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Assessment of evaluations for MYRRHA

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Assessment of evaluations for MYRRHA

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Contents

Abstract

Nuclear data of importance to the operation of MYRRHA, a research infrastructure supporting the development of Generation-IV reactors, were identified by sensitivity analysis. The data recommended in the main nuclear data libraries (i.e. JEFF, JENDL, ENDF/B, and TENDL) were compared and validated using experimental data reported in the literature and results of recent measurements. Recommendations for new experiments to solve inconsistencies between recommended and experimental data were specified. In addition, an assessment was made of the discrepancies and the means of improvement of nuclear data libraries for design, safety assessment and operation of new nuclear reactor systems such as MYRRHA.

1 Introduction

To address the increasing demand from nuclear research, industry and regulators, various projects have been initiated in recent years to address the increasing demand from nuclear research, industry and regulators to support neutronic calculations for the design and safety analysis of Advanced Fast Reactors and Advanced Fuel Cycle Scenarios. The uncertainty in nuclear data is one of the most important sources of uncertainty in reactor physics simulations [1], however, significant gaps between the current uncertainties and the target accuracies have been systematically shown [2]. The EC FP7 CHANDA (solving CHAllenges in Nuclear DAta) project [3] addresses the challenges in the field of nuclear data for nuclear applications. This project will allow European scientists and institutions to improve the nuclear data used in simulations in order to increase the accuracy of numerical assessments and consequently to improve the design and utilization of expensive experimental facilities (such as MYRRHA).

In particular, Work Package 10 (WP10) of CHANDA is focused on studying the nuclear data required for the development, safety assessment and licensing of the MYRRHA experimental reactor [4], a research infrastructure being developed at SCK•CEN, and on giving recommendations for data improvements. Additionally, support to the JEFF project [5] will be provided by identifying issues in nuclear data files for MYRRHA-relevant elements and isotopes [6].

2 The MYRRHA concept

MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications), a flexible, lead-bismuth cooled, experimental facility and a GEN-IV reactor system [7] is being designed at SCK•CEN, Mol, Belgium [4]. It is conceived to operate both in sub-critical, or Accelerator Driven System (ADS) mode, driven by a 600 MeV linear proton accelerator, and in critical mode, as a lead-bismuth cooled fast reactor. The updated core design is described in detail in Ref. [8]. As the primary design option, a mixed-oxide (MOX) fuel core is predicted, while the secondary option is to use conventional UO_2 fuel. For this study a simplified model [7], homogenised on fuel assembly level, has been used. The layout of the core is shown in Figure 1 for both critical and sub-critical configurations, while the vertical layout of the model (for the sub-critical core) is given in Figure 2.

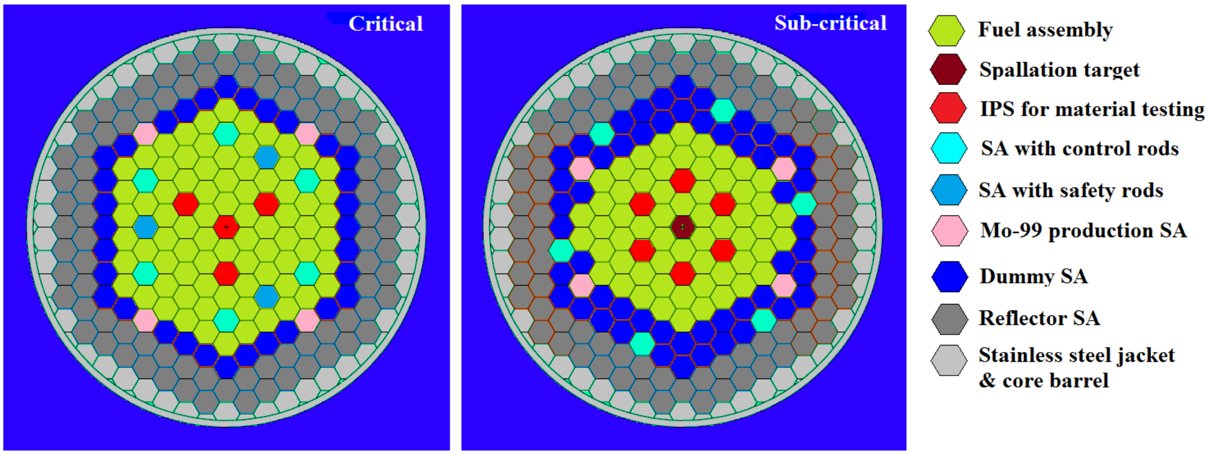

Figure 1: Critical (left) and sub-critical (right) MYRRHA MOX core layouts. SA stands for sub-assembly, and IPS for in-pile section.

