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Nuclear data adjustment exercise combining information from shielding, critical and kinetics benchmark experiments ASPIS-Iron 88, Popsy and SNEAK-7A/7B

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A B S T R A C T

Nuclear cross-sections are being re-evaluated repeatedly since decades, with the objective of improving the agreement with the measurements consistently to the nuclear model predictions and to extend their application domains. In recent years, the evaluations have been in many cases "tuned" to match in particular the critical benchmarks. However, the effective multiplication factor (k_{eff}) is a very global parameter and as such provides simply too many possible combinations and variations, all more or less in agreement with the differential cross section data measurements and the associated uncertainties. Adding more extensively other types of integral measurements, such as shielding and kinetics benchmarks, on the cross-section validation menu is expected to provide a complementary and a more complete view on the challenges linked with the radiation propagation calculations. This paper discusses the advantages of exploiting shielding benchmark experiments and effective delayed neutron fraction (β_{eff}) measurements for nuclear data (ND) testing and, eventually, for guiding the evaluations. The cross-section sensitivity and uncertainty analysis revealed some crucial differences in the k_{eff} and β_{eff} sensitivity profiles, as well as advantages of shielding benchmarks which makes them favorable for ND validation. The potential benefits of using these types of measurements to reduce the compensation effects was demonstrated through the ND adjustment exercise involving the Popsy and SNEAK-7A & -7B critical and kinetics, and the ASPIS Iron 88 shielding benchmarks. The differences among the available nuclear covariance data and their impact on the adjustment results were investigated to understand the dangers of (mis)interpreting the results of the adjustment and to conclude on the robustness and reliability of the mathematical adjustment procedure using the state-of-the-art nuclear covariance data.

1. Introduction

Validation of recent cross-section evaluations is based to a large extent on the k_{eff} measurements performed in critical benchmark configurations. This is mostly facilitated by the availability of high-quality evaluations of critical benchmarks in international databases such as ICSBEP (ICSBEP, 2015) and IRPhE (IRPhE, 2015), an easy access to the ready-to-use computational models and in general relatively fast computations.

Adjustment of ND using integral benchmarks can follow two different approaches, according to the objectives of the evaluation. For a special purpose library the chosen integral experiments should resemble as much as possible to the actual problems to be analysed using the library. If on the other hand the objective is to create a general-purpose library the interest is in a large variety of integral experiments with various, largely different and complementary sensitivity profiles.

Constantly increasing ND quality requirements and new nuclear reactor design, safety and radiation protection applications pose high expectations on permanent improvement in predictive power of the new evaluations. To achieve an improved agreement with experiments comparing to the past evaluations, all available experimental information is frequently used for modern general-purpose data evaluations, including not only the theoretical models and ND differential measurements, but also the integral benchmarks, traditionally reserved for the ND validation and special-purpose ND file preparation. Using the recent ND evaluations, the calculation-to-experiment (C/E) ratios for the large series of critical integral benchmarks are indeed excellent, with about 50% of the results situated within 1σ of the experimental uncertainty. For example, the comparison presented in (van der Marck, 2012) reveals that the calculated k_{eff} for about 900 out of the total of

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over 2000 critical benchmarks analysed using ENDF/B-VII.1, JENDL-4.0 and JEFF-3.1.1 are within one standard deviation (1σ) of the experimental plus MCNP statistical uncertainty. Although this seems to be an excellent performance, such good agreement of C/E is difficult to understand from the mathematical (statistical) point of view, unless either (1) the uncertainties of computations C (modelling and nuclear data) are very small, or (2) C and E are correlated, suggesting some adjustment or tuning procedure was used in the evaluation process. The total uncertainty to cover 68% of the C/E cases is around 1.8 σ of the experimental uncertainty, which would correspond to the average computational uncertainty of around 500 pcm, i.e. of a similar order of magnitude as the measurement uncertainties. Much larger dispersion of results is to be expected from the statistical point of view taking into account the realistic calculational uncertainties due to nuclear data (see for example the results presented in Chapter 4 and in Table 4). Manifestly, these "tunings" are not reflected in the cross-section covariance matrices, which include practically no cross-material correlation terms.

This fact would suggest some caution when using critical benchmarks for ND validation since they were to some extent already used in the evaluation process. Moreover, relying predominantly on the k_{eff} measurements for cross-section evaluation and validation may be misleading, since k_{eff} as a very global parameter provides simply too many degrees of freedom for a general-purpose ND tuning and adjustment use. Furthermore, many users are also not aware, or do not take into account the recommendation to refer to the benchmark model specifications rather than using blindly the (MCNP) computer code inputs provided with the ICESBEP (ICSBEP, 2015) and IRPhE (IRPhE, 2015) evaluations which are not always error-proof.

