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International Neutron Cross-Section Standards:

Measurements and Evaluation Techniques

Summary Report
Consultants' Meeting

13 – 15 October 2008

Prepared by

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November 2008

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Abstract

A Consultants' Meeting on International Neutron Cross-Section Standards: Measurements and Evaluation Techniques was held on 13-15 October 2008 at the IAEA Headquarters, Vienna, Austria. All presentations, discussions and recommendations of this meeting are given in this report. The purpose of the meeting was to review the status of the international cross-section standards released in 2006, and to consider the possibility of extending the energy ranges and including new reactions that could be considered for adoption as reference cross sections (or were used during the initial studies). This data development project has been endorsed by the International Nuclear Data Committee as an important activity to be maintained under the auspices of the Nuclear Data Section of the IAEA.

November 2008

TABLE OF CONTENTS

Abstract 3

1. Introduction 7
2. Neutron Cross-Section Standards: Recent Studies and Advances 7
2.1. Uncertainties 7
2.2. Most recent neutron cross-section measurements 8
2.3. n_TOF measurements of neutron cross-section standards 9
2.4. LANL model for prompt fission neutron spectra 9
2.5. Measurements of $^{235}U(n,f)$ prompt fission neutron spectra 9
2.6. Selection and evaluation of data for ^{252}Cf spontaneous fission and ^{235}U thermal neutron-induced fission 10
2.7. Cross sections for the $^{197}Au(n,\gamma)$ reaction 10
2.8. Gamma-ray production cross sections for the $^{56}Fe(n,n'\gamma)$, $^{52}Cr(n,n'\gamma)$ and other reactions 11
3. Specific Problem Areas 12
4. Discussions, Recommendations and Actions 12
4.1 Neutron cross-section standards 12
4.2. Standards evaluation for ^{252}Cf spontaneous fission spectra and reference evaluation for $^{235}U(n_{th},f)$ fission neutron spectra 14
4.3. $^{197}Au(n,\gamma)$ reaction as a reference for capture cross-section measurements at energies of importance to astrophysics (E_n < 200 keV) 17
4.4. Reference cross sections for prompt gamma-ray production in fast neutron-induced reactions 20
5. Common Problems Identified with the Standards and Reference Cross-Section Evaluations 21

Appendices

A. Final Agenda 23
B. List of participants 27
C. Presentations – Web Links 29

1. Introduction

The Consultants' Meeting was opened by Vladimir Pronyaev, as Scientific Secretary. He welcomed participants and gave a few remarks concerning the status of the project, and how future work would be organized. After completing the evaluation of the international neutron cross-section standards in 2004, work in support of the continuous updating of the experimental database for new evaluations of the standards, extension of the energy ranges, and maintenance of the international evaluations of the most important reference cross sections was strongly recommended by the International Nuclear Data Committee (INDC). This proposal has subsequently been implemented as a Data Development Project (DDP) within the Nuclear Data Section of the IAEA, with the opportunity taken to hold a Consultants' Meeting every two or three years in order to agree and coordinate the measurements and evaluations of the participants between such meetings. These studies can be undertaken because the work of participants is either part of their existing research activities or voluntary contributions from retired scientists who wish to finalize results and preserve their knowledge for future generations. The outcome of the DDP will not only be evaluated standard and reference cross-section files and associated documents, but also the experimental databases with data re-analysed by experts, corrected when necessary, and developed further by the addition of covariance matrices of their uncertainties and computer codes used for the data preparation and statistical processing. The final Agenda and list of participants are given in Appendices A and B, respectively. Resolutions to issues and problems listed in the Agenda are important for the ultimate success of the project. Allan Carlson was elected as Chairman, and the Agenda was adopted with minor corrections.

As Head of the Nuclear Data Section (NDS), Alan Nichols welcomed all participants to the IAEA, and explained that the approved existence of the cross-section standards project in the NDS programme had followed on from various recommendations from the nuclear physics community and the International Nuclear Data Committee (INDC) as a major external advisory body to the IAEA. INDC members had argued that revisions and updates of the standards are required on a regular basis, and that the 2006 revision had taken place too long a time interval after the previous release in 1991. The damaging impact of the on-going loss of expertise in this field might also be reduced by the organisation of continuous activities to update and extend the neutron cross-section standards, with more frequent releases. New experimental data obtained at the major measurement centres (LANL, IRMM, ORNL, CERN, NIST, Ohio University and PTB) are capable of providing a solid basis for the updating and extension of these standards.

2. Neutron Cross-Section Standards: Recent Studies and Advances

2.1. Uncertainties

Vladimir Pronyaev led the initial discussions concerning a series of comments on the cross-section standards as released, and also presented results of tests against well-defined criticality benchmarks (see attached viewgraphs). Since the completion of the previous standards evaluation for ENDF/B-VI in 1987, criticism has been levelled at the low uncertainties obtained in the course of these earlier evaluations, especially in the R-matrix model fit of the cross sections for the light nuclides. Very few relevant publications were presented at the two previous International Conferences on Nuclear Data for Science and Technology (Santa Fé, 2004; Nice, 2007) which might have aided in the resolution of the nature of these uncertainties. The justification for such low values is based on the fact that the covariance matrices of the uncertainties for the experimental data include all known correlations (cross-energy and cross-reaction). If all correlations are not included, the resulting uncertainties would be even smaller. Outliers were identified and their uncertainties were revised by introducing additional components of the uncertainty. The significant reduction of the percentage uncertainties in the R-matrix fit is explained not only in terms of the contribution of many other data from reaction channels that differ from the standard reaction channel, but also by strong correlations (large off-diagonal covariances) which appear in the model fit. Non-model and model fits lead to large differences in the variances, and generate uncertainties in good agreement if they are calculated over a broad energy spectrum.

Other critical comments concerned the large fluctuations in the percentage uncertainties (or variances) for the capture cross-sections obtained from the standards evaluation that should be smooth according to the existing physical models. All cross sections were smoothed for the final presentation of the cross sections obtained from the standards evaluation by means of a simple three-point mathematical model, while the uncertainties were not changed. Results from physical model calculations to smooth the cross sections and covariances could be used in this manner (paper presented and attached). Most recommended files obtained from the standards evaluation were adopted in the ENDF/B-VII general purpose library which has been tested in criticality safety benchmark experiments. Results from clean benchmarks (containing a minimum of other materials and most sensitive to the reactions obtained from the standards evaluation) were selected and presented in terms of the number of cases falling within specific intervals of deviation when determining k_{eff}. There are no biases in the distribution of the calculation to experiment ratios relative to one, and about 2/3rds of all cases fall within a bias of –0.3% to +0.3% for practically all types of benchmarks. Systems with thermal and intermediate neutron spectra and large quantities of ^{239}Pu are exceptions to this observation: reactivity is over-predicted on average by about 0.6%, depending on the size of the assembly. The general conclusion is that the cross sections obtained from the standards evaluation in the general purpose file as used in benchmark calculations do not lead to biases in the prediction of k_{eff} – they predict k_{eff} with an uncertainty of about 0.3% which is comparable with the uncertainties in the results of most clean benchmark experiments.