Important features of the MYRRHA reactor concept include the lead-bismuth coolant, use of MOX fuel, accelerator and flexibility of the core. Using a mixture of lead and bismuth as coolant (compared to light water or heavy water) increases the fraction of fissions caused by fast neutrons significantly and at the same time decreases (compared to light water) the parasitic absorption of neutrons in the coolant. The main drawback is the production of large quantities of activation products, most importantly ^{210}Po. The use of plutonium (with possibility to introduce also minor actinides) in MOX fuel is important for reprocessing of the fuel and minimization of the radiotoxicity of nuclear waste. The proton accelerator produces high-energy neutrons which are more efficient in transmutation of minor actinides, and are also useful for studying the high-energy neutron induced nuclear reactions. The accelerator (in combination with subcritical operation mode) also improves the safety of the reactor.

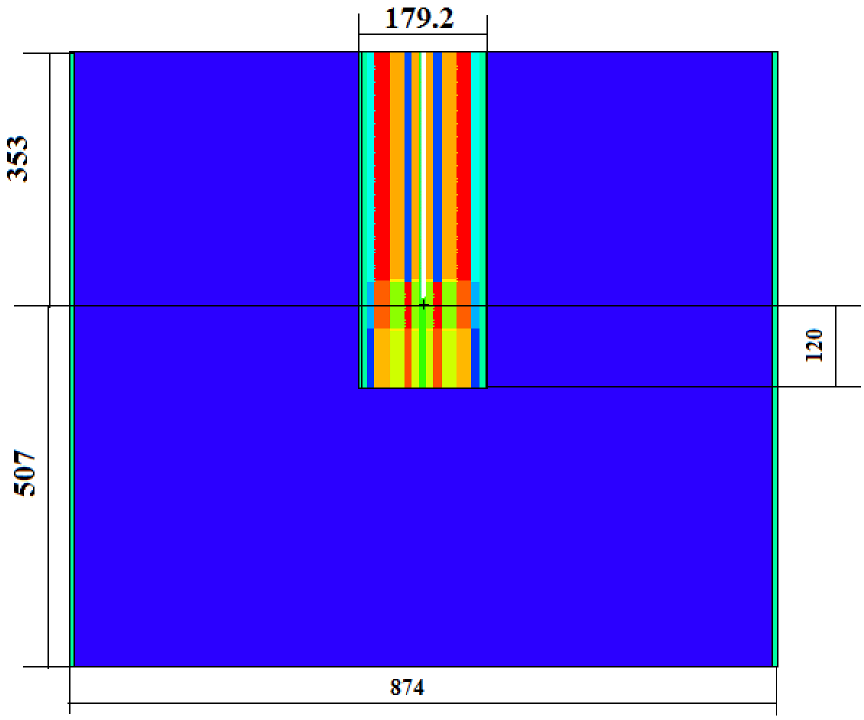

Figure 2: Vertical layout of the MYRRHA MOX model (dimensions given in cm). The colour of the components are consistent with Figure 1.

3 Simulation tools

For the sensitivity and uncertainty studies, the MYRRHA model has been used by both KENO-VI and MCNP[1] [9] radiation transport codes, the former one being used for the Monte Carlo transport calculations in the SCALE system [10]. Additionally, a cylindrical geometry model of MYRRHA critical configuration was constructed to be used in the neutron transport calculations performed by the PARTISN [11] and SUSD3D [12] codes, both part of the XSUN-2013 system [13]. This model was developed using equivalent concentric cylinders conserving the total mass of each material. Hence, no further homogenization was required. An adjustment of the arrangement of the cylinders was necessary in order to represent the MYRRHA critical core configuration with high-fidelity.

For the comparison of the nuclear data libraries and their impact on the MYRRHA multiplication factor k_{eff}, MCNP has been used. The cross section have been prepared using the SANDY code [14] which includes a capability to replace parts of the cross sections or other quantities from one library with part from another library and write them to a new, separate file. The NJOY [14] code system has been used for processing of nuclear data and preparation for use with the Monte Carlo code MCNP.

[1] MCNPX 2.7.0, MCNP 6.1 and MCNP 6.1.1beta were used in this work. The obtained results were statistically equivalent, consequently, no specification of the code version is mentioned from this point forward.

