IAEA
International Atomic Energy Agency

INDC(NDS)-0639
Distr. AC/AD/G/IN/J/RD/SC

INDC International Nuclear Data Committee

Summary Report of the First Research Coordination Meeting on

Testing and Improving the International Reactor Dosimetry and Fusion File (IRDFF)

IAEA Headquarters, Vienna, Austria

1 – 5 July 2013

Prepared by

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September 2013

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Printed by the IAEA in Austria
September 2013

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Abstract

In accordance with the recommendations of the International Nuclear Data Committee in May 2012, the Nuclear Data Section of IAEA has initiated a new Coordinated Research Project (CRP number F41031) with the main goal to test, validate and improve the international dosimetry library for fission and fusion (IRDFF). The output of this CRP will be a reference dosimetry database of cross sections and decay data with corresponding documentation. It will serve to the needs of fission, fusion and accelerator applications. The first Research Coordination Meeting (RCM) was held 1 to 5 July 2013 in IAEA. At this meeting, the attendees discussed the objectives of the whole CRP, presented their contributions and elaborated on consolidated recommendations and actions for implementation over the next 1.5 year period. This Summary Report documents the individual contributions and joint decisions made during this meeting.

September 2013

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I. Introduction

Motivation and objectives of CRP

The Nuclear Data Section of IAEA, in accordance with the recommendation of the International Nuclear Data Committee [1], has initiated a Coordinated Research Project (CRP) with the main goal being to test, validate, and improve the international dosimetry library for fission and fusion, which during historical evolution was called the International Reactor Dosimetry and Fusion File (IRDFF). CRP work is currently planned from 2013 through 2017. Additional information is available on the CRP web-page http://www-nds.iaea.org/IRDFFtest/. The CRP plans to get new energy integrated (integral) and pointwise (energy-dependent) cross section measurements as well as to collect all other experimental information relevant to data validation, but which has not historically been utilised.

The main CRP output will be the updated and validated database of dosimetry cross sections and decay data with corresponding documentation. This library will serve the needs of fission, fusion (International Thermonuclear Experimental Reactor, ITER; International Fusion Material Irradiation Facility, IFMIF) and accelerator applications (Accelerator Driven Systems, ADS; Spallation Neutron Sources, SNS).

Source and content of IRDFF

The IRDFF library is an extension of the International Reactor Dosimetry File (IRDF-2002) [2]. This extension includes 4 new reactions (^{67}Zn(n,p)^{67}Cu, ^{113}In(n,n')^{113m}In, ^{169}Tm(n,3n)^{167}Tm, ^{209}Bi(n,3n)^{207}Bi), 32 updated evaluations and an increase in the end-point energy of the library from 20 to 60 MeV [3, 4]. The energy extrapolation has been made in a formal way by using the TENDL-2010 cross sections and covariance matrices [5] after their normalization to match the IRDFF-2002 cross section values at the extension point (typically 20 MeV).

Despite the current IRDFF end-point energy of 60 MeV (with a few exceptions, including a 150 MeV end-point for ^{186}W(n,γ) and a 200 MeV end-energy for ^{31}P(n,p)^{31}Si, ^{92}Mo(n,p)^{92m}Nb, ^{235,238}U(n,f), ^{235,238}U(n,γ), ^{239}Pu(n,f)), the CRP will strive to evaluate and eventually add to the library the high threshold reactions with cross section plateaus located between 20 and 100 MeV, which will help meet requirements of the higher energy nuclear installations. Often these high threshold reactions are comprised of a set of several reactions (n,3-9n) on isotopes such as ^{197}Au, ^{169}Tm, ^{209}Bi, ^{59}Co, ^{63}Cu, ^{89}Y, ^{93}Nb. The set of such reactions are very convenient for neutron fluence monitoring and spectrum unfolding at accelerator-driven neutron sources.

The IRDFF contains 74 dosimetric and 3 absorption (cover materials) cross sections. IRDFF also includes total and elastic cross sections for materials or reactions with a resonance structure for evaluation of the self-shielding effect [6]. The following IRDFF dosimetry cross sections were incorporated from standards [7] and thus they have the highest precision out of all neutron data: ^{6}Li(n,t)^{4}He below 2.8 MeV, ^{10}B(n,α_0)^{7}Li and ^{10}B(n,α_1)^{7}Li below 1.0 MeV, ^{197}Au(n,γ)^{198}Au from 200 keV to 2.6 MeV, ^{235}U(n,f) at 25 meV and from 25 keV to 200 MeV, ^{238}U(n,f) from 1 MeV to 200 MeV.

The IRDFF also includes the decay data for unstable reaction products and selected fission products [2] as well as isotopic abundances [8]. Presently the IRDFF contains 82 isotopes and isomers. The source of information is nuclear structure data files ENSDF [9] (as Dec 2011), which has been converted to the ENDF-6 format for inclusion in IRDFF [10]. The decay library is a subject of further updating and expansion as part of this CRP.

Specific features of the IRDFF as a reference library

In the case of validation of dosimetry cross sections, that should have a rather high accuracy as references, specific attention (in accordance with regulatory standards such ASTM [11]) should be paid to:

- characterization of the neutron spectra together with their uncertainties and correlations: optimally, the spectra should be determined by a combination of experimental (e.g., TOF, proton recoils, Bonner spheres, foil activation ...) and calculation (e.g., simulation by Monte-Carlo code MCNP ...) methods; it is very important to quantify the main uncertainties and strong energy-energy correlations;
- propagating the dosimetry cross section uncertainty to the observed activity when the neutron environment is simulated;
- possible strong reaction-reaction cross sections correlations, which may result (i) from the use of dosimetry cross sections (sensors) for characterization of the neutron spectrum that is later used to validate another dosimetry cross sections or (ii) from the dosimetry cross section evaluation in joint analysis with other (standard) cross sections;
- establishing the complete reference decay data for the dosimetry reaction residuals for consistent use in evaluation and applications;
- processing of the IRDFF cross sections and decay data with uncertainties in formats that can be used by simulation or analysis codes in practical applications;

Energy domains, typical neutron fields and data status

Reactor (or accelerator) driven and spontaneous or induced fission spectra are used for validation as: (i) spectrum-averaged cross sections in standard (^{252}Cf(s.f.), thermal Maxwellian, 1/E) and reference (prompt fission neutron spectra from ^{235}U(n_{th},f)) fields; (ii) critical assemblies (e.g., collected in the ICSBEP database) in which the dosimetry reactions rates were measured; (iii) cold and thermal neutron fields in reactor facilities that were employed for the creation of the k_0-database for Neutron Activation Analysis, which may now be used for the validation of the dosimetry (n,γ) reactions; (iv) IRDF-2002 collection of the reference reactor spectra (available in IRDF-2002, but without uncertainties); (v) lead slowing-down experiments delivering the low resolution excitation functions for capture and fission in the energy range from 10 meV to 100 keV.

Maxwellian energy spectra (mean spectrum energy between 5 and 500 keV) are produced by proton beams impinging on thick ^{7}Li, ^{3}H, ^{18}O targets. The Maxwellian Averaged Cross Sections (MACS) accumulated in experiments for astrophysics, such as MACS for (n,γ) reactions, could be used for IRDFF validation.

Fusion energies (14 MeV and below) are simulated by bare quasi-monoenergetic D-T sources or by mixed fields, where the low energy component is formed by scattering of 14 MeV neutrons in materials with rather well known transport cross sections.

Medium energies (5 - 50 MeV) could be validated by quasi-monoenergetic p-^{7}Li source and in the broad energy spectra like d-Be, d-Al.

At high energies (from 15 to 200 MeV), where cross sections are very scarce and uncertain (such as (n,xn) reactions on ^{59}Co, ^{197}Au, ^{169}Tm and ^{209}Bi), neutron quasi-monoenergetic and broad energy sources (e.g., p-^{7}Li, p-U) are traditionally used for measuring and validating the reaction excitation functions.

The first Research Coordination Meeting (RCM)

The 1st RCM of the new IAEA CRP on “Testing and Improving the International Dosimetry library for Fission and Fusion (IRDFF)” was held at IAEA Headquarters, Vienna, Austria from 1 to 5 July 2013. The following twelve holders of CRP Agreements or Contracts attended this meeting: V. Chechev, C. Destouches, C. Konno, L. Greenwood, A. Kahler, N. Kornilov, M. Stefanik, P. Mastinu, R. Nchodu, A. Plompen, A. Trkov, and H. Yashima. P. Casoli (excused) could not attend. M. Angelone, P. Griffin, A. Klix, V. Pronyaev, F. Wissmann, and K. Zolotarev participated as observers. The IAEA was represented by S. Simakov (Project Officer), R. Capote Noy (Alternative Project Officer), R. Forrest, N. Otuka, and V. Semkova.

The Meeting was opened by R. Forrest, Head of the Nuclear Data Section (NDS) of the Department of Nuclear Sciences and Applications of the IAEA, by welcoming the participants and explaining the importance of this CRP for further testing and improvement of the IRDFF as a reference dosimetry library for many practical applications.

A. Öchs, who is responsible for administrative issues, made several announcements. This was followed by the self-introduction of participants.

The participants elected A. Trkov as the Chairman and L. Greenwood as the Rapporteur of this Meeting and approved its Agenda (Appendix 1). The list of participants and their affiliations is summarized in Appendix 2.

The objective and goals of the Meeting were outlined by S. Simakov.

During two and half days, participants gave presentations and had intensive discussions (Section II). The discussions resulted in a set of consolidated conclusions and recommendations (Section III). The references cited in Sections I to III are collected in Section IV, the summaries of participants’ presentations and proposals for CRP – in Section V.

The Nuclear Data Section acknowledged all participants for their cooperation and contributions to the Meeting.

The IAEA Nuclear Data Section especially wishes to stress the importance of national experimental facilities for production of new experimental data for dosimetry and hence for the successful implementation of this international project. We hope that the necessary resources for maintenance of these facilities and for carrying out precise measurements will be provided by the relevant authorities.

II. Individual Oral Presentations

This section contains short summaries of the individual oral presentations and followed discussions (the presentations are available on the CRP web-page at http://www-nds.iaea.org/IRDFFtest/).

Stanislav Simakov (IAEA), in the introductory speech, briefly described the history of the IRDFF. The library mainly contains data that have been extended to 60 MeV, although some data extend beyond this limit up to 200 MeV. The IRDFF library in ENDF-6 format presently contains 74 reactions and 3 cover materials that can be processed with the PREPRO and the NJOY data processing systems. A survey of reactions, potential problems and integral data was presented. Possible existence of broad spectral issues with integral tests (lower energies, broad energy dependence, etc.) was indicated.

The validation can be done using integral measurements and may include ^{235}U(n,f) and ^{252}Cf(s.f.) fission spectra, critical assemblies (such as Flattop and Godiva), CFRMF and ISNF facilities, 14 MeV neutron generators, etc. Many of such measurements were compiled in the EASY-2007 system and could be used for the validation of the IRDFF library as well.

In the discussion, the following issues were raised. (i) Extensions with TENDL at higher neutron energies may need to be updated. The IRDFF currently contains TENDL-2010 calculations, with some TENDL-2011 values, but TENDL-2012 is now available, such that the IRDFF may need to be updated to the current version. (ii) The need to extend the ^{252}Cf fission spectrum to energies above 20 MeV, since the cross sections are given to at least 60 MeV. The extension would affect the calculated spectrum-averaged cross sections with a high threshold, but such reaction cross sections are difficult to measure in practice because there are very few neutrons emitted with such high energies. The uncertainties on the ^{252}Cf spectrum above 20 MeV would also be very large, such that the values would not be meaningful. The extension would be just a numerical exercise for the sake of completeness, but of little practical significance.

Roberto Capote (IAEA) mentioned that uncertainties on neutron spectra can be a problem. The ^{252}Cf spontaneous fission neutron spectrum is the only real reference field in the current IRDFF library which meets the quality requirements. Correlation of spectra and measurements at higher energies may present problems. There is a need to validate all cross sections at energies above 20 MeV, since such data were not part of the original evaluations (in most cases), but were taken from the TENDL library with normalisation to achieve continuity. No real tests of the data have been done yet above 20 MeV.

New LANL characterizations and measurements are planned at critical assemblies. The main issue may be how to get the uncertainties and covariances for the neutron spectra in these assemblies. Heating issues prevent high fluence irradiations and thus limit the number of activation monitors and other detectors that can be used (A. Kahler and P. Griffin will follow up on this).

Konstantin Zolotarev (IPPE) presented new evaluations for ^{54}Fe(n,p), ^{58}Ni(n,2n), ^{67}Zn(n,p)^{67}Cu, ^{92}Mo(n,p)^{92m}Nb, ^{93}Nb(n,γ)^{94}Nb, ^{113}In(n,n')^{113m}In, ^{115}In(n,γ)^{116m}In and ^{169}Tm(n,3n) reactions that were recently performed. He pointed out that not much data are above 14 MeV and that some problems were noted in the resonance region.

Vladimir Pronyaev (IPPE) discussed the status of the (n,xn) reactions. The best mono-isotopic candidate materials have many reactions, such as ^{209}Bi, ^{197}Au, ^{139}La, ^{103}Rh, which could allow probing of several energy regions in a single sample irradiation. Reactions on ^{59}Co also were also suggested. New measurements would be needed in many cases to get high accuracy.

Larry Greenwood (PNNL) presented an overview of broad spectrum integral experiments at high neutron energies, using Be(d,n) and spallation neutron sources characterized by TOF. The STAYSL PNNL computer code is now available based on IRDF-2002 cross sections and covariances. A beta version is available with IRDFF and the software will be updated as new versions of IRDFF are issued.

Nikolay Kornilov (OU) reported on standard neutron fields investigated during last ~ 30 years in several labs (OU, IRMM, ANL) with different types of neutron detectors (which were also applied for measurements of neutron spectra from ^{252}Cf source and (d,n) reactions at 7 MeV). Recent analysis of experimental data for ^{27}Al(d,n), B(d,n), Be(d,n) reactions show some disagreement between measurements carried out with the NE213 type detectors and fission chambers. The disagreement between data is rather strong (up to 20%), therefore more experimental work is needed.

Rudolph Nchodu (iThemba LABS) described the iThemba LABS high-energy neutron facility. Cross section measurements and neutron metrology studies are done in collaboration with PTB. The neutron beam is produced with thin Li and Be targets, with beam currents of 3-5 μA. The facility can produce quasi mono-energetic neutron beams with energies below 100 MeV and about 1 ns time resolution. A neutron fluence of about 1000 n/cm^2/μA is estimated at 10 m.

Milan Stefanik (NPI Řež) presented research activities on cross section measurement and testing in the energy range 13 to 35 MeV using the Li(p,n) neutron sources and U120M cyclotron which delivers 11-37 MeV protons. The D_2O target is used to generate white neutrons and flux up to 1E+11 n/cm^2. There is also a p + Be neutron source with a white neutron spectra. The cross section adjustment is currently done with modified version of the SAND II code.

Hiroshi Yashima (Osaka University) presented measurements being made with the ^{7}Li(p,n) source from 100 to 400 MeV at RCNP cyclotron at Osaka University. Neutron spectra at several angles are measured in a 100 m tunnel by the time-of-flight (TOF) technique. Activation experiments for the ^{209}Bi(n,xn) reaction have been performed at 287 and 370 MeV neutron energies. Correction for influence of lower energy neutrons was done by exposure at angle 25°. Analysis of error components was performed. The plan for new measurements of ^{59}Co(n,xn) reactions at neutron energies from 90 to 200 MeV was proposed.

F. Wissmann noted that subtraction method may have systematic error – need to calculate corrections.

S. Simakov commented that LANL evaluation for the p-^{7}Li reaction cross sections was recently published.

Chikara Konno (JAEA/FNS) talked about the damage to equipment in the lab, which is 80 km from Fukushima, due to the earthquake in 2011: part of the equipment was damaged, misalignment of beam line, had to replace parts – now back in service. The FNS is a DT generator similar to RTNS-II: rotating target, water cooled, beam energy 350 keV, neutron yield 3 10^{+11} n/s. Over 200 reaction rates have been measured from 13.3 to 15 MeV in the 1980s using many separated isotopes as targets. Benchmark experiments have been done with Fe blocks. TOF experiments above 100 keV have been carried out with slabs such as graphite. New measurements around 14 MeV were proposed at FNS.

Maurizo Angelone (FNG) described 14 MeV and 2.5 MeV experiments at the Frascati Neutron Generator. The neutron source yield of up to 10^{+11} n/s is determined by measurement of associated alpha. Diamond detectors as well as foil activation (Al, Nb) are used for the spectrum characterization. Single crystal with Si diode, NE213 detector and also ^{238}U fission chamber employed for neutron yield measurements. The FNG neutron source is also well characterized by the Monte Carlo simulation of neutron spectra at different angles.

Frank Wissmann (PTB) spoke about neutron reference fields at the PTB Ion Accelerator Facility (PIAF). At PIAF, two ion accelerators are in operation. i) the VdG accelerator produces 3.75 MeV protons, deuterons, and alphas in DC and pulsed mode; ii) a cyclotron produces the same ion beams with energies from 3 MeV to 27 MeV, both DC and pulsed. Neutron reference fields are produced according to the ISO 8529 standard, with neutron energies from 24 keV to 19 MeV. Irradiations are performed in a huge low scatter hall. An intense collimated neutron field produced by d(13.5 MeV) + ^{9}Be, $\langle E_n \rangle \approx 5$ MeV, and p(19 MeV) + ^{9}Be, $\langle E_n \rangle \approx 10$ MeV, ion beams and high energy photons beams (4.4 MeV and 6-7 MeV), according to ISO 4037, are available as well. The reference cross sections for fast neutrons are: ^{1}H(n,n) – primary standard, ^{235,238}U(n,f) – secondary standards (best accuracy possible about 2% for neutrons). The detectors used as primary standards for neutron fluence are a recoil proton proportional counter for neutron energies below 1.2 MeV and a proton recoil proton telescopes for neutrons above 2 MeV.

At the cyclotron a time-of-flight spectrometer is installed with a neutron flight path from 11 m to 30 m, time resolution 1-2 ns and five neutron detectors at fixed angles. Since the cyclotron is movable around the target point the neutron scattering experiment can be carried out covering a wide angular range from 12.5° to 160°. Results for elastic and inelastic neutron scattering on ^{nat}Ti were presented as an example. Many other measured cross section data for 8-14 MeV mono-energetic neutrons are already in EXFOR.

Pierfrancesco Mastinu (LNL-INFN) overviewed the INFN Legrano Laboratory facilities which include three Van de Graaff accelerators, one linac, three experimental halls with various spectrometric equipment as well as planned RIB facility. At LEngaro NeutrOn Source (LENOS) at LNL-INFN the Maxwellian Averaged Cross Sections (MACS) are measured for astrophysics. Comparing MACS obtained by TOF and activation techniques, he concluded that “old” TOF measurements seem to overestimate the cross sections. Then he presented LENOS activation method by shaping the energy line of a proton beam to make a neutron spectrum closer to the Maxwellian and thus removing the necessity to correct MACS. This method has been tested at Van de Graaff facility (JRC-IRMM) and the analysis is on-going.

Under this CRP, the following work is planned: characterization and validation of the neutron field from ^{7}Li(p,n) reaction, MACS measurements and validation of nuclear data in the energy range $1 < E_n <$ 600 keV, use of the available neutron beam line for other measurements.

