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Evaluation of Neutron-induced Cross Sections and their Related Covariances with Physical Constraints

C. De Saint Jean,[1,*] P. Archier,[1] E. Privas,[1] G. Noguère,[1] B. Habert,[1] and P. Tamagno[1]
[1]*CEA, DEN, Cadarache, F-13108 Saint Paul les Durance, France*
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Nuclear data, along with numerical methods and the associated calculation schemes, continue to play a key role in reactor design, reactor core operating parameters calculations, fuel cycle management and criticality safety calculations. Due to the intensive use of Monte-Carlo calculations reducing numerical biases, the final accuracy of neutronic calculations increasingly depends on the quality of nuclear data used. This paper gives a broad picture of all ingredients treated by nuclear data evaluators during their analyses. After giving an introduction to nuclear data evaluation, we present implications of using the Bayesian inference to obtain evaluated cross sections and related uncertainties. In particular, a focus is made on systematic uncertainties appearing in the analysis of differential measurements as well as advantages and drawbacks one may encounter by analyzing integral experiments.

The evaluation work is in general done independently in the resonance and in the continuum energy ranges giving rise to inconsistencies in evaluated files. For future evaluations on the whole energy range, we call attention to two innovative methods used to analyze several nuclear reaction models and impose constraints. Finally, we discuss suggestions for possible improvements in the evaluation process to master the quantification of uncertainties. These are associated with experiments (microscopic and integral), nuclear reaction theories and the Bayesian inference.

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* Corresponding author: cyrille.de-saint-jean@cea.fr

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I. INTRODUCTION

Since the birth of nuclear physics, nuclear data activities have always been paramount: in the early years (from 1920-1945), the theoretical and experimental advances were related to the necessity of controlling atomic energy by building devices where reaction chain would be quantified (calculated) and mastered. This corresponds to what Emilio Segrè called having "good numbers."[1] Having "good numbers" was already associated at that time with the need to develop theoretical approaches (nuclear reaction models and fission theories), initiate the measurement of fundamental physical observables through microscopic experiments and quickly set up integral experiments (critical mass program of Los Alamos). These three activities still characterize the nuclear data evaluation (to have good numbers).

Nuclear data continue to play a key role, as well as numerical methods and the associated calculation schemes in reactor design, reactor core operating parameters calculations, fuel cycle management and criticality safety calculations (see Ref. [1] for example). This paper will focus on the nuclear data that are used in reactor physics applications and especially neutron cross sections evaluation. Even if the evaluation of thermal scattering data [2, 3], light elements neutron-induced cross sections, fission yields [4, 5], delayed particles (neutrons/gammas) are not presented in this paper, some presented issues are common and the discussed methods to solve them could be used.

Due to the intensive use of Monte-Carlo calculations reducing numerical biases, the final accuracy of neutronic calculations increasingly depends on the quality of nuclear data [1, 6]. The knowledge of neutron-induced cross sections in the 0 eV and 200 MeV energy region is reflected by the evaluation of their related uncertainties.

In Sec. II, a brief reminder of the nuclear data needed to calculate properly the neutron flux in a nuclear reactor core will be given. Then, major ingredients of the evaluation work, theoretical models (common theoretical description of major nuclear reaction models and some of their parameters), microscopic and integral measurements, will be presented. As this paper presents the evaluation of nuclear data based on the Bayesian inference, a general mathematical framework related to Bayesian parameters estimations will be first presented in Sec. III. Secs. II and III can be viewed as introductory chapters to present a simplified state of the art of evaluation and possible principal challenges and drawbacks.

Sec. IV will present one of the major issues when analyzing microscopic experiments: proper propagation of systematic uncertainties (normalization, background, ...). In the past, unrealistically low parameter uncertainties were obtained at the end of evaluation by not treating them accurately. Thus, in Sec. IV B, methodologies to treat systematic experimental uncertainty (referred to as marginalization technique) will be presented. In Sec. V, the use of integral experiments during the evaluation process will be presented and discussed. Compar-

[1] *"In an enterprise such as the building of the atomic bomb the difference between ideas, hopes, suggestions and theoretical calculations, and solid numbers based on measurement, is paramount."* E. Segrè