4 Identification of nuclear data, important for MYRRHA

In order to identify the most relevant nuclear data parameters (nuclides and quantities), a nuclear data sensitivity and uncertainty (S/U) analysis of the latest design of the MYRRHA cores [16] has been carried out using various codes and methodologies in order to identify most relevant nuclear data parameters (nuclides and quantities) of a model to response functions which reflect the behaviour of the neutron multiplication system on macroscopic scale. In our case, the response functions were the multiplication factor k_{eff} and the effective delayed neutron fraction β_{eff}.

The sensitivity coefficients for k_{eff} in the critical MYRRHA model, calculated within the Task 10.1 and presented in the Deliverable D10.1 [17] of the ongoing WP10 of CHANDA have been used to determine the list of nuclides and quantities important for MYRRHA from the neutronic properties point of view:

- ^{239}Pu:
  - average number of neutrons per fission ($\bar{\nu}$) in fast energy region;
  - (n,γ) in the resonance and fast energy region;
  - (n,f) in the fast energy region;
  - fission spectrum (χ);
- ^{238}U:
  - (n,n’) in the fast energy region;
  - (n,γ) in the resonance and fast energy region;
  - (n,n) in the resonance and fast energy region;
- ^{240}Pu:
  - $\bar{\nu}$ in the fast energy region;
- ^{238}Pu:
  - (n,f) in the resonance and fast energy region;
- ^{56}Fe:
  - (n,γ) in the resonance and fast energy region;
  - (n,n) in the resonance and fast energy region;
  - (n,n’) in the fast energy region.
- ^{241}Pu:
  - (n,f) in the resonance and fast energy region;
- ^{242}Pu:
  - (n,f) in the fast energy region.

Taking into account the flexibility of the MYRRHA facility in providing various irradiation environments, it is expedient to consider also:

- ^{209}Bi:
  - (n,γ) in the resonance and fast energy region;
  - (n,n’) in the resonance and fast energy region;
- ^{208}Pb:
  - (n,n) in the resonance and fast energy region;
  - (n,n’) in the resonance and fast energy region;

- ^{235}U:
  - $\bar{\nu}$ in the resonance and fast energy region;
  - (n,f) in the resonance and fast energy region;
  - (n,γ) in the resonance and fast energy region.

This list has also been confirmed by a similar study of the delayed neutron fraction sensitivities on nuclear data [18].

Starting from the above list of material reactions and quantities, the comparison of the nuclear data from different nuclear data libraries was performed. The JEFF-3.2 library [19], as most recent one, is taken as the reference, other considered libraries are ENDF/B-VII.1 [20], JENDL-4.0 [21] and TENDL-2014 [22]. Criticality calculations with critical MOX and UO_2 MYRRHA core configurations were performed with the MCNP6 code [9]. The cross sections were pre-processed using the NJOY processing system [14], while for the substitution of the data for individual reactions from different libraries the SANDY[2] code [14] developed at SCK•CEN has been applied.

The ongoing CIELO (*Collaborative International Evaluated Library Organization)* pilot project [23] aims at combining the efforts of nuclear data experimentalists and evaluators towards the production of new generation neutron data files for most important nuclides for reactor applications, including ^{56}Fe, $^{235,238}U$ and ^{239}Pu. Therefore, in order to avoid interferences with CIELO, CHANDA WP10 research is focused as much as possible on the other quantities present in the above list of quantities relevant for MYRRHA neutronics.

Bismuth and lead have been chosen as the main objects of study for improvement of nuclear data for MYRRHA since they are of vital importance (for neutron transport and even more for coolant neutron activation) and are not covered in the CIELO pilot project [23]. Existing experimental data resulting from neutron transmission experiments can be used to improve the existing evaluations cross section data. Additionally, new TOF transmission measurements for bismuth samples will be performed at the GELINA facility [24] at JRC Geel.

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5 Comparison of evaluated libraries and experimental data

5.1 Comparison of experimental and evaluated data

For the list of materials that are most relevant for MYRRHA (^{56}Fe, ^{204,206,207,208}Pb, ^{209}Bi, ^{235,238}U and ^{238,239,240,241,242}Pu), a detailed study of the available experimental data (in the EXFOR database [25] and other sources) has been performed for the quantities (cross sections, prompt, delayed and total fission neutron multiplicities) and reactions (capture, fission, elastic and inelastic scattering) of interest for MYRRHA. The data from contemporary major evaluated nuclear data libraries (JEFF-3.2, ENDF/B-VII.1, JENDL-4.0 and TENDL-2014) were compared with each other and with the experimental data. The details of this study of the nuclear data are described in detail in the CHANDA WP10 Deliverables D10.2 [26] and D10.3 [27].

