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J. E. Escher, F. S. Dietrich

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Jutta E. Escher and Frank S. Dietrich
Lawrence Livermore National Laboratory
P.O. Box 808, L-414, Livermore, CA 94551, USA

Abstract

The validity of the Surrogate Nuclear Reactions method in the Weisskopf-Ewing limit and the Surrogate Ratio method are examined for neutron-induced fission of uranium nuclei. Both methods are approximations to the full Surrogate Nuclear Reactions approach, which aims at determining cross sections for compound-nuclear reactions. A nuclear-reaction model is employed to simulate physical quantities that are typically measured in Surrogate experiments and to test commonly-used assumptions underlying the analyses of Surrogate experiments.

1 Introduction

Indirect methods play an important role in the determination of nuclear reaction cross sections. Often the cross section needed for a particular application cannot be measured directly since the relevant energy region is inaccessible or the target is too short-lived. To overcome the experimental limitations, several indirect methods have been employed in recent years. Approaches such as the ANC (Asymptotic Normalization Coefficient) method [1, 2], Coulomb dissociation [3], and the Trojan-Horse method [4] have yielded valuable cross-section information for various direct reactions. While recent efforts have primarily focused on direct-reaction cross sections, there is a clear need for cross sections of compound-nuclear reactions involving a wide variety of target nuclei.

The focus of this contribution is an indirect method that complements the above approaches, the *Surrogate Nuclear Reactions* method. The Surrogate method combines experiment with reaction theory to obtain cross sections for reactions that proceed through a compound nucleus. A simple version of the Surrogate idea was already used in the 1970s to estimate neutron-induced fission cross sections from transfer reactions [5]. The analysis of the experiments was based on the Weisskopf-Ewing approximation to the statistical Hauser-Feshbach description of the reactions of interest. Most recent efforts in this area rely on similar approximation schemes for extracting the sought-after cross sections from Surrogate experiments [6, 7, 8]. Since a complete Surrogate treatment is challenging [9], it is worthwhile considering such approximations. Typically, they are validated *a posteriori* by comparing the extracted cross sections with direct measurements where available. In this contribution, we will identify and critically examine the assumptions underlying the Weisskopf-Ewing and Ratio approaches for the example of (n,f) reactions involving uranium targets.

The next section gives a brief outline of the Surrogate approach. In Section 3, the Weisskopf-Ewing approximation is reviewed and calculations that test the validity of this approximation are presented. The Ratio approach is introduced and tested in Section 4. Some concluding remarks follow in Section 5.

2 The Surrogate Nuclear Reactions Idea

The "Surrogate Nuclear Reactions" method combines experiment with theory to obtain cross sections for compound-nuclear reactions, $a+A \to B^* \to c+C$, involving difficult-to-produce targets, A. In the Surrogate approach, B^* is produced by means of an alternative ("Surrogate") reaction, e.g. $d + D \to b + B^*$, and the desired decay channel ($B^* \to c + C$) is observed in coincidence with the outgoing particle b, see Figure 1. The reaction cross section is then obtained by combining the calculated cross section for the formation of B^* (from $a + A$) with the measured decay probabilies for this state.

The present contribution focuses on (n,f) reactions for uranium nuclei. In the past, both inelastic scattering and transfer reactions have been employed to obtain Surrogate estimates for fission cross sections. Other compound-nuclear reactions of interest include ^{85}Kr(n,γ)^{86}Kr and ^{153}Gd(n,γ)^{154}Gd, two reactions which play an important role in the astrophysical s process. A possible Surrogate reaction for the former example is ^{86}Kr(α,α')^{86}Kr*, while ^{154}Gd*, the compound nucleus relevant for the latter case, can be produced via the transfer reaction ^{155}Gd(^{3}He,α)^{154}Gd*.

