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Summary Report from the Consultants' Meeting
on
**International Neutron Cross-Sections Standards:
Extending and Updating**

13 – 15 October 2010
IAEA, Vienna, Austria

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March 2011

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Abstract

The meeting participants have considered the progress in the measurement and evaluation of neutron cross sections and spectra which can be used as standard or reference data. This includes extension of the ^{197}Au(n,γ) standard to the energy range below 200 keV, ^{235}U(n_{th},f) prompt fission neutron spectrum and neutron induced gamma-production cross sections. The work on this data development project for next two years has been agreed.

March 2011

CONTENTS

Introduction 7

Review of actions done 7

Results of new measurements for standards cross sections 7

Critique of standards evaluation 8

Measurements and evaluation of $^{235}U(n_{th},f)$ prompt fission neutron spectrum 8

Measurements and evaluation of $^{197}Au(n,\gamma)$ cross section 11

Progress in measurements and evaluation of gamma-production cross sections, which can be recommended as reference cross sections 12

Discussions of various problems related to standard and reference cross sections evaluation and actions needed to complete the work 14

1. New experimental data for basic standards re-evaluation 14
2. Measurements and evaluation of prompt fission neutron spectra 14
3. Measurements and evaluation of $^{197}Au(n,\gamma)$ cross section 16
4. Measurements and evaluation of reference gamma-production cross sections 17
5. Smoothing of the standards, reference cross sections and spectra obtained in the non-model evaluations 18

Goals to be reached by October 2012 19

APPENDICES

APPENDIX 1: Agenda 21

APPENDIX 2: List of Participants 25

APPENDIX 3: Presentations 27

Introduction

The Consultant's Meeting was opened by Roberto Capote. He welcomed participants and stressed the importance of the standards data development project and its relationship to the other projects running under the auspices of the Nuclear Data Section. Vladimir Pronyaev expressed the opinion that there has been real progress in the work done since the last meeting in 2008. It includes the delivering of many new experimental results and new techniques for the evaluation of prompt fission neutron spectra.

Allan Carlson was elected chairman and Anton Wallner as reporter. The provisional agenda was adopted with minor changes (see Agenda in the Appendix A).

Review of actions done

The status of actions prepared at the last meeting was reviewed. Most planned actions were implemented, but a few actions had ongoing status. Some actions on obtaining data for updating the standards are postponed, mostly because of delays with the analysis of the experimental data. Actions on the prompt fission neutron spectra measurements and evaluations are mostly completed, but the approach and the technique to be used in the evaluation are needed in the discussions and justifications. Large progress, well beyond the planned actions, was reached for ^{197}Au capture cross sections measurements and evaluations. New experimental data on capture cross section measurements were obtained or are nearly finalized using different methods and new techniques for the measurements. The actions on measurements of reference cross sections for gamma-production reactions are fulfilled but analysis of several data sets is not complete. The "on-going" status is assigned to the evaluation of these cross sections. Different types of smoothing for the evaluated standards and reference cross section data were proposed after the 2008 meeting. Due to this, the action on selection of the best one for each particular case received an on-going status.

Results of new measurements for standards cross sections

The results of measurements available since the last standards evaluation (mostly data obtained after 2004) were presented by Allan Carlson. Measurements have been made for all the cross section used in the evaluation process for the standards. They include the ^{238}U(n,γ) and ^{239}Pu(n,f) cross sections in addition to the standard cross sections. Most of the measurements are in agreement with the standards evaluation. Although the results of different new measurements are generally consistent with the standards evaluations, there are some energy ranges where new high precision measurements may influence at the central values and uncertainties of the evaluations. Much of the concern now is for the H(n,n), ^{3}He(n,p), C(n,n) and the fission cross sections. Significant work is underway or completed for the following measurements:

The ongoing work at Ohio University on the hydrogen standard now emphasizes the small angles in the CMS at about 14 MeV where very little data are available. This work required detection of the recoil neutrons. Problems with this cross section still exist in the hundred MeV region and the prospects for new measurements are very weak. There is a problem with some of the data used in the R-matrix evaluation of the ^{3}He(n,p) cross section. This causes problems with convergence in the calculations. The very small uncertainties in the total cross section measurements of Keith *et al*. may be a source of the problem. Hambsch plans LINAC measurements of the ^{6}Li(n,t) cross section from a few keV to 3 MeV. Some diagnostic work has been done and the deposits are being made at IRMM. Very accurate work on this cross section by Yue *et al.* continues. When completed, it is expected this will be the most accurate measurement at sub-thermal energy. They also plan measurements of the $^{10}B(n,\alpha)$ cross section using the same basic experimental setup. Work on the ^{10}B deposits is essential in order to obtain high accuracy. Hambsch continues data taking on the LINAC measurements of the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ cross sections up to about 3 MeV. Zhang has made improvements to his experiment so he can obtain $^{10}B(n,\alpha)$ measurements with a minimum of "particle leaking". Measurements are underway. Filtered beam measurements have been made of the C(n,n) angular distribution for 5 angles at 3 energies by Gritzay *et al*. The data differ significantly from the standards evaluation. The data are relative to lead scattering. Further work is being done on this experiment. The work on the gold capture cross section is composed of that in the standards energy region and the measurements supporting astrophysics applications at lower neutron energies. The lower energy work will be covered in another section of this report. The only new works on the gold capture cross section is an extension of the Massimi *et al* measurement into unresolved resonance region by Lederer and a measurement at GELINA beween 5 and 80 keV. The n_TOF work was included in a paper at the ND2010 conference and is discussed in much more detail in another section of this report. The Lederer results generally agree well with the standards evaluation. Measurements by Ullmann et al. of the $^{238}U(n,\gamma)$ cross section agree well with the standards evaluation. Further work will be done on this measurement to better define the normalization of the data. The only new work on fission cross sections is for $^{239}Pu(n,f)$. These measurements by Tovesson and Hill agree well with the standards evaluation up to about 10 MeV. Above 10 MeV their measurements are lower than the evaluation up to about 100 MeV. Fission cross section measurements are planned with Time Projection Chambers that should provide very accurate results.