5.2 Impact of different libraries on MYRRHA k_{eff}

After the direct intercomparison of libraries and the comparison with experimental data, the nuclear data libraries were used in MYRRHA computational models to estimate the impact of the differences in the libraries on the neutron balance in MYRRHA core. The critical core configuration has been chosen for this comparison since its neutron source can be more accurately modelled than for the subcritical core. Both the MOX and the UO_2 core configurations were considered. The JEFF-3.2 library has been adopted as the reference library. In Table 1 and Table 2, the effects of replacing nuclear data from JEFF-3.2 with another library for one nuclide at a time is shown for the MOX and UO_2 core, respectively. In general, the TENDL-2014 library differs the most from other libraries. Regarding isotopes, the largest effects are observed for ^{238,239,242}Pu (MOX only), ^{235}U (UO_2 only) and ^{209}Bi (both configurations).

Table 1: MCNP criticality calculations for the MYRRHA critical MOX configuration. Multiplication factors for different nuclear data libraries.

Library	**ENDF/B-VII.1**		**JENDL-4.0**		**TENDL-2014**	
Nuclide substituted	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}
None (all JEFF-3.2)	1.00980	0	1.00980	0	1.00980	0
^{56}Fe	1.00913	-0.00067	1.00831	-0.00149	1.00816	-0.00164
^{204}Pb	1.00998	0.00018	1.00959	-0.00021	1.00949	-0.00031
^{206}Pb	1.00948	-0.00032	1.01001	0.00021	1.00910	-0.00070
^{207}Pb	1.00957	-0.00023	1.00944	-0.00036		
^{208}Pb	1.01014	0.00034	1.01083	0.00103	1.01013	0.00033
^{209}Bi	1.00892	-0.00088	1.00800	-0.00180	1.01358	0.00378
^{235}U	1.00963	-0.00017	1.00964	-0.00016	1.00973	-0.00007
^{238}U	1.01020	0.00040	1.01075	0.00095	1.01111	0.00131
^{238}Pu	1.00825	-0.00155	1.00798	-0.00182	1.02049	0.01069
^{239}Pu	1.01257	0.00277	1.01562	0.00582	1.01623	0.00643
^{240}Pu	1.01018	0.00038	1.00761	-0.00219	1.00805	-0.00175
^{241}Pu	1.00921	-0.00059	1.00949	-0.00031	1.00786	-0.00194
^{242}Pu	1.01027	0.00047	1.00965	-0.00015	1.04048	0.03068

Table 2: MCNP criticality calculations for the MYRRHA critical UO_2 configuration. Multiplication factors for different nuclear data libraries.

Library	ENDF/B-VII.1		JENDL-4.0		TENDL-2014	
Nuclide substituted	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}	k_{eff}	Δk_{eff}
None (all JEFF-3.2)	1.01791	0	1.01791	0	1.01791	0
^{56}Fe	1.01709	-0.00082	1.01680	-0.00111	1.01720	-0.00071
^{204}Pb	1.01782	-0.00009	1.01751	-0.00040	1.01774	-0.00017
^{206}Pb	1.01755	-0.00036	1.01793	0.00002	1.01733	-0.00058
^{207}Pb	1.01771	-0.00020	1.01741	-0.00050	1.01533	-0.00258
^{208}Pb	1.01832	0.00041	1.01877	0.00086	1.01851	0.00060
^{209}Bi	1.01609	-0.00182	1.01679	-0.00112	1.02019	0.00228
^{235}U	1.01291	-0.00500	1.00916	-0.00875	1.01843	0.00052
^{238}U	1.01845	0.00054	1.01808	0.00017	1.01834	0.00043

A more detailed study of the impact of different nuclear data libraries on the MYRRHA k_{eff}, including the effect of changing individual quantities/reactions and energy regions for individual nuclides, is presented in the CHANDA WP10 Deliverable D10.2 [26].

6 Means of improvement of existing evaluations

6.1 Use of experimental data available in the literature

Nuclear data evaluations do not always make best use of available experimental data. There are several possible reasons for that. In some cases, all experimental data are not universally publically available. In other cases, there might be inconsistencies either between published experimental datasets or between experimental data and theoretical nuclear models which are not straightforward to resolve. Finally, deficiencies in the nuclear data evaluations may possibly also be merely consequences of evaluator's errors or lack of knowledge.