2.2. Most recent neutron cross-section measurements

Allan Carlson reviewed the results of the latest measurements underway or completed of relevance to the neutron cross-section standards, and data availability (viewgraphs attached). Measurements have been made related to all the neutron cross section standards since the completion of the international standards evaluation process. Significant efforts have been made in the following areas:

New measurements have been made of the angular distributions of neutrons elastically scattered on hydrogen near 14 MeV at the Ohio and Osaka Universities, and at about 200 MeV at the Indiana and Uppsala Universities. The hydrogen cross section is often considered a primary standard since so many standard cross sections are measured relative to it. Though the new measurements have improved the database, there is still a need for improved measurements in that entire energy region. Data are needed at small angles in the CMS near 14 MeV. There are still unresolved differences as large as 10% in back angle measurements from about 200 to 580 MeV. There is a particular need for data that extend over a large angular range and for data in the intermediate and high energy regions. Work has been completed on coherent scattering measurements and total cross section determinations for ^{3}He in NIST collaborations. These data can be used in an R-matrix evaluation of the ^{3}He(n,p) standard cross section. The evaluation of this cross section for the international standards of neutron cross sections was not completed due to data inconsistencies. These data may remove that problem. NIST measurements are being made of the ^{6}Li(n,t) cross section at 4 meV. Angular distribution measurements for that reaction at higher neutron energies have been completed at Peking University and LANL. The integrated LANL data suggest that the cross section should be higher at high neutron energies. Using the IRMM Van de Graaff and

LINAC facilities, branching ratio, angular distribution and cross section data have been and continue to be obtained for the $^{10}B(n,\alpha)$ reaction. Also $^{10}B(n,\alpha)$ cross section data have been obtained at Peking University in the MeV energy region and are being obtained at NIST at 4 meV. The $^{6}Li(n,t)$ and $^{10}B(n,\alpha)$ data should eventually allow these standards to be extended to higher energies. Measurements of the carbon total cross section have been made at RPI that agree very well with the ENDF/B-VII evaluation. n_TOF measurements of the gold capture cross section that are being analyzed may extend into the standards region. Measurements of the $^{238}U(n,\gamma)$ cross section relative to gold capture have been made at the University of Vienna which will have an impact on evaluations of both of these cross sections. Preliminary measurements have been made of the $^{238}U(n,f)$/ $^{235}U(n,f)$ cross section ratio at the n_TOF facility using two different techniques and also final data on this ratio have been obtained at PTB. They all tend to agree with early LANL data. Very accurate fission cross section measurements are planned in a LANL-LLNL collaboration.

2.3. n_TOF measurements of neutron cross-section standards

Both the status and availability of standards data measured as part of the n_TOF project were discussed in the presentation given by Alberto Mengoni (viewgraphs attached). Consistent results for the neutron capture reaction on gold in the resolved resonance region have been obtained within 2% by means of two different detectors, following the introduction of all necessary corrections. Capture cross sections in the unresolved resonance region above 10 keV could only be derived from measurements performed with C_6D_6 detectors (one of two different set-ups used at n_TOF). Preliminary results for the n_TOF measurements involving these two different techniques exhibit good consistency with the evaluated standards in the resolved energy region.

2.4. LANL model for prompt fission neutron spectra

Patrick Talou described the LANL model for prompt fission neutron spectra calculations (viewgraphs attached). The original model has been substantially improved with a more detailed definition of the fission process based on physical considerations and empirical results. This model can be tested by comparing the calculated prompt fission neutron spectra with experimental data, and also by determining the multiplicities in the fission neutron yields. The methodology adopted to evaluate the uncertainties of the fission neutron spectra fitted within the LANL model involves the application of the KALMAN filtering technique to propagate the experimental uncertainties in the determination of the uncertainty of the evaluated data. New experimental data that quantify the kinetic and excitation energy distributions of the fragments will soon become available to improve our knowledge of the initial conditions determining the prompt neutron emission (time-projection chamber at LANL/LLNL and Elise @ FAIR at GSI).

2.5. Measurements of $^{235}U(n,f)$ prompt fission neutron spectra

Preliminary measurements at IKI (Budapest) and IRMM (Geel) of $^{235}U(n,f)$ prompt fission neutron spectra for thermal and 0.5-MeV incident neutrons were presented by Franz-Josef Hambsch (viewgraphs attached). These measurements were carried out with three-detector systems, and data were obtained for neutron energies below 12 MeV at 90, 120 and 150 degrees to the neutron beam. Spectra at a neutron incident energy of 0.5 MeV show some dependence on the angle at which they were measured to a limit of about 5%. The data are consistent with earlier measurements when spectra measured at the same angles are compared (exclusive of the data set at 120 degrees). Data show some discrepancy against the predictions of the LANL model at high and low neutron energies which can possibly be resolved if the contribution from the scission neutron emission reaction can be quantified and added. The analysis of the results of measurements of the energy-angular distributions of fission neutrons relative to the fission fragments (e.g. different multi-dimensional neutron - fission fragment coincidence measurements) will help to produce more accurate estimates of the yield of scission neutrons. The mean neutron energies of the measured spectra continue to be less than the value extracted from the benchmark experiments.

2.6. Selection and evaluation of data for ^{252}Cf spontaneous fission and ^{235}U thermal neutron-induced fission

Wolf Mannhart presented the experimental database and the selection criteria used in the ENDF/B-VI evaluation of the neutron spectrum of the spontaneous fission of ^{252}Cf (viewgraphs attached). The evaluated database comprises six advanced TOF experiments performed between 1983 and 1990. Since this evaluation, only two additional TOF experiments have been performed (both published in 1990). The data from these experiments differ substantially at high neutron energies, with a hardening of the evaluated neutron spectrum above 15 MeV neutron energy.

