Testing the Extended SRM against the \( ^{238}\text{U}(^{3}\text{He},^{4}\text{He})^{237}\text{U}^* \) surrogate probabilities

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Abstract. Since its introduction in the seventies’, the so-called surrogate-reaction method (SRM) has motivated the development and improvement of theories in connection to direct reactions. A recent work by Bouland and Noguère, Phys. Rev. C \textbf{102}, 054608 (2020), has shown that the inclusion of experimental probabilities in the neutron cross section evaluation process can be better achieved using tools resulting from the efforts made over the two last decades. In particular, the authors have put forward a new prescription, named after the SRM as extended SRM (ESRM), to convert, with reasonable confidence, probabilities measured in direct reactions to pseudo-experimental neutron-induced reaction cross sections. Applied to the \( ^{174}\text{Yb}(^{3}\text{He,py})^{176}\text{Lu}^* \) transfer reaction, the ESRM has demonstrated much more precision than the early use of the SRM. In addition to the ‘direct’ analysis of reaction probabilities measured in direct reactions using the right modeling as developed in Phys. Rev. C \textbf{100}, 064611 (2019), it is worth to try converting the measured probabilities in pseudo experimental neutron-induced cross sections for neutron reactor data applications. In the present paper, first results, before conversion, are shown by applying the two ESRM equations to a fissile isotope.

1 Introduction

The last decades have seen considerable changes in the nature of the uncertainties related to nuclear reactor energy calculations. These uncertainties, mainly driven in the past by numerous approximations embedded in the various equations, have become less and less sensitive to the approximations, while the question of the uncertainties on the model parameters has become an issue. One way to constrain the parameters, and so to reduce nuclear data uncertainties, is to compare the prediction of an ‘observable’ with its measurement. In this framework, neutron-induced reaction cross sections are a fundamental observable to build a very large experimental database. However since the seventies’, an alternative type of observable, the so-called reaction deexcitation probability, has also contributed to enrich the fitting experimental database, especially for the fission channel. Indeed the measured fission probability is well-suited to assign fission barriers of fissile isotopes, since their inner- and outer-barrier heights \( (V_A \text{ and } V_B \text{ respectively}) \) at the ground state are significantly lower than \( S_n \), the neutron emission energy. Figure 1 illustrates this statement.

The present paper focuses on the use of an elaborated technique, recently described and named after the surrogate-reaction method, the ESRM \([1]\) as Extended Surrogate-Reaction Method. It provides a rigorous framework for surrogate-reaction data analysis. Following recent advanced studies, as the ones of Refs. \([2–4]\), the use of two different expressions of width fluctuation correction factor for the calculation of cross sections and decay probabilities, respectively, brings more confidence in the simultaneous analyses at low energy. In the Ref. \([1]\), demonstration was made of the capability of the method by application to the \( ^{174}\text{Yb}(^{3}\text{He,py})^{176}\text{Lu}^* \) transfer reaction. Here, first application of the ESRM equations (re-
viewed in next Section 2) is made to the decay of a heavy nucleus, the $^{237}\text{U}^*$, whose fission reaction opens above $\delta_n$. Comparisons are made in this work with the data by Marini et al. [5], in which the fission and $\gamma$-emission probabilities for the $^{238}\text{U}(^{3}\text{He},^{3}\text{He})^{237}\text{U}^*$ transfer reaction were measured simultaneously.

2 Extended Surrogate-Reaction Method (ESRM) equations

The ESRM procedure relies on the equations coupling two distinct observables that share the same excited compound system $A^*$ (CS). An important issue is the use of a unique and $S_J(J^p)$ in Fig. 2 as a unique surrogate for the fission, $W_{\text{surrogate}}(n)$, for the $\gamma$-emission or $W_{\text{surrogate}}(n',n)$ for a neutron-emission with the residual nucleus left in its ground state ($W_{\text{surrogate}}$ otherwise). To magnify the comparison, the SWFCF plot uses the entrance spin-parity distribution corresponding to the one applied in WFCF treatment (i.e.; the neutron-incident distribution).

We emphasize that in the ESRM equations, we indeed use a spin-parity distribution relevant to the surrogate reaction treated. The role of the radiative and fission channels that now carry the enhancement pattern and deviates from the customary WFCFs profile [7], is well visible (up to $+150\%$). As expected, the usual high-energy pattern is recovered when the total number of opened deexcitation channels increases; all the SWFCF tending thus to unity. From the features presented in Fig. 2, one understands the importance of correctly treating the width fluctuations in the calculation to reproduce with the minimum of biases the measured $\gamma$-ray emission and fission probabilities.