In case of MYRRHA-relevant nuclides, the latter can be observed in some evaluations of the lead isotopes. For example, in the resolved resonance region of ^{204}Pb (with a low natural abundance of 1.04%-1.65% [28]), serious deficiencies can be observed for the evaluations from the ENDF/B-VII.1 and JEFF-3.2 libraries (Figure 3) in comparison with the ORELA 200 m flight path TOF transmission measurements performed by Carlton et al. [29] using 71.41% enriched ^{204}Pb samples. Even though resonances well above 100 keV can perfectly be resolved, ENDF/B-VII.1 and JEFF-3.2 have upper limits of the RRR already at 50 keV and 100 keV, respectively. In the test version T1 for the new European library JEFF-3.3, another obvious error occurred: the so-called background cross section from JEFF-3.2 was changed and no longer fits the transmission factor at incident neutron energies between the energies of the resonance peaks. Similar problems were observed for other lead isotopes and ^{209}Bi. These problem were already reported to the JEFF committee[3] and fixed for the following test version, JEFF-3.3T2, where the JENDL-4.0 evaluation was taken as a basis with some modifications to improve the inelastic scattering cross section.

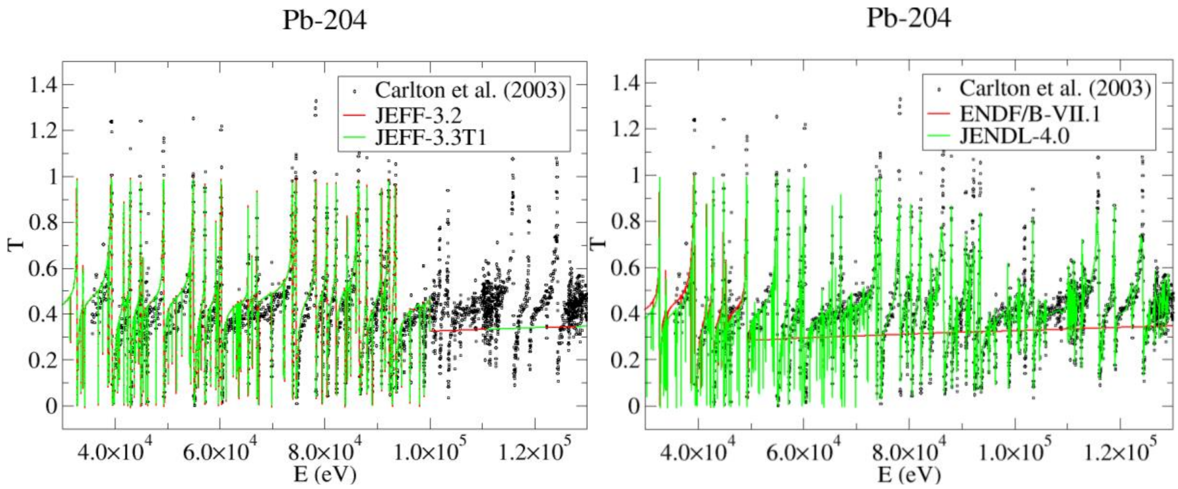

Figure 3: JEFF-3.2 and JEFF-3.3T1 (left), and ENDF/B-VII.1 and JENDL-4.0 (right) ^{204}Pb transmission comparison again experimental data by Carlton et al.

One further example, revealing the deficiencies in the ^{241}Pu(n,f) cross section in practically all current major evaluated nuclear data libraries in comparison with the recent energy dependent measurement by Tovesson and Hill [30], is shown in Figure 4. A more detailed study on the quality assessment of existing evaluations and possibilities or recommendations is presented in the CHANDA WP10 Deliverables D10.2 [26] and D10.3 [27].

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[3] Arjan Plompen, personal communication.