Analysis of the database of measurements of the neutron spectrum of $^{235}U(n_{th},f)$ resulted in only three TOF experiments performed since 1975 (viewgraphs attached). The level of documentation of the experiments is poor, which hardens the generation of qualified covariance matrices. High energy data (> 10 MeV) are in contradiction to the spectrum-averaged cross-section data. Spectrum data were compared with different versions of the Madland-Nix model, which minimizes the differences between model and integral spectrum data in the ENDF/B-VI evaluation. The quality of the spectral database of ^{252}Cf is much better than that of $^{235}U(n_{th},f)$. There are no TOF experiments since 1991, with the exception of an IRMM experiment of $^{235}U(n_{th},f)$ in progress.

2.7. Cross sections for the $^{197}Au(n,\gamma)$ reaction

Franz Käppler presented an evaluation of the reference cross section for the $^{197}Au(n,\gamma)$ reaction based on the results of precise measurements of the cross section averaged over the Maxwellian-like experimentally simulated spectrum with temperature near 25 keV (viewgraphs attached). Many neutron capture cross-section measurements for reactions important for astrophysics and reactor applications were undertaken relative to this group-averaged reference cross section. Discrepancies occur in comparisons with the present standards evaluation, which in turn has internal anomalies between the data in the experimental database used for the standards evaluation and the new accurate measurements using the time-of-flight method. New measurements done with different methods and detectors are required to assist in the resolution of these discrepancies.

Vladimir Pronyaev described the $^{197}Au(n,\gamma)$ cross-section evaluation for the standards database (report attached). Cross sections below 200 keV were not recommended for use in this standard, although an evaluation in the energy range from 2 to 200 keV is available. The standards evaluation is approximately 6% to 8% above the reference cross section adopted in capture cross-section measurements for astrophysics applications. There is also a discrepancy of the same magnitude between the results of most measurements of the $^{238}U(n,\gamma)/^{197}Au(n,\gamma)$ cross-section ratio by means of time-of-flight using the prompt gamma registration method and the ratio obtained in the combined fit of the standard. Both discrepancies can only be resolved with new time-of-flight measurements in which different detectors are used (total gamma-ray and total gamma-energy registration detectors), coupled with a careful analysis of detector efficiency and sensitivity to the neutrons as carried out for the resolved resonance region at IRMM and CERN.

The results of the CERN measurements and analysis of the $^{197}Au(n,\gamma)$ reaction cross section in the resolved resonance region were outlined by Alberto Mengoni (viewgraphs attached). Consistency between the averaged neutron capture determined by means of two different detectors is 2%, with differences in the capture kernels for individual resonances of the order of 5% to 15%. There is also good consistency with the result of independent measurements carried out at the IRMM with a total energy registration detector. Analysis and release of the results for energies above the resonance range are expected to resolve the present (6-8%) discrepancies.

Franz-Josef Hambsch presented the provisional results of studies undertaken by Peter Schillebeeckx and co-workers on the neutron capture of ^{197}Au by means of the time-of-flight method with C_6D_6 total gamma-energy detection scintillators located at GELINA, Geel (viewgraphs attached). A careful analysis was carried out to determine the efficiency of this detector (Borella *et al*., Nucl. Instrum. Methods Phys. Res., **A577** (2007) 626). Measurements have also been finalized for the resolved and unresolved resonance regions. Preliminary results for neutron capture cross sections in the energy range from 10 to 120 keV exhibit consistency with the standards evaluation within 2% to 3%, although the standards evaluation is 4% to 6% above the measured values for a few energy groups.

2.8. Gamma-ray production cross sections for the ^{56}Fe(n,n'γ), ^{52}Cr(n,n'γ) and other reactions

The methodology and results of an IRK evaluation of the 847-keV gamma-ray production cross section for the ^{56}Fe(n,n'γ) reaction and the 1454-keV gamma-ray production cross section for the ^{52}Cr(n,n'γ) reaction were described by Herbert Vonach (published as V. Pronyaev, S. Tagesen, H. Vonach, S. Badikov, Physik Daten, **13-8** (1995)). These evaluations involved carrying out combined fits of the directly measured gamma-production cross sections (reduced to the total inelastic cross sections by means of the known gamma-ray yield) with all other partial and total cross sections and related data. Thus, the various types of data measured by different methods contributed to the reduction of the uncertainty of the evaluated gamma-production cross sections. An updating of the evaluation of the 847-keV gamma-ray production cross section for the ^{56}Fe(n,n'γ) reaction by means of the Bayesian approach with the inclusion of new experimental data has produce a newly recommended data set that is suitable for adoption as a reference cross-section evaluation for prompt gamma-ray production over a wide energy range.

Ron Nelson has assessed the characteristics of the 847-keV gamma-ray production cross section for the ^{56}Fe(n,n'γ) reaction which complicate the use of this cross section as a secondary standard or reference cross section (viewgraphs attached). The main drawbacks are the presence of resonance structure in the cross section below about 5 MeV, the non-isotropic angular distribution in gamma yield which varies with the neutron energy, and the background from iron materials near the experiments. The contribution of the background in the Fe(n,n'γ) and Cr(n,n'γ) cross-section measurements at LANL are larger than considered originally (Fe(n,n'γ) data were published in 2004) and results for the Fe(n,n'γ) and Cr(n,n'γ) reactions with new corrections will be compared with independent measurements undertaken at IRMM, Geel, to resolve the discrepancies. A search for new reactions as potential reference cross sections has taken account of all specified requirements. The most appropriate candidates are monoisotopic Nb, Au and ^{48}Ti (slight preference for Nb), with a common disadvantage that there are relatively small numbers of measurements, the results of which are often discrepant. However, new measurements are planned at LANL for selected candidates.

Vladimir Pronyaev provided estimates of the relative yields of the 847- and 1454-keV gamma rays for the ^{56}Fe(n,n'γ) and ^{52}Cr(n,n'γ) reactions. At high neutron energies, the absolute yield is about 95% of the total inelastic scattering cross sections. The uncertainty of the resulting data depends strongly on the uncertainties in the emission probabilities of the gamma transitions and the uncertainty of the inelastic scattering cross sections for discrete and continuum levels. These results are also dependent on the parameters used in the statistical model calculations to describe the gamma transitions between the levels in the continuum and between the continuum and discrete levels. Under such circumstances, the uncertainty in the estimated gamma yields at high neutron energies can not be better than 2%, and should be taken into account when the evaluated total inelastic scattering cross section is converted to the production cross sections for these gamma rays.