Adrej Trkov (JSI) discussed in general the validation of cross section data by Integral Experiments. He suggested comparison of the constants derived from evaluated data files to the measured constants in the Kayzero database. The k_0 factors are proportional to the thermal capture cross sections and the Q_0 factors are the ratios of the resonance integrals to the thermal cross sections. He pointed out the need to precisely understand the definitions of the measured quantities and carefully perform the corrections, particularly the Westcott g-factors, cadmium filter correction factors, thermal flux depression factors, resonance self-shielding factors, and the treatment of the fission spectrum contribution to the reaction rates. The relation between the measured activities and the reaction rates require the knowledge of the gamma-emission probabilities. Should these be included in the decay data file of the IRDFF library? Comparison to the Kayzero database was done for the IRDF-2002 library and it should be repeated for IRDFF.

Comparisons can also be done to average cross sections measured in simulated stellar Maxwellian spectra and ^{252}Cf spontaneous fission neutron spectra; the latter require large corrections for capture reactions and should be done with great care. Measurements behind the fission plates in thermal reactors are harder to characterize because of inevitably larger room-return contribution and neutron streaming through the fission plate. A direct simulation by the Monte Carlo technique is recommended for the analysis. Experiments with D-T sources should be documented in full detail, including the source so that direct Monte Carlo simulations can be performed. The same applies to other accelerator sources.

Skip Kahler (LANL) informed participants that LANL will reanalyze critical assemblies data (Godiva, Flattop-25, Flattop Pu, Big 10, Godiva, Jezebel and other relevant ICBEP benchmarks) and assess uncertainties to compare with IRDFF; will also upgrade prompt fission evaluations. Old benchmark data may need revision due to nuclear data differences. The NJOY code will be used to process the IRDFF library.

Pat Griffin (SNL) defined types of neutron benchmark fields (standard, reference, controlled), categories of cross section data (obtained from absolute or relative measurements or at single energy point) and problems of model defect determination (no definition or method to determine model defects, there are problems with systematic uncertainties). He overviewed the methodology using integral metrics and spectral indices for cross section validation (the latter are useful if absolute normalization is uncertain, use chi^2/degrees of freedom as a metric, least square adjustment of ^{252}Cf gives good agreement, try eliminating worst differences and look at convergence).

He overviewed existing neutron benchmark fields and cross section data obtained in them. Standard fields: ^{252}Cf spontaneous fission; Intermediate Standard Neutron Field (ISNF) - ^{10}B shielded graphite moderated ^{235}U thermal fission spectrum; 14-MeV accelerated-produced mono-energetic field; thermal Maxwellian. Research Reactor fields: central cavity of the SPR-III fast burst reactor (now decommissioned); ACRR Central Cavity, which is similar to TRIGA, has 40 reactions with chi^2 of 1.68; Pb-B4C bucket (Pb to get rid of gammas) – 39 reactions; 26 in least squares analysis. Reference benchmarks (reanalysis is needed and a review of old critical data): CFRMF (30 reactions); GODIVA (9 points); JEZEBEL (9 points); VERA-1B (6 points); ZPR-III 6F (7 points); ZEBRA-2 (9 points) and others. Can we use reactivity worth? Not sure if possible. Controlled benchmarks: MDRF, PCA (7 reactions), VENUS-1 (6 reactions), HBR-2 (6 reactions), ORR-PSF/PCA, NESTOR, SCK-CEN and lots of other old data needs to be reviewed. In every benchmark neutron field we need to consider how to model the neutron spectrum!

Potential future improvements in the IRDFF Library. An uncertainty estimation must reflect (i.e., be derived from) the method, experimental or computational, used to produce the baseline estimate to which the UQ estimate applies. Suggests a need to: (i) modify procedure for appending model-based TENDL-2010 evaluations onto experimental-based evaluations (e.g., append at last acceptable data point, which is often 14-MeV); (ii) modify TENDL-2010 covariance to reflect this renormalization process – i.e., resulting correlation and increased systematic uncertainty.

Christophe Destouches (Cadarache) presented CEA installations. Cadarache: three experimental reactors (MINERVE, EOLE, MASURCA) for testing and platforms with instrumentation (sub miniature fission chambers), dosimetry measurements and detectors manufacturing. Valduc: CALIBAN reactor with pure HEU fuel, steel and B4C cover, operated in steady state 1.2E+11 n/cm^2 or pulsed 4E+14 n/cm^2 modes; SAMES – Electrostatic Accelerator producing 2.5 or 14 MeV neutrons; dosimetry laboratory. These facilities deliver experimental results for validation of dosimetry reactions: ^{54}Fe(n,p), ^{60}Co(n,g), ^{46}Ti(n,p), ^{63}Cu(n,a), ^{115}In(n,n’), ^{235}U(n,f), ^{238}U(n,f), ^{237}Np(n,f), ^{58}Ni(n,p)^{58m}Co and many others. Proposed the inclusion of the ^{117}Sn(n,n’)^{117m}Sn reaction - the complete experimental and modelling results will be soon available.

The planned research program was presented. New irradiations at facilities CALIBAN, SAMES, MINERVE and induced activity measurements at facilities MADERE and Valduc. Participation in Nuclear Data Validation and Analysis: feedback of the JEFF evaluation for some reactions, covariance files - comparison with the COMAC process, systematic test of proposed evaluations on MASURCA and PROTEUS spectra for X/U5 spectral indexes.

The IRDFF cross sections library first feedbacks: inconsistency observed in terms of C/E for ^{93}Nb(n,n’)^{93m}Nb (^{93m}Nb(n,γ) cross section is not known!), ^{103}Rh(n,n’)^{103m}Rh, ^{55}Mn(n,g)^{56m}Mn, ^{63}Cu(n,a)^{60}Co, ^{58}Ni(n,p)^{58}Co. Needs for new evaluations: ^{117}Sn(n,n’)^{117m}Sn, ^{242,243}Pu(n,g) and (n,f), photofission and NRF. Fission yields asked. Decay library: what is a reference NUDAT or NUCLEIDE(LNHB)?, inconsistency for ^{93m}Nb for x-ray intensities.

Axel Klix (KIT Karlsruhe) described the D-T neutron generator of Technical University of Dresen, located at the Helmholtz-Zentrum Dresden-Rossendorf with neutron intensity up to 1.E+12 n/s. The continuous and pulsed modes are available. Rotating target with up to 250 Ci of tritium is not always run at highest flux due to the cost. Deuteron energy - 320 keV. Neutron spectra is calculated around 14 MeV. There is a very small flux below 14 MeV. A silicon detector is used for associated charged particle measurements to monitor the neutron source. Facility is used for experiments relevant for fusion such as mock-up irradiations, instrumentation development and material activation. He plans to check data used in activation calculations with EASY code and European Activation File (EAF).

Question: Build-up of deuterium in target leads to DD neutrons? The procedure of the absolute neutron yield measurement?

Answer: This effect was taken into account by evaluating recorded pulse height spectra from the silicon detector for the associated alpha particle. The ratio technique Nb/Zr foils (as ASTM standard) is used as monitor for the mean fusion peak energy of the neutrons.

Valery Chechev (Khlopin Radium Institute) discussed decay data for IRDFF. Out of a total of 82 isotopes/isomers, there are 44 radionuclides with satisfactory ENSDF evaluations dated 2008-2012. For 14 isotopes the newly published ENSDF-2012-2013 evaluations should be converted into ENDF-6 format. Analysis is needed for the remaining 38 nuclides, decay data of which were evaluated in ENSDF before 2008. Best references are DDEP and ENSDF; the former is preferable however it does not include all desired nuclides. The impact of different evaluation methods on decay data was demonstrated for ^{132}Te.

The half-lives and the absolute intensity of the gamma rays (per decay) may be regarded as the main decay data which are required for the IRDFF Decay Library. New half-life experimental data of 2010-2012 have been published for 19 radionuclides and updated evaluations are required for them. Recently a serious problem was discovered in the NIST calibration method that affected the half-lives of a large number of long-lived isotopes.

There is an issue of consistency between cross section evaluations and decay data. Newer decay data could cause problems in use of cross section data, if values do not agree with those used for data evaluations.

Roberto Capote (IAEA) stressed that validation of IRDFF cross sections is needed in many different neutron fields. So far, validation has been undertaken at thermal energies, resonance region, and for two fission neutron fields: the ^{252}Cf(s.f.) and ^{235}U(n$_{th}$,f) fields [3]. The calculated integral cross sections in the ^{252}Cf(s.f.) reference neutron field exhibit improved agreement with evaluated experimental data when compared with the equivalent data from the IRDF-2002 library. Data inconsistencies or deficiencies of new evaluations have been identified for ^{63}Cu(n,2n), ^{60}Ni(n,p)$^{60m+g}$Co, ^{55}Mn(n,γ), and ^{232}Th(n,f) reactions [4].

The calculated integral cross sections in the ^{235}U(n$_{th}$,f) neutron field (spectrum from ENDF/B-VII.1[12]) show large disagreements with measured integral data above 10 MeV. We do not know whether there is a problem in the high energy tail of the evaluated ^{235}U spectrum or a problem in integral cross section measurements or both? (the same issue was observed with JENDL-4 ^{235}U(n$_{th}$,f) neutron spectrum).

There was some discussion on the shape of the evaluated ^{235}U fission spectrum: significant differences were highlighted between ENDF/B-VII.1 spectrum [12] and a recent N. Kornilov's evaluation based on experimental data [13, 14].

Arjan Plompen (IRMM). Current work is in progress on the ^{197}Au(n,γ). The ^{6}Li(p,n) and T(d,n) reactions are used as neutron sources. Diagnostics have been performed on neutron sources using ^{6}Li(p,n) scattering for SARAF and FRANZ facilities. Comparison of diamond detectors with TOF data is in progress. ^{252}Cf spectrum-averaged cross sections are being measured to 1-2% accuracy with about 1.E+8 n/s source strength. Activation measurements have been performed at the IRMM Van de Graaff with enriched and natural samples. The ^{6}Li(p,n) neutron spectra are being accurately characterized near threshold. SARAF is undergoing testing, especially for use with liquid Li targets. FRANZ is not yet in operation.

III. Results of common discussions: research coordination, recommendations and actions.

Participants submitted summaries of their proposed research activities for the CRP that will be attached to the report of the meeting.

The next meeting is planned in about 1.5 years from the first RCM; the final meeting is planned in about 3 years time, followed by the preparation of the finalized database and the documents.

It was recognized by the participants that, for validation purposes, we require reference spectra or well-characterized spectra by TOF or other means with covariance information, depending on the neutron energy.

The main output of the CRP is a validated reactor dosimetry library with proper documentation. The library will consist of one cross section file, a file of reference neutron spectra for validation, and a file with decay data and key fission yields of ^{235}U, ^{238}U, ^{237}Np and possibly ^{239}Pu (that is still a question of usage in the dosimetry practice).

The adopted energy grid should be 640 groups below 20 MeV, 0.5 MeV steps from 20 to 30 MeV, 1 MeV steps from 30 to 40 MeV, and 2 MeV steps from 40 to 100 MeV, and 5 MeV above 100 MeV.

A number of reference or standard neutron fields for data validation were addressed as discussed below.

^{252}Cf Spontaneous Fission Reference Neutron Spectrum

At present, the ^{252}Cf spontaneous fission neutron spectrum is the only real reference spectrum that fulfils all quality requirements. It is desirable to use it to do more measurements for validation. There is a need for new measurements of ^{60}Ni(n,p)^{60}Co, ^{92}Mo(n,p)^{92m}Nb, ^{103}Rh(n,n')^{103m}Rh, and ^{232}Th(n,f) reactions to resolve existing discrepancies and to validate the capture cross sections in the 100 keV energy range. Many of the IRDFF reactions (all capture and ^{6}Li(n,t), ^{10}B(n,α), ^{59}Co(n,3n)^{57}Co, ^{67}Zn(n,p)^{67}Cu, ^{89}Y(n,2n)^{88}Y, ^{115}In(n,2n)^{114m}In, ^{169}Tm(n,3n)^{167}Tm, ^{209}Bi(n,3n)^{207}Bi reactions) have not been validated in a ^{252}Cf reference field [3, 4].

Opportunities to perform new experiments with ^{252}Cf are limited due to the limited availability of new sources. Our community encourages the labs in Řež to undertake reaction rate measurements in a ^{252}Cf neutron field.

Actions:

- A. Plompen (IRMM) will propose a project to set up the ^{252}Cf neutron source in collaboration with PTB to perform measurements. The list of reactions to be measured will consider the reactions discussed above.
- N. Kornilov (OU) will attempt to measure the high-energy tail (10 MeV to 14 MeV) of the ^{252}Cf spectrum by the TOF technique.
- R. Capote and S. Simakov will communicate the new reaction requests to High Priority Request List (HPRL) by NEA.

Thermal cross sections and resonance integrals

Table 5 in the IRDFF report [3] contains thermal Maxwellian averaged cross sections and resonance integral values. There is some question about the proper definition of the resonance integral for validation purposes. Comparisons of the IRDFF resonance integrals with the values of S. Mughabghab [15] are useful, but not considered as "validation" since it is essentially a comparison of one set of resonance parameters with another. The definition of the resonance integral by S. Mughabghab is inconsistent with what is measured, for example, by the Cd-ratio technique. For neutron capture reactions, the Kayzero database contains independent integral experiments that can be used for validation of the thermal cross sections and resonance integrals of the IRDFF library; the only additional physical parameters needed are the gamma-emission probabilities [6]. The ^{58}Fe(n,γ) and ^{93}Nb(n,γ) resonance integrals are examples where the agreement with the Kayzero database is good, but there is disagreement with the S. Mughabghab evaluation. The resonance analysis for ^{58}Fe was recently done by M. Moxon specifically to resolve the discrepancies in the measurements and is considered reliable [16]. The CRP should establish communication with the k_0 Users Group to discuss actions for mutual improvement of both databases.

Actions

- A. Trkov will contact the k_0-Users Group and maintain a database comparing the thermal cross sections and the resonance integrals in IRDFF with the values derived from the most recent version of the Kayzero database.

Lead Slowing Down Experiments

Lead slowing down experimental data may also be useful for validation.

Actions

- Andrej Trkov will investigate applicability of the Grenoble experiments to IRDFF validation.
- A. Kahler will investigate whether LANL data can be used for validation.

14 MeV: Status and Proposed Work

Integral 14 MeV benchmark data for carbon by JAEA (C. Konno) are relatively clean since carbon transport is well-known and neutron spectra are measured by TOF.

EAF validation measurements [17] can be used for validation of IRDFF cross sections near 14 MeV (KIT, A. Klix).

FNG (M. Angelone) benchmark experiments can be used for IRDFF validation. A simple and clean experimental calibration campaign can be performed by measuring activation reaction rates and comparing them with MCNP results using FENDL (JEFF as well) coupled to IRDFF. Measurements with DD source can also be performed for the IRDFF validation.

The SINBAD data collection may be useful for validation. Benchmarks which address materials in the IRDFF database could be compared.

A. Trkov pointed out that ^{55}Mn measurement on the OKTAVIAN facility is in the SINBAD database, but the comparison is meaningful only if the data in the IRDFF are fully consistent with the transport data for the same nuclide. There are other benchmarks in which reaction rates were measured, but such benchmarks validate the combination of the transport data and the dosimetry reactions and should be used with care

Actions

- A. Klix will maintain the table of 14 MeV cross sections comparing IRDFF data with the experimental data used to validate the EAF library.
- C. Konno will organize measurements of the reaction rate ratio measurements on the FNS facility inside the graphite and lithium oxide blocks.

- C. Konno will perform cross section measurements around 14 MeV that are relevant for IRDFF.
- M. Angelone will measure reaction rate ratios on the FNG facility (the list of reactions is to be determined) and provide any clarification on the already completed benchmarks in the SINBAD database.
- M. Angelone will check the influence of replacing older dosimetry libraries with IRDFF in the analysis of the FNG benchmark experiments.
- S. Simakov will check which benchmarks in the SINBAD database are suitable for validating the IRDFF data.

Measurements in the ^{235}U fission spectrum

There are many experimental issues making it more difficult to determine accurate C/E values. MCNP calculations are required to determine the actual spectrum in the facility used for testing. A.Trkov (JSI) proposes additional measurements and calculations to obtain improved C/E values. Irradiations are also proposed in the CALIBAN facility (C. Destouches, P. Casoli). MCNP calculations including any spectral adjustment must be fully documented.

Attention was directed to the energy angular selection effect by N. Kornilov as a possible distortion factor for macroscopic experiments.

There is an on-going effort at LANL to reanalyse older data from critical assemblies (A. Kahler). Spectra for inclusion in IRDFF, such as ICSBEP, need to be documented and qualified if there are problems for validation.

Older data from facilities such as Sigma-Sigma, CRFRM or ISNF, which were included in IRDF-2002, may require recalculation of the neutron spectra using modern data. Additional measurements and calculations will be performed for the Sandia reactors by P. Griffin (SNL). Is it possible to include updated YAYOI data from Japan (will require reanalysis of the neutron spectrum)? There is a question on whether neutron spectra provided with IRDF-2002 should be included or not. An effort is needed to determine whether the neutron spectra have sufficient documentation for reanalysis using modern cross sections for Monte Carlo calculations as well as covariance files. P. Griffin will review Sandia reactor spectra. S. Kahler will review the ICSBEP benchmark spectra.

The CRP is interested in measurements of integral capture cross sections in the MINERVE reactor facility as part of the MAESTRO irradiation program under the CHANDA project.

Actions

- A. Trkov will organize an experimental campaign to perform measurements behind the fission plate of the TRIGA reactor in Ljubljana, including the full Monte Carlo analysis of the experiments.
- C. Destouches and P. Casoli will analyze existing measurements and perform new measurements in the Caliban facility. Measurements will also be analyzed from MASURCA, EOLE and MINERVE.
- C. Destouches will communicate the interest of this CRP in the CHANDA project.
- C. Destouches will use the MASURCA and PROTEUS spectra for systematic validation of IRDFF cross sections.
- A. Kahler will provide the results of the re-analysis of the older LANL critical experiments in which the reaction rates were measured. The ICSBEP documentation will be reviewed and upgraded.

- P. Griffin and L. Greenwood will review the spectra that are currently in the IRDFF library (such as ORR/PSF).
- P. Griffin will perform additional measurements at the Sandia reactors and validation of IRDFF cross sections
- V. Pronyaev, in communication with C. Konno will review the spectrum from the YAYOI facility.
- V. Pronyaev will review data from Russian facilities.

Accelerator Neutron Spectra

Cross section measurements (before and after corrections) and neutron spectra need to be reported with experimental results. Capture reactions are especially of interest. Full documentation is desired for validation for IRDFF as well as future work.

Actions

- P. Mastinu (INFN) and A. Plompen (IRMM) will provide the results of the measurements of MACS at 30 keV and other higher stellar temperatures.
- S. Simakov will retrieve and review raw experimental data relevant for IRDFF from EXFOR to perform checks with the Kadonis database.
- H. Yashima (Kyoto U) will perform measurements at 90 MeV and 140 MeV. Targets should include Bi and Co.
- R. Nchodu (iThemba LABS) in cooperation with F. Wissmann (PTB) will perform measurements in the energy range from 40 to 200 MeV, including a measurement at 90 MeV for comparison with the measurements at Kyoto. Targets should include Au, Bi, Co, and Tm.
- M. Stefanik (NPI Řež) will perform measurements at 20 to 35 MeV with Au, Bi, Co, Tm, and Fe.
- N. Kornilov (OU) will provide white neutron spectra from Be(d,n) at 7 MeV, and B(d,n) and Al(d,n) at 7.44 MeV measured with a new method. A new detector will be developed and investigated as a first step.
- L. Greenwood (PNNL) will provide neutron TOF spectra and activation measurements for Be(d,n) experiments at 7, 30, and 40 MeV and spallation experiments with 113 MeV protons on U and Al targets. Other Be(d,n) data will be included where possible from EXFOR or other sources.