Critique of standards evaluation

Up to now, the low uncertainties obtained in the standards evaluations have been considered by some as a drawback of that evaluation. This was discussed by the participants. In the case of the light nuclides, where R-matrix fits were used in the evaluation, it may be that this was caused by the use of experimental data considered as shape data, with the normalization parameter determined in the fit. In the general case, the omission of important correlations, which may exist for some components of the uncertainties of different measurements, will lead to uncertainty reduction. For the evaluation of the standards, cross-data-set correlations were introduced, where they were needed. Some implicit "proof" that the uncertainties of the standards are not strongly underestimated can be obtained from comparisons of the uncertainties of the data from integral and "clean" benchmark experiments with the results of calculations using the standard cross sections. In many cases they are do not differ much from each other.

Measurements and evaluation of $^{235}U(n_{th},f)$ prompt fission neutron spectrum

Peter Schillebeeckx presented the final results of measurements of the $^{235}U(n,f)$ PFNS done by Hambsch *et al.* in a JRC-IRMM collaboration at the cold neutron facility (T=100 K) of the 10 MW Budapest Research Reactor. The data obtained disagree in some respects with PFNS data for thermal neutrons from different evaluated data libraries. However, the data agree well with most experimental results. The obtained results show that spectra are more soft, having a higher yield in the energy range below 1 MeV. They also have a larger yield above about 9 MeV but the uncertainties are quite large in that energy region. There was discussion about the reaction mechanisms and the models which may enhance the higher yield of neutrons in the low-energy part of the spectra such as neutron emission before full acceleration. Also concern was expressed about how to design an optimized experimental set up for measurements of the spectra or integral reaction rates, which may explicitly characterize the PFNS at low fission neutron energies. It was noted that the PFNS can not predict integral data or benchmark experiments very well.

The results of measurements of ^{235}U(n,f) PFNS relative to the ^{252}Cf(sf) standard PFNS at the Gatchina research reactor were shown by Alexander Vorobyev. The measurements of the prompt neutron spectra were performed at 11 fixed angles between the neutron and light fragment direction in the range from 0^0 to 180^0 in 18^0 intervals. After the measured energy distributions for 11 fixed angles were corrected for the energy and angular resolution of neutron detector the total prompt neutron spectra were obtained by summing over angle. Although the geometry for measurements with ^{235}U and ^{252}Cf samples was the same, the corrections for the energy and angular resolutions do not cancel in the ratio. So the total correction is energy dependent and comprises no more than 3% in the measured energy range. The comparison of the obtained data with experimental results obtained by other groups, which were normalized to the recommended value of the total average neutron multiplicity, ν_{tot} = 2.421, demonstrates that there is well agreement (within experimental errors) between all experimental data in 1.5 – 8 MeV energy range. However, there is some discrepancy in energy region below 1 MeV. The energy and angular correlated differential data obtained can be used for improving models under consideration for calculation of prompt fission neutron emission. Generally, the results obtained are consistent with the ENDF/B-VII.0 PFNS within the limits of the uncertainty. Again, the spectrum at low energies is softer than the evaluation however the agreement at high energies is quite good. There is some difference in the yield relative to the old NIIAR measurements in the energy range 1.5 – 8 MeV. Introducing corrections for the energy-angular resolution and energy bin-width corrections may affect the results that have been discussed.

Roberto Capote presented a Monte Carlo approach that is being developed to perform model evaluations based on estimation of the model parameters and uncertainties combined with a Bayesian least-squares fit of the experimental data. The approach allows in a simple way to take into account the intrinsic model correlations in the least-squares fitting of the experimental data without introducing strong model influence in the evaluation in the energy ranges where experimental data are given. Also the approach can provide adjusted model predictions in the energy ranges where experimental data are absent. In discussions, it was proposed, that the approach can be tested with PFNS data.

An approach for combined non-model evaluation of the prompt fission neutron spectra for ^{252}Cf(s,f), ^{235}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f) using the GMA code was presented by Vladimir Pronyaev. In this approach, the generalized least-squares fit of experimental data for PFNS of ^{235}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f), and non-model and non-smoothed evaluation of the PFNS of ^{252}Cf(sf) done by Wolf Mannhart in 1987 was implemented. The evaluation of ^{252}Cf(sf) PFNS is based on all suitable experimental data available in 1987. Since that time no new accurate measurements have been done. Most data for ^{235}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f) PFNS are obtained relative to ^{252}Cf(sf) PFNS as a standard. Because of this, the evaluations of the three PFNS are coupled in the combined fit with evaluated data for ^{252}Cf(sf) PFNS introduced as pseudo-experimental data set. The changes in the ^{252}Cf(sf) PFNS standard in the combined fit are small, because of its relatively small uncertainty. Some procedure for smoothing of the spectra and introducing a constraint in the form of the normalization of the spectra to 1 in the least-squares fit was proposed. The main discussions after the presentation were devoted to the smoothing procedure being used which changes substantially the covariance matrix of the uncertainties of the evaluated data. In particular, the use of the shape of the model function with the assigned small uncertainties leads to a strong reduction of the variances of the smoothed evaluated data.