3. Specific Problem Areas

Common problems that may appear in the evaluation of the standards and reference cross sections were presented and discussed. Roberto Capote noted difficulties with the combined fit of absolute data and their ratios (see attached viewgraphs). Problems of non-linearity caused by the inclusion of ratios in the fitting procedure may lead to substantial distortion of the probability distribution function from a Gaussian and a bias in the determination of the central value of the evaluated data compared with a linear least-squares fit. This is a general problem when evaluating data, but special attention should be paid to the standards since there are challenging requirements concerning the uncertainties.

Vladimir Pronyaev described how the results of physical model calculations can be used to smooth the evaluated cross sections and covariance matrices to obtain the final recommended set of standards and evaluated reference data (see attached paper). Three-point mathematical smoothing was initially applied to the cross sections without adjusting the covariances. Smoothing uses the results of physical model calculations, and retains the “kinks” in the capture cross sections near thresholds of inelastic scattering levels. Covariances for neighbouring energy points are also smoothed.

A proposal has also been made to include the results of high-resolution cross-section measurements in the resolved resonance region for heavy nuclides within the combined fit of the standards cross sections (see attached paper). These data are usually used in R-matrix fits to obtain R-matrix parameters without conversion to energy-dependent cross sections, and therefore they can not be used in the standards evaluation. Using the cross sections and covariances that can be obtained from the R-matrix evaluations, these high-resolution data can be used in the combined standard evaluation over the resolved resonance region, so that their extensive energy-based correlations improve the evaluation at higher energies.

4. Discussions, Recommendations and Actions

The participants discussed the recommendations and actions needed to reach the primary objectives of developing and maintaining the IAEA data set of international neutron cross-section standards. Lists of recommendations and actions for each major topic discussed are given below, based on extensive discussions and agreement between participants.

4.1 Neutron cross-section standards

The importance of maintaining and improving the neutron cross section standards suggests that experimental efforts be strongly encouraged. Also information on the database that was and will be used for international evaluations of the neutron cross section standards should be preserved and improved. Improvements to the evaluation process should be obtained and documented. The following views were expressed:

- Improvements in the hydrogen scattering cross section should be made because these data are considered a primary standard. New data should be entered into the database. Since extensions to higher energy are important, efforts should be made to ensure that the cross sections obtained using different calculational methods are consistent.

- New ^{3}He data should be incorporated into the evaluation process. Efforts should be made to incorporate these data into an evaluation of the standard.

- Work on the $^{6}Li(n,t)$ and $^{10}B(n,\alpha)$ cross sections may allow these cross sections to be extended to higher energies.

- LANL measurements of the $^{6}Li(n,t)$ cross section above 1 MeV differ from the standards evaluation. Efforts should be made to obtain final data for this experiment and also the Peking University and NIST measurements.

- Measurements are being made of the branching ratio, angular distribution and cross section for the $^{10}B(n,\alpha)$ reaction at IRMM. Also $^{10}B(n,\alpha)$ cross-section data have been obtained at Peking University in the MeV energy region and are being obtained at NIST at 4 meV.

- New data on the carbon scattering cross section are in agreement with the existing evaluation. A new evaluation does not seem warranted. The data will be stored in the IAEA site for possible use in the future, but can not be used in the existing evaluation process.

- n_TOF measurements of the gold capture cross section that are being analyzed may extend into the standards region.

- Measurements of the $^{238}U(n,\gamma)$ cross section relative to gold capture have been made at the University of Vienna which will have an impact on evaluations of both of these cross sections.

The various recommendations and actions from these discussions are shown in the following table:

No.	**Action**	**Responsible**	**Date**
1	Obtain Ohio University 14.9-MeV and Osaka University 14.2-MeV hydrogen angular distribution data, and place them in the standards database.	A.D. Carlson, V.G. Pronyaev	January 2009
2	Monitor progress being made on Time Projection Chamber measurements of the hydrogen cross section proposed at Ohio University.	A.D. Carlson	March 2010
3	Encourage comparison of Strakovsky (Arndt analysis) and Hale (EDA) calculations of the hydrogen cross section using the same database.	A.D. Carlson	February 2009
4	Encourage Hale to obtain covariances for standards data including hydrogen.	A.D. Carlson	March 2009
5	Monitor progress resolving the hydrogen scattering problem at high neutron energies.	A.D. Carlson	January 2010
6	Make new ^{3}He data available for evaluation of the standard.	A.D. Carlson	December 2008

7	Obtain $^{6}Li(n,t)$ data for LANL, Peking University and NIST measurements, and place them in the standards database.	A.D. Carlson, V.G. Pronyaev	March 2009
8	Monitor and eventually provide IRMM branching ratio, angular distribution and cross section data for the $^{10}B(n,\alpha)$ reaction. Add to the standards database.	F.-J. Hambsch, A.D. Carlson, V.G. Pronyaev	February 2010
9	Obtain $^{10}B(n,\alpha)$ cross section data from the Peking University and NIST experiments. Add to the standards database.	A.D. Carlson, V.G. Pronyaev	March 2009
10	Obtain measurements of the $^{238}U(n,\gamma)$ cross section relative to gold capture made at the University of Vienna, and place them in the standards database.	A.D. Carlson, V.G. Pronyaev, F. Käppler	May 2009
11	Determine the highest energy that Au(n,γ) cross section data can be obtained from the n_TOF project. Obtain data and place them in the standards database.	A. Mengoni, V.G. Pronyaev	May 2009
12	Complete work on smoothing the Au(n,γ) and $^{238}U(n,\gamma)$ standard cross sections. Ensure that smoothing of the covariances is reasonable and can be justified. Consider fission cross sections also.	V.G. Pronyaev	May 2009
13	Monitor progress being made on Time Projection Chamber measurements of the fission cross sections in the LANL/LLNL measurement programme.	A.D. Carlson	December 2009
14	Obtain final data on the $^{238}U(n,f)/^{235}U(n,f)$ cross section ratio from the two n_TOF projects, and place them in the standards database.	A. Mengoni, V.G. Pronyaev	August 2009
15	Follow-up on the proposal to include resolved energy region data in the standards evaluation using the cross sections and covariances from R-matrix evaluations.	V.G. Pronyaev	February 2009
16	Monitor additional activity on the standards, and make the results available.	A.D. Carlson, V.G. Pronyaev	March 2010

4.2. Standards evaluation for ^{252}Cf spontaneous fission spectra and reference evaluation for $^{235}U(n_{th},f)$ fission neutron spectra

A significant segment of the meeting was devoted to the evaluation, calculation and updating of the experimental database for ^{252}Cf spontaneous and $^{235}U(n_{th},f)$ neutron-induced fission neutron spectra. The following aspects of these data were discussed:

- latest developments in the modelling of the fission spectra based on the yields and excitation energy of the fission fragments, consideration of the possible emission of prescission neutrons, and contribution of the reaction mechanisms leading to the hardening of the fission neutron spectra;

- preliminary results of experimental studies of the thermal and 0.5-MeV neutron-induced fission neutron spectra of ^{235}U undertaken at IRMM and LANL;

- observed inconsistencies (possibly angular dependence) of the fission neutron yields in the IRMM measurements at 0.5 MeV, and their consistency with earlier experimental data obtained at different angles;

- evaluation methodology of fission neutron spectra based exclusively on experimental data. The least-squares procedure can only be applied to data which contain all relevant corrections of the measurement process;

- possible use of the multi-parameter fit with inclusion of all reaction mechanisms for point-wise presentation of the evaluated data;

- possible inclusion of other old and new experimental data in the database;

- difference in the mean neutron energy of the ^{235}U thermal neutron-induced fission neutron spectra obtained in evaluations of the microscopic data compared with the value estimated from reactor experiments;

- differences in the quality of the experimental data and evaluations for ^{252}Cf and ^{235}U fission neutron spectra - consideration of the former as standard spectra and the latter as reference spectra;

- large differences between experimental data and theoretical models at low (< 0.5 MeV) and high (> 10 MeV) neutron energies.

A series of conclusions, recommendations and actions were approved:

- LANL to consider the possibility of multi-parameter fits to the fission neutron spectra by means of the LANL model, and account for the contribution of other possible reaction mechanisms;

- IRMM and LANL to finalize the processing of their experimental data, and send the results to the Sub-group on fission spectra (Actions 1 to 3);

- analyze the quality of the fission neutron measurements carried out at the NIIAR (Starostov, Nefedov and Bojkov), and include the data in the fission neutron spectrum database if such an analysis shows that all important corrections have been made and the data (measurements with scintillation detectors and a fission chamber used as a neutron detector) can be renormalized to the new standards (Actions 4 to 5);

- existing database of ^{252}Cf neutron spectrum (ENDF/B-VI) can be used as *a priori* in future Bayesian approaches of updating the evaluation with new experimental data (Action 6);

- integral cross sections measured in standard ^{252}Cf(sf) and ^{235}U(n_{th},f) fission neutron spectra are good benchmarks for evaluated dosimetry cross sections and fission neutron spectra – plots of the ratios of calculated to experimental integral cross sections as a function of the mean neutron energy of the integrated response provide a general indication of the quality of the evaluated microscopic or integral cross sections, while the slope of the spline line relative to a constant level of 1 shows the quality of the evaluation of the fission neutron spectra shape – all known results represent supportive evidence that there is either no or a small over-prediction of the hardness of the ^{252}Cf(sf) spectra and probably some under-prediction of hardness of the ^{235}U(n_{th},f) spectra for neutrons with energies above 10 MeV (Actions 7 to 10);

- experimental and evaluated data on integral cross sections should be used to improve the evaluation of the standard and reference fission neutron spectra, especially in the regions where the uncertainties in the microscopic spectral data are very large (Action 11);

- measurements of 0.5-MeV neutron-induced ^{235}U(n,f) fission neutron spectra would be very useful in the analysis of contributions of different neutron emission mechanisms – physical models tuned through the fit of the results of these measurements may define the fission spectra induced by thermal neutrons (Action 12);

- the experimental database for the evaluation of ^{252}Cf(sf) and ^{235}U(n_{th},f) fission neutron spectra should be extended by adding new experimental data sets (Action 13);

- multiparameter physical model fit of the results of the general least-squares evaluation of the fission neutron spectra should include possible contributions of different mechanisms for the emission of neutrons (Action 14);

- even if the multiparameter physical model fit with inclusion of different mechanisms of neutron emission is not completely adequate for the fitted spectra, it can be used for smoothing and interpolation in preparation of the final evaluation in point-wise form (Action 15).

No.	**Action**	**Responsible**	**Date**
1	IRMM to finalize and provide data on the energy-angular distribution of fission neutrons in ^{235}U fission induced by 0.5-MeV neutrons	F.-J. Hambsch	May 2009
2	IRMM finalize and provide data on energy-angular distribution of fission neutrons in ^{235}U fission induced by thermal neutrons	F.-J. Hambsch	October 2009
3	LANL to finalize and provide data on ^{235}U fission neutron spectra	R. Nelson	May 2010
4	Translate Russian paper to English (B.I. Starostov, V.N. Nevedov and A.A. Bojcov, YK, **3** (1985)) which contains the final results of all measurements undertaken at NIIAR in two cycles of measurements, with different scintillator detectors used to detect the fission neutrons and fission chambers used to register the fission events; send translation to all Sub-group members	V.G. Pronyaev	October 2008
5	IRMM to check the NIIAR data used in the IRMM fission spectra evaluation	F.-J. Hambsch	October 2008
6	NDS to act as custodian of the evaluation of fission neutron spectra for ^{252}Cf(sf) and ^{235}U(n_{th},f) (spectra and covariances) by Wolf Mannhart. The experimental database of the ENDF/B-VI evaluation of ^{252}Cf(sf), without the smoothing process, will be made accessible on the standards Web site	A. Mengoni, V.G. Pronyaev	January 2009

7	NDS to publish the evaluations of ^{252}Cf(sf) and ^{235}U(n_{th},f) fission neutron spectrum integral cross sections (with cross-reaction covariance matrices) by Wolf Mannhart as an INDC(GER) report, and store these data sets on the standards Web site	A. Mengoni, V.G. Pronyaev	February 2009
8	Analyze values and uncertainties of the experimental integral cross sections as a function of the mean neutron energy of the high-threshold reactions	W. Mannhart	February 2009
9	NDS and IPPE to send Wolf Mannhart the IRDF-2002 database and other reaction files prepared for the update of IRDF-2002 (ten threshold reactions, and fission and capture reactions based on standards and ORNL evaluations)	R. Capote, V.G. Pronyaev	November 2009
10	IPPE to send Wolf Mannhart the comparison of the calculated and experimental integral cross sections obtained for the latest evaluations of dosimetry reaction cross sections	V.G. Pronyaev	November 2009
11	Consider possible inclusion of integral cross sections in the evaluated database of the neutron spectra of ^{252}Cf(sf) and ^{235}U(n_{th},f)	W. Mannhart	July 2009
12	Use the multiparameter model to fit the existing data on ^{235}U(n,f) fission neutron spectra, and assess the opportunity of reducing the 0.5-MeV experimental data to thermal neutron-induced fission via extrapolation	P. Talou, F.-J. Hambsch, N. Kornilov	May 2010
13	Extend the experimental database and obtain a new evaluation of the ^{252}Cf(sf) and ^{235}U(n_{th},f) fission neutron spectra based exclusively on experimental data	W. Mannhart	May 2010
14	Fit non-model evaluations of fission neutron spectra and covariances with a physical model that considers contributions from all possible mechanisms of neutron emission	P. Talou, F.-J. Hambsch, N. Kornilov	June 2010
15	Apply results of the model fit to the smoothing of evaluated spectra and the final presentation of the spectra in detailed point-wise form	W. Mannhart, P. Talou	August 2010

