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Progress of Covariance Evaluation at the China Nuclear Data Center

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Covariance evaluations at the China Nuclear Data Center focus on the cross sections of structural materials and actinides in the fast neutron energy range. In addition to the well-known Least-squares approach, a method based on the analysis of the sources of experimental uncertainties is especially introduced to generate a covariance matrix for a particular reaction for which multiple measurements are available. The scheme of the covariance evaluation flow is presented, and an example of n+^{90}Zr is given to illuminate the whole procedure. It is proven that the accuracy of measurements can be properly incorporated into the covariance and the long-standing small uncertainty problem can be avoided.

I. INTRODUCTION

Covariances are important in many modern nuclear applications, especially in the nuclear data adjustment study [1] and the Generation-IV reactor designs because of its direct connection to the key targets, economy and security [2]. Several important libraries such as COMMARA-2.0 [3], BOLNA [4] and AFCI-1.2 [5] have been released and applied to activities of Working Parties on International Nuclear Data Evaluation Co-operation (WPEC). Many of the evaluated nuclear data libraries, listed in Table I, also contain the covariance data; while relatively large number of nuclei in ENDF/B-VII.1, JEFF-3.2 and JENDL-4.0u2 have covariances, they are rather scarce in CENDL-3.1 and ROSFOND-2010. In order to produce the covariance files for major nuclei in CENDL, the covariance evaluation project has been carried out at the China Nuclear Data Center (CNDC) in recent years.

Although some inherent problems in the Least-squares (L-S) method are difficult to solve completely [6], it is widely used to build a model-based covariance since the uncertainties of both model calculations and measurements can both be incorporated into the covariance in a simple way. Therefore, we employ L-S in our evaluation scheme. In addition, we have also been developing another way to extract covariances directly from the Analysis of the Sources of Experimental Errors (ASEE) to estimate covariances of a reaction to which multiple measurement exist. We study ASEE to avoid the risk of the underestimated uncertainty problem in the L-S approach, and to make the covariance reflect the present accuracy of experimental data. In this approach, various types of nuclear experiments and their uncertainty sources are evaluated according to the reactions being studied. As an example to illuminate ASEE, we apply our method to the experimental data of the ^{90}Zr(n,2n)^{89}Zr reaction, which are obtained with the activation technique. In addition, we show the model-based covariance of ^{90}Zr(n,inl)^{90}Zr* to explain our L-S method.

The paper is organized as follows: In Sect. II we describe the scheme of covariance evaluation flow at CNDC and introduce the related codes. Then, in Sect. III we present the covariance evaluation for ^{90}Zr(n,2n)^{89}Zr to explain ASEE. The following Sect. IV gives the covariance of ^{90}Zr(n,inl)^{90}Zr* by L-S. Finally, an overall covariance evaluation at CNDC is summarized in Sect.V and the future plans are given.

II. COVARIANCE EVALUATION AT THE CNDC

Covariance evaluations at the CNDC are accompanied by the evaluation of nuclear data (cross sections, angular distributions, etc.). The main procedure is shown in Fig. 1. One can see that the evaluation starts with collection of both experimental data in EXFOR and other libraries. The measurement-based ASEE approach or the model-based L-S approach is adopted to generate the covariance depending on the status of measurements.

The ASEE approach is utilized to deal with the reactions for which plenty of experimental data are available. Three steps are involved in ASEE, as shown in the purple boxes on the left-hand side of Fig. 1. First,

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TABLE I. The status of covariance evaluation in the international evaluated neutron data libraries.