The analysis of the results obtained in the combined fit of the PFNS with GMA and experimental data used in this evaluation was given by Wolf Mannhart. He pointed out that the model smoothing procedure and in particular the specific covariance matrix assigned to the calculated results leads to the unrealistically small variances (per-cent uncertainties) of the smoothed evaluation. Another important point is that some data used as absolute measurements in the fit are in reality the absolute ratios of $^{235}U(n_{th},f)$ to $^{252}Cf(sf)$ PFNS because the $^{252}Cf(sf)$ spectrum was used for the detector efficiency determination. These data should be introduced in their primarily measured form as ratios. Some experimental data obtained with lithium glass detectors have structures in the vicinity of the large resonance in the $^{6}Li(n,t)$ cross section. The data should be reanalyzed to remove this artificial structure. The discussion was about what is the best presentation of the spectra evaluated without the use of the model. Introducing constraints in the form of normalization of the spectra without smoothing of the spectra and covariances often leads to an increase of the artificial structures in the spectra. The use of smoothing may lead to changes that are too strong in the non-model evaluated covariances.

The discrepancy between measured $^{235}U(n_{th},f)$ fission neutron spectrum averaged cross sections for reactions with mean energy of response between 2 and 15 MeV was analysed in the paper presented by Wolf Mannhart. The experimental data obtained in a series of measurements done in different and supposedly well characterized spectra were compared. It was shown that some discrepancies can be reduced if experimental data are renormalized to the same standards and decay radiation data used in the measurements of the averaged cross sections. But above 10 MeV (mean energy of response) the discrepancy between measurements increases substantially, even between the data obtained with thermal converters, where the hard part of the spectra is not disturbed substantially by neutron scattering and the correction for this can be calculated. Unfortunately, because some important measurements are not well documented, it is difficult to come to definite conclusions about the source of such discrepancies. A discussion was held on the possibility of doing new experiments with reactions having high mean energies of neutron response.

As a result of general discussions on the use of the GMA methodology for combined evaluation of the PFNS, a consensus was reached that for the first step only fitting of the $^{252}Cf(sf)$ and $^{235}U(n_{th},f)$ PFNS should be done, to avoid solving too many problems at the same time. Inclusion of the $^{239}Pu(n_{th},f)$ and $^{233}U(n_{th}, f)$ can be done in the following step. The non-model, non-smoothed and non-normalized evaluation including central values and the covariance matrix of uncertainties can be used in the next stage for different model fits, smoothing and for normalization. There was a large range of opinions about an acceptable level of influence of smoothing for the covariances, ranging from that a) any smoothing should not change the covariance matrix of uncertainties obtained in the non-model fit to b) modern models describing the PFNS can be applied for smoothing in a way such that they will not affect the data and covariances where there are large uncertainties in the model predictions. The smoothing procedures can be best tested first with a non-model evaluation of the $^{252}Cf(sf)$ PFNS, which is better known than the $^{235}U(n_{th},f)$ PFNS because it is possible to have better conditions for the $^{252}Cf(sf)$ PFNS experiments. Requests for new experiments optimized for PFNS measurements at low energy (below 1 MeV) and high energy (above 4-8 MeV) should be submitted for inclusion in the High Priority Request List (HPRL). A similar request for spectrum averaged cross sections using the $^{235}U(n_{th},f)$ PFNS with mean energy of the reaction response in the region of 100 – 500 keV and above 10 MeV should be made.

Measurements and evaluation of $^{197}Au(n,\gamma)$ cross section

Anton Wallner presented the results of $^{235}U(n,\gamma)$ and $^{238}U(n,\gamma)$ measurements relative to the $^{197}Au(n,\gamma)$ cross section for two Maxwell-Boltzman simulated spectra with thermal neutrons and kT close to 25 keV, and a broad neutron spectrum with mean energy at about 450 keV. Measurements were also made for cold neutrons but results are available only for $^{238}U(n,\gamma)$ at this time. The novel accelerator mass spectrometry method was used. The thermal values for these reaction cross sections are well known from the standards evaluation and can be used for testing of the method. The absolute ratio measurements can be converted using the gold capture cross section. Doing simultaneous activation measurements using samples of ^{197}Au, ^{235}U and ^{238}U, absolute ratios of the $^{235}U(n,\gamma)$, $^{238}U(n,\gamma)$ and $^{197}Au(n,\gamma)$ cross sections can be determined. This is an important independent measurement of the ratio of the $^{238}U(n,\gamma)$ to $^{197}Au(n,\gamma)$ cross sections which are very discrepant in the present standards database and which may influence an evaluation of the $^{197}Au(n,\gamma)$ standard cross section. Preliminary results for the 25 keV simulated spectrum and the 450 keV point are consistent with the standards evaluation for the $^{238}U(n,\gamma)/^{197}Au(n,\gamma)$ ratios.

Claudia Lederer presented preliminary results of n_TOF (CERN) measurements of the $^{197}Au(n,\gamma)$ cross section with an uncertainty 4 - 5% in the unresolved resonance energy range (6 – 500 keV) with a C_6D_6 detector. The results are on average 4 – 5% above Macklin's data (which were renormalized with k=0.989 and used as a standard in capture measurements for astrophysical applications for kT=25 keV Maxwell-Boltzmann spectrum) below 80 keV, above by 2 – 3% for 80 – 160 keV, but below by 2 – 4% for 160 – 320 keV. In many energy groups, they differ more than at 1 – 1.5% (uncertainty of the $^{197}Au(n,\gamma)$ standard evaluation) from the standards evaluation but still are within the limits of uncertainty of the measurements (4 – 5 %). The cross section folded with the Ratinsky and Kaeppeler kT=25 keV simulated spectrum for the n_TOF measurements is 2% below the standards folded cross section and 4.7% above the Macklin's folded cross section. The uncertainty in the n_TOF folded result is 4%. The uncertainty of the n_TOF measurements can be reduced through the analysis of data considering different detector thresholds. The discussions concerned the determination and separation of the background from scattered neutrons and in-beam gamma-rays, which is relatively large and may have some structure. Preliminary results of new measurements at PTB of the shape of the neutron spectrum resembling a Maxwellian spectrum with kT=25 keV obtained by the $^{7}Li(p,n)$ reaction for E_p=1912 keV were reported. Compared with the old Ratinsky and Kaeppeler (1987) FZK (KIT) results, the new spectra integrated with a larger number of angles are slightly softer, but the spectrum averaged integral for the $^{197}Au(n,\gamma)$ cross section (taken from ENDF/B-VII.0 library) is only 0.5% higher. A comparison with thick target yields calculated using the PINO code and evaluated microscopic differential cross sections was done. The agreement between experimental and calculated spectrum is good. Additional corrections can be made for the final results using a full simulation in the Monte Carlo approach of the conditions of the experiment. The discussions concerned the contribution of scattered neutrons which can be different in different geometries (different flight paths in spectra measurements and very short distances in the sample irradiation conditions).

