factor for fission different from unity should then be investigated.

7. Connection with other evaluations

Other meetings dedicated to non-fissile isotopes strongly connected to the actinide evaluations are planned. A. Trkov presented the case of Fe. In the frame of the CIELO project, the ^{56}Fe evaluation was revisited. However, some inconsistency in the 1/v shape of the capture cross section needs to be clarified. He also pointed out the need for a better description of the ^{57}Fe inelastic cross sections. A new ^{56}Fe evaluation from IRSN is available for testing.

8. Conclusions and recommendations

8.1. Treatment of the unresolved resonance range

The treatment of the unresolved resonance range was extensively discussed during the meeting. However, it was difficult to recommend best practices, except the one that consists in extending the upper energy limit of the RRR as high as reasonably achievable considering the availability of data with sufficient resolution. Above the RRR, different evaluation strategies were discussed and some constraints identified, such as the need to preserve the capture-to-fission ratio. However, no consensus was found and a few actions are proposed below to solve the problem.

8.2. New experimental needs

In addition to the experimental needs already expressed via the HPRL (such as the capture cross section over a wide energy range and the neutron multiplicity at least from the thermal energy up to 50 eV), new needs have emerged from the discussion as follows.

For ^{239}Pu:

- Transmission measurement around the first resonance (0.3 eV) with a thin homogenous sample (sample such as the one used at JRC-Geel for measuring ^{241}Am);
- Transmission measurement below 20 eV in order to measure the resonance interferences in the low energy part of the total cross section (especially between the 1st and 2nd resonance);
- High resolution ^{239}Pu fission measurements in the unresolved resonance range from 2 keV to 50 keV in order to provide a better description of the broad intermediate structures;
- Investigate the possibility to extract experimental information on the (n,γf) process.

For ^{233}U

- Transmission measurements in the low energy part of total cross section (below 20 eV);
- Measurements of fission cross sections in the low energy range.

For ^{235}U

- Transmission measurement in the low energy range in order to have a single and consistent data set from thermal energy to 20 eV.

8.3. Recommendations for future evaluations

A new set of evaluations for fissile actinides is expected in the frame of the INDEN project and some recommendations for the evaluators are listed below:

- Use the latest version of the Thermal Neutron Constant;
- For ^{235}U, minor issues were identified in the capture cross section below 10 eV and between 100 eV and 200 eV;
- For ^{239}Pu, investigate the possibility of using the (n,γf) reaction in the evaluation procedure and to calculate the neutron multiplicity "on the fly".

9. Short terms actions

The followings actions were proposed for the next INDEN meeting:

- Collect ^{238}U data to improve the resonance parameters above 500 eV: transmission data from Harvey (1988), capture data from nTOF and fission data from nTOF;
- Calculations of the self-shielding corrections for transmission data measured with samples of different thicknesses. Tantalum, Gold and ^{238}U data are good candidates. The description of the proposed benchmarks will be shared among the participants of this meeting;
- Review the existing description of the unresolved resonance range, verify the consistency between MF=2 and MF=3 and proposed solutions that better describes the structures observed in the microscopic data, especially the broad intermediate structures observed in fission;
- Propose new sets of ^{239}Pu and ^{233}U resonance parameters and plan benchmarking activities.

"Summary of the presentation on the $^{235}U(n,\gamma)$ cross section measurement at the CERN n_TOF facility", D. Cano Ott on behalf of the n_TOF collaboration

The results of the $^{235}U(n,\gamma)$ cross section measurement performed at the n_TOF facility with a micromegas fission tagging (MGAS) and total absorption calorimeter (TAC) have been presented. The measurement was carried out with two different configurations:

- 10 ^{235}U samples placed within MGAS detector, for reaching a very high tagging efficiency.
- 2 ^{235}U samples inside MGAS detectors and a stack of 8 samples without any fission tagger.