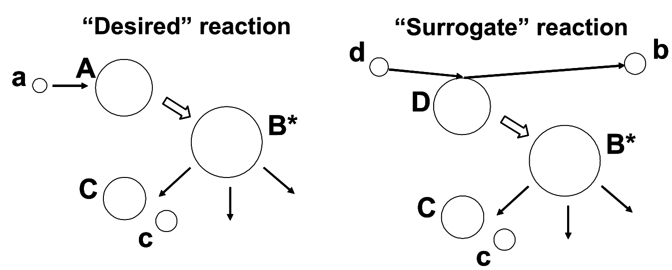

Figure 1: Surrogate reaction mechanism. The first step of the desired reaction, $a+A \to B^* \to c+C$, is replaced by an alternative ("Surrogate") reaction, $d+D \to b+B^*$, that populates the same compound nucleus, B^*. The subsequent decay of the compound nucleus into the relevant channel, $B^* \to c+C$, is measured and used to extract the desired cross section.

In the Hauser-Feshbach formalism, the cross section for the "desired" reaction $a + A \to B^* \to c + C$ takes the form:

$$\sigma_{\alpha\chi}(E_a) \quad = \quad \sum_{J,\pi} \sigma_\alpha^{CN}(E_{ex}, J, \pi) \;\; G_\chi^{CN}(E_{ex}, J, \pi) \; , \tag{1}$$

with α denoting the entrance channel $a + A$ and χ representing the relevant exit channel $c + C$. The excitation energy of the compound nucleus, E_{ex}, is related to the projectile energy E_a via the energy needed for separating a from B: $E_a = E_{ex} - S_a(B)$. In many cases the formation cross section $\sigma_\alpha^{CN} = \sigma(a + A \to B^*)$ can be calculated to a reasonable accuracy by using optical potentials, while the theoretical decay probabilities G_χ^{CN} for the different channels χ are often quite uncertain. The objective of the Surrogate method is to determine or constrain these decay probabilities experimentally.

The probability for forming B^* in the Surrogate reaction (with energy E_{ex}, angular momentum J, and parity π) is $F_\delta^{CN}(E_{ex}, J, \pi)$, where δ denotes the entrance channel $d+D$. The quantity

$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) \;\; G_{\chi}^{CN}(E_{ex}, J, \pi) \; , \tag{2}$$

which gives the probability that the compound nucleus B^* was formed with energy E_{ex} and decayed into channel χ, can be obtained experimentally by observing the number of $\delta-\chi$ coincidence events, $N_{\delta\chi}$, relative to the number of Surrogate reaction events, N_δ. The direct-reaction probabilities $F_{\delta}^{CN}(E_{ex}, J, \pi)$ have to be determined theoretically, so that the branching ratios $G_{\chi}^{CN}(E_{ex}, J, \pi)$ can be extracted from the measurements.

In practice, the decay of the compound nucleus is modeled and the $G_{\chi}^{CN}(E_{ex}, J, \pi)$ are obtained by fitting the calculations to reproduce the measured decay probabilities and subsequently inserted in Eq. (1) to yield the desired cross section [9]. Alternatively, approximations to the full Surrogate formalism outlined here can be employed. The Weisskopf-Ewing approximation and the Surrogate Ratio approach are considered below.

3 The Weisskopf-Ewing Approximation

Historically, the Weisskopf-Ewing theory of compound-nucleus reactions [10] preceeds the Hauser-Feshbach theory [11]. In certain situations, the Weisskopf-Ewing description yields useful approximations to the results obtained in the full Hauser-Feshbach formalism. Most Surrogate experiments carried out to date have been analyzed using this approximation.

3.1 The Surrogate formalism in the Weisskopf-Ewing limit

The Hauser-Feshbach expression for the desired cross sections, Eq.1, conserves total angular momentum J and parity π. Under certain conditions the branching ratios $G_{\chi}^{CN}(E_{ex}, J, \pi)$ can be treated as independent of J and π and the cross section simplifies to

$$\sigma_{\alpha\chi}^{WE}(E_a) \quad = \quad \sigma_{\alpha}^{CN}(E_{ex}) \, \mathcal{G}_{\chi}^{CN}(E_{ex}) \tag{3}$$

where $\sigma_{\alpha}^{CN}(E_{ex}) = \sum_{J\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi)$ is the reaction cross section describing the formation of the compound nucleus at energy E_{ex} and $\mathcal{G}_{\chi}^{CN}(E_{ex})$ denotes the $J\pi$-independent branching ratio for the exit channel χ. This is the Weisskopf-Ewing limit of the Hauser-Feshbach theory [12]. It provides a simple and powerful approximate way of calculating cross sections for compound-nucleus reactions. In the context of Surrogate reactions, it greatly simplifies the application of the method: It becomes straightforward to obtain the $J\pi$-independent branching ratios $\mathcal{G}_{\chi}^{CN}(E_{ex})$ from measurements of $P_{\delta\chi}(E_{ex})$ [$= \mathcal{G}_{\chi}^{CN}(E_{ex})$, since $\sum_{J\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) = 1$] and to calculate the desired reaction cross section. Calculating the direct-reaction probabilities $F_{\delta}^{CN}(E_{ex}, J, \pi)$ and modeling the decay of the compound nucleus are no longer required.