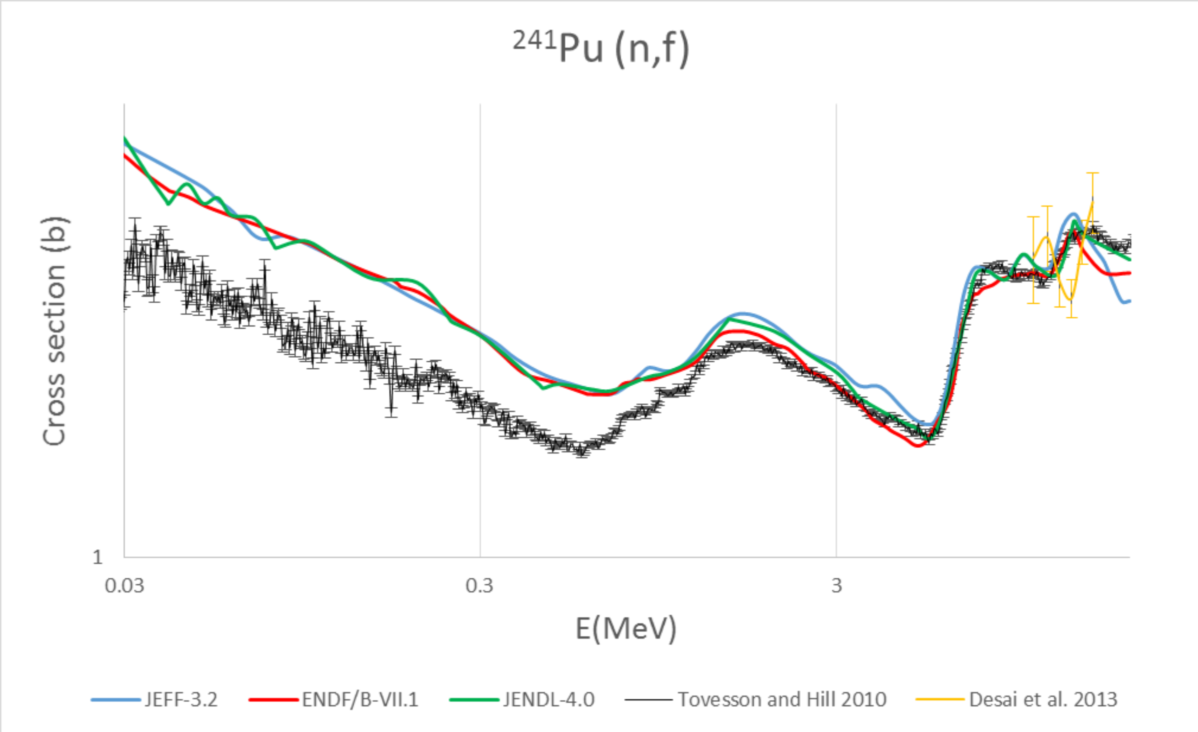

Figure 4: Comparison between existing $^{241}Pu(n,f)$ existing evaluations and (relatively) new experimental data in the fast energy region.

6.2 New measurements at GELINA

Transmission measurements will be performed at the time-of-flight GELINA facility [24] to determine the total cross section for neutron-induced reactions with ^{209}Bi in the resonance energy region. The experiments will be carried out at a 50 m measurement station of the GELINA facility using a ^{6}Li glass scintillator. The aim is to improve the total and the elastic scattering cross section of ^{209}Bi which is the dominant reaction in the resonance energy region.

^{209}Bi has been chosen for several reasons. As an important component of the lead-bismuth coolant, it is one of the most important materials for MYRRHA from the nuclear criticality point of view, and most important for coolant activation. Furthermore, ^{209}Bi samples are relatively cheap and easy to produce, and also easy to handle. ^{209}Bi is the only naturally occurring isotope of bismuth (which means no need for isotope enrichment process) with desirable physical and chemical properties in metallic form, while its half-life is long enough to be considered stable from practical point of view.

The resonance parameters derived from the transmission measurements will be used to improve the existing nuclear data evaluations – a recommendation for the JEFF project for the version 3.3 of the nuclear data library will be given.

6.3 The CIELO project

The ongoing CIELO (*Collaborative International Evaluated Library Organization)* pilot project [23] aims at improving nuclear data for nuclides most important for nuclear industry, including MYRRHA-relevant nuclides ^{56}Fe, $^{235,238}U$ and ^{239}Pu. JRC Geel is actively involved in improvement of the evaluation for ^{238}U and also partly contribution to the validation of the ^{56}Fe evaluation.

7 Summary and conclusions

In the framework WP10 of the EU CHANDA project, efforts were made to improve nuclear data for the MYRRHA reactor concept. First, the most important nuclear data were identified by a sensitivity and uncertainty analysis. In addition, a thorough literature search of available experimental data and nuclear data for the most important materials was performed. For some materials, notable deficiencies in evaluated nuclear data libraries and/or differences between evaluated and experimental data have been observed. Based on the present study recommendations, mainly related to Bi and Pb isotopes, were already given to the JEFF working group. These recommendations will be taken into account in the production of the test version for the new library JEFF-3.3.