A methodology for measuring the absolute α-ratio was developed/improved, leading to the accurate determination of the fission detection efficency ε_f and subtraction of the prompt fission γ-ray background. For reaching such an accuracy it was necessary to consider the changes in γ-ray cascades registered in the TAC as a function of the threshold in the fission detector. If not taken into account, such a dependence introduces a variable bias in the calculated α-ratio. An example of the dependence of the shape of the γ-ray spectrum as a function of the threshold in the fission detector is given in Figure 1. The $^{235}U(n,\gamma)$ cross section was normalised to the $^{235}U(n,f)$ fission cross section integral:

$$\int_{7.8eV}^{11eV} \sigma_f(E_n)\,dE_n = (246 \pm 1)\; barns \cdot eV$$

and computed from the following expression for the experimental α-ratio:

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

Where:

- C_T Total counts (TAC)
- C_B Background counts (TAC)
- C_f Fission counts (FTMG)
- **ε_γ TAC detection efficiency**
- **ε_f FTMG dection efficiency**
- Φ Neutron fluence.

The detection efficiency of the capture electromagnetic cascades was calculated very accurately by Monte Carlo simulation. Figure 2 shows the comparison of the data (coloured points) to the Monte Carlo simulations (solid black lines) for different conditions on the crystal multiplicity.

The n_TOF data have been included in the evaluation of the ENDFB/VII.0 library (IAEA CIELO) in the range between 2.2 and 20.0 eV. As a result, the ^{235}U capture cross-section has been increased by ~8%.

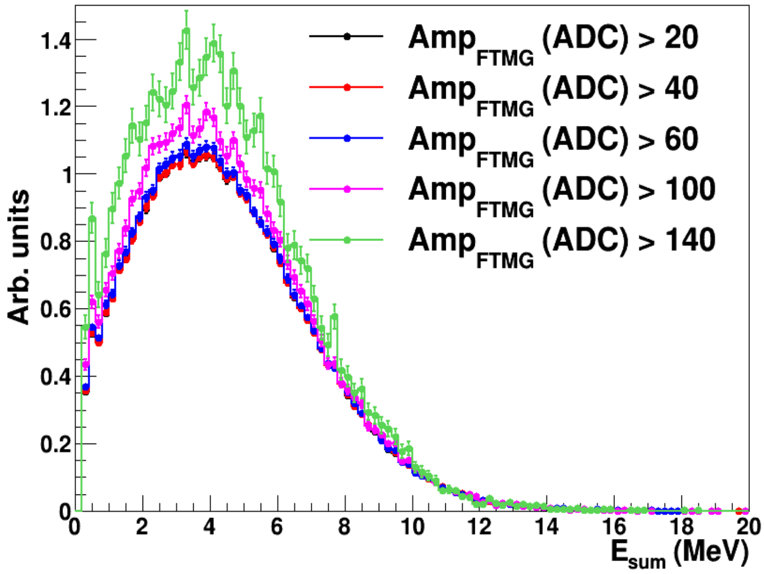

FIG. 1. Total energy deposited in the calorimeter as a function of the threshold set in the MGAS detector.