Evaluation and validation of the high threshold dosimetry reactions

There are several high energy threshold reactions that are extremely convenient for spectrum unfolding and flux monitoring above 20 MeV. Often this is a set of several reactions (n,2-9n) on one isotope such as ^{197}Au, ^{169}Tm, ^{209}Bi, ^{59}Co, ^{63}Cu, ^{89}Y or ^{93}Nb. Their cross sections have rather "flat" plateaus which cover different intervals in the energy range from 20 to 100 MeV. Usage of only a few detectors (foils) makes it possible to unfold the whole broad spectra. The new measurements planned under this CRP (see above) and experimental data already existing in EXFOR or literature allow the evaluation, validation, and inclusion of such reactions in IRDFF.

Actions (V. Pronyaev)

- Validation of the IRDFF evaluations done with PADE-2 for ^{59}Co(n,2n) and ^{59}Co(n,3n) evaluations using Bayesian GLUCS fit with TENDL model calculations as a prior in the energy range threshold to 100 MeV.

- Validation of the IRDFF evaluations done with PADE-2 for ^{197}Au(n,2n) and ^{197}Au(n,3n) evaluations using Bayesian GLUCS fit with TENDL model calculations as a prior in the energy range threshold to 100 MeV.
- Preliminary evaluation of the ^{197}Au(n,4n), ^{209}Bi(n,2n), ^{209}Bi(n,3n), ^{209}Bi(n,4n), ^{209}Bi(n,5n), ^{209}Bi(n,6n) and ^{209}Bi(n,7n) using Bayesian technique with the results of model evaluation taken as a prior.

Decay Data

Decay data used in the analysis are often discrepant. The situation is even worse with the gamma-emission probabilities and it is proposed to compile the recommended data in the IRDFF library.

Actions

- Valery Chechev (Khlopin Radium Institute) will compile decay data for the 82 residual isotopes in the IRDFF. Additional isotopes will need to be added for the proposed additions to IRDFF. The key gamma lines (highest yields) are commonly used for neutron dosimetry. Additional gamma lines may also be needed for cascade summing corrections. The consistency of half lives and absolute gamma intensities will be checked with the data evaluations and values will be updated if necessary.

- The IAEA will review key fission yields for a small list of fission products to determine the best values to include with IRDFF. Otherwise, references will be provided to the IAEA Safeguards, ENDF/B-VII.1 or other databases. Christophe Destouches will provide a list of needed fission products.

Newly performed evaluations and updating of IRDFF

New evaluations made by K. Zolotarev (IPPE) for ^{54}Fe(n,p)^{54}Mn, ^{58}Ni(n,2n)^{57}Ni, ^{67}Zn(n,p)^{67}Cu, ^{92}Mo(n,p)^{92m}Nb, ^{93}Nb(n,γ)^{94}Nb, ^{113}In(n,n')^{113m}In, ^{115}In(n,γ)^{116m}In and ^{169}Tm(n,3n)^{167}Tm should be included in IRDFF.

Actions

- NDS/IAEA together with K. Zolotarev will replace old evaluations in IRDFF by new ones.

Suggestion of New Reactions for Inclusion in IRDFF

The following reactions were suggested for inclusion in IRDFF:

- ^{27}Al(n,γ)^{28}Al - often present in facilities, short-lived (2.24 min)
- ^{94}Zr(n,γ)^{95}Zr and ^{96}Zr(n,γ)^{97}Zr - first resonance at high/low (2.3/0.3 keV) energies
- ^{70}Zn(n,γ)^{71}Zn - first resonance at energy above 10 keV but low abundance (0.62%)
- ^{117}Sn(n,n')^{117m}Sn - low threshold (0.3 MeV), convenient half-life (14 days) and γ-energy 314 keV)
- ^{93}Nb(n,γ)$^{94g+m}$Nb and ^{94}Nb(n,γ)^{94m}Nb - for burn up calculations
- ^{113}In(n,γ)^{114m}In – perspective reaction for reactor dosimetry due to the appropriate half-life 49.51 ± 0.01 days and lonely decay line 190 keV with intensity 15.56 ± 0.15%. Its rate, measured using the ^{nat}In activation detector, will give additional information for ^{115}In(n,γ)^{116m}In.

Actions

- A. Trkov will recommend evaluation of the ^{27}Al(n,γ)^{28}Al, ^{94}Zr(n,γ)^{95}Zr, ^{96}Zr(n,γ)^{97}Zr and ^{70}Zn(n,γ)^{71}Zn for inclusion in IRDFF

- C. Destouches will recommend evaluation of the ^{93}Nb(n,γ) $^{94g+m}$Nb, ^{94}Nb(n,γ)^{94m}Nb and ^{117}Sn(n,n‘)^{117m}Sn reactions
- K. Zolotarev will evaluate the ^{113}In(n,γ)^{114m}In reaction

Request for ^{28}Si(n,p) Reaction Cross Section Evaluation and Validation

The fusion community has requested inclusion of the ^{28}Si(n,p)^{28}Al reaction for neutron monitoring purposes during planned fusion experiments.

Actions

- K. Zolotarev (IPPE) agreed to evaluate the data for this reaction.
- A. Klix (KIT) will perform cross section measurements around 14 MeV.
- C. Konno (JAEA) will perform validation experiments in a graphite assembly on FNS.

General Comments

Participants of the CRP will inform and communicate with the dosimetry communities (ASTM, EWGRD) the needs and activities of the CRP.

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V. Participants' Summaries

Evaluation of the excitation functions for dosimetry reactions

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New evaluations of cross sections and their uncertainties have been carried out for eight dosimetry reactions: ^{54}Fe(n,p)^{54}Mn, ^{58}Ni(n,2n)^{57}Ni, ^{67}Zn(n,p)^{67}Cu, ^{92}Mo(n,p)^{92m}Nb, ^{93}Nb(n,γ)^{94}Nb, ^{113}In(n,n')^{113m}In, ^{115}In(n,γ)^{116m}In and ^{169}Tm(n,3n)^{167}Tm. Excitation functions of the ^{67}Zn(n,p)^{67}Cu, ^{92}Mo(n,p)^{92m}Nb, ^{113}In(n,n')^{113m}In and ^{169}Tm(n,3n)^{167}Tm reactions were evaluated for dosimetry application at first. Uncertainties in the cross sections for all new evaluations are given in the form of relative covariance matrices.

In the period before the 2nd RCM the next work is foreseen.

An excitation function for the ^{28}Si(n,p)^{28}Al reaction is proposed to evaluate in the energy range from threshold (3.99924 MeV) to 21 MeV. The data base for evaluation will be formed by correction of original experimental data to the new standards. Experimental data obtained with samples of natural Si composition needed correction for contribution from ^{29}Si(n,np+pn+d)^{28}Al reaction. This means that excitation function of this reaction must be done also. Evaluation of cross sections of these reactions and related uncertainties will be carried out by means of PADE-2 code.

Reaction ^{113}In(n,γ)^{114m}In is very perspective for reactor dosimetry application because of two reasons. At first due to the ^{114m}In decay parameters which are rather suitable for activation measurements. Half-life of ^{114m}In is equal to $T_{1/2} = (49.51 \pm 0.01)$ days and gamma spectrum accompanying decay has only one line with energy 190.27 keV and intensity (15.56 ± 0.15)%. And at the second the ^{113}In(n,γ)^{114m}In reaction rate may be measured by using one activation detector simultaneously with the ^{115}In(n,γ)^{116m}In reaction. Neutron radiative capture on ^{113}In will be analysed in the energy range 1.E-05 eV – 20 MeV taking into account resonance parameters, isomeric ratios $\sigma_g(E)/\sigma_{m+g}(E)$, $\sigma_m(E)/\sigma_{m+g}(E)$, total and partial cross sections. As a result of this work it is planned to evaluate cross section data for reaction ^{113}In(n,γ)$^{114m+g}$In and its partial components ^{113}In(n,γ)^{114g}In and ^{113}In(n,γ)^{114m}In with related uncertainties.

High-energy (n,xn) dosimetry reactions

V.G. Pronyaev

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Bayesian computer code GLUCS (update 2006, S. Tagesen) and generalized least squares code (GMA, W. Poenitz, 1997; CSEWG, 2002; V. Pronyaev, 2004) can be used for evaluation of (n,xn) high-energy dosimetry reactions at the set of mono-isotopic natural elements. For this the results of model calculations with computer codes GNASH, TALYS and EMPIRE and covariance matrices of uncertainties obtained by experts' estimation or Monte Carlo method can be used as prior evaluations in the fit of the experimental data. The method can be verified by comparison with the results of evaluations obtained with PADE-2 method for (n,2n) and (n,3n) reactions using the same experimental data in the fit. Although the evaluated percent uncertainties of (n,xn) reaction for $x > 3$ may be in the range 10 - 30%, these reactions can be rather informative in the spectra unfolding because their bell or step-wise shapes.

CRP on Testing and Improving the IRDFF

L.R. Greenwood

Pacific Northwest National Laboratory,
USA

Institution: Pacific Northwest National Laboratory is a multi-disciplinary laboratory operated by the US Department of Energy with about 4500 staff, located in Richland, Washington.

Facilities: Radiochemical laboratories, hot cells, fume hoods in Category II Nuclear Facility with extensive nuclear counting equipment (alpha, beta, gamma), ICP/OES & MS, TIMS, TEM, and many other types of instruments. 14 MeV neutron source (1.E+10 n/s). Access to fission reactors and particle accelerators at nearby laboratories.

Research: Reactor dosimetry experiments are being conducted at fission reactors, 14 MeV neutron sources, and critical assemblies (COMET, FLATTOP)

Proposed Work for CRP:

1. Provide data and review of published integral testing experiments at Be(d,n) and spallation neutron sources.
    - Be(d,n), E_d = 7 MeV Argonne National Laboratory
    - Be(d,n), E_d = 16 MeV Argonne National Laboratory
    - Be(d,n), E_d = 30 MeV UC Davis Cyclotron
    - Be(d,n), E_d = 40 MeV Oak Ridge National Laboratory
    - 14 MeV T(d,n) at RTNS II and PNNL
    - Spallation Neutron sources:
    - LANL TOF with 113 and 256 MeV p on thick targets of Al and DU
    - ANL/IPNS activation measurements with the identical Al and DU targets and well-defined geometries for Al, Au, Co, Cu, Fe, In, Nb, Ni, Ti, and Zr foils at angles from 0 to 150°
    - Data have been provided for inclusion in EXFOR database

2. STAYSL PNNL Software Suite
    - New version of STAYSL now available from PNNL and IAEA
    - Currently based on IRDF-2002 cross sections and covariance files
    - Proposed upgrade with IRDFF to 60 MeV
    - Modules for all steps required to go from raw counting data to adjusted neutron spectra
    - Generalized least-squares adjustment with full covariance specifications

3. Integral Testing
    - Compare measured activation data with TOF neutron spectra as described above
    - Assist with testing by others using our data in EXFOR
    - Update and revise STAYSL PNNL as necessary with any revisions to IRDFF
    - Apply new IRDFF data for neutron dosimetry experiments at fission reactors, 14 MeV and critical assembly experiments to look for consistency and differences with IRDF-2002 and other files.

Standard neutron field for high energy (current status, how to increase an accuracy)

N.V. Kornilov

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USA

Research in the Physics and Astronomy department at Ohio University is primarily focused on Astrophysics, Condensed Matter Physics, Nuclear Physics, and Biophysics.

The Nuclear Physics research efforts at Ohio University are organized under the Institute of Nuclear and Particle Physics (INPP). Faculty members Brune, Grimes, Ingram, Massey, and Voinov work in the area experimental low-energy nuclear physics, on subjects of both basic and applied interest. David Ingram also does research in condensed matter physics, and presently serves as the Department Chair.

Edwards Accelerator Laboratory

The 4.5-MV tandem van de Graaff accelerator (Fig. 1) located in the Edwards Accelerator Laboratory. The laboratory includes a vault for the accelerator, two target rooms, a control room, a chemistry room, an electronics shop, an undergraduate teaching laboratory, and offices for students, staff, and faculty. The Laboratory building supplies approximately ~1000 m^2 of lab space and ~500 m^2 of office space.

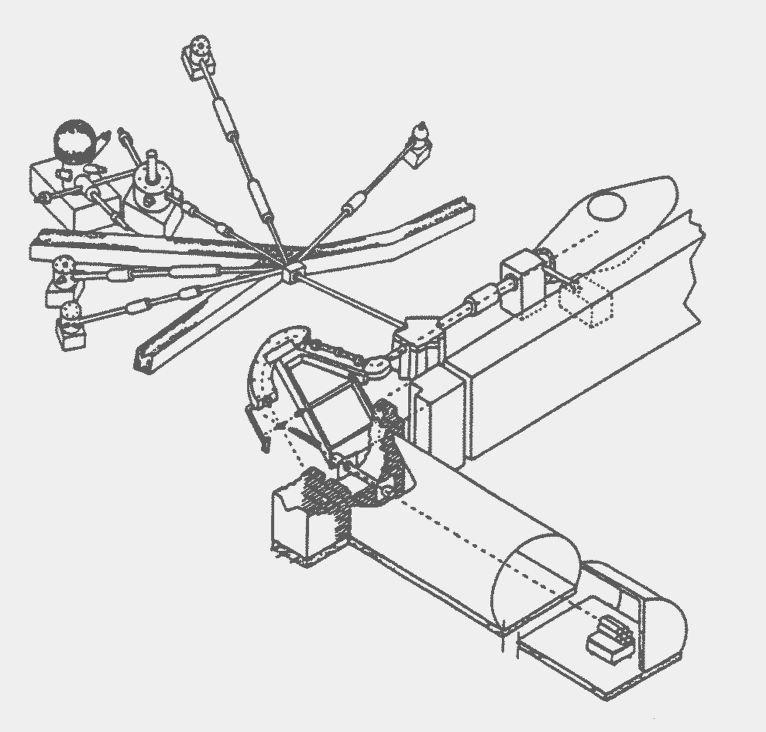

Figure 1. Ohio University Accelerator Lab showing the swinger and Time-of-Flight Tunnel.

An NSF-funded project to convert the accelerator to a Pelletron charging system has been completed. The new charging system was installed in fall 2011. This upgrade should provide improved stability (particularly at higher terminal voltages) and require less maintenance. We are expecting the conversion to require two months of down time.

This machine is equipped with a sputter ion source and a duoplasmatron charge-exchange ion source for the production of proton, deuteron, ^{3,4}He, and heavy ion beams. Pulsing and bunching equipment are capable of achieving 1-ns bursts for proton and deuteron beams, 2.5-ns bursts for ^{3,4}He beams, and 3-ns bursts for ^{7}Li. The Pelletron charging system was completed in spring 2012. We have achieved stable operation at terminal voltages up to 4.5 MV. The SF_6 compressor and gas-handling system were refurbished in April 2005.

The Laboratory is well equipped for neutron time-of-flight experiments. A beam swinger magnet and time-of-flight tunnel allow flight paths ranging from 4 to ~30 m. The tunnel is very well shielded, and the swinger-magnet assembly allows angular distributions to be measured with a single flight path.

Detection Equipment

Neutron Detection.

Several types of neutron detectors are available, including lithium glass and NE213. We have recently purchased six neutron detectors from Eljen Technology which have NE213 equivalent scintillator. A cylindrical stilbene detector of size ~2.54 cm diameter by ~2.54 cm thick was also acquired that has proved to have excellent PSD. We have also purchased three ~2.54 by ~2.54 cm cells which can be viewed with two photo tubes. These cells are filled by NE213, benzene and deuterated benzene and are intended to be used in the H(n,n)H experiment. We have now purchased three MESYTEC pulse-shape discrimination modules which are ideal for instrumenting neutron time-of-flight experiments with liquid scintillators.

Fission Chambers.

We have developed two new fission chambers to meet the needs of our program. The first fission chamber was for the ^{252}Cf source. This chamber was modelled after a chamber which had been used at Geel, Belgium by Nikolay Kornilov in previous work. We designed a cylindrical thin walled (0.25 mm thick). The total mass near the fission source has been reduced to a minimum. This has been used in the neutron detector calibrations.

The second fission chamber was to be used as a monitor detector with a ^{238}U. This fission chamber was constructed to reduce the mass around the fission foil. This is to reduce the neutron multiple scattering. The main support is a thin ring which has penetrations for the high voltage and the gas inlet and outlet. Three support pieces are split to hold the fission foil securely. Two pieces of aluminium foil are cut to size and are held in place by a spring wire to close off the volume of the fission chamber. This fission chamber will be placed close to the neutron source as a monitor of the neutron flux.

Gamma-Ray Spectroscopy.

We have purchased a second 10.2 cm-diameter × 10.2 cm-length BGO detector. We also purchased an annular plastic scintillator to be used as a cosmic-ray veto with our BGO detectors. In addition, we now have a 5.1 cm diameter × 5.1 cm-length Lanthanum-Bromide scintillator for gamma-ray detection. Three intrinsic Ge detectors are available for high-resolution gamma-ray studies (two coaxial detectors of 40% and 75% relative efficiency and one15 mm-thick 2000 mm^2-area planar detector). One beam-line is primarily devoted to gamma-ray spectroscopy experiments.

Charged-Particle Time-of-Flight Spectrometer.

In addition to a standard scattering chamber for charged-particle measurements, we have also built a 10-arm time-of-flight (TOF) spectrometer. This instrument allows for the simultaneous measurement at 10 angles. Silicon surface-barrier detectors are located at the ends of each tube which can stop protons with energies of up to 13 MeV. The flight path for each tube can be chosen to be 0.3, 1.0, or 1.8 m. The measurement of total energy and time of flight is a powerful tool for particle identification, particular for low particle energies where E-ΔE Si telescopes are problematic. We have achieved resolutions of 30 keV or better for every detector, for 5 MeV alpha particles. In addition we have designed mounts for four

NE213 scintillators and Ge detectors in order to measure neutrons and gamma-rays, respectively. We have recently obtained two CsI scintillators and one 5 mm-thick lithium-drifted Si detector. These detectors will allow us to measure protons with energies greater than 10 MeV.

Currently, a further upgrade is underway to instrument at least 8 of the ten legs with particle telescopes. Using the **ΔE-E** technique to identify particles has the advantage over the **E-TOF** technique that it does not require a TOF measurement, and hence, the detectors can be brought much closer to the target to increase the solid angle. The main disadvantage of the **ΔE-E** technique is that the particles have to penetrate the thin **ΔE** detector and still produce a signal in the **E** detector for proper identification. Hence, the technique is limited to particle energies above a certain threshold which depends on the particle type and thickness of the **ΔE** detector.

In order to push this threshold down as much as possible, we purchased two 30-μm and six 50-μm **ΔE** detectors from ORTEC. They are complemented by eight new 400 μm E-detectors which allow us to do particle identification between 5 and 25 MeV for α-particles and between 2 and 12 MeV for protons. In order to identify higher energy protons, we back the Si telescopes by CsI scintillator detectors. Their energy resolution should be sufficient to discriminate hydrogen isotopes above 15MeV kinetic energy.

Computers.