4.3. ^{197}Au(n,γ) reaction as a reference for capture cross-section measurements at energies of importance to astrophysics (E_n < 200 keV)

A large discrepancy of 6% to 8% exists between analyses adopted to obtain ^{197}Au(n,γ) standards in the energy range between 3 and 200 keV, and therefore these data are not recommended for use as either a standard or reference cross section. This energy range is important for astrophysics applications, and the discussions concentrated on the analysis of these discrepancies and their exclusion. The following views were expressed:

- there is about the same degree of discrepancy between experimental data in the standards database for the measurements of the ^{238}U(n,γ) to ^{197}Au(n,γ) ratio and the ratio evaluated in the least-squares fit, which shows that ratio data obtained by means of the time-of-flight method with prompt gamma-ray detection contradict other data adopted in the fit (mostly the results derived from the capture cross-section measurements of each nuclide) – either these ratio measurements suffer from some systematic error (e.g. estimation of the detector efficiency for gamma-ray spectra produced in neutron capture by ^{197}Au and ^{238}U), or there are ill-defined problems with the absolute capture cross-section measurements obtained by the activation method;

- recent publications (e.g. "The use of C_6D_6 detectors for neutron induced capture cross section measurements in the resonance region" by A. Borella *et al.*, Nucl. Instrum. Methods Phys. Res., **A577** (2007) 626) show that some earlier data obtained by means of time-of-flight measurements with total gamma-ray energy detectors may suffer from systematic errors in the determination of the detector efficiency;

- good consistency has been found between the results of precise experiments to determine the simulated Maxwellian spectrum-averaged cross section (MACS) at kT = 25 keV (Ratynski and Käppeler) and the microscopic cross-section measurements of Macklin by means of a total gamma-ray energy absorption detector – these results have been corrected, appear to be free from systematic errors, and are considered as a serious argument in favor of continued use of the ^{197}Au(n,γ) reference cross section;

- release of new experimental data measured on the n_TOF facility (CERN) with two different detectors, at the GELINA LINAC (IRMM), with the DANCE detector (LANL), and by means of accelerator mass spectrometry of targets irradiated with thermal and simulated MACS (same energy and energy distribution as that used by Ratynski and Käppeler) with kT = 25-keV neutron fluxes at the VERA (University of Vienna) may help resolve the current discrepancies;

- percentage uncertainties of the standards evaluation in the energy range from 3 to 200 keV are rather low (0.7% to 1.5%), and arise from reductions in the statistical uncertainties due to the use of many data sets – data fits in the presence of unknown systematic errors were discussed;

- large fluctuations (resonance-like structures) in the ^{197}Au(n,γ) cross sections at energies below 20 keV prevent this reaction from being used as a wide ranging cross-section reference unless these data averaged in wide energy groups

- parameters of 4.9-eV resonance in the n+^{197}Au channel, often used as a "black" resonance for background separation, should be included as reference parameters This work is not intended to improve the saturated resonance technique for absolute fluence determination, but could be valuable for accurate background determination.

Various conclusions, recommendations and actions were agreed:

- ^{197}Au(n,γ) group energy-averaged evaluated cross section over the energy range from 1 to 200 keV can be used as reference cross sections – energy group bins are recommended of 0.5 keV for 1 to 3 keV; 1 keV for 3 to 10 keV; 2 keV from 10 to 20 keV; 5 keV from 20 to 50 keV; 10 keV from 50 to 100 keV; and 20 keV from 100 to 200 keV incident neutron energy;

- existing discrepancies between the measured ratios of ^{238}U(n,γ)/^{197}Au(n,γ), ^{238}U(n,γ) and ^{197}Au(n,γ) absolute cross sections, and ^{197}Au(n,γ) integral cross sections) will be difficult to resolve without new cross-section measurements carried out by means of different methods and detectors – analysis of the sensitivity of the results to the different types of data within the standards database will result in a better understanding of the origin of the discrepancies (Actions 1 to 3);

- improved knowledge of the operating characteristics of the total gamma-ray energy and gamma-ray detectors would provide the means of assessing the quality of the data obtained earlier with these two systems (Action 4);

- integral cross-section measurements obtained as an averaged well-defined spectrum with mean energies in the keV range can be used in microscopic cross-section fits (Action 5);

- despite the low sensitivity to the "black" resonance parameters used to determine the fluence for cross section determination, recommended parameters for the 4.9-eV and immediate higher-level resonances are useful in the standards evaluation for an accurate determination of the background. (Action 6).

No.	Action	Responsible	Date
1	Maintain close contact with experimental groups carrying out experiments or processing the data – send results to project participants when they become available	F.-J. Hambsch, F. Käppeler, A. Mengoni, R. Nelson, A.D. Carlson	until December 2009
2	Extract the data used in the standards fit of ^{197}Au(n,γ) with experts' comments on their reductions to the primary data; separate data on the basis of the measurement methods, and study the sensitivity of the final evaluation to the different types of data used in the fit	V.G. Pronyaev, F. Käppeler	February 2009
3	Include new and corrected experimental data for ^{238}U(n,γ) and ^{197}Au(n,γ) cross sections in the standards fits	V.G. Pronyaev	January 2010
4	Estimate the quality of the ^{238}U(n,γ) and ^{197}Au(n,γ) cross sections measured by means of different methods and types of detector, as included in the standards database	V.G. Pronyaev (extract data from GMA database), F. Käppler, H. Vonach, A.D. Carlson	May 2009
5	Study the feasibility of including the results of high-precision integral cross-section measurements in the least-squares fit of capture cross sections with the GMA code – use this option if needed	V.G. Pronyaev	December 2009
6	Add the resonance parameters recommended for use as "black" resonances to the standard evaluation to establish backgrounds	A. Mengoni, V.G. Pronyaev	December 2009

4.4. Reference cross sections for prompt gamma-ray production in fast neutron-induced reactions

Discussions focused on the status of the reaction cross sections used as references, and the advantages and drawbacks of using these cross sections, or choosing new candidates suitable for the role of reference cross sections in the energy range from a few to 20 MeV. The following important issues were discussed in detail:

- use of directly measured and derived cross sections (e.g. obtained from studies of total inelastic scattering), as determined by different methods in the combined fit of the gamma-production cross section;
- requirements in order for the gamma-production reaction cross section to be selected as a reference cross section, and consideration of the best candidates;
- experimental database and computer codes available for evaluation of the reference gamma-production cross sections.