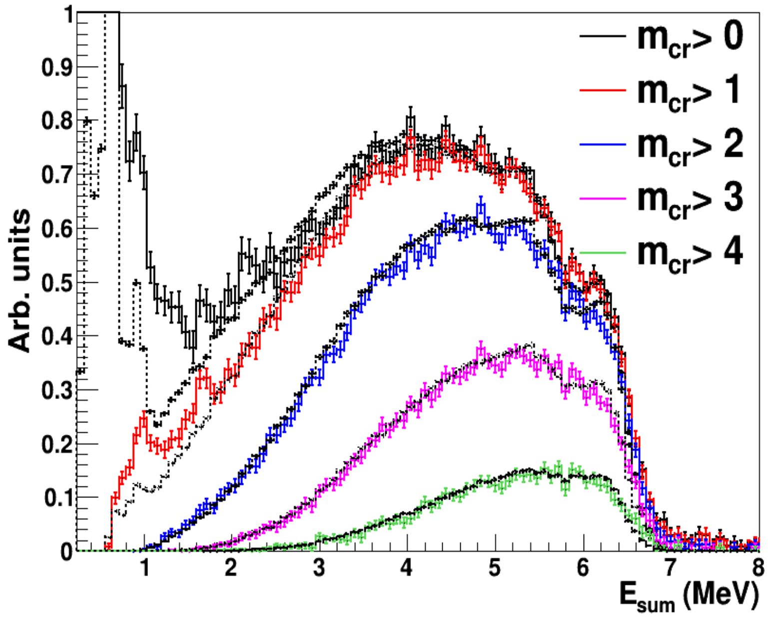

FIG.2. Coloured histograms: total absorption spectra due to the $^{235}U(n,\gamma)$ electromagnetic cascades measured in the TAC as a function of the crystal multiplicity. Solid lines: results from the Monte Carlo simulations for the same conditions on the crystal multiplicity.

See presentation by D. Cano Ott on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/docs/Cano-INDEN-2018.pdf

"Proposed updates on resonance parameter evaluations for fissile actinides", M. Pigni (ORNL, US)

Inelastic state and higher partial waves: a quantum number scheme to include the 1st inelastic state of ^{235}U at 76 eV and three fission widths was generated. For group spins with total angular momentum J=3^-,4^- this created 3 incident neutron channels and 9 outgoing fission channels. Within this quantum number scheme, the effects of the inclusion of higher partial waves and increased number of fission widths were tested on three J=4^- adjacent resonances in the neutron energy range between 15—17 eV. Based on the values of the cross section for three reaction channels, the elastic scattering was about 30% of the total for all three resonances. For the other reaction channels, the strength of the fission and capture channel is about the same for the first resonance, while in the two remaining resonances one of the channels (capture or fission) is dominant. After the fitting procedure, the test showed differences of the resonance widths found by including only s-wave and both s-wave and d-wave. The test led to similar fits for all three reaction channels. The values of the resonance fission widths showed that total fission strength is shared among the three fission widths for all partial waves (Figure 1).