Peter Schillebeeckx presented new results of absolute measurements of the $^{197}Au(n,\gamma)$ cross section in the energy range 5 – 80 keV at the GELINA facility. Large attention was paid to the measurements and analysis of the background, self-shielding and scattering corrections in this energy range. The saturated resonance technique was used for normalization of the cross section at the 4.9 eV resonance and the $^{10}B(n,\alpha)$ cross section with an approximate 1/v energy dependence was used as the neutron flux monitor for extrapolation of the absolute normalization from 4.9 eV to other energies. The cross section at 0.0253 eV deduced with the use of this technique is 99±1 b. It is in good agreement with the 98.66±0.14 b standard value. Comparison with the standards evaluation shows, that the new values are generally below by about 1 – 3 % for neutrons with energy less than 40 keV and above by about 1 – 2 % for energies higher than 40 keV. The results are in excellent agreement with earlier work at the GELINA facility by Borella *et al.* Discussions concerned the background separation using the filter techniques.

The general discussions on the $^{197}Au(n,\gamma)$ cross section showed that there has been good progress on new results with additional work on background determination and detailed analysis of corrections and uncertainties due to scattering and self-shielding. Franz Kaeppeler presented the programme of measurements in the framework of EUFRAT for 2011, which includes new measurements, calculations and analysis of kT=25 keV simulated spectra as well as spectrum averaged $^{197}Au(n,\gamma)$ cross sections by the activation method. It also includes a search for unrecognized systematic uncertainties, which may lead to biases of the measured averaged cross sections. Results of two independent measurements (n_TOF and GELINA) done with the time of flight technique and white neutron spectrum sources plus new measurements of the simulated kT=25 keV Maxwellian spectrum averaged cross section by the activation method should provide determinations of the $^{197}Au(n,\gamma)$ cross section in broad energy groups for the energy range 3 – 200 keV with an uncertainty of about 1 – 2 %.

Progress in measurements and evaluation of gamma-production cross sections, which can be recommended as reference cross sections

The status of the experimental data obtained for the 1434 keV gamma-line production cross section for ^{52}Cr at GELINA and published in NP, A786, p. 1, (2007) was presented by Allan Carlson based on the journal article and information obtained from the authors. Because of the thick sample used in the fission chamber for neutron flux determination, the method used for extrapolation to zero pulse height is important. The method used in this experiment is a concern. Also the correction for the loss of fragments in the deposit and backing was not made. Revision and introducing of these corrections should lead to the decreasing of the gamma-production cross section and better agreement with the existing evaluations. Plompen has recently made efficiency measurements for this fission chamber at PTB which should be available in December of 2010.

A report by Ron Nelson on the status of LANL measurements of gamma-production cross sections in neutron inelastic scattering and (n,2n) reactions for ^{56}Fe, ^{52}Cr, ^{93}Nb, ^{197}Au and ^{48}Ti was presented by Allan Carlson. Because ^{56}Fe and ^{52}Cr cross sections were independently measured at GELINA, the measurements can be also used for resolving of the possible discrepancies once the fission chamber efficiency problem is resolved. More accurate background subtraction, accounting for the presence of the iron in the experimental environment was done for the LANL data published in 2004. The corrected 847 keV gamma-line production cross section for $^{56}Fe(n,n')$ now agrees well with the data in the major evaluated data libraries in the energy range 4 to 15 MeV and is slightly below them between 15 and 20 MeV. Analysis of the ^{52}Cr(n,n') data is in progress now. There is a preliminary conclusion that the use of the gamma-production cross sections for ^{93}Nb and ^{197}Au as a reference is not suitable, because of feeding from isomers populated in the irradiation of the samples and for ^{197}Au the presence of interfering gamma-lines in the background, respectively. The important preliminary conclusion is that reactions for ^{nat}Ti with large yields of two gamma-lines, 984 keV from ^{48}Ti(n,n') and 160 keV from ^{48}Ti(n,2n) and ^{47}Ti(n,n') reactions are most suitable for use as reference cross sections. New relative gamma-production cross section data on Cr-Ti was acquired with GEANIE at LANSCE – analysis is planned.

The general discussions were concerned with the determination of the energy dependence of the ratio of the gamma-production cross section to the total inelastic scattering cross section (or (n,2n) for gamma-production in (n,2n) channel) in the model calculations using evaluated and theoretical values. A small uncertainty in the knowledge of this ratio (1 - 2 %) will allow the combined least-squares fit of other partial and total cross sections with known constraints between them to reduce the uncertainty of the reference gamma-production cross section to 2 - 5 % in broad-group presentation.