Nevertheless, some of the nuclear data relevant for the operation of MYRRHA can still be improved. In some cases, the evaluated data do not reflect the quality of the available experimental data. For some other materials (i.e. ^{209}Bi), the data can be improved by performing new time-of-flight experiments. Other improvements are covered by projects running in parallel, in particular the CIELO project.

References

[1] I. Kodeli, "Sensitivity analysis and uncertainty propagation from basic nuclear data to reactor physics and safety relevant parameters," Report OECD Nuclear Energy Agency (NEA), https://www.oecd-nea.org/nsd/reports/2007/nea6053/Session-II-Methods-for-Uncertainty-Assessment/Paper-5_kodeli.pdf (2007).

[2] H. Harada and A. Plompen, "Meeting Nuclear Data Needs for Advanced Reactor Systems," Report NEA/NSC/WPEC/DOC 446 (2014).

[3] CHANDA project, EC Community Research and Development Information Service, http://www.cordis.europa.eu/project/rcn/110083_en.html (2013).

[4] J. Engelen, H.A. Abderrahim, P. Baeten, D. De Bruyn and P. Leysen, "MYRRHA: Preliminary front-end engineering design," Int. J. Hydrogen Energy 40, 15137–15147 (2015).

[5] A.J. Koning, "The JEFF evaluated nuclear data project," in: Proceedings of the International Conference on Nuclear Data for Science and Technology 2007, Nice, France, p. 721 (2007).

[6] CHANDA DOW, Seventh Framework Programme (FP7/2007-2013), Grant agreement no: 605203. Annex I – Description of Work (2013).

[7] U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum (GIF): "A Technology Roadmap for Generation IV Nuclear Energy Systems", https://www.gen-4.org/gif/jcms/c_9260/public, (2002).

[8] G. Van den Eynde, E. Malambu, A. Stankovskiy, R. Fernández and P. Baeten, "An updated core design for the multi-purpose irradiation facility MYRRHA," J. Nucl. Sci. Technol. 52, 1053–1057 (2015).

[9] D.B. Pelowitz, "MCNP6 User's Manual," Version 1, Report LA-CP-13-00634, Los Alamos National Laboratory (2013).

[10] Oak Ridge National Laboratory (ORNL), "Scale: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, Version 6.1," Report ORNL/TM-2005/39, Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785 (2011).

[11] R.E. Alcouffe, R.S. Baker, J.A. Dahl, S.A. Turner and R.C. Ward, "PARTISN 5.97, 1-D, 2-D, 3-D Time-Dependent, Multigroup Deterministic Parallel Neutral Particle Transport Code," Report LA-UR-08-07258, Los Alamos National Laboratory. Available from NEA/Data Bank Computer Code Collection as CCC-0760/01 (2008).

[12] I. Kodeli, "Multidimensional Deterministic Nuclear Data Sensitivity and Uncertainty Code System: Method and Application," Nucl. Sci. Eng. 138, 45–66 (2001).

[13] I. Kodeli and S. Slavič, "Computer Environment Integrating Several Deterministic Transport and Perturbation Codes Distributed by the NEA DB," in: Proceedings of the 22nd International Conference of Nuclear Energy for New Europe 2013, Bled, Slovenia (2013).

[14] L. Fiorito, G. Žerovnik, A. Stankovskiy, G. Van den Eynde and P.E. Labeau, "Nuclear data uncertainty propagation to integral responses using SANDY," submitted to Annals of Nuclear Energy.

[15] R. E. MacFarlane, "The NJOY Nuclear Data Processing System, Version 2012," Report LA-UR-12-27079, Los Alamos National Laboratory (2012).

[16] A. Stankovskiy and G. Van den Eynde, "Neutronic model of MYRRHA design," Report SCK•CEN/4463803, revision 1.6 (2014).

[17] P. Romojaro, F. Álvarez-Velarde, I. Kodeli, A. Stankovskiy, C.J. Díez, N. García-Herranz, G. Žerovnik and G. Van den Eynde, "Report on sensitivity analysis of MYRRHA with list of key reactions," Deliverable D10.1. CHANDA EU project N° 605203 (2015).

[18] I. Kodeli, "Effective delayed neutron fraction (Beff) sensitivity and uncertainty analysis of the MYRRHA reactor," Complementary Report on Deliverable D10.1, CHANDA EU project N° 605203 (2015).