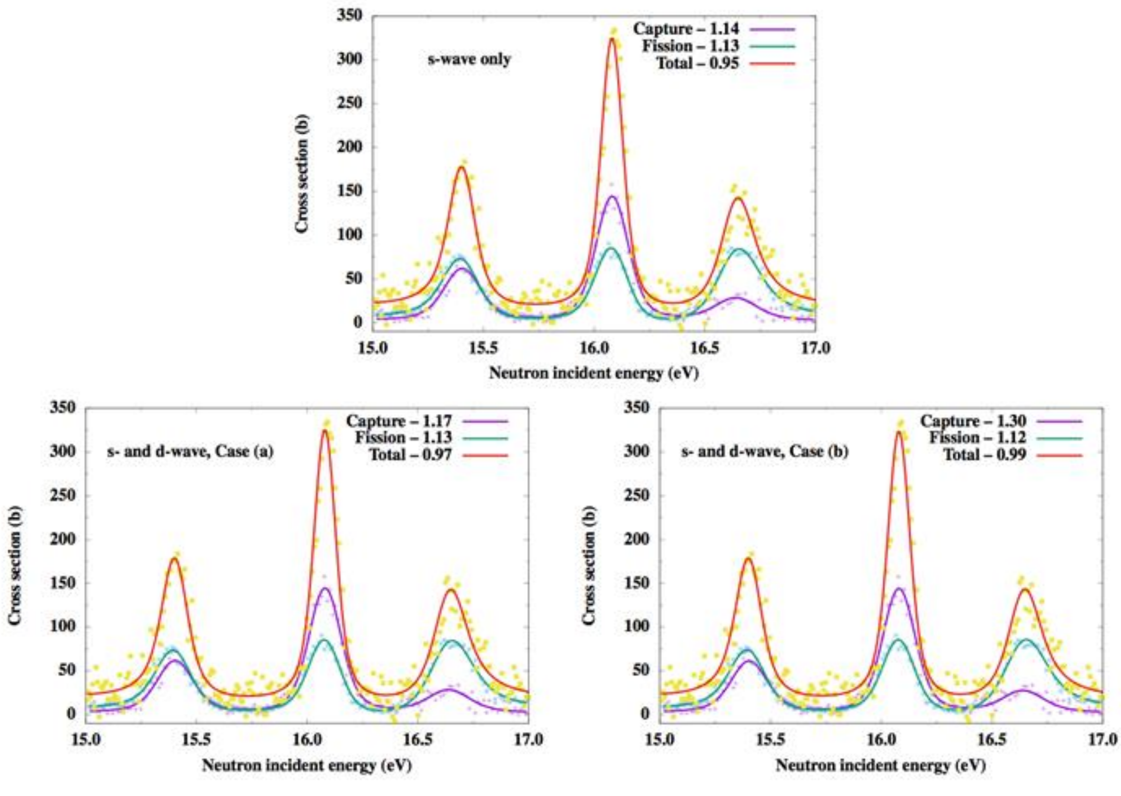

FIG. 1. Example of results obtained on ^{235}U with the SAMMY code.

Fluctuating ν_p: an attempt to describe the energy-dependent fluctuating $\nu_p(E)$ coupled to resonance parameter by using the Fort's formalism for ^{235}U and ^{239}Pu was presented. Results on fluctuating $\nu_p(E)$ calculated by reconstructed cross sections from SAMMY by using ENDF/B-VIII.0 evaluations were shown in comparison with experimental data (Figure 2). For ^{239}Pu the inclusion of the spin effect and the (n,γf) reaction effect reasonably described Weston's measured data. On the contrary, for ^{235}U the effect of the (n,γf) reaction seems to be negligible and modest fluctuating structures can be described only by the spin effect.

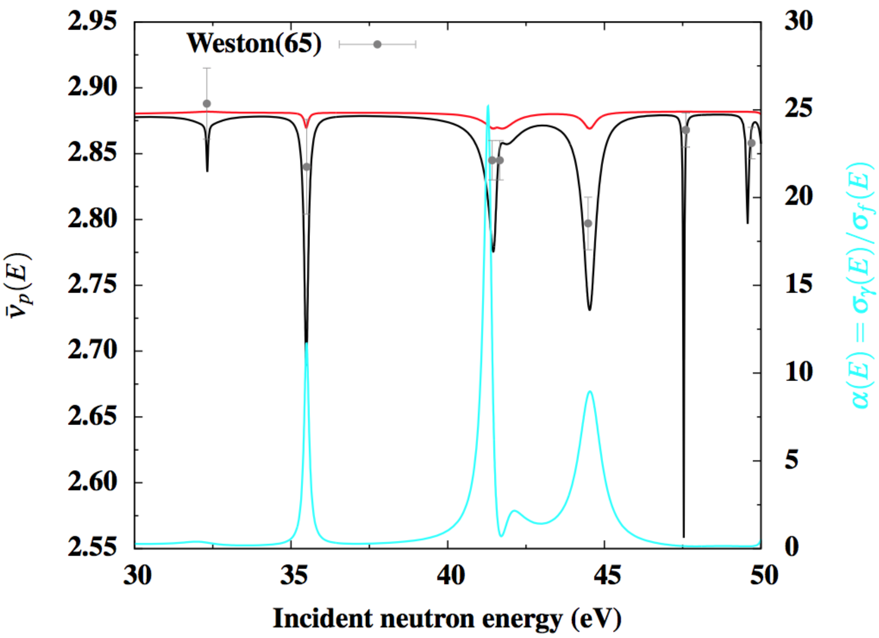

FIG. 2. Prompt neutron multiplicity as a function of the neutron energy.

Conclusions: due to the similar results in the χ^2 from the fitted cases, the inclusion of the higher partial waves is necessary only to include the channel spins for the first inelastic at 76 eV. The fit of the neutron widths and the third fission width seems not be necessary. The description of $\nu_p(E)$ fluctuations for ^{239}Pu using Fort's formalism seems adequate. Due to the modest fluctuation behavior of the $\nu_p(E)$ for ^{235}U fort's formalism can be used by including only the spin effect and additional experimental data are needed.