3.2 Testing the validity of the Weisskopf-Ewing assumption

Most applications of the Surrogate method so far have been based on the assumption that the Weisskopf-Ewing limit is valid for the cases of interest. Here we present a test of this assumption for the ^{235}U(n,f) reaction. While the branching ratios $G_{\chi=fission}^{CN}(E_{ex}, J, \pi)$ cannot be directly measured in a fission experiment, they can be extracted from a calculation of the (n,f) cross section and their $J\pi$-dependence can be studied. To this end, we simulated a nuclear reaction. We extracted the branching ratios from a full Hauser-Feshbach calculation of the ^{235}U(n,f) reaction that was calibrated to an evaluation of experimental data. The model used a deformed optical potential and the level schemes, level densities, gamma strength functions, fission-model parameters, and pre-equilibrium parameters were adjusted to reproduce the available data on n-induced fission for energies from E_n= 0 to 20 MeV. An excellent fit can be achieved for all but the lowest energies ($E_n < 1$ MeV), where the deviations are no larger than 5-10%.

We took the extracted $G^{CN}_{fission}(E_{ex}, J, \pi)$ values to represent the "true" branching ratios. Figure 2 gives the results for the ^{235}U(n,f) reaction for fission proceeding through negative parity states in the compound nucleus ^{236}U. We observe that the branching ratios exhibit a significant $J\pi$ dependence. In particular, for low neutron energies, $E_n = 0 - 5$ MeV ($E_n = E_{ex}(^{236}U) - S_n(^{236}U)$, where S_n is the neutron separation energy in ^{236}U), the $G^{CN}_{fission}(E_{ex}, J, \pi)$ differ in both their energy dependence and their magnitude for different $J\pi$ values. With increasing energy, the differences decrease, although the discrepancies become more pronounced near the thresholds for second-chance and third-chance fission. The branching ratios for positive parity states (not shown) are very similar.

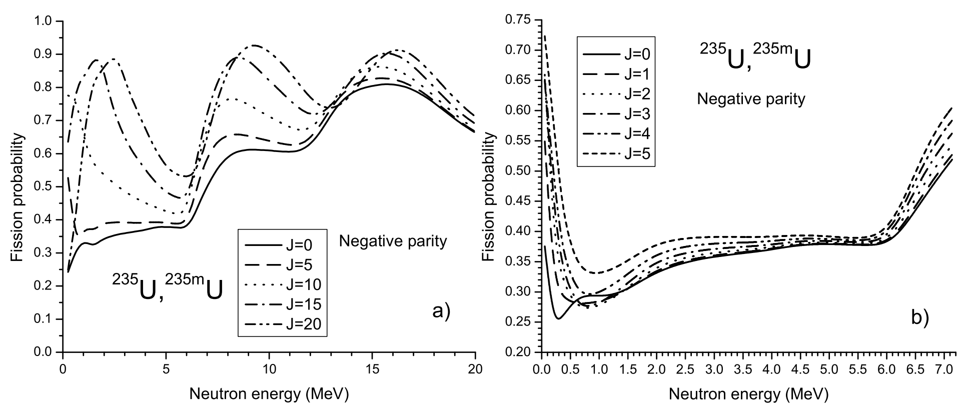

Figure 2: Calculated branching ratios $G^{CN}_{fission}(E_{ex}, J, \pi)$ for fission of ^{236}U (following n+^{235}U). a) Results are shown for negative parity states with total angular momenta $J = 0, 5, 10, 15, 20$ in the compound nucleus ^{236}U*. b) Results for negative parity states with small total angular momenta, $J = 0, 1, 2, 3, 4, 5$.