Discussions of various problems related to standard and reference cross sections evaluation and actions needed to complete the work

1. New experimental data for basic standards re-evaluation

Most new experimental data obtained are in good agreement with the standards evaluation. As a result of discussions the following actions have been prepared:

No.	Action	Responsible	Date
1	Obtain Ohio University 14.9 MeV angular distribution data using neutron detection, when they are completed.	A. Carlson	September 2012
2	Monitor the IRMM measurements of the ^{10}B(n,α) cross sections. Eventually get the data.	F.-J. Hambsch A. Carlson	July 2012
3	Obtain NIST ^{6}Li(n,t) data.	A. Carlson	July 2011
4	Obtain NIST ^{10}B(n,α) cross section data.	A. Carlson	August 2012
5	Communicate with Gritzay about C(n,n) measurements. Determine if they can be used in a new evaluation.	A. Carlson	Sept. 2011
6	Obtain covariance data for the C(n,n) standard	G. Hale A. Carlson	July 2012
7	Monitor progress on TPC work	A. Carlson	Dec. 2011
8	Obtain Ullmann ^{238}U capture data	A. Carlson	Oct. 2011
9	Monitor progress on extension in energy of the hydrogen standard and covariances.	A. Carlson	Dec. 2011
10	Communicate with additional experimental groups working on measurements of standard and reference cross sections and collect data, uncertainties and details of the experiments needed for the evaluation of the standards	A. Carlson	June 2012
11	To add in the GMA database the results of all last experiments and obtain new least-squares fit of the standard cross sections	V.G. Pronyaev	August 2012

2. Measurements and evaluation of prompt fission neutron spectra

Discussions on the ^{235}U(n_{th},f) prompt fission neutron spectrum evaluation ended with the following conclusions:

–technique of using a combined evaluation of prompt fission neutron spectra for ^{252}Cf(sf), ^{235}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f) with the GMA code is appropriate because most PFNS measurements for thermal neutron induced fission were done relative to the ^{252}Cf standard spectrum;

–to avoid the situation where too many problems in the combined fit may appear simultaneously, initially, the combined fit should be implemented for ^{252}Cf(sf) and ^{235}U(n_{th},f) spectra, and then after that, ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f) could be sequentially added to the evaluation;

–the work on analysis of the experimental database for prompt fission neutron spectra, with reduction of the data to the primarily measured quantities or to the new standards, as well as a critical analysis of the corrections and uncertainties should be continued;

–because existing models show very small variation in the shape of the prompt fission neutron spectra with change of incident neutron energy from thermal to 0.5 MeV, experimental data for 0.5 MeV incident neutrons can be included in the fit at the later stage of the combined evaluation;

–the model calculations of the prompt fission neutron spectra and adjustment of the contribution of the reaction mechanisms and model parameters should be done first for the ^{252}Cf(sf) PFNS since that PFNS is known with higher accuracy than those determined for neutron induced reactions;

–the use of the model for data smoothing should be taken with care; the model fit should follow the general trends in the spectra shape obtained in the non-model evaluation. A few approaches can be used in the model smoothing: a mathematical spline for central values without changes of the covariance matrix of the uncertainty, a physical model fit with the model covariance matrix of uncertainties generated in the Monte Carlo calculations with a stochastic spread of the model parameters inside their uncertainties or with the model dependence best adjusted to the experimental data and a specially designed covariance matrix, which keeps only strong correlations between neighboring points;

–the study and comparison of the results of smoothing should be tested first with a non-model evaluation of the ^{252}Cf(sf) prompt fission neutron spectrum and then, after justifying the best approach, the smoothing could be applied to the prompt fission neutron spectra evaluated for neutron-induced reactions;

–new measurements of prompt fission neutron spectra should be optimized in such a way that they can obtain accurate data for low ($E_n < 1$ MeV), or for high ($E_n > 6$ MeV) energy ranges of the spectra;

–this also refers to the measurements of fission spectrum averaged cross sections, - in this case new spectrum averaged reaction cross sections with a large response to the fission spectra below 1 MeV (such as direct measurements in the beam of fission neutrons with ^{6}Li(n,t) and ^{10}B(n,α) detectors or using activation detectors with specific capture reactions having their largest reaction rates below 1 MeV and not sensitive to thermal neutrons, e.g. ^{19}F(n,γ), ^{45}Sc(n,γ) and ^{187}Re(n,γ)) could be proposed);

–accurate characterization of the prompt neutron spectra from fission induced by thermal neutrons with good geometry should be done; existing data show large descrepancies between the results of measurements done in specially designed setups created to produce the minimum possible perturbation of the prompt fission neutron spectrum and most of the other measurements without that condition

List of actions: Measurements and evaluation of prompt fission neutron spectra:

No.	Action	Responsible	Terms
1	Send participants the results of ^{252}Cf/^{235}U absolute ratio measurements of prompt fission neutron spectra done at IKI for 100 K neutrons and effective energy of IKI spectra for 1/v cross section	F.-J. Hambsch, N.V. Kornilov	June 2011
2	Obtain the results of the last LANL measurements for ^{235}U(n,f), ^{239}Pu(n,f) and ^{233}U(n,f) (note LANL is not doing thermal measurements)	A. Carlson	December 2011
3	Reduce all experimental data on ^{235}U(n_{th},f) PFNS to their original measured quantities and to analyze and revise the uncertainties	W. Mannhart, V.G. Pronyaev	June 2011
4	Finalize a combined fit of ^{252}Cf(sf) and ^{235}U(n_{th},f) PFNS	V.G. Pronyaev, W. Mannhart	September 2011
5	Reduce all experimental data for ^{233}U(n_{th},f) and ^{239}Pu(n_{th},f) PFNS to the original measured quantities and to analyze and revise the uncertainties	W. Mannhart, V.G. Pronyaev	December 2011
6	Finalize a combined fit of ^{252}Cf(sf), and ^{235}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f) PFNS	V.G. Pronyaev, W. Mannhart	May 2012
7	Send to participants of PFNS CRP the non-model evaluation by Mannhart of the ^{252}Cf(sf) PFNS for adjusting and testing of the models and smoothing procedures	R. Capote, V.G. Pronyaev	December 2010
8	Make intercomparisons of different smoothing procedures of the non-model evaluation of the ^{252}Cf(sf) PFNS	R. Capote, W. Mannhart, V.G. Pronyaev	May 2011
9	Prepare final non-model, smoothed and normalized evaluation of the ^{252}Cf(sf), and ^{235}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{233}U(n_{th},f) PFNS	V.G. Pronyaev, W. Mannhart	June 2012
10	Obtain full information from K. Kobayashi about conditions of his measurements of spectrum averaged cross sections and the characterization of the PFNS spectra in his different set-ups	N. Otsuka	December 2010
11	Propose for inclusion in the HPRL direct and activation measurements of the PFNS averaged cross sections most sensitive to the low-energy part of the spectra (as preliminary measurements: ^{6}Li(n,t), ^{10}B(n,α), ^{19}F(n,γ), ^{21}Sc(n,γ) and ^{187}Re(n,γ))	W. Mannhart, V.G. Pronyaev	May 2011
12	Propose for inclusion in the HPRL measurements of the PFNS optimized for reaching the best accuracy at the low or high energy part of the spectra	W. Mannhart, V.G. Pronyaev	May 2011