See presentation by M. Pigni on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/docs/Pigni-INDEN-2018.pdf

"Status and the need to re-evaluate resonance parameters of U238 for energies above 500 eV", P. Schillebeeckx (JRC-Geel, Belgium)

For ^{238}U a new evaluation in the resonance region was produced by JRC Geel in collaboration with INRNE Sofia, NDS/IAEA and KAERI. The evaluation in the URR is described by Sirakov et al. (Eur. Phys. J. A 53 (2017) 199). In the RRR only parameters in the energy region below 500 eV were revised. This revision is described by Kim et al. (Eur. Phys. J. A 52 (2016) 170). The resonance shape analysis code REFIT was used to determine resonance parameters by adjusting them in a least squares fit to the experimental capture yield obtained at GELINA by Kim et al. and the transmission data of Olsen et al. obtained at ORELA. Up to 1200 eV the capture and transmission data could be parameterised by using one set of resonance parameters, without applying any additional background and normalisation correction. The ration of the neutron strength gΓn obtained by Kim et al. and those derived by Derrien et al. (ORNL/TM-2005/241), which is the basis of the evaluations in the latest libraries, is shown in Figure x+1. There is a very good agreement below 500 eV. However, above 500 eV a systematic decrease as a function of neutron energy is observed. At the time of the previous evaluation no additional data was available to confirm the neutron widths obtained by Kim et al.. Therefore, only the parameters for resonances below 500 eV were revised. The parameters for resonances above 500 eV can be revised by including in the evaluation process the recent capture data of Mingrone et al. (Phys. Rev. C95 (2017) 034604) and Wright et al. (Phys. Rev. C96 (2017) 064601) obtained from measurements at nTOF applying the total energy detection principle and total absorption principle, respectively. In addition, an improved description of the fission widths can be obtained by including also the fission cross section data obtained at nTOF.

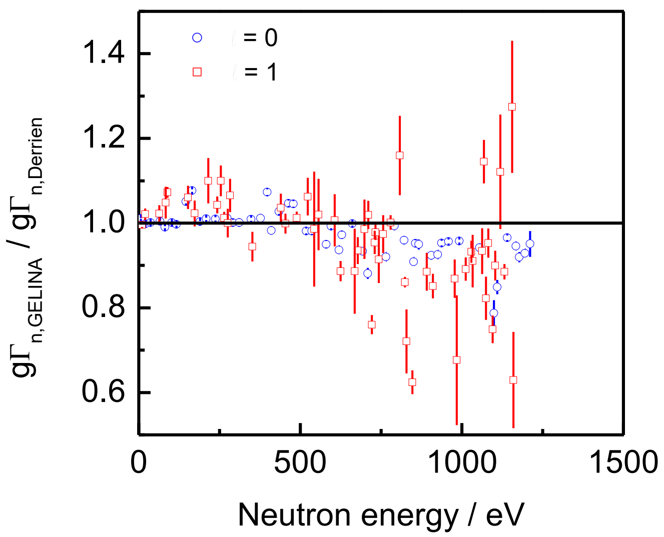

FIG. 1. Ratio of the resonance strengths obtained by Kim et al. and those derived by Derrien et al. as a function of the neutron energy.

See presentation by P. Schillebeeckx on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/docs/Schillebeeckx-INDEN-2018.pdf

"Status of the AMUR code toward cross-section evaluation for heavier nuclei", S. Kunieda (JAEA, Japan)

AMUR is one of the resonant analysis code based on the R-matrix theory which is under development in JAEA. The code was initially designed for the evaluation on the light-nuclei where the (n,γ) cross sections is less important and no fission process exist. Quite recently, S. Kunieda started to expand capability of the code toward the analysis of heavier nuclei. He reported that the code is already include the Reich-Moore (LRF=3) and R-matrix limited (LRF=7) options defined in ENDF format. The code is also designed to calculate the Doppler broadening with the free-gas approximation. Through comparison with calculated results of PREPRO (Figure. 1) and also with available experimental cross-sections, he confirmed that the code is now able to reconstruct cross-sections from resonance parameters for heavier nuclei without computational problems.