A general consensus regarding the proper use of the integral benchmarks in the ND evaluation process has thus not yet been reached by the international community and is the subject of several international studies, such as those performed in the scope of the OECD/NEA Working Party on Evaluation Cooperation (WPEC) Subgroups SG26, SG33 (Salvatores et al, 2014), and recently SG39 on "Methods and approaches to provide feedback from nuclear and covariance data adjustment for improvement of nuclear data files") (Working Party on Evaluation Cooperation (WPEC)). These studies make use of the nuclear data sensitivity and uncertainty methodology based on the first order perturbation theory, which provide an insight in the importance of the physical phenomena involved in the neutron transport. Combined with the integral experimental data these methods already proved its merits in the process of the validation and improvement of the prediction accuracy of the target reactor parameters. In the past the cross-section adjustment methodology has been widely used in the design of new nuclear reactor systems such as a fast reactor. Studies performed within SG26 and SG33 already pointed out the danger of possible compensating effects in the adjustments and the crucial role of the covariance data used, both those associated to the nuclear data and those associated to the integral experiments. The purpose of WPEC SG39 is to study, on a selected set of test cases, the robustness of using the integral benchmarks to providing feedback to nuclear data evaluations (Working Party on Evaluation Cooperation (WPEC); Palmiotti et al., 2017).

The present study was motivated by the SG39 activities and aims at demonstrating the advantages of using diverse benchmark experiment types (critical, kinetics and shielding) to reduce the compensation effects in the adjustment, as well as pointing to some limitations of the mathematical procedure regarding the quality of the presently available covariance data.

2. Advantages and inconveniences of different integral benchmarks

The effective multiplication factor (k_{eff}) is only one of the important reactor safety factors requiring accurate nuclear data. Other measured reactor quantities which could provide additional and largely complementary information relevant for nuclear data improvement include, for example, the reaction rate and spectra measurements, as well as kinetic parameters such as effective delayed neutron fraction (beta effective - β_{eff}). The potential advantages of using simultaneously the k_{eff} and β_{eff} measurements for improving nuclear data was discussed in (Kodeli, 2013, 2017) based on several examples of fast reactor studies, such as FLATTOP-Pu, Big-ten, SNEAK-7A & -7B, Topsy, MYRRHA and others. The studies made use of k_{eff} and β_{eff} sensitivity and uncertainty computations performed by means of the SUSD3D code. It was concluded in these papers that due to their high sensitivity and very different shapes of sensitivity profiles some β_{eff} experiments could provide a complementary information to critical experiments, suggesting that a combined use of both measurements can be optimal for the validation and improvement of nuclear data. β_{eff} measurements can thus be used to validate not only the delayed neutron yields (delayed nu-bar -$\overline{\nu}_d$) as typically done in the past (ref. (Sakurai and Okajima, 2002; Fort et al., 2002)), but also other nuclear data. Inelastic and elastic scattering cross sections of ^{238}U are particularly interesting examples of the reactions with very different sensitivity profiles and causing high uncertainties, where β_{eff} measurements could contribute to improve nuclear data evaluations. The drawback of the β_{eff} measurements is their relatively high measurement uncertainty, usually around 5%, which is comparable or higher than the computational uncertainties, although for some benchmarks lower values are reported (e.g. as low as 1% for Big-ten benchmark, however this estimation is probably too optimistic or referring to only part of the total uncertainty).

Another class of measurements which played a crucial role in nuclear data evaluation and validation particularly in the past are the reactor shielding benchmark experiments. Descriptions of over 100 such benchmarks are available in the Shielding INtegral Benchmark Archive and Database (SINBAD) (SINBAD database, 2013; Kodeli et al., 2013) collection, but the progress in the project was slow in the recent years and needs to be revitalised. Many of these measurements, although some of them rather old, are very relevant and useful for the modern ND validation. In general, the measured reaction rates or spectra (in particular for deep penetrations) are highly and more selectively sensitive to nuclear cross-sections of particular types and isotopes, which represents their main advantage over the k_{eff} measurements, but are on the other hand computationally more demanding. Contrary to the k_{eff}, the β_{eff} and the shielding benchmarks have recently been less widely used in the cross-section evaluations, which makes the latter more convenient for the validation purposes.

Some advantages and inconveniences of the above three measurement types are summarized in Table 1.

Validation against different types of measurements is therefore expected to provide a complementary view and wider scope nuclear data validation. For validation and demonstration purpose, the following experimental measurements were considered in an exercise dedicated to study the performance of the nuclear data validation and adjustment techniques:

Table 1
Advantages (+) and inconveniences (−) of different benchmarks. ΔC and ΔE refer to the calculational and experimental uncertainty, respectively.

Benchmark	+	−
Critical	Many benchmarks in ICESBEP & IRPhE, fast and easy calculations/interpretations	ΔC ~ ΔE global parameter
Kinetics	$S_\beta \neq S_k$ Relatively fast calculations	ΔC ~ ΔE global parameter
Shielding	ΔC > > ΔE	Complex calculations, long CPU times, complex uncertainty evaluation (in particular for older experiments)