Figure 2 illustrates an important point: It is not *a priori* clear whether the Weisskopf-Ewing limit applies to a particular reaction in a given energy regime. E.g., restricting one's consideration to reactions induced by neutrons with kinetic energies above several MeV does not guarantee the validity of the Weisskopf-Ewing limit. While it may be possible to apply the Weisskopf-Ewing approximation to a reaction that populates a narrow range of $J\pi$ states, this description will break down for cases which involve a wide range of angular-momentum values (compare panels a) and b) of Figure 2). If the states that are populated in the compound nucleus before the decay have large angular momenta, the condition $J \lesssim \sigma_{\rm cutoff}$ required for the Weisskopf-Ewing limit to be a good approximation to Hauser-Feshbach [12] is no longer satisfied and the branching ratios may depend on $J\pi$. Furthermore, the Weisskopf-Ewing assumption breaks down near the threshold for second-chance and, to a lesser degree, third-chance fission.

The quantity $P_{\delta\chi}(E)$, which is measured in a Surrogate experiment, can be calculated in our simulation: $P_{\delta,fission}(E_{ex}) = \sum_{J,\pi} F^{CN}_{\delta}(E_{ex}, J, \pi)\, G^{CN}_{fission}(E_{ex}, J, \pi)$, where the $G^{CN}_{fission}(E_{ex}, J, \pi)$ denote the extracted fission branching ratios and

$F_{\delta}^{CN}(E_{ex}, J, \pi)$ is the probability for populating compound nuclear states in the relevant Surrogate reaction. For the purpose of a sensitivity study, we chose the four probability distributions shown in Figure 3a. Calculating the desired fission cross section via the formula $\sigma_{(n,f)}^{WE}(E_{ex}) = \sigma_{n+target}^{CN}(E_{ex})\, \mathcal{G}_{fission}^{CN}(E_{ex})$, with $\mathcal{G}_{fission}^{CN}(E_{ex}) = P_{\delta,fission}(E_{ex})$, then corresponds to a Surrogate analysis in the Weisskopf-Ewing approximation. The compound-nucleus formation cross section is $\sigma_{n+target}^{CN}(E_{ex}) = \sum_{J\pi} \sigma_{n+target}^{CN}(E_{ex}, J, \pi)$, where the individual $\sigma_{\alpha}^{CN}(E_{ex}, J, \pi)$ were taken to be the formation cross sections that were used for the fit mentioned above.

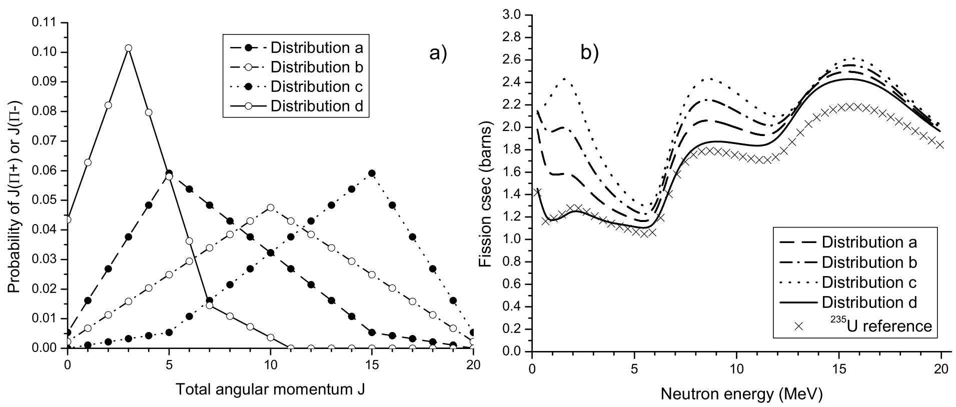

Figure 3: a) Distributions of total angular momentum for the compound nucleus ^{236}U*. The mean angular momentum is $\langle J \rangle$ = 7.03, 10.0, 12.97, and 3.30 for distributions a, b, c, and d, respectively; positive and negative parities are taken to be equally probable. The distributions were chosen solely to perform a sensitivity study. b) Weisskopf-Ewing estimates of the ^{235}U(n,f) cross section, using the distribution of angular momenta shown in Figure 3a. The crosses represent the "reference" ^{235}U(n,f) cross section from the fit.