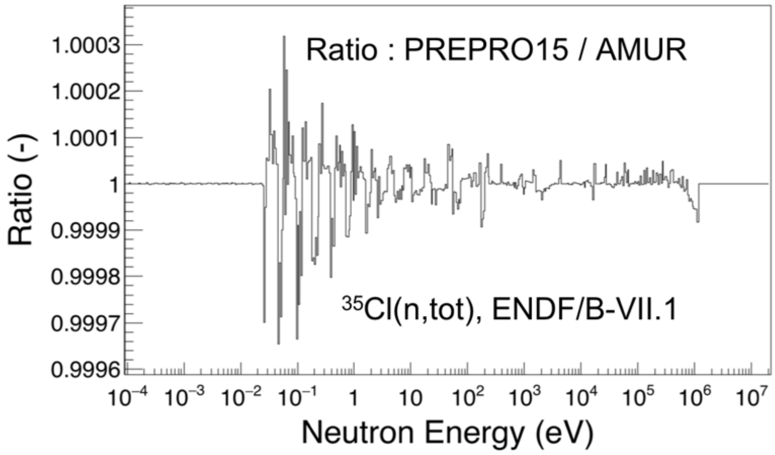

FIG. 1. Ratio of reconstructed cross-sections between PREPRO and AMUR for ^{35}Cl(n,tot)

Since the code has been developed in the object-oriented framework, higher flexibility may be expected to simulate experimental conditions such as the contamination in the sample material. In the next step, he plans to have capability for simulating self-shielding and multiple-scattering effects in the sample, since they are absolutely necessary for practical data analysis/evaluation.

See presentation by S. Kunieda on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/docs/Kunieda-INDEN-2018.pdf

"Status of the ^{239}Pu evaluation in the resonance range for JEFF", G. Noguere (CEA Cadarache, France)

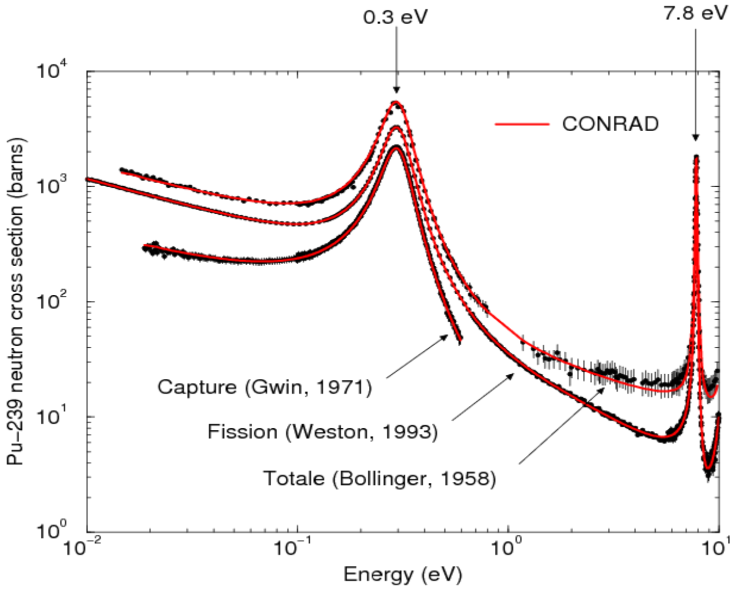

FIG. 1. Example of ^{239}Pu neutron cross sections calculated with the CONRAD code and compared with EXFOR data.