Every student, postdoc, staff member, and faculty member has a modern PC-based computer system (Linux, Mac, or Windows operating system) on their desk. Many additional computers are available for special purposes (e.g. data acquisition, data analysis).

Several new Intel “Core i7” processor systems were purchased to replace some ageing computer systems and enhance our computer capabilities. These systems were also fully expanded with RAM (12 GBytes) to allow programs requiring large amounts of memory to run without swapping to disk.

Several new standalone DAQ systems were placed in operation for new experiments. DAQ software has also been enhanced to allow new hardware and add new features. We also have a “Distributed DAQ” data acquisition system which consists of up to 15 dual-PC nodes connected via Ethernet to a central computer used for system control and data display. Each node is an independent computer with Distributed DAQ hardware that is dedicated to a single detector or detector-telescope system. This system is running the Linux version of the Ohio University DAQ software (see http://www.daqlinux.com). The Distributed DAQ hardware consists of a board with two charge-to-time converters (MQT300A) and one multi-hit eight-channel time-to-digital converter (MTD133B) from LeCroy. The charge converter has 3 selectable ranges and an optional variable range. Each charge converter has a maximum dynamic range of over 500.This system can operate at high data rates, has excellent time stability, and eliminates cross talk between detectors. It is particularly advantageous for time-of-flight experiments.

Proposed activities in the frame of CRP

Standard Neutron Spectra or fields (SNS) for neutron energy range < 20 MeV were measured in different laboratories for several targets (see table).

Table. Reactions and parameters of neutron fields.

Reaction	Lab	E_d, MeV	Angular	Q, MeV	E_n, Max, 0-deg	E_n, Max, 120-deg
^{9}Be(d,n)^{10}B	OU, ANL, IRMM	7	Yes	4.361	11.35	8.06
^{10}B(d,n)^{11}C	OU	7.44	No	6.464	13.69	10.47
^{11}B(d,n)^{12}C	OU	7.44	No	13.73	21.19	17.16
^{27}Al(d,n)^{28}Si	OU	7.44	No	9.360	16.85	15.22

The comparison of these neutron spectra and average cross sections measured in these fields allow us to conclude that high accuracy 2-3% in whole energy range 0-20 MeV is not reached. The main problem is connected with the measurement of the neutron detector efficiency in the whole energy range up to 20 MeV and higher.

Therefore one may formulate following steps for realization of the SNS.

1. Development of new type of neutron detector which efficiency may be calculated with reasonable accuracy;
2. Verification of the detector efficiency at neutron energies ~ 9 MeV and ~ 14 MeV;
3. Measurement of ^{9}Be(d,n), ^{nat}B(d,n), and ^{27}Al(d,n) spectra at 0-deg and 7 - 9 MeV deuteron energy;
4. Investigation of the d-build up;
5. Comparison with old experimental data and conclusion about data accuracy;
6. Simulation of SNS with theoretical calculations (EMPIRE);
7. Evaluation of SNS and recommendation for practical application;
8. Application of this SNS for practical verification of IRDFF;

Measurements of neutron cross sections at iThemba LABS

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Measurements of neutron cross-sections were previously made at iThemba LABS at 40 to 150 MeV energy ranges. The proposed project plans to measure reaction cross sections using quasi-monoenergetic neutrons in the energy range of 40 to 200 MeV and to achieve reduction in uncertainty levels to below 10%. These measurements will be a contribution to a set of activities for the “Testing and Improving International Dosimetry Library for Fission and Fusion” community. The unique features of the iThemba LABS neutron beam facility and the existing HPGe detector system are ideal to achieve these plans.

Fast Neutron Facility at iThemba LABS

The iThemba LABS neutron facility (iTL) can provide quasi-monoenergetic neutron beams of energies 25 – 200 MeV, using the (p,n) reaction on thin Li and Be targets. Detailed information on the quasi-monoenergetic fields at the iThemba LABS facility can be found in the papers by Nolte *et al*. [1], and Mosconi *et al*. [2]. Fig. 1 shows the layout of the iTL neutron vault. The beam line is 1.5 m from the ground and has about the same distance to the roof. Measurement can be made in 4 degree steps from 0 to 16 degrees. Measurements are usually carried out at an 8 m distance from the target. Energies available so far are from 40 MeV to 200 MeV. The beam is pulsed with 33 ns between pulses at 200 MeV which increases as the energy decreases. Pulsed beam available is 1 in 3, 1 in 5 or 1 in 7 depending on the energy. The beam metrology is traceable to national standards via the fluence and energy distributions made by the Physikalisch-Technische Bundesanstalt (PTB).

The relative fluence energy distribution can be measured up to 70 MeV with a scintillation detector, and above this energy, by a combination of scintillation detector and fission chamber. Sample spectra of beams produced with a 3 mm Li target are shown in Fig. 2. The peak is made up of neutrons emitted at zero degrees from the ^{7}Li(p,n)^{7}Be reaction going to the ground and first excited states of ^{7}Be. The continuum is made up of neutrons from the breakup of ^{7}Li, which is mainly isotropic up to an angle of 16 degrees. The yield of any product radionuclide from an (n,x) reaction, produced by irradiation in the zero degree beam, therefore includes components due to reactions initiated by both the high energy peak neutrons and the continuum, while the yield resulting from irradiations in the 16 degree beam is dominated by reactions initiated by the low-energy continuum alone. Thus subtracting the yield produced in the 16 degree beam (after appropriate normalization) from that simultaneously produced at zero degree results in a yield determined for quasi-monoenergetic neutron energy.

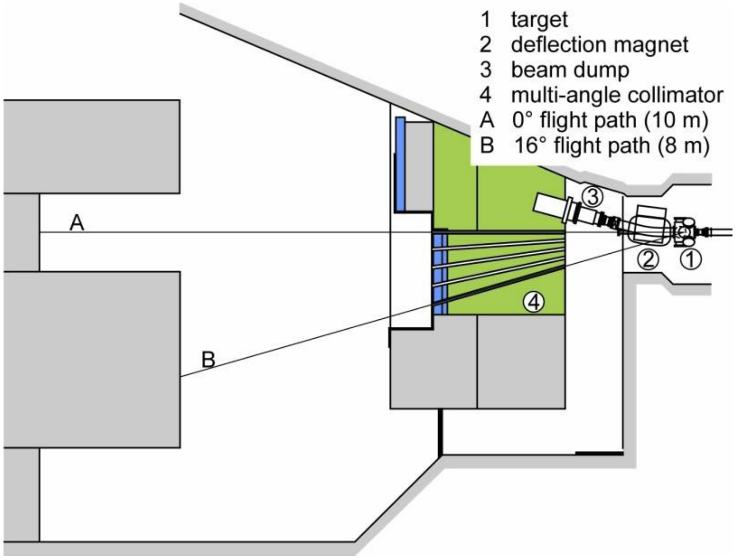

Figure 1. Sketch (not to scale) of the iThemba LABS neutron beam facility.

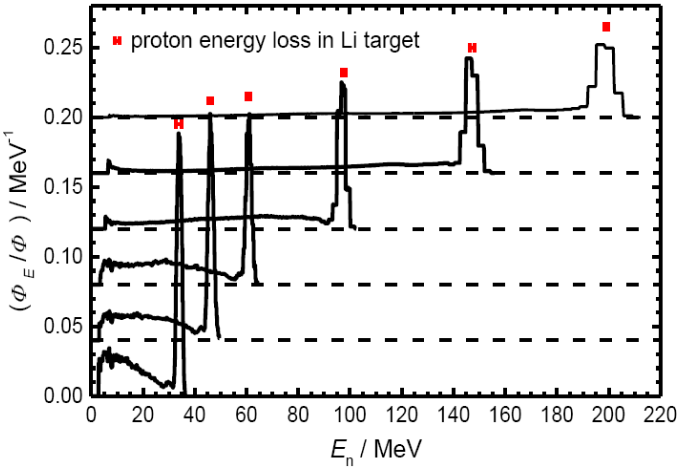

Figure 2. Normalised spectral neutron distribution at different energies produced at iThemba LABS with a 3 mm Li Target. The intrinsic width, indicated by the red horizontal bars, refers to the spread in neutron energy induced by the target thickness.

For the 97 MeV beam, the full width half maximum of the peak is about 4 MeV, and the fraction of the total fluence within the peak is about 0.4 increasing to 0.5 at 197 MeV. For the higher energies, this fraction can be effectively increased to ~ 0.7 by using a difference method, subtracting the instrument response for the 16° beam from that at 0°. For the 16° beam, the quasi-monoenergetic peak is greatly reduced but with much less reduction in the lower energy continuum as shown in Fig. 3.

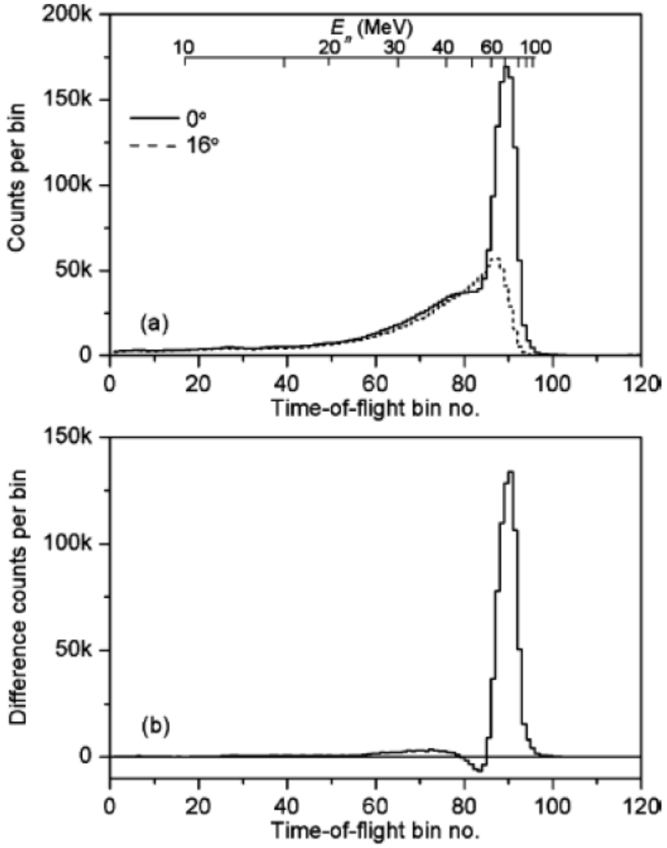

Figure 3. Neutron spectra at iTL for incoming proton energy of 65.99 MeV and a Li target thickness of 6 mm. (a) Spectra at two different angles are shown and (b) the difference spectra (J.M. Sisterson et al. [3]).

Cross section measurements

Measurements of cross-sections for neutron-induced reactions in copper were made at neutron energies of 70.7 and 110.8 MeV by Sisterson et al. [3] and neutron cross sections due to ^{A}Ge(n,xn)^{68}Ge reactions by Dormula et al. with 39.9 MeV neutrons. Typical uncertainties for the peak fluence, peak to continuum ratio, fluence monitor and HpGe detector are 7%, 4%, 2% and 4%, respectively for the copper activation measurements. iThemba LABS has a low-level counting laboratory equipped with a HpGe detector. The irradiated samples are enclosed in a lead castle to reduce the background, enabling measurements of gamma rays from samples with low activities.

Measurements of cross sections for the (n,xn) reactions for the Co, Au, Bi and Tm targets using quasi mono-energetic neutron beams of 40 to 200 MeV will be made at iThemba LABS for the IRDFF CRP. Beam monitoring and characterization will be done using the time-of-flight technique with the NE213 scintillator and the fission chamber available at iThemba LABS. Pulse separation will be used to avoid the frame-overlap problem and achieve low detection thresholds. The irradiation of the samples will be carried out without pulse separation to increase the beam current and the produced activity. Fig. 4 shows the gamma ray spectrum measured with the HpGe detector after the irradiation of Co with neutrons from the ^{7}Li(p,n)^{7}Be reaction with 66 MeV protons impinging on 8 mm Li target. The sample was placed at ~ 4.0 m from the target chamber (neutron production point) at the entrance of the 16° collimator. The two peaks in the spectrum are identified as being from the ^{59}Co(n,3n)^{57}Co reaction. The two gamma transitions are from the 136 keV 5/2- state; the first transition is to the 3/2- state at 14 keV, emitting a gamma ray of 122 keV and the second one is to the ground state (1/2- state), emitting a gamma ray of 136 keV. The transition that leads to the emission of a 122 keV gamma ray has a relative intensity of 86% and the transition that leads to an emission of a 136 keV gamma ray has a relative intensity of 11%. The resolution of the peaks in Fig. 4 indicates that the resolution of the HpGe detector at iThemba LABS is sufficient for identifying gamma ray transitions from the neutron induced radionuclides of interest for this CRP. The measurements will be done in collaboration with researchers from the PTB and the collaboration may also include researchers from Institut de Radioprotection et de Sûreté Nucléaire (ISRN).

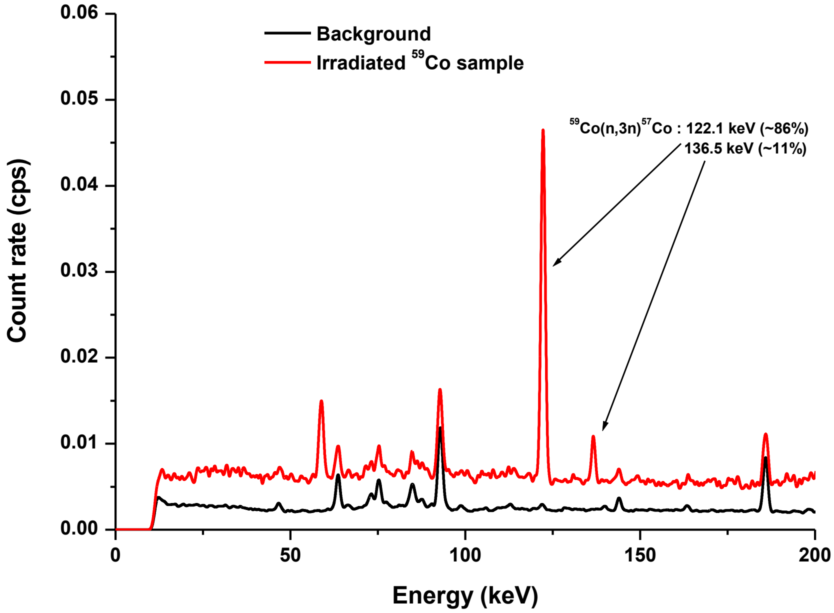

Figure 4. Gamma ray spectrum emitted by the Co sample irradiated at iThemba LABS with neutrons from the ^{7}Li(p,n)^{7}Be reaction with 66 MeV protons and 8 mm Li target.

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Experimental validation of IRDFF cross-sections in quasi-monoenergetic neutron fluxes in 20 – 35 MeV energy range

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Abstract: The scope of the work is the validation of the cross-sections for neutron dosimetric reactions (n,*x*n) on ^{59}Co, ^{169}Tm, ^{209}Bi, ^{54}Fe, and ^{197}Au in the energy range of 20–35 MeV. All these isotopes will be irradiated using the NPI quasi-monoenergetic neutron source. Specific γ-activities of induced residual nuclides will be investigated by means of the HPGe detectors. Extraction procedure based on the SAND-II unfolding code will be used to obtain the cross-sections from measured activities. For the determination of the neutron spectral flux at sample position, the MCNPX simulation backed by the time-of-flight measurements will be employed. The expected uncertainties are evaluated to be within 10–15%.

Introduction

The cyclotron-based fast neutron generators of the broad- and quasi-monoenergetic spectra are operated at the NPI Fast Neutron Facility utilizing the variable-energy proton beam (up to 37 MeV) and the D_2O (flow), Be (thick), and ^{7}Li (C backed) target stations [1]. The intensity and the energy range of the produced neutron fields are suitable for the integral and differential validation of the neutron cross-sections within the Accelerator Driven Transmutation Technology (ADTT) and fusion-relevant (International Fusion Material Irradiation Facility - IFMIF) research programs.

Experimental equipment and methods at the NPI

A basic experimental facility of the NPI is the Cyclotron U-120M which has been in operation since 1960; in 1975, it was upgraded and since that it has worked in the isochronous regime. It provides the protons, deuterons, respectively ^{3}He ions with energies in the range of 6–25 MeV (3 μA), 12–20 MeV (3 μA), respectively 18–55 MeV (1 μA) in the positive ion mode of acceleration. In the negative ion mode of acceleration, the protons and deuterons with energies of 6–37 MeV (15 μA) and 11–22 MeV (10 μA) with good beam-current stability are obtained and thus utilizable for neutron fields production at the suitable targets.

For quasi-monoenergetic neutrons production, the p + ^{7}Li source reaction is used; the self-supporting 2 mm thin lithium target together with the alcohol cooled carbon beam-stopper is bombarded by protons with energies up to 37 MeV and intensities of 8 μA. The infrared temperature sensor recently built-in to the target station made possible to on-line monitor the temperature characteristics of the lithium target, and made possible to safety increase the proton-beam current on the target from routinely used 5 to 8 μA (for the next experiments, the beam current up to 10 μA is intended). The generated quasi-monoenergetic neutron field presents the important tool for cross-section data measurement in the neutron energy range of 18–35 MeV; it is studied via the Monte Carlo calculations and on-line detection techniques (the MCNPX neutron spectral flux is validated against both the time-of-flight measurement with the NE213 scintillation probe and against the proton recoil telescope with thin silicon detectors measurement). The flux density at the sample positions of 48 mm achieves the value of 10^9 neutrons/cm^{2}s in the QM peak [1].

Next, the p(37 MeV)-D_2O white neutron source is the unique neutron generator which does not have any analogue all over the world. It produces the IFMIF relevant neutron field, has energy range up to 33 MeV with mean energy of 14 MeV and spectral flux density of fast neutrons of about 10^{11} cm^{-2}s^{-1} [1, 2]. It is designed for integral validation of nuclear data, and is often used for studies of radiation hardness of electronics against the intensive neutron field. The neutron spectral characteristics for irradiation positions in the vicinity of source target were studied deeply. By using the phenomenological curves of the reaction rates ratios respectively the spectral flux ratios supported by the MCNPX predictions, it is possible to extrapolate the neutron spectrum from the basic position into any other requested irradiation position in free space of the primary neutron beam.

The third neutron source at the NPI is built based on the reaction of p + Be. The so-called beryllium target station was primarily using in the energy range up to 20 MeV suitable for the ADTT program. Nevertheless, in 2012 the successful test with the proton beam energy of 35 MeV and intensity of 9.26 μA was carried out, and in addition by employing the multi-foil activation technique, the novel neutron field up to 34 MeV with neutron flux density of approximately 10^{11} $cm^{-2}s^{-1}$ was developed [3]. The spectral characteristics are studied now. Similarly as in case of p(37 MeV)-D_2O, the p(35 MeV)-Be white neutron spectrum is also available for the integral validation of activation cross-section data.

All three target stations of NG-2 fast neutron generator play the key role within the neutron programs at the NPI. Besides that, the experiments are backed by the following experimental methods and supporting devices. The dosimetry foils activation technique with a long tradition at the Department of Nuclear Reactions of the NPI is utilizing for routine monitoring of neutron fields, sensitive measurements of neutron spectra from high to low neutron energy (precise but time consuming method), and first of all for activation cross-section data measurement as well. Activation foils are analyzed by two calibrated HPGe semiconductor detectors both with relative detection efficiency of 50 % and energy resolution of 2 keV for γ-line of 1.332 keV from ^{60}Co. Recently constructed pneumatic post has shifted the activation measurement capabilities towards the short-lived isotopes. For the on-line measurements of neutron fields, the proton recoil telescope was built; however, the time-of-flight method together with the NE213 scintillation probe was taken into account and tested, and finally preferred as a flexible technique for neutron spectra measurement.