Results for the ^{235}U(n,f) cross section obtained from the simulated Surrogate experiment are compared to each other and to the "reference" cross section in Figure 3b. The influence of the spin-parity distribution in the compound nucleus on the extracted cross sections is significant; again, this reflects the fact that the Weisskopf-Ewing approximation is not strictly valid in this case. We observe that the inferred cross sections for distributions a, b, and c are too large, by as much as 40% for energies above 5 MeV and up to a factor of two for smaller energies. The results for distribution d are in very close agreement with the expected cross section for $E_n = 0 - 8$ MeV, and too large by about 10-15% for higher energies. While the extracted cross sections are least sensitive to the underlying $J\pi$ distributions in the energy range $E_n = 13 - 20$ MeV, they consistently overestimate the cross section by 10-15%. These discrepancies are primarily due to preequilibrium neutron emission in the neutron-induced reaction. Preequilibrium effects for the desired reaction, which reduce the reference cross section, have been included in the fit mentioned above, but are not contained in the type of Surrogate measurements simulated here.

4 The Surrogate Ratio Approach

The "Surrogate Ratio method", or simply "Ratio method", makes use of the Surrogate idea and requires the validity of the Weisskopf-Ewing limit. An important motivation for using the Ratio method is the fact that it eliminates the need to accurately measure N_δ, the total number of $d + D \to b + B^*$ reaction events, which has been the source of the largest uncertainty in Surrogate experiments performed recently. Under the proper circumstances it also reduces or removes dependence on the angular distribution of fission fragments, which is not well characterized in the present experiments.

In Refs. [7] and [8], the Ratio method was used to obtain an estimate of the ^{237}U(n,f) cross section. Inelastic deuteron [7] and α [8] scattering experiments on ^{238}U and ^{236}U were carried out and fission fragments from the decay of ^{238}U* and ^{236}U* were detected in coincidence with the outgoing direct-reaction particle. The results were found to be in good agreement with a theoretical estimate by Younes *et al.* [13].

4.1 The Ratio idea

The goal of the Ratio method is to determine the ratio

$$R(E) \quad = \quad \frac{\sigma_{\alpha_1\chi_1}(E)}{\sigma_{\alpha_2\chi_2}(E)} \tag{4}$$

of the cross sections of two compound-nucleus reactions, $a_1 + A_1 \to B_1^* \to c_1 + C_1$ and $a_2 + A_2 \to B_2^* \to c_2 + C_2$. An independent determination of one of these cross sections then allows one to infer the other by using the ratio R. In the Weisskopf-Ewing limit, the ratio $R(E)$ can be written as:

$$R(E) \quad = \quad \frac{\sigma_{\alpha_1}^{CN}(E)\, \mathcal{G}_{\chi_1}^{CN}(E)}{\sigma_{\alpha_2}^{CN}(E)\, \mathcal{G}_{\chi_2}^{CN}(E)} \;, \tag{5}$$

with branching ratios $\mathcal{G}_\chi^{CN}$ that are independent of J and π and compound-nucleus formation cross sections $\sigma_{\alpha_1}^{CN}$ and $\sigma_{\alpha_2}^{CN}$ that can be calculated by using an optical model.

To determine $\mathcal{G}_{\chi_1}^{CN}/\mathcal{G}_{\chi_2}^{CN}$, two experiments are carried out. Both use the same direct-reaction mechanism, $D(d,b)B^*$, but different targets, D_1 and D_2 to create the relevant compound nuclei, B_1^* and B_2^*, respectively. For each experiment, the number of coincidence events, $N_{\delta_1\chi_1}^{(1)}$ and $N_{\delta_2\chi_2}^{(2)}$, is measured. The ratio of the branching ratios into the desired channels for the compound nuclei created in the two reactions is given by

$$\frac{\mathcal{G}_{\chi_1}^{CN}(E)}{\mathcal{G}_{\chi_2}^{CN}(E)} \quad = \quad \frac{N_{\delta_1\chi_1}^{(1)}(E)}{N_{\delta_2\chi_2}^{(2)}(E)} \times \frac{N_{\delta_2}^{(2)}(E)}{N_{\delta_1}^{(1)}(E)} \;. \tag{6}$$