3 Solving the ESRM equations for a heavy nucleus

Since the paper [1] has demonstrated the efficacy of the ESRM equations for a medium-mass nucleus, demonstration must be made that it works when the fission channel is in competition with the other deexcitation channels. The ultimate goal, by using the ESRM equations, is to provide the unknown model parameter that is missing for the final agreement between the calculation and the experiment, either in terms of cross sections and deexcitation probabilities. Ideally this approach must be carried out for all the open channels over the widest energy range. Although this is a goal for the future, no neutron-emission probabilities are yet simultaneously measured with the fission and the $\gamma$-emission channels. Therefore, this comparison focuses on those observed channels. An example of poorly-known data involved measurements with the fission and the $\gamma$-ray emission and fission probabilities.
Neutron-induced fission cross section $J$ channel CS. Preliminary results are shown in Fig. 3. Neutron-induced capture cross section and fission probability from 5.5 MeV, reaching the fission plateau at 9 MeV. Beyond the economical argument, there is some will to increase the amount of $^{236}$U material in fresh UO$_2$ fuel. Beyond the use of the most appropriate direct-reaction reaction or the surrogate reaction, neutron-induced average cross sections and surrogate-reaction probability calculations have been performed, simultaneously, for the $^{237}$U$^+$ CS. Preliminary results are shown in Figs. 3 and 5 for the cross sections and Fig. 6 for the deexcitation probabilities. The latter results do not carry the biases brought by the early use of the surrogate-reaction method (as shown in Figure 5 of Ref. [10]), that was solely based on the Weisskopf-Ewing hypothesis of the independence of the decay-channel probability on the CS spin-parity distribution [11]. Indeed the agreement between the calculations and the experimental data for the $\gamma$ channel is now reached although the exact pattern of the entrance direct-reaction $J^\pi$ distribution remains an open question. Beyond the use of the most appropriate direct-reaction calculations and experimental data for the $\gamma$ channel is now reached although the exact pattern of the entrance direct-reaction $J^\pi$ distribution remains an open question.
with the other variables, $\sigma_n^{e}$, $W_{n,surr}^{\gamma}$, and $W_{n,surr}^{\gamma}$, assessed by the formalism, is on the right path. Demonstration has been made above that the knowledge of all quantities except one, which in present case is the spin-parity distribution corresponding to the $^{238}\text{U}(^{4}\text{He},^{4}\text{He})$ reaction, can provide valuable feedback on the missing information.

Our new capability of simultaneously and coherently analyse deexcitation probabilities and neutron-induced partial cross sections is a major asset for the difficult task of evaluating the neutron-induced reaction cross sections within the nowadays nuclear data target accuracy. In the past that kind of comparative analysis was generally made using various model approximations, as the ones involved in the early use of the surrogate-reaction method [15]. Using the ESRM equations ensures our capability to extract the best non-biased information from surrogate-reaction data. Reference [6] also gives the ESRM transformation to convert surrogate-reaction data into pseudo-reaction neutron-induced cross section data as an easy complement to the existing experimental cross section database needed for an evaluation based solely on cross section data. We expect to be able to make this transformation in a close future.

4 Conclusions

By using the ESRM equations (Eqs. (1) and (2)), our actual capability to infer, with reasonable accuracy, any unknown quantity among $\sigma_n^{e}$, $\sigma_{n,surr}^{\gamma}$, $B_c^{\gamma}$ and $F_{n,surr}^{\gamma}$, Assuming that the various terms of the ESRM equations (Eqs. (1) and (2)) are all calculated (or predicted) for the $^{237}\text{U}^+$ with a reasonable precision (either set from reference nuclear data or fine-tuned in the work) except for the spin-parity entrance distribution of the surrogate reaction, $F_{n,surr}^{\gamma}(E_n,J^\pi)$, we can evaluate the influence of the distribution used as input to Eq. (2). In the present case, the experimental database refers to the measurement by Marini et al. [5] of the $^{238}\text{U}(^{4}\text{He},^{4}\text{He})$ reaction. Figure 6 shows two calculations, one using a $J^\pi$ distribution from the literature [13] and the other resulting from a pick-up calculation using the in-house QPVR module of the AVXSF-LNG code [12]. The two distributions differ in terms of mean value and standard deviation. From Figure (6), it is clear that the input of the $J^\pi$ distribution from the literature [13], although not perfect [14], shows a better agreement with the experimental data than the calculation based on the QPVR prediction.

References