Neutron cross-section measurement for IRDFF

A new cross section library, the "International Reactor Dosimetry and Fusion File release1.0 (IRDFF 1.0)" has been developed for reactor dosimetry and fusion applications [4]. The improvements over the IRDF-2002, which are important for this work are mainly the extension of the upper energy range from 20 MeV to 60 MeV and the inclusion of several new dosimetry reactions.

It is a known fact that experimentally obtained cross-section data are rare and uncertain especially above neutron energy of 20 MeV. Several introduced evaluations therefore need additional validations based on new and less uncertain differential cross section measurements. The NPI provides the experimental validations of cross-section data with neutron generator for quasi-monoenergetic neutrons, in particular the neutron dosimetric reactions (n,3n) and (n,4n) on ^{59}Co, ^{169}Tm, ^{209}Bi, ^{54}Fe, and ^{197}Au in the energy range relevant to the IFMIF (20–35 MeV) are investigated. The activation foils method together with the HPGe γ-spectroscopy and the TOF measurement of neutron field by the Bicron detector and validated in the MCNPX calculations are utilized. The first experiment was performed in the first half of 2013, two experiments are planned for the second half of 2013, and remaining three experiments will be carried out in 2014. Furthermore, the integral validation measurement in white neutron field of p(35 MeV)-Be or p(37 MeV)-D_2O are also considered.

The cross-sections values will be extracted from the activities of residual nuclei measured with the HPGe detectors using the analysis procedure based on the modified SAND-II code. Data of energy-dependent cross-sections in the energy range of 20–35 MeV for reactions (n,xn) on ^{59}Co, ^{169}Tm, ^{209}Bi, ^{54}Fe, and ^{197}Au will be obtained with expected uncertainty in the range of 10–15%.

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Activation cross section measurements by high energy neutrons

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A quasi-monoenergetic neutron field using ^{7}Li(p,n) reaction for the higher energy range of 100 to 400 MeV has been developed at the RCNP cyclotron facility of Osaka University. Proton beams extracted from the ring cyclotron are transported to the neutron experimental hall and hit a 1.0 cm-thick ^{7}Li placed in the swinger which is in a vacuum chamber. Protons passing through a target are bent to the beam dump using a swinger magnet to measure the proton beam intensity with a Faraday cup. The beam current is kept up to 1 μA. Neutrons produced at 0° from the target are extracted into the 100 m tunnel through a 10 × 12 cm aperture in a 150 cm-thick concrete wall located 4.5 m away from the target. The clearing magnet in the movable collimator serves to reduce charged particles contaminating the neutron beam. The movable collimator and the swinger magnet allow neutron emissions to be measured through angles between 0° and 30°. The neutron time-of-flight (TOF) measurements for ^{7}Li(p,n) reaction in the energy above 1 MeV were performed using NE213 organic liquid scintillators.

This neutron field has been applied for a systematic measurement of neutron activation cross sections, needed for the estimation of residual radioactivities in accelerator facilities, decipherment of cosmic-ray irradiation histories when evaluating the amounts of cosmogenic nuclides stored in extra-terrestrial matter and dosimetry of high energy neutron fields.

The energy spectra of this neutron field are not purely monoenergetic, with both a high energy peak coming from ^{7}Li(p,n) reaction, and a low energy tail resulting from the consequent break-up reaction. Thus, two different irradiation experiments were obtained by using two different neutron beams at 0˚ and 25˚ (or 30˚). In irradiation experiments, activation samples were placed at an angle of 0˚ to the proton beam to measure activities induced by both high energy peak neutrons and low energy neutrons, while to measure activities induced by low energy neutrons only, samples were placed at an angle offset 25˚ (or 30˚) from the direction of the proton beam. The distance between Li target and samples and irradiation time are 7-8 m and 20-30 hours. Average proton beam intensity was about 1 μA. During the irradiation time, the proton beam current at the beam dump was recorded with a digital current integrator, connected to a multi-channel scaler (MCS) to monitor the fluctuations of the proton beam currents.

After irradiation, the gamma rays emitted from the irradiated samples were measured with a high-purity germanium (HPGe) detector. The samples were measured several times in order to identify newly created radioactive nuclides by their half-lives. Reaction rates of radioactive nuclides produced in the samples were determined from the gamma-ray spectra and decay curves, after first accounting for any beam current fluctuations during the irradiation and corrections in the peak efficiency of the HPGe detector.

To remove the component of nuclides produced by the low energy tail, the 25° (or 30°) spectra is normalized to the one measured at 0° by equalizing the neutron fluence in low energy region, then the corrected result is then obtained by subtracting the normalized 25° (or 30°) spectra from the 0° spectra. Thus, the subtraction of the nuclide component produced by a beam angled at 25° (or 30°) from one angled at 0° gives a yield produced only by high energy peak neutrons.

Contributing to the estimate of uncertainty in the cross section measurements are the counting statistics (< 20%), detector efficiency (Ge detector - 10%, NE213 detector - 15%), beam current monitoring (5%) and correction for contribution of low energy tail (10%).

The cross sections of Bi(n,xn) reaction for 287, 370 and 386 MeV and Co(n,xn)reaction for 386 MeV were obtained by previous experiments. Neutron activation experiments are planned by using 90 and 140 MeV p-Li neutron beam. In these experiments, cross sections of Co(n,xn) and Bi(n,xn) reactions which are dosimetry reactions in IRDFF will be measured.

Research plan on IRDFF testing and improving at JAEA/FNS

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1. Fusion Neutronics Source facility at JAEA and research activities related to this CRP

1. 1 Fusion Neutronics Source facility

The Fusion Neutronics Source (FNS) facility was installed at the current Nuclear Science Research Institute of Japan Atomic Energy Agency in 1981 in order to investigate the neutronics characteristics for candidate materials of fusion reactors including nuclear data measurements and has been successfully operated for 30 years. FNS is an accelerator-based D-T neutron source. It consists basically of a 400 keV high current electrostatic deuteron accelerator, heavy-duty tritium metal target assemblies, tritium handling and processing devices, experimental equipment and a building which houses the source facility at the same time plays an important role in the experimental arrangement by its shield structure and various ports imbedded in it.

There are two types of the Ti-T metal targets:

a) A large-size rotating target of RTNS-1 type with a special sliding vacuum seal. The size of the target is 310 mm in diameter. The tritium of about 1,000 curies (37 TBq) is absorbed in the target. The target is cooled by high speed water flow.
b) A small-size stationary target of about 30 mm in diameter and about 10 curies (370 GBq) of tritium cooled by high speed water flow.

The beam and neutron source performances for the typical case are summarized in Table 1. The minimum pulse width and repletion time at the 80-degree beam line are 4 ns and 8 µs, respectively, and the peak current is 80 mA. The beam spot size is about 15 mm in diameter for each.

Table 1. Typical beam and neutron performances.

	0° beam line, DC mode	**80 ° beam line, DC mode**
Deuteron Beam energy	350 keV	350 keV
Max beam current	20 mA	2 mA
Max neutron yield	4 x 10^{12} n/sec	4 x 10^{11} n/sec

1. 2 Research activities related to this CRP

So far a lot of fusion neutronics experiments were carried out; blanket nuclear property experiment, simple benchmark experiment, Time-Of-Flight (TOF) experiment, activation cross section measurement, direct nuclear heating measurement, induced activity measurement, ITER shielding experiment, and so on. These experimental data have been useful for nuclear data evaluation and benchmark. Particularly activation cross section measurement and simple benchmark experiment are very related to this CRP.

2. Research plan

2.1 Plan 1

We will compare cross section data around 14 MeV previously measured at FNS with IRDFF. If necessary, the cross section measurement around 14 MeV will be carried out. We will also irradiate natural foils (ex. titanium foil) with DT neutrons in order to measure cross section data of reactions such as $^{nat}Ti(n,x)^{46}Sc$. We can totally check if cross section data around 14 MeV are good or not. Note that this method is not good for (n,γ) reactions because of low energy neutrons from room wall etc. The expected experimental errors of measured cross section data are the following:

- Neutron source : ~ 2 %
- Gamma detector efficiency : ~ 2 %
- Gamma count : ~ 1 %
- Total error : ~ 3 %

2.2 Plan 2

Reaction rate measurement inside some experimental assemblies, neutron spectra in which are well specified in the benchmark experiment, such as graphite and Li_2O. We can check if cross section data below 15 MeV is good or not, by comparing measured and calculated (MCNP) reaction rates. Expected experimental errors of measured reaction rates are the following.

- Neutron source : ~ 2 %
- Gamma detector efficiency : ~ 2 %
- Gamma count : ~ 2 %
- Total error : ~ 4 %

We also have to consider the error of ~ 5 % for the calculated reaction rates.

2.3 Schedule

We have the following schedule. If possible, we will accelerate this schedule because FNS may be shut down for our limited budget during this CRP.

- 2013 Selection of reactions which should be tested at FNS
- 2014 Cross section measurement around 14 MeV
- 2015 Reaction rate measurement inside some experimental assemblies
- 2016 Reporting

Feasibility of IRDFF validation by benchmark/mock-up experiments performed at the 14 MeV Frascati Neutron Generator (FNG)

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1. The FNG facility

The Frascati Neutron Generator (FNG) is a 14-MeV neutron generator based upon the $T(d,n)^4He$ fusion reaction. It was designed and built by ENEA Frascati for conducting neutronics experiments and to validate nuclear data in the field of thermonuclear controlled fusion. FNG is in operation since 1992.

The FNG facility (Fig. 1) is also used for qualification, calibration, and radiation damage resistance tests of nuclear detectors and components, and for studies on new neutron (and gamma) detectors.

Fig. 1. Picture of the FNG facility (left); Detail of the Target (right).

The design of the breeding blanket and neutron shield of fusion reactors (e.g. ITER) needs experimental verification of the cross sections used for nuclear calculations and the validation of calculation methods used for the neutron transport. To do so, a special experimental activity is required, namely "benchmark experiments" and/or Mock-up experiments. A number of such experiments were successfully carried out at FNG since 1992, all related to Fusion tokamaks.

FNG produces up to $1\ 10^{11}$ n/s 14 MeV neutrons in continuous or pulsed mode (minimum pulse length 6 μsec) using a deuteron beam accelerated up to 300 keV impinging on a solid tritiated target. FNG produces a nearly isotropic 14 MeV neutron output (forward anisotropy ~3%) from point-like source (beam size ~1 cm^2).

The neutron production (both absolute and time dependent) is measured and recorded by a number of neutron flux monitors. The absolute neutron yield is measured by using the so-called associated charged particle techniques and provides the absolute yield at ±3.0%. A Silicon detector (SSD type), located inside the beam tube is used. The time dependent neutron yield is recorded by means of a U-238 fission chamber (FC), one scintillator (NE-213) and the SSD too. Both FC and NE-213 detectors are also relatively calibrated respect to the SSD detector. Independent measurement of the neutron yield is also routinely performed by activation techniques using ^{93}Nb(n,2n)^{92}Nb or ^{27}Al(n,α)^{24}Na activation foils.

FNG is housed in a large shielded hall (11.5 x 12 m^2 and 9 m high) and the target is more than 4 m far from walls, floor and ceiling. This was done to reduce as much as possible the neutron background due to neutron reflection from the walls. Furthermore, the target holder has a very light design to reduce the contamination of the spectrum due to neutron scattering.

The steady-state operation of FNG is affected by the consumption of the target. A target half-life (halving of the neutron emission) is about 25 hours at the maximum deuteron beam (1 mA). The target consumption is linear versus time. The maximum neutron yield achievable with a single tritiated target is about 5*10^{15} neutrons/target.

FNG can also produce 2.5 MeV neutrons by using deuterated targets by means of the D(d,n)^{3}He fusion reaction. In this case the neutron yield is about a factor 100 less intense, producing a maximum neutron flux of 5*10^7 neutrons cm^{-2} s^{-1} at a neutron yield of 1*10^9 n/s in continuous or pulsed mode. The neutron production is forward peaked (~ 20%) with a forward neutron energy of about 3 MeV. The steady-state operation is constant in time since the deuterium consumed is re-implanted by the beam.

The absolute neutron yield is measured by activation technique, irradiating Indium foils (^{115}In(n,n')^{115}In reaction).

The information reported above is summarized in the following Table.

Table. Main FNG parameters.

	D-T operation	**D-D operation**
Max neutron yield	1 10^{11} n/s	1 109 n/s
Max neutron flux → volume	5 10^9 neutrons cm^{-2} s^{-1} → 1 cm^3	5 10^7 neutrons cm^{-2} s^{-1} → 1 cm^3
Max irradiation volume → flux	A few cm^3 → 10^7/s/(4π*m^2)	A few cm^3 → 10^5/s/(4π*m^2)
Max irradiation time - targets	25 hours - one	continuous
Average utilization/year	> 200 hours/years	
Free time available for irradiation	200 hours/years	
Maximum achievable fluence	1*10^{15} n/cm^2 on a 1 cm^3 sample	1*10^{13} n/cm^2 on a 1 cm^3 sample

Both the DT and DD reactions used at FNG are simulated by a Monte Carlo routine originally written by the FNG team and recently upgraded thanks to a collaboration with Dr. A. Milocco (JSI Ljubljana, *present address: DIAMOND Light Source Facility, Harwell, UK*). The subroutine is linked to MCNP/MCNPX codes routinely used for experiment analysis at FNG. An example of calculated neutron flux spectra around the FNG target is shown in Fig. 2. A working version of the FNG source model became widely available in the Shielding Integral Benchmark Database (SINBAD) and it was recommended for the analysis of the benchmark integral experiments carried out at FNG.

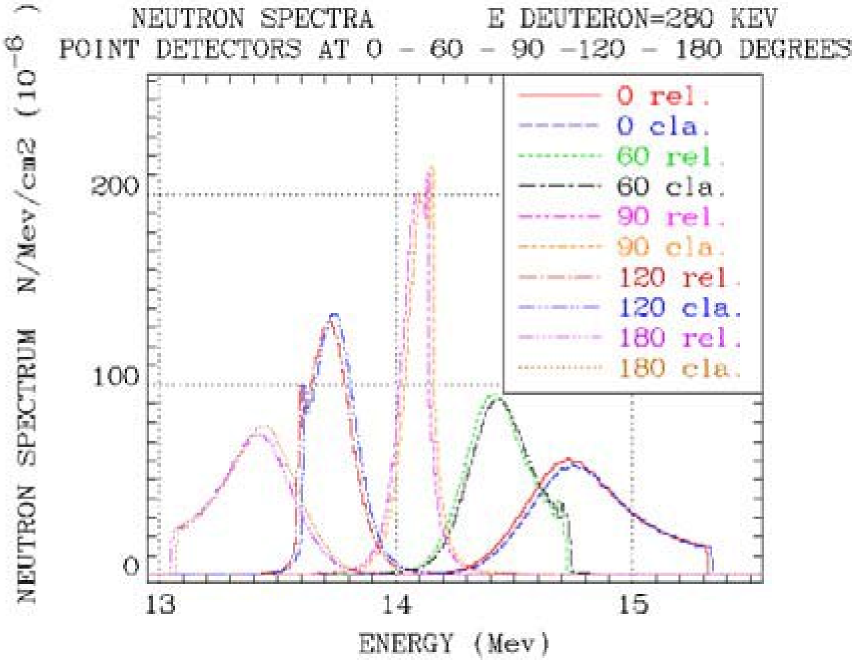

Fig. 2. Calculated neutron flux spectra at different angles around FNG target.

2. FNG researches and proposed activities in the frame of CRP

The contribution of FNG to the IRDFF validation in the energy range relevant to Fusion neutronics can be summarized as follows:

a) The calibration campaign of the FNG neutron source can be repeated with the goal to test the new IRDFF file. A simple and clean experimental calibration campaign can be performed by measuring activation reaction rates around the FNG target so to take advantage of the energy-angle correlation of the DT reaction in the Lab-frame. The experimental data can be compared with MCNP results using FENDL (JEF as well) coupled to IRDFF.

Intercomparison with results obtained using previous versions of IRDF file can be performed too.

A reduced experiment can also be performed using 2.5 MeV neutrons produced by DD reaction but in this latter case the expected uncertainty is larger.

A list of possible reactions (open to modification/suggestion) that can be of interest is reported below:

(n,2n): ^{197}Au, ^{186}W, ^{59}Co, ^{58}Ni, ^{93}Nb, ^{90}Zr, ^{64}Zn, ^{55}Mn
(n,α): ^{27}Al, ^{59}Co, ^{54}Fe, ^{63}Cu,
(n,p): ^{54,56}Fe, 58Ni, ^{46,47,48}Ti, ^{90}Zr, ^{197}Au
(n,n'): ^{115}In ….
(n,γ): ^{197}Au, ^{186}W, ^{113}In, ^{55}Mn

b) A second approach is based on the re-analysis, by using IRDFF, of some clean benchmark experiments performed at FNG in the past such as the W or TBM experiments whose dosimetric quantities were calculated using old versions of the IRDF file (e.g. IRDF-2002). The new C/E data can provide information about IRDFF also in comparison with the previous results.

Last, but not least, a new benchmark experiment using pure Copper is to be carried out in 2014 at FNG. Also this experiment can be analysed using IRDFF.

c) Bonner sphere can be also used for reproduce slowed down spectra in polyethylene. Alternatively graphite can be used to arrange small blocks where slowed down neutron spectra can be used to measure different type of reaction rates (see list above)

d) To complete the list of proposals, at ENEA Casaccia at the Metrology Institute is available a "reference" thermal neutron flux spectrum. The thermal flux is 1.2 10^4 n/cm^2/s. The accuracy is good (less than ± 2%). This reference source can also be proposed for thermal sensors cross section validation.

Points a) and b) have the highest priority for the purpose of the CRP program.

The neutron laboratory of Technical University Dresden

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2) Technische Universität Dresden, Institute for Nuclear and Particle Physics, Dresden
Germany

The laboratory is mostly used for fusion neutronics experiments. Recent examples are neutron and gamma-ray spectra measurements in a neutronics mock-up of the European Helium-Cooled Lithium-Lead Test Blanket Module (TBM) for ITER, activation of blanket materials in fusion neutron fields and development of instrumentation for the European TBM. The latter includes also a neutron activation system for spectral flux monitoring.

Facility and equipment

The main experimental device in the neutron laboratory of TUD is a Cockroft-Walton type deuteron accelerator manufactured by High Voltage Engineering. It can accelerate deuterons up to 350 keV with a maximum current of approximately 10 mA. The accelerator is fully computer controlled via CAN bus and optical fiber connection. The acceleration tube of the machine is vertically mounted, the deuteron beam is then bend 90 degrees and then a quadrupole lens focuses it on the tritium target. Three designs of tritium target assemblies are available.

A small assembly which was originally mounted on the old neutron generator of TUD in the former laboratory in Pirna (Saxony) can accommodate a solid tritium target of a diameter of 2.5 cm. These targets carry a few Ci of tritium.

A wobble target assembly is available since 2007. It hosts a tritium target of 7 cm diameter. The wobble mechanism allows to move the tritium target so that cooling is more efficient and the target can be operated at a higher deuteron currents than a non-moving target. The tritium load on the targets is typically 22 Ci.