The experimental conditions are adjusted such that the relative number of reaction events, $norm = N_{\delta_1}^{(1)}/N_{\delta_2}^{(2)}$, can be determined by accounting for differences in beam intensities and beam times, as well as numbers of atoms in each target. The ratio of the decay probabilities then simply equals the ratio of the coincidence events and $R(E)$ becomes:

$$R(E) \quad = \quad \frac{\sigma_{\alpha_1}^{CN}(E)\, N_{\delta_1\chi_1}^{(1)}(E)}{\sigma_{\alpha_2}^{CN}(E)\, N_{\delta_2\chi_2}^{(2)}(E)} \;, \tag{7}$$

where we have set $norm = 1$.

4.2 Testing the validity of the Surrogate Ratio Approach

To test the validity of the Ratio approach, we consider the cross sections for ^{233}U(n,f) and ^{235}U(n,f). This choice has the advantage that we study nuclei which are similar to those featured in recent experiments, but for which all of the relevant cross sections are known from direct measurements. We employ the ^{236}U fission probabilities plotted in Figure 2 and carry out a Hauser-Feshbach calculation for ^{233}U(n,f), analogously to the one for ^{235}U(n,f) described earlier. We thus obtain a ^{233}U(n,f) reference cross section, as well as ^{234}U fission probabilities $G^{234U}_{fission}(E,J,\pi)$ (not shown), which allow us to determine the ratio

$$r = \frac{P^{236U}_{\delta,fission}(E)}{P^{234U}_{\delta,fission}(E)} \quad = \quad \frac{\sum_{J,\pi} F^{236U}_{\delta}(E,J,\pi) G^{236U}_{fission}(E,J,\pi)}{\sum_{J,\pi} F^{234U}_{\delta}(E,J,\pi) G^{234U}_{fission}(E,J,\pi)} \tag{8}$$

for each of the four angular momentum distributions shown in Figure 3a.

For simplicity, we have taken the compound nucleus formation cross section to be independent of the target nucleus, $\sigma^{CN}_{n+^{233}U} = \sigma^{CN}_{n+^{235}U}$, throughout our study. Since $P_{\delta\chi} = \mathcal{G}^{CN}_{\chi}$ holds in the Weisskopf-Ewing approximation, we obtain

$$R(E) \quad = \quad \frac{\sigma^{CN}_{n+^{235}U}(E)\; \mathcal{G}^{236U^*}_{fission}(E)}{\sigma^{CN}_{n+^{233}U}(E)\; \mathcal{G}^{234U^*}_{fission}(E)} = r \; . \tag{9}$$

Each $J\pi$ distribution considered, $p = a, b, c, d$, yields a ratio $R^{(p)}$, from which we deduce the desired cross section $\sigma^{(p)}(^{235}\mathrm{U(n,f)}) = R^{(p)} \times \sigma(^{233}\mathrm{U(n,f)})$. The deviations of the resulting cross sections from each other provides a measure of how sensitive the Ratio approach is to violations of the Weisskopf-Ewing approximation, while the comparison with the reference cross section allows for an assessment of the overall quality of the cross sections obtained from a Ratio analysis.

Our results shown in Figure 4. We observe that the $J\pi$ distributions have a much smaller effect on the cross sections deduced here than on the cross sections obtained from a Surrogate analysis in the Weisskopf-Ewing limit; *i.e.* the Ratio method is less sensitive to the details of the spin-parity distributions. We find relatively good agreement between the simulated Ratio results and the expected cross sections for energies above about 3 MeV. The largest discrepancies, which may be as large as 50%, occur where the Weisskopf-Ewing approximation is no longer valid, *i.e.* at small energies ($E_n \leq 3$ MeV) and for angular-momentum distributions with high average J values. We also find differences of up to about 25% near the threshold for second-chance fission. At the same time, the cross section associated with distribution d is in excellent agreement with the expected result for energies up to about 7-8 MeV, where preequilibrium effects set in.

For situations in which the Weisskopf-Ewing limit provides at least a rough approximation, *e.g.* for $E_n = 5$–20 MeV in the case considered here, the Ratio method further reduces the discrepancies between the extracted and expected cross sections, thus providing significantly improved results. Effects that, in the Surrogate Weisskopf-Ewing approach, cause deviations from the correct results seem to affect the ^{235}U(n,f) and ^{233}U(n,f) cross sections in a similar manner and hence cancel in part in the Surrogate Ratio treatment. This is in particular notable for the preequilibrium decays, the effects of which were pronounced in the Weisskopf-Ewing approach and are significantly smaller here.