As a consequence of this debate, the following conclusions, recommendations and actions were agreed:

- evaluation methodology based on a combined least-squares fit of directly measured and derived data increases reliability, and decreases the uncertainty of the evaluated gamma-production cross section (Action 1);
- an experimental database (cross sections and covariance matrices of their uncertainties) prepared from data published up to 1994 for iron and chromium isotopes and until 2000 for titanium isotopes is available as GLUCS/IRK (Action 2);
- although the 847-keV gamma-ray production cross section for the ^{56}Fe(n,n'γ) reaction is not ideal for use as a reference (because of the significant presence of iron in the experimental environment), this cross section is recommended for use as a reference – extremely well studied, and the IRK evaluation (1995) can be used as *a prior* to monitor improvements (Actions 3 and 4);
- new candidates for reference gamma-production cross sections can include both (n,n'γ) and (n,2nγ) reactions on the same nucleus, and can be chosen on the basis of the desirable properties for reference cross sections and the availability of experimental data (Action 5);
- evaluations of new reference gamma-ray production cross sections can be carried out as combined fits with derived cross sections (gamma-ray production cross sections obtained from total inelastic scattering cross sections if gamma-ray yield is well defined, etc.) (Action 6).

No.	Action	Responsible	Date
1	Methodology developed at the IRK based on the general least-squares fit of all relevant data with the updated GLUCS code to be made available	H. Vonach, S. Tagesen, V.G. Pronyaev	January 2009
2	Experimental databases to be made available for cross-section evaluations of Fe, Cr and Ti isotopes	H. Vonach, S. Tagesen, V.G. Pronyaev	January 2009

3	Prepare recommendations on the use of the results of measurements of the 847-keV gamma-ray production cross sections for the ^{56}Fe(n,n'γ) reaction (LANL, 2002)	R. Nelson	June 2009
4	Use 1995 IRK evaluation for the 847-keV gamma-ray production cross sections for the ^{56}Fe(n,n'γ) reaction as *a prior* when updating the evaluation with the inclusion of new experimental data	H. Vonach, S. Tagesen, V.G. Pronyaev	December 2009
5	Review and propose new reactions for use as reference gamma-production cross sections over a wide energy range	R. Nelson, A.D. Carlson	January 2009
6	Prepare an evaluation of the gamma-ray production cross sections for the (n,n'γ) and (n,2nγ) reactions with the same nucleus selected as a reference cross section over a wide neutron energy range	R. Nelson, H. Vonach, S. Tagesen, V.G. Pronyaev	June 2010

5. Common Problems Identified with the Standards and Reference Cross-Section Evaluations

Discussions focused on the use of the results of evaluations in the resolved resonance region based on the analysis of high-resolution experimental data in the standards evaluation and on use of the results of physical model calculations for smoothing of the cross sections and covariances for their final presentation.

The following general problems were discussed with respect to the standards and reference cross section evaluations:

- differences between standard and reference cross sections;

- possible use of high-resolution data that are currently not a part of the experimental database for the standards evaluation through the combined fit with inclusion of group-averaged cross-section data and covariances calculated from the evaluated resonance parameters;

- attention should be paid to those data in energy regions where contributions from the missed resonances may change the average cross sections;

- reliability of the physical model fits and the use of physical model calculations to smooth the evaluated data and covariances;

- co-ordination of the work and communication between participants in the project;

- schedule for the next meeting of participants in the Data Development Project to advance the International Neutron Cross-Section Standards.

Recommendations:

- use the term “reference evaluated data” for evaluated data that can not formally be placed in the category of “standards” (e.g. cross section is not smooth, and can only be used as an energy-averaged (group) cross section), but are used in relative data measurements;

- use in the combined fit of the standards with care and preliminary analysis, results of the model evaluation of the resolved resonance region of the high-resolution data not included in the standards database;

- use the results of the physical model calculations as shape data to smooth the cross sections of neighboring points in accordance with the local physical behavior predicted by the model, but without placing too strong a modelling constraint on the evaluated data as a whole;

- use e-mail exchange as the means of communication between project participants – work between participants of different Sub-projects will be coordinated by Vladimir Pronyaev (pronyaev@ippe.ru);

- IAEA Nuclear Data Section to send letters to relevant experimental groups requesting speedier data processing and release of experimental results of importance to the on-going neutron cross-section standards project;

- invite contributions to the project from theoreticians, experimentalists and evaluators who have not taken part in the Consultants' Meeting, but are known to be actively working in the field;

- propose that the IAEA Nuclear Data Section consider holding another Consultants' Meeting in 2010.

Appendix A

International Atomic Energy Agency

Consultants' Meeting on

International Neutron Cross-Section Standards:

Measurements and Evaluation Techniques

IAEA Headquarters
Vienna, Austria

13 – 15 October 2008

FINAL AGENDA

Monday, 13 October

08:30 - 09:00	**Registration** *Gate 1*	
09:00 - 09:15	**Opening** *Room B0482*	
	Remarks by organizers	*Alan Nichols and Vladimir Pronyaev*
	Election of Chairman	
	Adoption of Agenda	*Chairman*
09:15 - 10:30	**Present standards and update of standards**	
	Critical comments on standards and analysis of benchmarks sensitive to standards cross sections	*Vladimir Pronyaev* 15 min.
	Status of the neutron cross-section standards	*Allan Carlson* 15 min.
	Availability of standards cross sections from n_TOF project	*Alberto Mengoni* 15 min.
10:30 - 11:00	Coffee break, administrative matters	
11:00 - 12:30	**Status of standard evaluations for ^{252}Cf spontaneous and ^{235}U(n_{th},f) fission neutron spectra**	
	Fission neutron spectra calculations and evaluation	*Patrick Talou* 30 min.
	^{235}U(n,f) prompt neutron emission spectra	*Josch Hambsch* 30 min.
	Status of the evaluation of the neutron spectra of ^{252}Cf(sf)	*Wolf Mannhart* 30 min.
12:30 - 14:00	Lunch	

14:00 - 15:30 **Standards evaluation for the ^{252}Cf spontaneous and ^{235}U(n$_{th}$,f) fission neutron spectra**

Status of the evaluation of the neutron spectrum of ^{235}U(n,f)+n$_{th}$ — *Wolf Mannhart*, 30 min.