Both target assemblies were manufactured at the machine shop of the department of nuclear and particle physics of TUD. The target assembly for the rotating target was made by NUKEM GmbH. It can accommodate a target disk of 15 cm diameter. A typical tritium load is 250 Ci. Alternatively, the target assemblies can be loaded with deuterium targets to produce DD reaction neutrons with energy 2.5 MeV.

All three target assemblies are water-cooled. In case of the steady (small) and wobble target assemblies the neutron source is primarily monitored with a silicon detector registering the charged particle emissions from the target. These are alpha particles when the tritium target is fresh and a mixture of alpha particles and protons after several hours of operation. The deuteron bombardment of the target during operation leads to considerable loading of deuterium so that DD reactions contribute to the neutron emission. One of the two main branches of the DD reaction emits a proton so that a monitoring of the DD / DT neutron ratio can be done by recording pulse height spectra of the silicon detector with a multi-channel analyser.

Additionally monitoring is provided by a U-238 fission chamber for all cases. Calibration of the monitors is based on Nb foil activation.

The tritium target is located in the center of the experimental hall with side lengths of 8 m × 10.5 m × 9 m.

Recently a pneumatic sample transport system (rabbit system) was commissioned. Its main components are a sample storage for 30 rabbits, a revolver selector for the transportation lines and a high power fan for driving the rabbits. It is controlled via a programmable logic controller. Rabbits can be sent to an irradiation end which is flexible to be placed in any position with respect to the tritium target of the neutron generator thereby utilizing the shift in the DT fusion peak depending on the angle with respect to the deuterium beam. There are two gamma spectroscopy stations with a High-Purity Germanium (HPGe) detector in each. Gamma spectra can be accessed. They are controlled by Canberra Lynx digital signal processors which provide signal processing and high voltage.

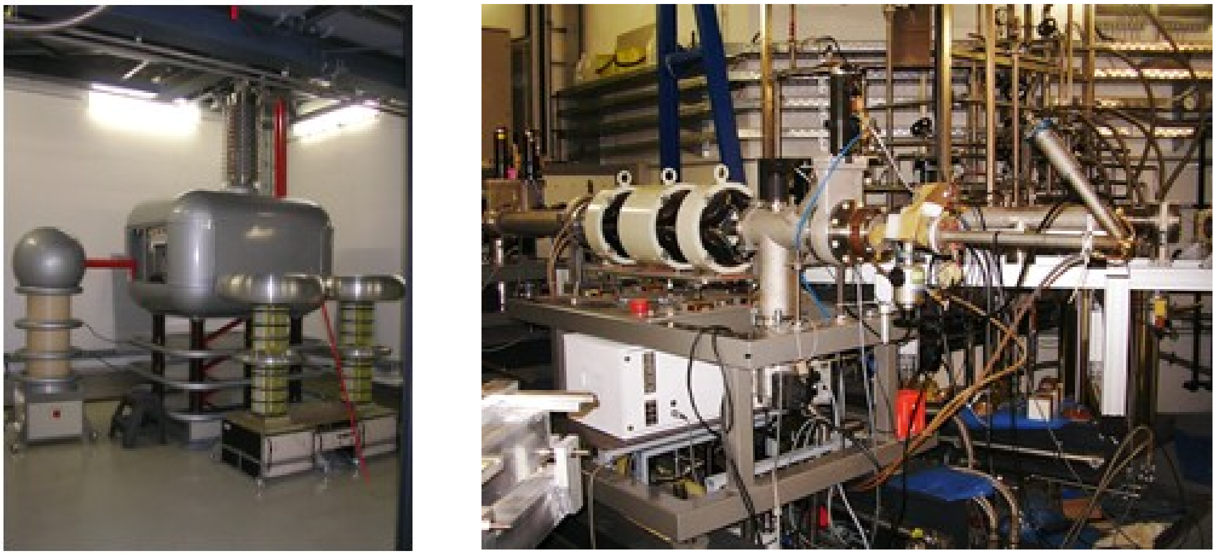

Fig. 1. The neutron generator of Technical University of Dresden. The deuterium accelerator is shown on the left. The right photograph shows the beam-line with quadrupole magnets and the small tritium target assembly.

Several NE-213 liquid scintillation counters with different dimensions are available for neutron/gamma pulse height spectra measurements. For one of them a detailed response matrix is available which was constructed at PTB Braunschweig. So far, analog electronics was used for pulse processing (pulse shape discrimination and amplification). The signals were recorded with a Fastcomtec MPA-3 multiparameter analyser. Recently, a CAEN DT5720 digitizer with pulse shape analysis firmware has been commissioned.

In addition to the neutron generator, an Americium-Beryllium source with 1.72×10^{11} Bq of ^{241}Am and a ^{252}Cf source with currently 1.34×10^{8} Bq, and various gamma sources are available for experiments and calibration.

LENOS and BELINA facilities for measuring Maxwellian Averaged Cross Section

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4) **Keele University, Keele, Staffordshire, ST5 5BG, UK**
5) **Nuclear Data Section, IAEA , Vienna Austria**

The Laboratori Nazionali di Legnaro is one of the 5 laboratories of Instituto Nazionale di Fisica Nucleare (INFN), Italy; the one devoted to nuclear physics. The Lab has 4 accelerators: a 14 MV tandem, a 7 MV Van de Graaff, a 2 MV electrostatic and a superconductive linac. The electrostatic accelerators are able to accelerate ions up to Li, while the tandem and linac can accelerate heavy ions up to Ni.

The smaller energy machines, namely the 7 MV (CN accelerator) and the 2 MV (AN2000 accelerator), are mostly devoted to nuclear physics applications. Within the CN accelerator, the neutron beam line for astrophysics (BELINA) is under development. The BELINA beam line will be devoted to the measurement of Maxwellian averaged cross section at several stellar temperatures, using a new method to generate the Maxwell-Boltzmann neutron spectra developed within the framework of the LENOS project. BELINA well characterized neutron spectra can also be used for validation of evaluated data as requested by the IRDFF CRP. The proposed new method deals with the shaping of the proton beam energy distribution by inserting a thin layer of material between the beam line and the lithium target. The thickness of the foil, the foil material and the proton energy are chosen in order to produce quasi-Gaussian spectra of protons that, impinging directly on the lithium target, produce the desired MBNS (Maxwell Boltzmann Neutron Spectra). The lithium target is a low mass target cooled by thin layer of forced water all around the beam spot, necessary to sustain the high specific power delivered to the target in CW (activation measurements). The LENOS method is able to produce MBNS with tuneable neutron energy ranging from 25 to 60 keV with high accuracy. Higher neutron energies up to 100 keV can be achieved if some deviation from MBNS is accepted.

Recently, we have developed an upgrade of the pulsing system of the CN accelerator. The system has been tested already and works well, allowing to slow down the repetition rate of the pulsed beam from 3 MHZ to a few Hz in steps of 330 ns. The mean current slows down accordingly, but at 3 MHz the beam time width is less than 2 ns and the mean current is up to 600 nA at 5 MeV proton energy. In CW mode, at about 3 MeV the maximum deliverable current is about 3 μA, mainly due to radioprotection limitation.

We are going to complete the construction of the BELINA beam line and we are going to use the pulsed beam to measure the neutron field at 30 keV first. Then we will move to higher stellar temperatures. As soon as the neutron field will be carefully characterized, we will start the measurement campaign of Maxwellian Averaged Cross Sections (MACS), starting with Au which is used as a reference in such measurements.

In order to achieve lower uncertainty, the BELINA line is equipped with a cold trap to avoid vapour condensation on the energy shaper and/or target. The beam line is made of carbon fiber and detectors are developed especially for the measurement of the Maxwellian neutron spectra. Since commonly used Li-glass has low efficiency for neutrons coming from the high energy tail of the MB distribution, a new detector has been developed, manufactured and tested. It is a BaF_2 detector coupled with removable 1 cm thick enriched boron-10 disk. Neutron are detected by TOF using the 480 keV gamma line associated with the $^{10}B(n,\gamma)$ reaction. Thanks to the large amount of ^{10}B, the efficiency of the detector is orders of magnitude higher than a Li-glass. We plan to use it for the MBNS measurements together with a Li-glass to have a cross check of the measured neutron spectra.

The beam line is equipped with a state of the art DAQ, based on flash ADC produced by CAEN with a sampling rate from 1 to 2 GHz, giving a time resolution of 0.5 - 1 ns. The real time resolution is actually better, since the pulse shape of each signal is fitted, giving us the possibility of resolving part of the pile-up, when present.

Summarizing, the LENOS project will make available measured Maxwellian neutron spectra with very high flux at several stellar temperatures in a very well characterized neutron spectra that can be used to achieve validation goals of the IAEA CRP.

The IRMM contribution to the CRP

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Belgium

The IRMM has measured a considerable number of neutron activation cross sections in the period from 1996 to 2009 with important contributions by A. Fessler, P. Reimer and, in particular, V. Semkova. Enriched and natural samples were used to separate channels leading to the same radioactive end-product. A few hundred data points were collected for (isotopes of) F, Na, Mg, Al, SI, P, Cl, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Nb, Mo, Tc, Sn, Ba, Hf, Ta, W, and Pb. All these reactions had a threshold and were studied with an emphasis on energies above 13 MeV. In recent years we also studied a reaction ^{241}Am(n,2n)^{240}Am on a radioactive isotope. We further support measurements of reaction cross sections using accelerator mass spectrometry by A. Wallner. Recently we published a first paper on the ^{197}Au(n,γ)^{198}Au reaction cross section in a semi-Maxwellian 25 keV neutron spectrum showing consistency of our result with the present standards evaluation.

The current focus is on improving the accuracy of our activation cross section measurements so that we can support the development of reference dosimetry reactions and thereby improve the overall accuracy of neutron measurements relative to such dosimeters. A first set of measurements is underway for the ^{197}Au(n,γ)^{198}Au cross section at 535 keV in collaboration with PTB and NPL and supported by the EMRP METROFISSION project. Here the emphasis is on neutron fluence measurements by reference instruments of PTB and NPL while making use of an accurate positioning device prepared at IRMM. The insights developed in the analysis of this work will be contributed to the CRP.

Important for the improvement of accuracy is the knowledge of the neutron spectrum employed in activation measurements. Here, we have recently studied with SOREQ, Hebrew University and the Goethe University and the Karlsruhe Institute of Technology, the Li(p,n) neutron source reaction at threshold and we have developed tools for simulating the neutron spectrum for this so-called semi-Maxwellian 25 keV spectrum. An on-going study concerns the impact of scattering from backing and structural materials that need to be employed in the high power linear accelerator based sources under development at SOREQ (SARAF) and at the Goethe University. The results of these studies will be communicated to the CRP along with new activation measurements that take benefit from the improved knowledge. IRMM also supported studies by P. Mastinu and J. Praena for the development of a modified arrangement for the Li(p,n) source to be used at Legnaro and at Sevilla (see elsewhere in this report).

For the bulk of the measurements we have done at IRMM we have used the T(d,n) neutron source. Recently with M. Pillon, M. Angelone and A. Krasa we investigated the neutron spectrum from this source for low deuteron energies using the ^{12}C(n,α)^{9}Be reaction. The results may easily be called surprising. For deuteron energies below 1.5 MeV the neutron spectrum can be markedly softer than expected from the nominal composition of a titanium-tritium target. This points at tritium in significant concentrations in the backing material. The effect is poorly understood since the mobility of hydrogen in the backing (gold) is very low, and so is the equilibrium concentration. Nevertheless, fresh targets (targets not exposed to any beam) still show this effect. One possible theory is the formation of an alloy of Au and Ti during the evaporation of the Ti onto the Au backing. Since Ti readily absorbs hydrogen this may explain the high tritium concentration in the Au backing. These points are currently under investigation and the results will be communicated to the CRP.

In addition to this development we are working on a new fluence measurement device consisting of a stack of single crystal diamond detectors to be used as a telescope for a proton recoil detector. The radiation hardness of these detectors and their compactness allows these to be placed at the location of the foils to be activated. Progress for this development will be reported to the CRP. The combination of improved neutron source characterisation and improved fluence measurements will allow us to improve activation cross section measurements. A few demonstration cases will be contributed to the CRP.

Finally, we are investigating the possibility of carrying out spectrum averaged cross section measurements in the ^{252}Cf neutron spectrum or a closely related spectrum generated by the ^{27}Al(d,n) reaction. The partners are PTB, NPL, CIEMAT, ENEA and IRMM. A proposal will be submitted to the EMRP and will be evaluated later this year. Given the lack of experience with such measurements most of the project will be devoted to exploring the limits of accuracy that may be achieved. The ^{252}Cf sources involved have a strength of about 10^8 n/s. In case of a successful proposal the results will be communicated to the CRP.

Neutron Metrology at PTB

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The Physikalisch-Technische Bundesanstalt (PTB) is the national metrology institute of Germany and was founded in 1887 by Werner von Siemens and Hermann Helmholtz. It was the first metrology institute world-wide. By law PTB has to ensure the uniformity of metrology in Germany. One of the main tasks of PTB is to ensure the traceability of measurement results to the international system of units, i.e. the SI system, through national standards. PTB is organized in 8 divisions; one of them is division 6 responsible for the metrology of "Ionizing Radiation".

PIAF – PTB Ion Accelerator Facility

The department 6.4 "*Ion Accelerators and Reference Radiation Fields*" is responsible for the metrology – the science of measurement – and for dosimetry of neutron and ion radiation, and it deals with questions related to radiation protection, radiation therapy, radiation biology, technology and research.

Protons (p), deuterons (d) and alpha-particles (α) are accelerated by means of a Van de Graaff accelerator with accelerating voltages between 0.1 MV and 3.75 MV. An energy-variable cyclotron furnishes ion beams with energies of up to 27 MeV. With the two accelerators, the following ion beams are, as a matter of routine, made available for experiments and/or irradiations:

Protons:	0.1 MeV to 19 MeV
Deuterons:	0.2 MeV to 13.5 MeV
α-particles:	0.2 MeV to 27 MeV

For the manifold applications, the ion beams are guided through the beam guiding system into the respective experimental areas (Fig. 1.). At the end of the beam tubes, the ion beams impinge on materials ("targets“) in which they generate neutrons or high-energy photon radiation by nuclear reactions. The two accelerators are equipped with facilities for beam pulsing which allow experiments with a temporal resolution of 1 ns to 3 ns to be performed and time-of-flight method to be applied to determine the energy distribution of the neutron fields.

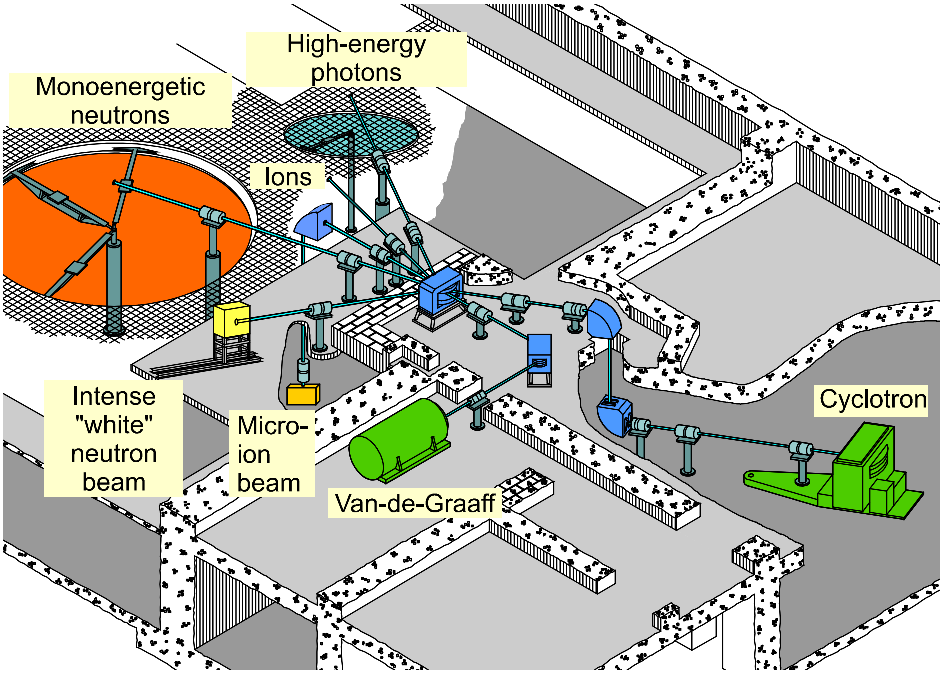

Figure 1. A survey of the accelerator facility.

Reference Radiation Fields

Monoenergetic neutrons are generated via the nuclear reactions of ^{7}Li(p,n)^{7}Be, ^{3}H(p,n)^{3}He, ^{2}H(d,n)^{3}He and ^{3}H(d,n)^{4}He. Due to the large experimental hall with large distances between the place of the experiment and the walls, floor and ceiling, a very low backscatter background (< 5%) exists at the place of experimentation. The monoenergetic neutron fields with energies between 24 keV and 19 MeV comply with the requirements described in ISO 8529. The neutron fluence is measured by means of recoil proton detectors so that all measurements are based on the (n,p) scattering cross section. The reference fields are used to determine the energy dependence of the response of neutron detectors. The spectrum of the investigated systems extends from radiation protection dosimeters to detector systems for basic research in fusion technology or in nuclear and high-energy physics. More complex detector systems are characterized by neutron beams pulsed with time, making use of the time-of-flight method.

In addition to the monoenergetic neutron fields, collimated high-intensity neutron beams with broad energy distribution can be generated. These beams are especially suited for the calibration of ionization chambers for neutron dosimetry as well as for the investigation of neutron-induced radiation damages in semi-conductor components.

Reference fields for high-energy neutrons (neutron energies from 20 MeV to 200 MeV) are made available in cooperation with iThemba LABS in South Africa (see contribution by R. Nchodu).

In addition, the accelerator facility of PTB is used for the generation of high-energy gamma radiation by the nuclear reactions $^{12}C(p,p'\gamma)^{12}C$ ($E_\gamma = 4.4$ MeV) and $^{19}F(p,\alpha\gamma)^{16}O$ ($E_\gamma = 6 – 7$ MeV). These fields serve above all for the calibration of radiation protection dosimeters to be used in nuclear power plants.

Time-of-Flight Spectrometer

The time-of-flight (TOF) spectrometer installed at the cyclotron (Fig. 2) allows differential neutron scattering cross sections, neutron emission spectra and neutron activation cross sections in the energy range between 2.7 MeV and 15 MeV to be measured. The neutrons are generated by means of the $^{15}N(p,n)$ and $^{2}H(d,n)$ reactions. The facility is optimized for the energy range from 6 MeV to 15 MeV, in which no monoenergetic neutrons can be generated by nuclear reactions.

The time of flight of the scattered neutrons, and thus their kinetic energy, is measured on a flight path 12 m in length. Due to the solid collimation system, neutrons are only detected in five different directions. To increase the number of the scattering angles, the cyclotron was mounted on a circular disk to make moveable. By a suitable selection of the cyclotron position, this allows measurements to be performed with scattering angles between 12.5° and 160°.

The nuclear data measured with the TOF spectrometer are submitted to the international data collections for experimental nuclear data (EXFOR) and taken into account for the establishment of libraries of evaluated nuclear data as, for example, JEFF (**J**oint **E**uropean File for **F**ission and **F**usion) or ENDF (**E**valuated **N**uclear **D**ata **F**ile).

Figure 2. The cyclotron and TOF spectrometer.