Version	ENDF/B−VII.1	JENDL−4.0u2	JEFF−3.2	CENDL−3.1	ROSFOND−2010
Release Year	2011	2012	2014	2009	2010
Total Nuclei	423	406	472	240	686
Nuclei with Covariances	190	95	218	6	4

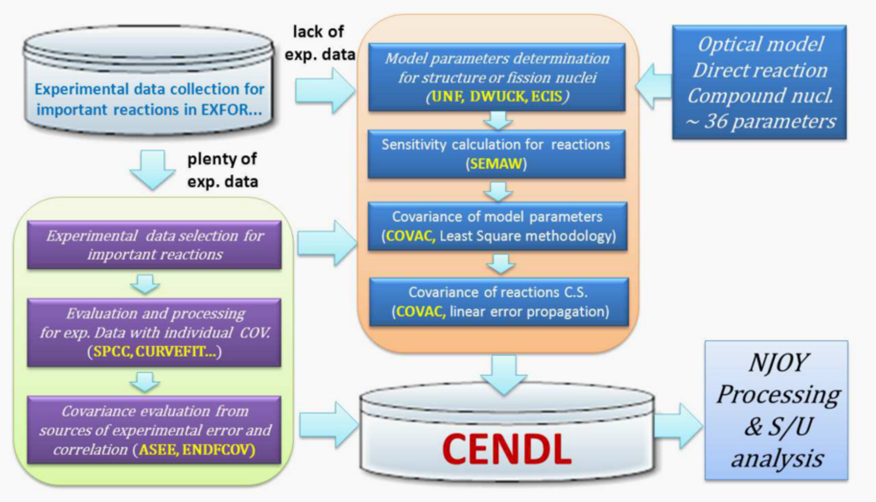

FIG. 1. (Color online) Scheme of covariance evaluation flow at CNDC.

well-measured experimental data are selected through a preliminary analysis of experimental conditions (accelerator, neutron flux and detector, etc.). Through the elaborate evaluations of each selected measurement and processing the evaluated data via the spline fitting code SPCC [7] or the polynomial fitting code CURVEFIT [8], we achieve the recommended data. The experimental covariance V_{exp} can also be obtained from these selected data by analyzing the sources of experimental uncertainties. The most difficult and time-consuming work in this procedure is to extract the uncertainty and correlation from experimental error and construct V_{exp}. Hence, we make special efforts to study the way to deal with the different uncertainties that are inherent to various experimental conditions, which will be illuminated in Sect. III. Moreover, the recommended cross sections and covariances are converted into the ENDF-6 format by the code ENDFCOV [9].

On the other hand, the reactions with few experimental data are treated with the L-S approach. As shown in the blue boxes at the center of Fig. 1, this procedure includes four steps: the nuclear model calculations, the sensitivity calculations of model parameters, and the covariance calculations for both the model parameters and cross sections with L-S. The ordinary L-S is adopted in our evaluation and the formula can be found in the literature [10]. We developed a code SEMAW [11] to calculate the sensitivities of parameters in the nuclear reaction codes UNF [12], DWUCK [13] and ECIS [14]. About 36 model parameters are handled in SEMAW, which are related to the optical model, the direct and compound nuclear reaction models. Moreover, the code COVAC [11] is specially designed to calculate the covariance with L-S.

We include the reactions of (n,tot), (n,el), (n,γ), (n,inl), (n,p), (n,α), (n,2n), (n,np), (n,nα), (n,3n), and (n,f) in the fast neutron energy range in our analysis. Only the cross sections are considered for now. After incorporation into CENDL, the covariances can be processed to make the multi-group covariances with NJOY [15], and they can be utilized for the sensitivity and uncertainty (S/U) analysis and other applications.

III. COVARIANCE EVALUATION FOR ZR-90 IN THE FAST NEUTRON ENERGY REGION

^{90}Zr is the most abundant element of natural isotopes of zirconium, which is the ideal structural material in the nuclear reactor design. Its data have already been stored in all evaluated nuclear data libraries including CENDL-3.1. The major neutron emission reactions are the (n,inl) and (n,2n) channels. The following contents will focus on producing the covariances of these two cross sections.

These experimental data are firstly searched for in EXFOR. There are 38 measurements of ^{90}Zr(n,2n)^{89}Zr available until now, whereas none for ^{90}Zr(n,inl)^{90}Zr*. Hence, we choose ASEE to estimate the covariance of ^{90}Zr(n,2n)^{89}Zr and L-S to calculate the covariance of ^{90}Zr(n,inl)^{90}Zr*.