3. Measurements and evaluation of ^{197}Au(n,γ) cross section

It was agreed that the final results for most measurements will be made available within one year. Because the cross sections will be obtained at different laboratories using different methods of measurements, background determination and cross section normalization, it is expected that based only at these data, the accuracy of the ^{197}Au(n,γ) cross section in wide energy groups will be limited to 2 – 3 %. Because the cross section has physical fluctuations, at least in the energy range below 20 keV, the choice of the energy bin structure for cross section presentation is important for neutron energies above the resolved resonance region (3 keV at present).

The following actions are planned to be implemented to finalize the measurements and evaluation:

No.	Action	Responsible	Date
1	Select the energy bin structure for the ^{197}Au(n,γ) cross section presentation, comparison and evaluation, taking into account the data obtained in "low" resolution measurements of capture cross section for astrophysical applications	F. Käppeler C. Lederer, P. Schillebeeckx,	May 2011
2	Finalize and distribute the results of time of flight measurements of ^{197}Au(n,γ) cross section done at CERN and Geel.	C. Lederer, P. Schillebeeckx, A. Carlson	October 2011
3	Present details of the n_TOF (CERN) neutron flux determination	F. Kaeppeler, C. Lederer	October 2011
4	Finalize the results of measurements of energy-angular distributions of the neutron yield from a thick ^{7}Li target in the (p,n) reaction with E_p=1912 keV and different flight paths; evaluate the neutron spectra for the case of ^{197}Au irradiation in close geometry	C. Lederer, F. Kaeppeler	May 2011
5	Report the progress of ^{197}Au(n,γ) activation measurements at IRMM taking into account all possible corrections	F. Kaeppeler	October 2011
6	Calculate and validate the spectra produced via the ^{7}Li(p,n) reaction in thick targets for different proton energies and "shaped" proton beams	P. Mastinu	October 2011
7	Present the final results for the ^{238}U(n,γ)/^{197}Au(n,γ) and ^{238}U(n,γ)/^{235}U(n,γ) ratios obtained with the accelerator mass spectrometry technique for cross sections averaged in a simulated Maxwellian spectrum with kT=25 keV and also at about 450 keV with a broad energy spectra. The results at thermal and with a cold neutron beam will be of interest for validation of the method.	A. Wallner	January 2011
8	Update the standards evaluation and in particular the ^{197}Au(n,γ) and ^{238}U(n,γ) cross sections in the GMA combined fit with the inclusion of new experimental data	V.G. Pronyaev	August 2012

4. Measurements and evaluation of reference gamma-production cross sections

The new re-analysis of the corrections which are needed for the gamma-production cross section measurements done at Geel and LANL for ^{56}Fe(n,n'γ) and ^{52}Cr(n,n'γ) have shown that the data with revised corrections are generally in good agreement with the results of the old IRK-IPPE evaluations done for the JEFF library in 1992 – 1995. Because the IRK-IPPE evaluations are based on non-model generalized least-squares fits of data for all reactions and their combinations available before 1995, they can be updated using the Bayesian approach for inclusion of new experimental data. This also relates to the ^{48}Ti(n,n'γ) reaction, which was evaluated at IRK in 2002. Since 1995 new experimental data have been obtained for branching coefficients in gamma-transitions schemes for states populated near neutron binding energies. Also the model calculations can be used for estimation of branching transitions, where they are not known from experiment. Based on this, new estimations of the probability of gamma-transition from the first excited to ground state in ^{56}Fe, ^{52}Cr and ^{48}Ti can be obtained and used in the combined fit of reaction cross sections. Although the ^{48}Ti(n,n'γ) and ^{48}Ti(n,2n'γ) reactions are considered the best candidates for gamma-production reference cross sections in the energy range from threshold of the (n,n') reaction to 20 MeV, at the first stage of our work it may still be useful to perform evaluations for the ^{56}Fe(n,n'γ) and ^{52}Cr(n,n'γ) reactions, for which a large body of experimental data exists.

Results of discussions summarizing the actions which should be implemented to finalize the measurements and evaluations:

No.	Action	Responsible	Date
1	Request from the IRK(VERA) the latest version of the GLUCS code for use in the evaluation of gamma-production cross sections and send it to the Nuclear Data Section of the IAEA (R. Capote, S.P. Simakov)	A. Wallner	January 2011
2	Calculate and estimate the energy dependence of the probability of gamma-transitions between the first excited and ground states for ^{56}Fe, ^{52}Cr and ^{48}Ti for inelastic scattering of neutrons and for ^{47}Ti after the ^{48}Ti(n,2n) reaction	R. Capote, S.P. Simakov, V.G. Pronyaev	October 2011
3	Present the final results of measurements of gamma-production cross sections for ^{56}Fe, ^{52}Cr and ^{48}Ti done at LANL and Geel for the incident neutron energy range between threshold and 20 MeV	R. Nelson, A. Carlson	October 2011
4	Using the IRK-IPPE evaluation of the total inelastic scattering cross section and its covariance matrix of uncertainties for ^{56}Fe and ^{52}Cr and the estimated probability of gamma-transitions as a prior, evaluate with the use of the Bayes procedure the gamma-production cross section after including the new experimental data in the fit. Send the results of the evaluation to the participants for discussions	V.G. Pronyaev, R. Nelson	May 2012
5	Using the IRK evaluation of the total inelastic scattering cross section, the (n,2n) cross section and their covariance matrix of uncertainties for ^{48}Ti and the estimated probability of gamma-transitions as a prior, evaluate with the use of the Bayesian procedure the gamma-production cross section for the ^{48}Ti(n,n') and ^{48}Ti(n,2n) reactions after including the new experimental data in the fit. Send the results of evaluation to the participants for discussions	V.G. Pronyaev, R. Nelson	August 2012