Recommended Literature

An overview of neutron metrology from thermal energies up to 400 MeV is given in a series of articles in a special issue of the journal Metrologia:

- David J. Thomas, Ralf Note, Vincent Gressier: *Neutron Metrology*. Metrologia **48** (2011) ff.
- A summary of the cross section measurements performed at the TOF spectrometer is given in the paper by D. Schmidt:

- D. Schmidt: *Determination of Neutron Scattering Cross Sections with High Precision at PTB in the Energy Region 8 to 14 MeV*.
- Nuclear Science and Engineering **160** (2008) 349 – 362
- High-energy neutron facilities providing quasi-mononenergetic neutron beams up to 400 MeV are summarized in a publication of EURADOS, the European Radiation Dosimetry Group (see www.eurados.org):
- Pomp S., Bartlett D.T., Mayer S., Reitz G., Röttger S., Silari, M., Smit F.D., Vincke H., and Yasuda H.: *High-energy quasi-monoenergetic neutron fields: existing facilities and future needs*.
- EURADOS Report 2013-02 (2013); can be downloaded from www.eurados.org

Validation of the Dosimetry Cross Sections by Integral Experiments

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A new version of the dosimetry library IRDFF has been released from the IAEA, featuring more reactions (compared to the older IRDF-2002), an extended energy range to 60 MeV, re-evaluation of several reaction channels with greatly improved covariance information, etc. The aim of the present CRP is the validation of the IRDFF library in order to enhance its reliability for the purposes it serves.

Reaction rate measurements in well-defined neutron fields are a common method of validating the cross sections. This technique has been implemented to some extent in the preparation of the IRDFF library from the published data, namely the use of the published average cross sections in the ^{252}Cf spontaneous fission neutron spectrum, thermal cross sections and resonance integrals. There is synergy with the community performing neutron activation analysis by the k_0 standardisation technique. To some extent the k0 database has been used for a preliminary validation of the capture reactions in the IRDFF library, but one has to be very careful about the definition of the constants since the interpretation and the derivation of the commonly-used constants is often misleading.

The proposed contribution of the Jožef Stefan Institute (JSI) is on the consistent definitions of the constants that allow unique interpretation of the measured reaction rate ratios (particularly for the capture reactions), together with advanced analysis techniques including Monte Carlo simulations of the experiments. The contribution can include the codes that are used at (JSI) for the purpose, namely the GRUPINT code for the analysis of measured reaction rate rations and spectrum unfolding and the RR_UNC code for the calculation of the uncertainties in the calculated reaction rates due to the uncertainties in the cross sections and in the neutron spectrum.

LANL Contribution to Testing and Improving the International Dosimetry Library for Fission and Fusion

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LANL has a long-standing interest in selected threshold reaction cross sections, such as many of those that are defined in existing Dosimetry Cross Section files. Therefore LANL expects to play an active role in the testing of selected evaluated dosimetry cross section files that will appear in the IAEA's next generation Dosimetry file, the International Reactor Dosimetry Fission and Fusion File, IRDFF.

A preliminary version of this file is currently available, designated IRDFF, v1.02. LANL has processed this file to create dosimetry class (.y) ace files for the continuous energy MCNP Monte Carlo transport code. Dosimetry class files differ from the traditional continuous energy (.c) class files in that they are NOT suitable for use in transport calculations … rather they are used exclusively for accumulating tally information. As such, .y class files are simpler than .c files and the associated NJOY processing is also simpler.

A generic NJOY input deck is given in Table 1. As the original IRDFF source files are already defined to be at 300 K, and since .y class files do not require linearization and a uniform energy grid, the NJOY job consists of an optional call to MODER to extract the specific material of interest. A second MODER call creates a duplicate input file which is followed by a call to ACER (with iopt=3) to create the .y class output. A pre-release version of NJOY2012 was used to process these files which have been shared with the IAEA. Subsequently we learned that when NJOY99.393 is used the ^{nat}Gd and ^{238}U files required additional memory. An NJOY99 patch file to accomplish this additional memory allocation has been created and will be publicly released shortly.

In past years, LANL has operated a number of simple (both geometrically and materially) critical assemblies, including Godiva (a bare HEU sphere), Jezebel (a bare, predominately ^{239}Pu, sphere) and various "Flattop" assemblies. The Flattop cores consist of one of HEU, ^{239}Pu or ^{233}U surrounded by a ^{nat}U reflector and are designated Flattop-25, Flattop-Pu and Flattop-23, respectively. Several experiments performed during the 1950s through early 1970s included fission product detectors and/or foil irradiations in various locations through these assemblies. Much of this data only exists in informal (and internal) LANL memos and is generally reported in the form of "spectral indicies", or the ratio of the reaction rate of interest to ^{235}U(n,f). As part of its contribution to this CRP, LANL is re-examining these data and will make them available to the technical community. A key component of this re-analysis is to understand the state of selected nuclear data at the time these experiments were performed so that changes in these data over the decades is properly accounted for in determining final spectral indicies.

Another useful data source for dosimetry file testing is the ICSBEP's FUND-IPPE-FR-MULT-RRR-001 benchmark. This experiment utilized an unmoderated Pu-metal core to irradiate a number of materials. The irradiations were performed in the early 1980s and results were published in the early 1990s. These experiments have already been used during testing of the recently released ENDF/B-VII.1 file, but there are several open items related to the original analysis of these experiments that, if resolved, will increase confidence in the underlying measurements. LANL will prove a detailed list of questions to IPPE (Pronyaev) who will investigate whether additional information beyond that in the ICSBEP evaluation is available.

Table 1. Sample NJOY Input to Create an MCNP Dosimetry Class (.y) ACE file

```
--
-- NJOY processing of the IRDFF dosimetry file into ACE format
-- - IRDFF is one large file with many materials
-- - use moder to extract the material of interest
-- - make two copies for ACER
--
moder
1 -21
'IRDFF v1.02 for mat xxx'
20 xxx
0/ end of moder
--
-- make a second copy of this material
moder
-21 -22
--
-- acer/dosimetry processing
acer
-21 -22 0 31 32/ card 1
3 1 1 .10/ card 2
'IRDFF v1.02 data for material xxx'/ card 3
xxx 300./ card 10
--
-- end of job
stop
```

Use of Neutron Benchmark Fields for the Validation of Dosimetry Cross Sections

P.J. Griffin

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USA

The IRDFF dosimetry cross section library includes more reactions than the previous IRDF-2002 library and extends the applicable energy range for the incident neutrons up to 60 MeV. As this library is released to the public it is important that the scope and extend of the validation of these cross sections be documented and available to the user community. This is the major tasking for this Coordinated Research Project (CRP). Since differential cross section data, e.g. monoenergetic neutron cross section measurements, were considered in the preparation of the evaluated cross sections, we look for validation, primarily, to comparisons with integral measurements obtained in benchmark neutron fields. When doing validation it is important to note that any validation data must be accompanied by a quantitative statement on the uncertainty in the measured and the calculated quantity. Historically, when comparisons with integral benchmarks have been made, the analyst used as the metric of interest a spectral index [1]. A spectral index is the ratio of the spectral averaged cross section for two different reactions gathered in a neutron field under identical exposure conditions. This metric has been used since it eliminates the uncertainty in the metric due to the knowledge of the intensity (fluence) of the neutron benchmark field.

This metric can also reduce the uncertainty due to a lack of high fidelity characterization of the neutron spectrum in the benchmark field when the energy-dependent sensitivity of the cross sections appearing in both the numerator and denominator of the spectral index ratio cover a similar energy range. A good example of the historical use of spectral indices for cross section validation can be found in Reference 1.

For well characterized neutron fields, the neutron metrology community can obtain validation data by looking at comparisons of the direct spectrum-averaged cross sections. The ^{252}Cf spontaneous fission standard neutron benchmark field shows excellent agreement between the measured and calculated spectrum-averaged cross sections. When one looks at calculated-to-experimental (C/E) ratios for the spectrum-averaged cross section in the less well characterized ^{235}U thermal fission spectrum, one can see a systematic energy-dependent trend in the C/E ratios [2]. This trend can lead one to suspect a systematic problem in the spectrum. Note that the issue here is the spectrum as exhibited in the macroscopic benchmark field and conclusions drawn here should not necessarily be attributed to the microscopic ^{235}U thermal fission cross section [3]. One approach that can isolate the consistency of the spectrum-averaged cross sections in a less well characterized neutron field, compensating for the *a priori* uncertainty in the knowledge of the neutron spectrum, is to do a least squares-based spectrum adjustment for the neutron field. This approach, when applied to the ^{235}U thermal fission spectrum, can be seen to remove the systematic trend seen in the reported C/E ratios [4] and provides a better metric to be used in the validation of the cross section representation. One critical caveat here is that one cannot use an *a priori* spectrum in this least squares adjustment that was derived through the use of spectrum-averaged cross sections unless this correlation between spectrum and cross sections is properly taken into account. Thus one has to be very careful that an adjusted cross section obtained from a cross section validation activity is clearly labelled as such and never makes its way back into the literature as an unbiased spectrum representation.

Informed by the above discussion on useful metrics to be investigated in support of cross section validation, the next task is to identify a set of additional neutron benchmark fields, beyond the ^{235}U thermal fission and ^{252}Cf spontaneous fission fields, for which there exists a sufficient database of cross section measurements that can be used to provide a meaningful validation of the cross sections. A survey of the literature provides a number of candidate datasets and identifies the following additional neutron fields as very promising:

- Sandia Pulsed Reactor (SPR-III) Central Cavity
- Sandia Annular Core Research Reactor (ACRR) Central Cavity and Pb:B_4C Bucket
- Coupled Fast Reactivity measurements Facility (CFRMF)
- Godiva II, a bare uranium assemble developed at Los Alamos National Laboratory and now located at the Device Assembly Facility (DAF) at the Nevada Test Site (NTS).
- Pool Critical Assembly (PCA) (NUREG/CR-5454)
- VENUS-1 pressurized water reactor (PWR) mockup (NUREG/CR-4827)
- H.B. Robinson Westinghouse Reactor (HBR-2) (NUREG/CR-6453)

Sandia National Laboratories proposes, as part of its consultancy to this CRP, plans to look at the first two reference fields above. In addition, we will examine the fidelity of the computational models and the associated reaction measurements for the other benchmark fields identified above and to address the feasibility of extending the C/E analysis to some of these other potential reference benchmark fields.

In addition to mining the available data, and since the IRDFF contains some new dosimetry reactions that have not been thoroughly investigated in existing neutron benchmark fields, we will identify the reactions within the IRDFF library (and associated energy regions) that have not been adequately validated in the ^{252}Cf spontaneous fission and ^{235}U thermal fission benchmarks fields and examine the feasibility of gathering additional validation-quality spectrum averaged cross section measurements in the Sandia ACRR reactor reference benchmark fields. This has the potential to extend the scope and fidelity of this CRP's focus on cross section validation. Example reactions where we expect to be able to gather addition validation-quality data at the Sandia reactors include: ^{59}Co(n,2n), ^{65}Cu(n,2n), ^{90}Zr(n,2n), ^{93}Nb(n,2n), ^{55}Mn(n,2n), and ^{60}Ni(n,p).

Reference

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3. N. Kornilov, International Journal of Nuclear Energy Science and Engineering, Vol. 2, December 2012, pp. 97-100.
4. P.J. Griffin, C.D. Peters, D.W. Vehar, IEEE Transactions on Nuclear Science, Vol. 59, pp. 1167-1174, August 2012.

This work was supported in part by the U.S. Department of Energy under contract DE-AC04-94AL85000. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

CEA proposed contribution to the Testing and Improving the International Dosimetry Library for Fission and Fusion (IRDFF)

C. Destouches, P. Casoli, G. Noguere

CEA/DEN-CAD/DER
France

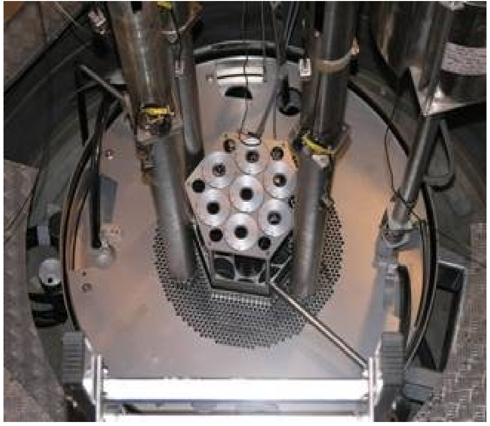
The CEA/DEN-CAD/DER proposes to contribute to the experimental validation of IRDFF cross sections in the reactor domain. The CEA will provide a set of recent and well documented experimental data, mainly reaction rates for several classical dosimetry reactions (^{198}Au(n,g), ^{59}Co(n,g), ^{58}Ni(n,p), ^{54}Fe(n,p), ^{115}In(n,n'), ^{27}Al(n,p), ^{238}U (n,f),…) obtained in well characterized reactor neutron spectra from thermal spectrum to almost pure 235U fission spectrum including classical light water reactor one. The provided experimental data will be taken from selected irradiation experiments already performed in the following CEA nuclear reactors, MINERVE, EOLE, MASURCA, CALIBAN (published in ISCBEP, in collaboration with the CEA/DAM team), and the reactor of the Joseph Stephan Institute (through JSI collaboration).

The CEA team will bring its expertise in nuclear data evaluation (JEFF project) and in the experimental physic (irradiation campaign, activity measurements, analysis) as following:

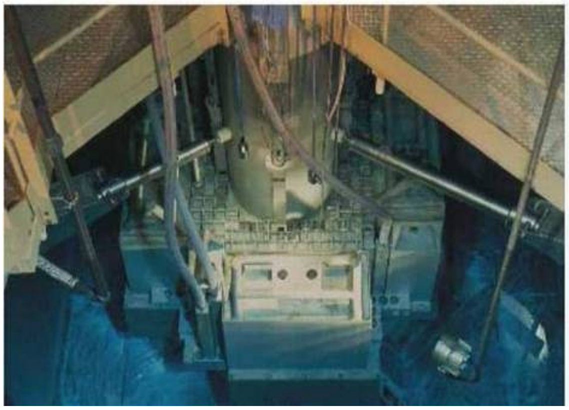
- **DER/SPEX** (C. Destouches, G. Grégoire): Reactor Dosimetry (PWR, MTR, ZPR), Nuclear Instrumentation development (MTR-ZPR), Activity measurement (g ,X) and Irradiation Program preparation (ZPR – EOLE- MINERVE-MASURCA)
- **DER/SPRC/LEPH** (G. Noguere, P. Leconte, D. Bernard): Nuclear data evaluation and validation (JEFF3.2,COMAC), Neutron code validation (TRIPOLI / APOLLO)
- **DMA/SMNC** (P. Casoli, G. Rousseau) : Reactor Dosimetry (MTR, ZPR), Activity measurement (gamma,X) and Irradiation Program preparation (ZPR – CALIBAN)

The CEA facilities will make available experimental data obtained in its 4 ZPR reactors and access to some of them (CALIBAN and MINERVE):

EOLE dedicated to core neutron physic studies (P < 1 KW)

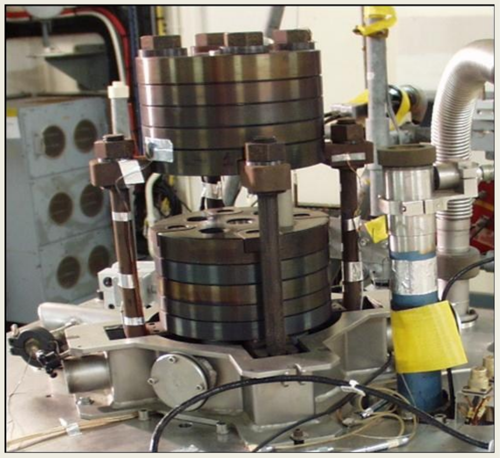


MINERVE dedicated to nuclear data measurements (LWR – 100 W)



MASURCA - a fast reactor mockup of 5 kW (Cadarache), presently under refurbishment

CALIBAN - ^{235}U metallic reactor (Valduc), pulse & steady state operating metallic reactor (P< 600W)



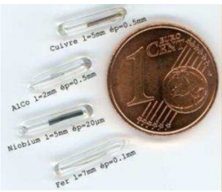
The CEA will bring access to the following platforms:

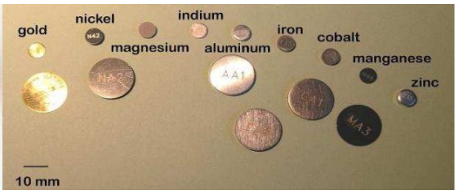
- 1 platform for dosimetry treatment (MADERE - Cadarache) and 1 Dosimetry Laboratory (Valduc) allowing γ and X-ray activity measurements for solid dosimeters in the following range: [10 keV - 2 MeV] and [0,1 Bq – 1E+8 Bq]. Gamma Dosimetry (TLD) and PIN diodes reading techniques are also available (Valduc).

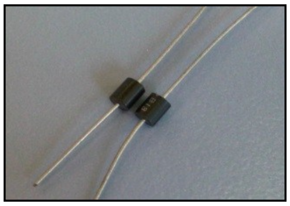
MADERE (Cadarache)

Dosimetry Lab. in Valduc

These laboratories could also provide non fissile solid dosimeters for neutrons or gamma.





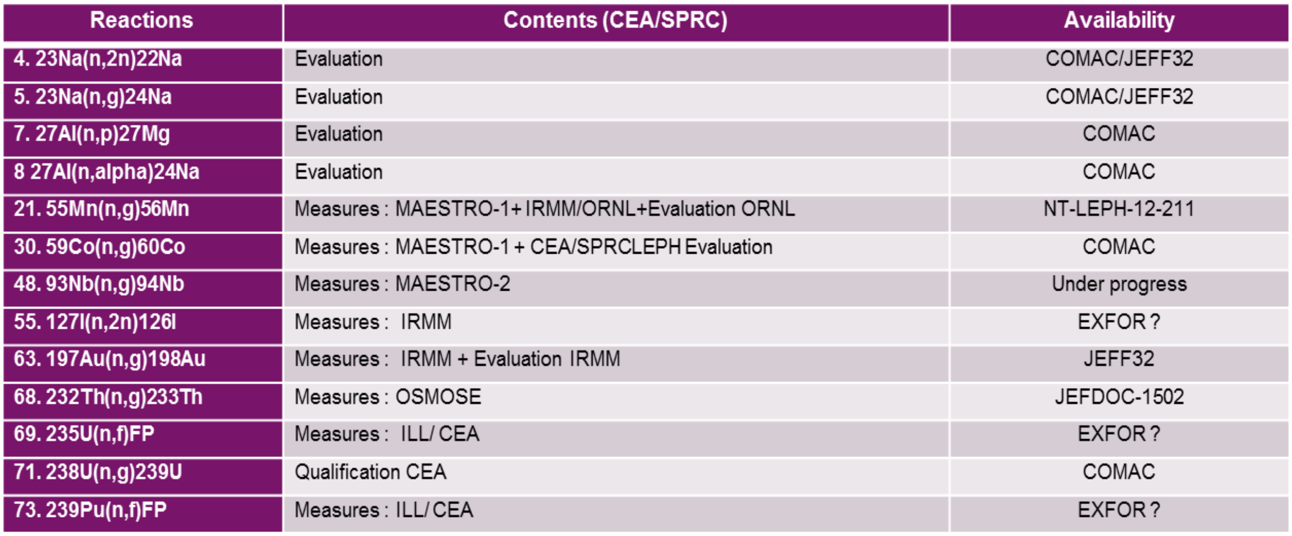


Expertise acquired on the detectors manufacturing (fission chambers) and instrumentation (development & qualification) could be used if needed.