[19] OECD NEA, The JEFF-3.2 Nuclear Data Library, NEA Data Bank, https://www.oecd-nea.org/dbforms/data/eva/evatapes/jeff32/ (2014).

[20] M.B. Chadwick et al., "ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data," Nuclear Data Sheets 112, 2887-2996 (2011).

[21] K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohasawa, T. Murata, H. Matsunobu, A. Zukeran, S. Kamada and J.I. Katakura, "JENDL-4.0: A New Library for Nuclear Science and Engineering," Journal of Nuclear Science and Technology 48, 1-30 (2011).

[22] A.J. Koning, D. Rochman, S.C van der Marck, J. Kopecky, J.Ch. Sublet, S. Pomp, H. Sjostrand, R. Forrest, E. Bauge, H. Henriksson, O. Cabellos, S. Goriely, J. Leppänen, H. Leeb, A. Plompen, R. Mills and S. Hilaire, "TENDL-2014: TALYS-based evaluated nuclear data library," www.talys.eu/tendl-2014.html (2014).

[23] M.B. Chadwick et al., "The CIELO Collaboration: Neutron Reactions on ^{1}H, ^{16}O, ^{56}Fe, $^{235,238}U$, and ^{239}Pu, " Nuclear data Sheets 118, 1-25 (2014).

[24] W. Mondelaers and P. Schillebeeckx, "GELINA, a neutron time-of-flight facility for high-resolution neutron data measurements," Notiziario Neutroni e Luce di Sincrotrone 11, 19-25 (2006).

[25] EXchange FORmat database (EXFOR), maintained by the Network of Nuclear Reaction Data Centers, http://www-nds.iaea.org/exfor/.

[26] P. Romojaro, C.J. Díez, N. García-Herranz, G. Žerovnik, P. Schillebeeckx, J. Heyse, F. Álvarez-Velarde, I. Kodeli, A. Stankovskiy, L. Fiorito and G. Van den Eynde, "Report on sensitivity analysis of MYRRHA with list of key reactions," Deliverable D10.2. CHANDA EU project N° 605203 (2016).

[27] P. Romojaro, N. García-Herranz, G. Žerovnik, P. Schillebeeckx, J. Heyse and I. Kodeli, "Report on sensitivity analysis of MYRRHA with list of key reactions," Deliverable D10.3. CHANDA EU project N° 605203 (2016).

[28] K.J.R. Rosman and P.D.P. Taylor, "Isotopic Compositions of the Elements 1997", Pure and Applied Chemistry 70, 217 (1998).

[29] R.F. Carlton et al., "Neutron resonance spectroscopy for n+^{204}Pb: Total and differential elastic scattering cross sections," Physical Review C 67, 024601 (2003).

[30] F. Tovesson and T.S. Hill, "Cross Sections for $^{239}Pu(n,f)$ and $^{241}Pu(n,f)$ in the Range E_n = 0.01 eV to 200 MeV," Nucl. Sci. Eng. 165, 224-231 (2010).

List of abbreviations and definitions

ADS	Accelerator-Driven System
CIELO	Collaborative International Evaluated Library Organization
CHANDA	solving CHAllenges in Nuclear DAta
EC	European Commission
ENDF/B	Evaluated Nuclear Data File/B-version
GELINA	Geel Electron LINear Accelerator
IPS	In-Pile Section
JEFF	Joint Evaluated Fission and Fusion file
JENDL	Japan Evaluated Nuclear Data Library
JRC	Joint Research Centre
KENO	a multigroup Monte Carlo code, part of SCALE package
MCNP	Monte Carlo N-Particle transport code
MOX	Mixed OXide
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
ORELA	Oak Ridge Electron Linear Accelerator
PARTISN	PARallel, TIme-Dependent SN transport code system
RRR	Resolved Resonance Region
SA	Sub/Assembly
SANDY	SAmpler of Nuclear Data and uncertaintY
SCALE	Standardized Computer Analyses for Licensing Evaluation
SCK•CEN	Belgian Nuclear Research Centre
SUSD3D	1-, 2-, 3-Dimensional Cross Section Sensitivity and Uncertainty Code
TENDL	TALYS-based Evaluated Nuclear Data Library
TOF	Time-Of-Flight
XSUN-2013	Windows interface environment for transport and sensitivity-uncertainty software TRANSX-2, PARTISN and SUSD3D
WP10	Work Package 10

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