Since the release of the JEFF-3.1.1 libraries in 2005, long term efforts were performed for improving the ^{239}Pu evaluation within the JEFF project. The aim was to solve several physical issues by preserving the good performances of the JEFF-3.1.1 library on PST benchmarks and MOX fuel calculations. New ^{239}Pu resonance parameters coming from the working group WPEC/SG34 were adopted in the JEFF-3.2 library (Figure 1). For the first time, a single set of resonance parameters was produced up to 2.5 keV together with a resonance parameter covariance matrix. For JEFF-3.3, a new set of parameters were included in the library. The goal was to increase the resonance range in order to correctly describe broad intermediate structures observed in the fission cross section up to 5 keV. Additional work is needed to finalize the ^{239}Pu resonance parameters of JEFF-3.3.

An improve description of the 1st resonance around 0.3 eV is difficult to achieve because no new experimental data is available. A single transmission data set can be used. It was measured by Bollinger in 1958. The capture cross section was recently re-measured at the DANCE facility. However, the lower energy is close to 10 eV. Older capture data sets have to be used for normalization purpose. Same problems occur for the accurate determination of the prompt neutron multiplicity. Limited data sets are available with poor accuracy, therefore the modelisation of the fluctuations of υ_p, by introducing the (n,γf) process, provide large uncertainties. From the microscopic point of view, such issues cannot be solved without new high quality data. As a consequence, the difficulty to correctly describe the shape of η as a function of temperature could explain the systematic bias with the temperature observed in Reactivity Temperature Coefficients of MOX fuel measured in the EOLE reactor (CEA Cadarache).

See presentation by G. Noguere on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/docs/Noguere-INDEN-2018.pdf

“Update on the recent ^{235}U CIELO evaluation” Y. Danon (RPI, US)
See presentation by Y. Danon on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/docs/Danon-INDEN-2018.pdf

“Current benchmarking activities at the IAEA”, A. Trkov (IAEA, Vienna)
See presentation by A. Trkov on: https://www-nds.iaea.org/index-meeting-crp/CM-INDEN-2018/

Consultants' Meeting

INDEN I
On the resonance parameters of actinides

IAEA Headquarters, Vienna, Austria
8 to 11 May 2018
Meeting Room VIC MOE19

Preliminary AGENDA

Tuesday, 8 May

09:00 – 09:30 **Registration** (IAEA Registration desk, Gate 1)

09:30 - 10:00 **Opening Session**

Welcoming address – A. Koning, IAEA/NDS-SH
Introduction – A. Trkov, IAEA/NDS
Election of Chairman and Rapporteur
Adoption of Agenda /Administrative matters

10:00 – 12:30 **Presentations by participants** (~ 30 min each)

- D. Cano Ott, *Results on ^{235}U – problems encountered*
- M. Pigni, *Proposed Updates on Resonance Parameter Evaluations for Fissile Actinides*

12:30 – 14:00 ***Lunch***

14:00 - 17:30 **Presentations by participants** (cont'd)

- Y. Danon, *Update on the recent ^{235}U CIELO evaluation*
- S. Kunieda, *Plan/status of the AMUR code toward the evaluation of heavier nuclei*
- P. Schillebeeckx, *Status and the need to re-evaluate resonance parameters of ^{238}U for energies above 500 eV*

Coffee breaks as needed

Wednesday, 9 May

09:00 - 12:30 **Presentations by participants** (cont'd)

- G. Noguere, *Status of the ^{239}Pu evaluation in the resonance range for JEFF*
- R. Capote, *IAEA Neutron Data Standards 2018 and the impact on current/future evaluations*
- A. Trkov, *Current benchmarking activities at the IAEA*

12:30 – 14:00 ***Lunch***

14:00 - 17:30 **Round table discussions**

Coffee breaks as needed

19:00 ***Dinner at a restaurant (see separate information sheet)***

Thursday, 10 May

09:00 - 12:30 **Round table discussion** (cont'd)

12:30 – 14:00 ***Lunch***

14:00 - 17:30 **Drafting of the Summary Report**

Coffee breaks as needed

Friday, 11 May

09:00 - 13:00 **Drafting of the Summary Report** (cont'd)

13:00 **Closing of the meeting**

Coffee break as needed

Consultants' Meeting

INDEN I

On the resonance parameters of actinides

8 to 11 May 2018

IAEA, Vienna, Austria

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