The CEA proposes to take part to the different IRDFF evaluation work phases defined by the CRP on the following items:

- **Experimental Nuclear data**
  - <u>Results of CALIBAN (ICSBEP) cavity irradiation (G. Rousseau – P. Casoli – C. Destouches) - to be published</u>
    - ^{54}Fe(n,p), ^{60}Co(n,g), ^{46}Ti(n,p), ^{63}Cu(n,a), ^{115}In(n,n'),…
    - ^{235}U(n,f), ^{238}U(n,f), ^{115}In(n,n')
    - ^{237}Np(n,f) (CEA/DEN Cadarache measurements)
    - ^{58}Ni(n,p)^{58m}Co : half life + branching ratio evaluation
  - <u>Proposition of integration of ^{117}Sn(n,n') ^{117m}Sn based on integral experimental data (G. Rousseau – G. Gregoire – P. Casoli - C. Destouches) - to be published</u>
    - $E_{\mathrm{Threshold}} = 0.314$ MeV, $T_{1/2}=14$ d, $E_{g1}=158$ keV ($I_{g1}=86\%$), $E_{g2}=156$ keV ($I_{g2}=2.1\%$)
    - Natural tin : 10 isotopes but ^{117}Sn enriched sample (93 % at) available
    - Nuclear data available to be checked and upgraded
    - Available Irradiation tests
      - TRIGA MK-II – IJS - 2011
      - CALIBAN – CEA/Valduc 2011
      - ISIS MTR - CEA/Saclay 2012
  - <u>Partial results of MAESTRO program (MINERVE) through 7FP-CHANDA –WP – Integral Capture Cross Section Measurements (P. Leconte, G. Noguere, C. Destouches)</u>
    - ***^{109}Ag, ^{197}Au***, ^{151}Eu, ^{153}Eu, ^{133}Cs, ^{51}V, ^{64}Zn, ^{94}Zr,^{96}Zr, ^{98}Zr,^{100}Mo
    - Participation to the experimental program in 2014
  - <u>Results of one EOLE dosimetry irradiation (A. trkov, C. Destouches, G. Gregoire)</u>
    - Analysis performed through IJS –CEA collaboration
    - 13 simultaneous reactions covering the entire neutron spectrum [0-20 MeV]: ^{27}Al(n,α)^{24}Na; ^{59}Co(n,γ)^{60}Co; ^{54}Fe(n,p)^{54}Mn; ^{115}In(n,n')^{116m}In; ^{115}In(n,γ)^{116}In; ^{24}Mg(n,p)^{24}Na; ^{55}Mn(n,γ)^{56}Mn; ^{58}Ni(n,p)^{58}Co; ^{197}Au(n,γ)^{198}Au; ^{103}Rh(n,n')^{103m}Rh; ^{51}V(n,α)^{48}Sc; ^{64}Zn(n,p)^{64}Cu; ^{64}Zn(n,γ)^{65}Zn.

- **Validation / Data analysis (G. Noguere, P. Leconte, D. Bernard)**
  - <u>Participation to Nuclear Data Analysis</u>
    - Feedback of the JEFF evaluation for some reactions
    - Covariance files: Comparison with the COMAC process
    - Systematic test of proposed evaluations on MASURCA and PROTEUS spectra (1966 groups): X/U5 spectral indexes



Reactions	Contents (CEA/SPRC)	Availability
4. 23Na(n,2n)22Na	Evaluation	COMAC/JEFF32
5. 23Na(n,g)24Na	Evaluation	COMAC/JEFF32
7. 27Al(n,p)27Mg	Evaluation	COMAC
8 27Al(n,alpha)24Na	Evaluation	COMAC
21. 55Mn(n,g)56Mn	Measures : MAESTRO-1+ IRMM/ORNL+Evaluation ORNL	NT-LEPH-12-211
30. 59Co(n,g)60Co	Measures : MAESTRO-1 + CEA/SPRCLEPH Evaluation	COMAC
48. 93Nb(n,g)94Nb	Measures : MAESTRO-2	Under progress
55. 127I(n,2n)126I	Measures : IRMM	EXFOR ?
63. 197Au(n,g)198Au	Measures : IRMM + Evaluation IRMM	JEFF32
68. 232Th(n,g)233Th	Measures : OSMOSE	JEFDOC-1502
69. 235U(n,f)FP	Measures : ILL/ CEA	EXFOR ?
71. 238U(n,g)239U	Qualification CEA	COMAC
73. 239Pu(n,f)FP	Measures : ILL/ CEA	EXFOR ?

- **New Measurements (P. Casoli, C. Destouches, G. Gregoire, D. Bernard)**
  - Irradiation facility access – CEA/DAM Valduc (CALIBAN reactor and SAMES accelerator)
    - 2013: one week on CALIBAN for CEA/DEN Cadarache
    - 2014: one week asked on CALIBAN for CEA/DEN Cadarache
    - After 2014: a decision has to be taken about the future of the facilities
  - Irradiation facility access – MINERVE – possible but limited
    - Thermal column (still to be fully characterized)
  - Activity Measurement – MADERE facility – possible but limited
    - Activity Measurement : X and g measurement of solid dosimeters
    - Dosimeter providing
  - Activity Measurement – CEA/DAM Valduc
    - Activity measurements concerning the irradiations for CEA/DEN Cadarache

- **Feedback and analysis on existing Cross section library, Decay Library and Fission Yield (All)**

Problem of Improving IRDFF Decay Library: List of Radionuclides, Status of the Available Evaluated Decay Data, Needs for New (Updated) Evaluations

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Russia

WHAT'S THE PROBLEM?

Decay data containing in the current IRDFF are based on ENSDF evaluations. The main problem is here related to the **heterogeneity** of the recommended decay data for different nuclides, both due to the different *ENSDF* evaluation **dates** and the different evaluation **methods**. The first means omitting latest available experimental data for earlier evaluations and the second means lack of uniform assessment procedures.

The best way to improve any decay data library would be a **synchronous re-evaluation** of decay data for all selected nuclides **together with new measurements** if necessary. Such "ideal" scheme was established for the *International Decay Data Evaluation Project* (DDEP) cooperation, in which 200 applied radionuclides were considered [1-3]. Similar work for a limited number of the dosimetry reaction residuals (approximately 90) could be done but it would require the almost analogous efforts of representatives of several radionuclide metrology laboratories.

How to improve the *IRDFF Decay Library* without such a great effort, within this CRP?

Avoiding irregularities on methods does not succeed, but all modern experimental and evaluated data can be taken into account.

From the IRDF-2012 list of 82 isotopes/isomeric states, there are available 44 radionuclides with satisfactory ENSDF evaluations of 2008-2012. 2008 is chosen as since this year the Band-Raman Internal Conversion Coefficients (BRICC) [4] have been used for decay scheme analyses. An importance of using BRICC is confirmed now by experimental data [5].

Of the 44 above radionuclides for the fourteen ones, the new published ENSDF-2012-13 evaluations should be converted into ENDF-6 format.

Analysis is needed for remained 38 nuclides, decay data of which were evaluated in ENSDF before 2008. In addition, there are 4 residuals from the 4 new reactions extended IRDF-2002: ^{67}Cu, ^{113m}In, ^{167}Tm and ^{207}Bi. For ^{167}Tm and ^{207}Bi new (updated) evaluations are needed.

STATUS OF THE AVAILABLE EVALUATED DECAY DATA

At present, for radionuclide decay data, there are available two sources of high-quality information: ENSDF and DDEP data. In terms of a specific selection group of nuclides, ENSDF comprehensive data have the disadvantage of unequal reliability data for radionuclides having different mass numbers. In regard of an evaluation technique, this file aims at the values with the least uncertainty (simple weighting or direct selection of the best value) while the DDEP evaluation method assumes one or another adjustment of published experimental uncertainties due to, for example, the *Limitation of Relative Statistical Weights Method* (LRSW) procedure. To the metrology community, DDEP data are more attractive but these do not cover all the nuclides.

NOTES OF SOME MAIN DECAY DATA

Half-lives and the absolute intensity of the gamma rays (per decay) may be assigned to the main decay data which are required for the *IRDFF Decay Library.*

New half-life experimental data of 2010-2012 have been published for **19** radionuclides and for them updated evaluations are required.

Recently a serious problem was discovered that the source holder used for calibrations in the NIST (USA) $4\pi\gamma$ ionization chamber has not been stable since 1967 [6]. This has affected the results of a large number of half-life measurement results previously reported and used in compilations of nuclear data. Corrections are required for a number of long-lived radionuclide half-lives including those contained in the *IRDFF Decay Library*: ^{22}Na, ^{54}Mn, ^{60}Co, ^{110m}Ag, ^{144}Ce, ^{207}Bi.

The absolute intensity of the gamma rays is an important decay characteristic which is determined often from evaluation based on relative γ ray intensities and internal conversion coefficients. The transformation from relative to absolute Iγ values assumes the knowledge of a normalization factor N which is deduced from examination of the decay scheme:

$$\sum_i I_{\gamma_i}\left[1+\alpha_{T\,i}\right]+(P_\beta+P_\alpha+P_{EC})=\frac{100\%}{N}$$

The total internal conversion coefficients α_{Ti} should be taken as BRICC with the so called “Frozen orbital” approximation [4]. However in earlier evaluations, they were interpolated from Rösel *et al.* tables [7]. Therefore, this requires testing and improving the normalization factor *N* and thereby absolute intensities of gamma rays evaluated in earlier ENSDF evaluations.

NEEDS FOR CORRECTIONS OR NEW FULL EVALUATIONS

Table below summarizes the results of our analysis of needs for corrections or new full evaluations for the isotopes/isomeric states contained in the *IRDFF Decay Library.*

CONCLUSION

For improving the *IRDFF Decay Library* it is required or would be desirable to:

- convert new ENSDF evaluations-2012-2013 for 14 radionuclides into ENDF-6 format for the *IRDFF Decay Library*
- adjust the recommended half-live values for 19 radionuclides (to be done new evaluations of $T_{1/2}$)
- test ENSDF evaluations done before 2008 (38 radionuclides) for validity
- perform new (updated) full decay data evaluations if necessary (approximately 13 radionuclides).

Most of this research can be done under the IAEA contract within the current IRDFF CRP and in the framework of the DDEP cooperation by co-workers of the Centre for Radionuclide Data at the Khlopin Radium Institute (KRI) for 4 years.

Table. Needs for corrections and new (updated) decay data evaluations for improving the IRDFF Decay Library.

IRDFF nuclides	**Updating required or desirable**	**Decay character-ristic**	**Full evaluation required or desirable**
1) ^{3}H	+	$T_{1/2}$, β, Q	✓
2) ^{18}F	+	$T_{1/2}$, β, Q	✓
3) ^{22}Na	+	$T_{1/2}$	
4) ^{24}Na	–?		
5) ^{27}Mg	–		
6) ^{31}Si	↔		
7) ^{32}P	–		
8) ^{46}Sc	+	$T_{1/2}$	
9) ^{46m}Sc	–?		
10) ^{47}Sc	–?		
11) ^{48}Sc	–?		
12) ^{45}Ti	–?		
13) ^{51}Cr	+	$T_{1/2}$, Iγ	✓
14) ^{54}Mn	+	$T_{1/2}$, Iγ	✓
15) ^{56}Mn	+	$T_{1/2}$	
16) ^{53}Fe	–		
17) ^{53m}Fe	–		
18) ^{59}Fe	–?		
19) ^{57}Co	+	$T_{1/2}$, Iγ	
20) ^{58}Co	–	-	
21) ^{58m}Co	–	-	
22) ^{60}Co	+	$T_{1/2}$	
23) ^{60m}Co	–?		
24) ^{57}Ni	–?		
25) ^{62}Cu	↔		
26) ^{64}Cu	+	All	✓
27) ^{67}Cu	+	$T_{1/2}$	
28) ^{74}As	+?	Branching	

IRDFF nuclides	Updating required or desirable	Decay character-ristic	Full evaluation required or desirable
29) ^{88}Y	+	$T_{1/2}$, $I\gamma$?	
30) ^{89}Zr	↔		
31) ^{89m}Zr	↔		
32) ^{95}Zr	–		
33) ^{97}Zr	–		
34) ^{92}Nb	↔		
35) ^{92m}Nb	↔		
36) ^{93m}Nb	↔		
37) ^{94}Nb	+	$T_{1/2}$	
38) ^{94m}Nb	–		
39) ^{95}Nb	–		
40) ^{95m}Nb	–		
41) ^{97}Nb	–		
42) ^{97m}Nb	–		
43) ^{103}Ru	+	$T_{1/2}$, $I\gamma$?	
44) ^{106}Ru	–		
45) ^{103m}Rh	–		
46) ^{106}Rh	–		
47) ^{106m}Rh	–		
48) ^{110}Ag	↔		
49) ^{110m}Ag	+	$T_{1/2}$	
50) ^{113m}In	↔		
51) ^{114}In	↔		
52) ^{114m}In	↔		
53) ^{115}In	↔		
54) ^{115m}In	↔		
55) ^{116}In	–		
56) ^{116m1}In	–		
57) ^{116m2}In	–		
58) ^{132}Te	+?		
59) ^{126}I	–?		
60) ^{131}I	+	All	✓

IRDFF nuclides	Updating required or desirable	Decay character-ristic	Full evaluation required or desirable
61) ^{132}I	+	$T_{1/2}$, $I\gamma$?	
62) ^{132m}I	–?		
63) ^{131m}Xe	–?		
64) ^{137}Cs	+	All	✓
65) ^{137m}Ba	+	ICC, $I\gamma$?	
66) ^{140}Ba	+	$T_{1/2}$	
67) ^{140}La	+	$T_{1/2}$	
68) ^{141}Ce	+	All	✓
69) ^{143}Ce	↔		
70) ^{144}Ce	+	$T_{1/2}$	
71) ^{140}Pr	+	$T_{1/2}$	
72) ^{143}Pr	↔		
73) ^{144}Pr	–?		
74) ^{144}mPr	–?		
75) ^{167}Tm	+?		
76) ^{168}Tm	–		
77) ^{182}Ta	–		
78) ^{182m1}Ta	–		
79) ^{182m2}Ta	–		
80) ^{187}W	–		
81) ^{196}Au	+	$T_{1/2}$	
82) ^{196m1}Au	–?		
83) ^{196m2}Au	–?		
84) ^{198}Au	+	$T_{1/2}$, $I\gamma$?	
85) ^{198m}Au	–		
86) ^{199m}Hg	–?		
87) ^{204m}Pb	–		
88) ^{207}Bi	+	all	✓
89) ^{233}Th	+	all	✓
90) ^{233}Pa	+	all	✓
91) ^{239}U	+	all	✓
92) ^{239}Np	+	all	✓

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Appendix 1

IAEA
International Atomic Energy Agency
Atoms for Peace

First Research Coordination Meeting on

"Testing and Improving the International Dosimetry Library for Fission and Fusion (IRDFF)"

1 - 5 July 2013
IAEA Headquarters, Vienna, Austria

AGENDA

(*presentation's time is approximate and includes questions and breaks***)**

Monday, 1 July 2013

09:00 - 09:30	**Registration**
09:30 - 10:30	**Opening session** Welcome address - **Robin Forrest**, Section Head (NDS) Administrative announcements - **Alexander Oechs** (NDS) Self-introduction of Participants - **all** Election of Chairperson and Rapporteur - **all** Approval of Agenda - **all** Objectives of CRP - **Stanislav Simakov** (NDS)

Session 1: Presentations of Research Proposals

10:30 - 11:30	**Konstantin Zolotarev, IPPE -** "New evaluations for $^{54}\text{Fe}(n,p)^{54}\text{Mn}$, $^{58}\text{Ni}(n,2n)$ and $^{93}\text{Nb}(n,\gamma)^{94}\text{Nb}$ reactions"
11:30 - 12:30	**Vladimir Pronyaev, IPPE** - "High-energy (n,xn) dosimetry reactions"
12:30 - 14:00	*Lunch break*
14:00 - 15:00	**Larry Greenwood, PNNL** - "Integral Testing of IRDFF Cross Sections and New STAYSL_PNNL Software Suite"
15:00 - 16:00	**Nikolay Kornilov, Ohio University -** "Standard neutron field for high energy (current status, how to increase an accuracy)"
16:00 - 17:00	**Rudolph Nchodu, iThemba LABS -** "Measurements of neutron cross sections at iThemba LABS"
17:00 - 18:00	**Milan Stefanik, NPI Řež** - "Experimental validation of IRDFF cross-sections in quasi-monoenergetic neutron fluxes in 20-35 MeV energy range"

Coffee breaks as needed

Tuesday, 02 July 2013

Session 1: Presentations of Research Proposals

9:00 - 10:00 **Hiroshi Yashima, Kyoto University** – "Activation cross section measurements by high energy neutrons"

10:00 - 11:00 **Chikara Konno, JAEA** - "Research plan on IRDFF testing and improving at JAEA/FNS"

11:00 - 12:00 **Maurizo Angelone, FNG -"**Feasibility of IRDFF validation by benchmark/mock-up experiments performed at the 14 MeV Frascati Neutron Generator"

12:00 - 13:00 **Frank Wissmann, PTB - "**Neutron Metrology at PTB"

13:00 - 14:00 *Lunch break*

14:00 - 15:00 **Pierfrancesco Mastinu, INFN** - "LENOS and BELINA facilities for measuring Maxwellian averaged cross section"

16:00 - 17:00 **Andrej Trkov, JSI** – "Validation of the Dosimetry Cross Sections by Integral Experiments"

17:00 - 18:00 **Skip Kahler, LANL** - "LANL Contribution to Testing and Improving the IAEA International Dosimetry Library for Fission and Fusion"

17:00 - 18:00 **Patrick Griffin, SNL** - "Use of Neutron Benchmark Fields for the Validation of Dosimetry Cross Sections"

Coffee breaks as needed

Wednesday, 03 July 2013

9:00 - 10:00 **Christophe Destouches, Cadarache** - "Proposed CEA contribution to the CRP IRDFF1.0 Experimental Validation"

10:00 - 11:00 **Axel Klix, KIT** - "The D-T neutron generator laboratory of TU Dresden"

11:00 - 12:00 **Valery Chechev, Radium Institute** - "Problem of improving IRDFF Decay Library: list of radionuclides, status of the available evaluated decay data, needs for new (updated) evaluations."

13:00 - 14:00 *Lunch break*

14:00 - 17:00 **Session 2: Discussion of expected outputs and research coordination**

Coffee breaks as needed

18:00 - ***Hospitality event:*** *Visit to "Zur Alten Kaisermühle" (http://www.kaisermuehle.at/)*

Thursday, 04 July 2013

9:00 - 10:00 **Arjan Plompen, IRMM -** "The IRMM contribution to the IRDFF CRP"

09:00 - 12:30 **Session 2: Discussion of expected outputs and research coordination**

12:30 - 14:00 *Lunch break*

14:00 - 18:00 **Session 2: Drafting of the Summary Report of the Meeting**

Coffee breaks as needed

Friday, 05 July 2013

09:00 - 12:30 **Session 2: Review of the Meeting Summary Report**

16:00 ***Closing of the Meeting***

Appendix 2

IAEA
International Atomic Energy Agency
Atoms for Peace

First Research Coordination Meeting on

Testing and Improving
the International Reactor Dosimetry and Fusion File (IRDFF)

1 – 5 July 2013, Vienna, Austria

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