5. Smoothing of the standards, reference cross sections and spectra obtained in the non-model evaluations

Different approaches to the smoothing of the standards, reference cross section and spectra obtained in the non-model least-squares fits were discussed. They include simple three-point smoothing or spline fits through the central values without changes of the covariances, smoothing using the shapes predicted in physical model calculations and specially designed covariance matrices which smooth the data and covariances only between neighbouring points, smoothing with the use of model calculations and a covariance matrix which keeps the model-type correlations. Smoothing of the prompt fission neutron spectra and covariances evaluated in a non-model fit of experimental data is needed if a constraint that the normalization is equal to 1 will be used. Without this smoothing, the normalization may lead to an increase of non-smoothness of the spectra. A general agreement was reached, that the smoothing should introduce minimal impact on the uncertainties obtained from a basic experimental data evaluation. It generally means that all changes in the matrix introduced by smoothing will occur for elements near its diagonal in the form of smoothing of elements of the matrix and their sum will not be changed by much.

The following actions are planned to select the most appropriate approach for smoothing:

No.	Action	Responsible	Date
1	Distribute to the participants the results of the non-model evaluation of the PFNS for ^{252}Cf(sf) (spectrum and covariance matrix of uncertainties)	V.G. Pronyaev	December 2010
2	Smooth the ^{252}Cf(sf) spectra by different methods and compare the results (smoothed central values and covariance matrix of uncertainties)	R. Capote, W. Mannhart, V.G. Pronyaev	May 2011
3	Discuss the results and make recommendations	All project participants	August 2011

Goals to be reached by October 2012

1. Revised evaluation of the traditional standards with inclusion of all new experimental data.
2. Combined non-model evaluation of prompt fission neutron spectra for ^{252}Cf(sf), ^{233}U(n_{th},f), ^{239}Pu(n_{th},f) and ^{235}U(n_{th},f) as reference spectrum.
3. Evaluated ^{197}Au(n,γ) cross section data in the energy range 3 – 200 keV which can be used as a reference cross section in the measurements of capture cross sections for other nuclei in astrophysical applications.
4. Reference gamma-production cross sections for inelastic neutron scattering by ^{56}Fe, ^{52}Cr, ^{48}Ti and the (n,2n) reaction at ^{48}Ti.
5. Results of smoothing procedures and their application for cross sections and spectra.

APPENDIX 1

Consultants' Meeting on

"International Neutron Cross-Section Standards: Extending and Updating"

IAEA Headquarters, Vienna, Austria
13 – 15 October 2010

Meeting Room VIC M0E61

AGENDA

Wednesday, 13 October

08:00 - 09:00 **Registration** (IAEA Registration desk, Gate 1)

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

Welcoming address – R.A. Forrest
Introductory Remarks – R. Capote Noy, V. Pronyaev
Election of Chairman and Rapporteur
Adoption of Agenda

09:30 - 10:45 **Implementation of actions from last CM** (no technical details):

- Compilation of new experimental data for GMA database (15 actions)
- ^{252}Cf (s,f) and ^{252}U(n_{th},f) prompt fission neutron spectra measurement and evaluation (15 actions)
- ^{197}Au(n,g) reaction as reference cross section (6 actions)
- Reference cross sections for prompt gamma-ray production in fast neutron-induced reactions (6 actions)

Review of the results of measurements obtained or near completion since last CM (A. Carlson, 30 min)

2006 release of standards and their publications by the IAEA (2006) and updated version in Nuclear Data Sheets (2009) – comments and critique from reviewers and users (all participants, 10 min)

10:45 - 11:15 Coffee break, administrative matters

11:15 - 12:45 ^{235}U(n_{th},f) prompt fission neutron spectra induced by thermal neutrons: reliability of the spectra in the energy region above 8 MeV (P. Schillebeeckx, 30 min)

^{235}U(n_{th},f) prompt fission neutron spectra measured with multi-detector registry systems (A. Vorobyev, 30 min)

General discussions (30 min):

Dependence of the PFNS in the energy range below 1 MeV and above 8 MeV.
Possibility of low uncertainty measurements of the differential spectra in the energy below 1 and above 8 MeV.
Benchmark experiments for testing of the PFNS in the low and high-energy range.

12:45 – 14:00 ***Lunch***

14:00 – 15:45 General approach to data evaluation based on model calculations and experimental data Unified Monte Carlo method and GLS (R Capote, 30 min)

Combined GMA evaluation of prompt fission neutron spectra for fissile nuclides induced by thermal neutrons and ^{252}Cf(sf) (W. Mannhart, V.G. Pronyaev): general approach and preliminary results (V.G. Pronyaev, 30 min); existing problems and what is still needed to do (W. Mannhart, 30 min).

The discrepancy of $\langle\sigma\rangle$ measurements in the ^{235}U neutron field at high neutron energies (W. Mannhart, 15 min)

15:45 – 17:30 **Discussions:** GMA methodology of the combined evaluation of the prompt fission neutron spectra for fissile nuclides and ^{252}Cf: can it be improved, accepted? Other alternatives for evaluation of the standard ^{252}Cf(sf) and recommended ^{235}U(n_{th},f) prompt fission neutron spectra.