General discussions:

- perfection (or imperfection) of nuclear models
- best approach to the evaluation: preparation of covariance matrices of the experimental data for ^{252}Cf(sf) and ^{235}U(n$_{th}$,f) fission neutron spectra (absolute, shape, absolute ratio, ratio shape)
- consistency of <E$_n$> for ^{235}U(n,f) fission neutron spectrum obtained from microscopic evaluation and from reactor-type benchmarks (see also "Fission Neutron Spectra of ^{235}U", SG-9 WPEC, 2003)
- use of ^{252}Cf(sf) and ^{235}U(n$_{th}$,f) spectrum-averaged cross sections for benchmarking and final adjustment of fission neutron spectra

15:30 - 16:00 Coffee Break

16:00 - 17:30 **Discussions: Standards evaluation for the ^{252}Cf spontaneous and ^{235}U(n$_{th}$,f) fission neutron spectra**

<u>Tuesday, 14 October</u>

09:00 - 10:50 **^{197}Au(n,γ) reaction as a reference for capture cross section measurements at energies of importance for astrophysics (E$_n$ < 200 keV)**

Compilation of ^{197}Au(n,γ) reference cross section for applications in astrophysics — *Franz Käppeler*, 20 min.

^{197}Au(n,γ)standard cross section and experimental data — *Vladimir Pronyaev*, 20 min.

Preliminary results of n-TOF ^{197}Au(n,γ) cross-section measurements — *Alberto Mengoni*, 20 min.

Improved cross-section data for ^{197}Au + n reaction for neutron energies from thermal to 200 eV — *Franz-Josef Hambsch*, 20 min

10:50 - 11:10 Coffee break

11:10 - 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)**

- extension of the standards
- terminology
- if uncertainties evaluated in the combined fit of the standards are similar to ^{235}U(n,f) uncertainties, reaction is inconvenient for use as standard
- uncertainty of TOF capture cross section measurements with prompt gamma-rays registration technique
- discrepancies between experimental data for ^{197}Au(n,γ) absolute, ^{238}U(n,γ)/^{197}Au(n,γ) and others

12:30 - 14:00 Lunch

14:00 - 15:20 **Reference cross sections for prompt gamma-ray production in neutron-induced reactions**

IRK (1995) evaluation of total inelastic scattering cross sections in ^{56}Fe and ^{52}Cr, 0.847-MeV gamma-line production cross section for ^{56}Fe(n,n'γ) reaction, and 1.454-MeV gamma-line production cross section for ^{52}Cr(n,n'γ) in the energy range from threshold to 20 MeV — *Herbert Vonach*, *Siegfried Tagesen*, 20 min

Fast neutron-induced gamma-ray reference cross sections — *Ron Nelson*, 30 min

Evaluation of energy dependence of the yield of 0.847-MeV gamma line in ^{56}Fe, and 1.454-MeV gamma line in ^{52}Cr total inelastic scattering — *Vladimir Pronyaev*, 15 min

Performance of the unified Monte Carlo method of data evaluation — Roberto Capote, 15 min

15:20 - 15:40 Coffee break

15:40 - 17:00 **Discussions: Reference cross sections for prompt gamma-ray production in neutron-induced reactions**

- ^{56}Fe and ^{52}Cr as candidates; other proposed cross sections
- consistency between results of LANL measurements and IRK evaluation
- use of GLUCS and IRK evaluation as a prior for combined least-squares fit
- evaluated uncertainties for total inelastic scattering cross section (1.5 – 5% for ^{56}Fe and 4 – 10% for ^{52}Cr): are they realistic? What is contribution of the uncertainty of gamma-line yield in gamma-line production cross section uncertainty?

18:00 - 21:00 Dinner

Wednesday, 15 October

09:00 - 10:30 **Discussions of various problems related to standards evaluation**

- use of physical models and covariances smoothing
- inclusion of results of R-matrix evaluation in resonance region
- others

10:30 - 11:00 Coffee break

11:00 - 12:30 **Preparation of recommendations and actions to finalize evaluations (if needed working groups on each topic can work separately)**

12:30 - 14:00 Lunch

14:00 - 16:00 **Preparation of recommendations and actions of meeting, and their final approval**

Appendix B

International Atomic Energy Agency

Consultants' Meeting on
International Neutron Cross-Section Standards:
Measurements and Evaluation Techniques

IAEA Headquarters
Vienna, Austria

13 – 15 October 2008

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Participants at the Consultants' Meeting on International Neutron Cross-Section Standards: Measurements and Evaluation Techniques
from left to right:
1st row (sitting) - Josch Hambsch, Siegfried Tagesen, Herbert Vonach, Wolf Mannhart and Allan Carlson;
2nd row (standing) – Ron Nelson, Alberto Mengoni, Vladimir Pronyaev, Alan Nichols, Franz Käppeler, Roberto Capote and Patrick Talou

APPENDIX C

PRESENTATIONS – Web Links

1. V.G. Pronyaev, Critical comments on standards and analysis of benchmarks sensitive to the standard cross sections
2. A.D. Carlson, Status of the neutron cross section standards
3. A. Mengoni, Status and availability of the standard cross sections obtained in the n_TOF project
4. P. Talou, Fission neutron spectra calculation and evaluation
5. F.-J. Hambsch, ^{235}U(n,f) prompt neutron emission spectra
6. W. Mannhart, Status of the evaluation of the neutron spectrum of ^{252}Cf(sf)
7. W. Mannhart, Status of the evaluation of the neutron spectrum of ^{235}U(n_{th},f)
8. F. Käppeler, Compilation of the ^{197}Au(n,γ) reference cross section for application in astrophysics
9. V.G. Pronyaev, ^{197}Au(n,γ) standard cross section and experimental data
10. P. Schillebeeckx, Standard for ^{197}Au(n,γ) in the resonance region
11. R.O. Nelson, Fast neutron-induced gamma-ray reference cross sections
12. V.G. Pronyaev, Estimation of the energy dependence of the yield of 0.847-MeV γ-line in ^{56}Fe and 1.454-MeV γ-line in ^{52}Cr in neutron inelastic scattering using experimental data and results of statistical model calculations
13. R. Capote, Performance of the unified Monte Carlo method of data evaluation
14. V.G. Pronyaev, Smoothing of the standard cross sections
15. V.G. Pronyaev, R-matrix fit of heavy elements and evaluation of the standards

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