Coffee break as needed

Thursday, 14 October

09:00 - 10:40 ^{197}Au(n,γ), ^{238}U(n,γ) and their ratio measurements: impact at the evaluation of ^{197}Au(n,γ) reaction as a reference for capture cross section measurements at energies of importance for astrophysics (E_n < 200 keV) (A. Wallner, 25 min)

Results of n-TOF ^{197}Au(n,γ) cross-section measurements: structures in the cross sections above 20 keV, structures in the background Results of measurements of simulated Maxwellian (kT = 25 keV) spectrum averaged ^{197}Au(n,γ) cross section using different methods (C. Lederer, 25 min)

Final results of ^{197}Au + n reaction cross section measurements to 200 keV incident neutron energy (P. Schillebeeckx, 25 min)

New analysis of ^{197}Au(n,γ) cross-section measurements in keV energy range with account of latest measurements (F. Kaeppeler, 25 min).

10:40 – 12:30 **Discussions: ^{197}Au(n,γ) reaction as a reference for capture cross section** measurements in the energy range of importance to astrophysics (1< E_n < 200 keV). Consistency between ^{197}Au(n,γ), ^{238}U(n,γ) measurements and their ratios in the energy range 10 – 100 keV.

Coffee break as needed

12:30 – 14:00 ***Lunch***

14:00 - 15:30 **Discussions:** $^{197}Au(n,\gamma)$ reaction as a reference for capture cross section measurements in the energy range of importance to astrophysics ($1< E_n <$ 200 keV). Consistency between $^{197}Au(n,\gamma)$, $^{238}U(n,\gamma)$ measurements and their ratios in the energy range 10 – 100 keV.

15:30 - 17:00 Latest LANSCE measurements of gamma-production cross sections, which can be used as reference cross sections (A. Carlson, 30 min)

Revision of the results obtained for 1.454-MeV gamma-line production cross section for $^{52}Cr(n,n'\gamma)$ in the energy range from threshold to 20 MeV by L.C.Mihailescu et al., Nucl. Phys., A786, p. 1 (2007) (A. Carlson, 10 min)

Discussions: Reference cross sections for prompt gamma-ray production in neutron-induced reactions (40 min)

Coffee break as needed

19:00 ***Dinner in the city***

Friday, 15 October

09:00 - 11:00 **Discussions of various problems related to standards evaluation**

- Use of physical models for final presentation of "model-independent" evaluated cross sections, spectra and covariances through their smoothing, - to provide the smoothness needed to cross sections and spectra used as standard and to avoid unphysical divergence of the spectra at their normalization. This type of smoothing will not change general energy dependence, but smoothes the unphysical fluctuation of the cross sections and spectra
- Use of physical models with the adjustment of the parameters in the fit of the "model-independent" cross sections (e.g. Watt or Madland-Nix model for prompt fission neutron spectra and statistical model for capture cross section)
- Other problems needed to be discussed

11:00 – 12:30 Discussion of the next terms for standard and reference cross-sections and spectra release, and how this work can be organized

Coffee break as needed

12:30 – 14:00 ***Lunch***

14:00 – 16:00 Preparation of work plan and responsibilities for next release of new standards and reference cross sections and spectra

Closing of the meeting

APPENDIX 2

Consultants' Meeting on

"International Neutron Cross-Section Standards: Extending and Updating"

IAEA Headquarters, Vienna, Austria
13 – 15 October 2010
Meeting Room VIC M0E61

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Participants of the Consultants' Meeting on International Neutron Cross-Section Standards: Extending and Updating (from left to right):
1st row (sitting) – P. Mastinu, R. Capote Noy, V. Pronyaev and A. Carlson;
2nd row (standing) –F. Käppeler, P. Schillebeeckx, A. Wallner, C. Lederer, A. Vorobyev, W. Mannhart and N. Otsuka

APPENDIX 3

PRESENTATIONS

Presentations of the participants are available at: http://www-nds.iaea.org/standards/CM2010)

1. A.D. Carlson: Recent Measurements of Cross Sections Relevant for An Evaluation of the Neutron Cross Section Standards

2. A.D. Carlson: Discussion of the 52Cr(n,n'γ) Experiment of Mihailescu et al.

3. F.-J. Hambsch, C. Matei, N. Kornilov, S. Oberstedt, Sh. Zeynalov: Prompt fission neutron emission spectrum of ^{235}U(n,f) at thermal energies

4. F. Kaeppeler: ^{197}Au(n, γ) measurement in the quasi-stellar neutron spectrum for kT=25 keV

5. C. Lederer: The ^{197}Au(n, γ) cross-section in the unresolved resonance region

6. W. Mannhart: The mystery of the errors in the GMA evaluation of the PFNS of U-235

7. W. Mannhart: Discrepancy of $\langle\sigma\rangle$ measurements in the U-235 neutron field at high neutron energies

8. W. Mannhart: Status of the Evaluation of the Neutron Spectrum of ^{235}U + n_{th}

9. R.O. Nelson: Fast Neutron-Induced Gamma-Ray Reference Cross Sections

10. V.G. Pronyaev: ^{197}Au(n, γ) Standard Cross Section and Experimental Data

11. V.G. Pronyaev: Combined evaluation of prompt fission neutron spectra for ^{235}U(n_{th},f), ^{239}Pu(n_{th},f), ^{233}U(n_{th},f) and ^{252}Cf(sf)

12. C. Lampoudis, S. Kopecky, C. Massimi, M. Moxon and P. Schillebeeckx: Capture cross section measurements for ^{197}Au at GELINA from 5 – 80 keV

13. A.S. Vorobyev, O.A. Shcherbakov, A.M. Gagarski, G.V. Val'ski, G.A. Petrov: Prompt neutron emission in thermal neutron-induced fission of ^{235}U(n_{th}, f)

14. A. Wallner: Neutron Capture Studies of ^{235}U and ^{238}U via AMS

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