5 Summary and Outlook

Motivated by the renewed interest in the Surrogate Nuclear Reactions approach, we investigated the approximations commonly employed in applications of the method. In particular, we examined the validity of the Surrogate method in the Weisskopf-Ewing limit and the Surrogate Ratio method for neutron-induced fission of uranium nuclei. We employed a nuclear-reaction model to simulate physical quantities that

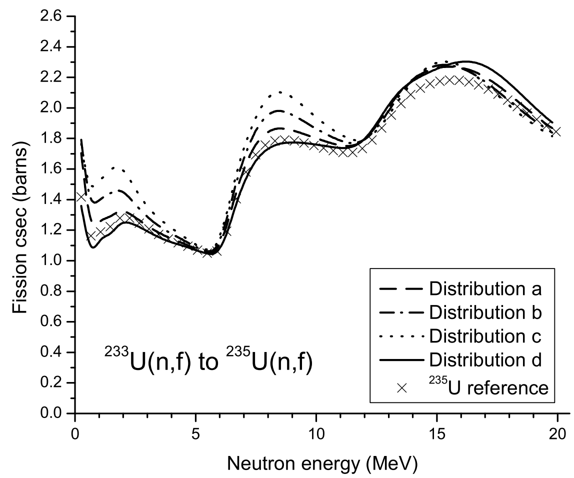

Figure 4: Estimates of the ^{235}U(n,f) cross section obtained from the Ratio method, using the distribution of angular momenta shown in Figure 3a. The crosses represent the "reference" ^{235}U(n,f) cross section from the fit.

are typically measured in Surrogate experiments. The simulations allowed us to alter quantities that are experimentally not easily modified in a controlled manner, such as the angular-momentum distribution in a compound nucleus before it decays, and to study their effect on the observables of interest. We employed the calculated observables in a manner that mirrors a typical Surrogate analysis and extracted the sought-after cross section using both the Weisskopf-Ewing and the Ratio approximations.

We found that it is not *a priori* clear how well the Surrogate approach in the Weisskopf-Ewing limit will work for a particular reaction in a given energy regime. The validity of this approximation depends on the energy of the compound nucleus created, as well as on the range of $J\pi$ values that is populated in the reaction(s) under consideration. For the case investigated here, ^{235}U(n,f) with E_n=0-20 MeV, and the circumstances assumed, the extracted cross section deviated from the expected result by up to a factor of two. Identifying a Surrogate reaction that produces a compound nucleus with a $J\pi$ distribution similar to the one produced in the desired (n,f) reaction will (not surprisingly) yield the best results for the extracted cross section.

Applying a Surrogate Ratio analysis to the simulated physical quantities resulted in a fission cross section that was in much better agreement with the expected result than the cross section inferred from the Surrogate Weisskopf-Ewing analysis. Variations in the $J\pi$ distributions had a smaller effect on the extracted cross section and the deviations due to preequilibrium effects were diminished as well. The improved agreement is due to cancellation effects in the Ratio approach.

The calculations presented here illustrate that further work is required to fully understand and improve upon the approximations employed in most Surrogate applications. The Surrogate method is very general and can in principle be employed to determine cross sections for all types of compound-nucleus reactions on a large variety of nuclei; its greatest potential value lies in applications to reactions on unstable isotopes. There is currently much interest in low-energy (n,γ) reactions on specific s-process branch point nuclei, such as ^{85}Kr, ^{95}Zr, ^{153}Gd, etc. Using a Surrogate approach might be an alternative to difficult direct measurements (in normal or inverse kinematics). Such applications, however, are challenging and will require a more comprehensive treatment of the Surrogate formalism. Specifically, it involves taking into account differences in the angular momentum J and parity π distributions between the compound nuclei produced in the desired and Surrogate reactions. Predicting the J^π distribution resulting from a Surrogate reaction is a nontrivial task since a proper treatment of direct reactions leading to highly excited states in the intermediate nucleus B involves a description of particle transfers, and inelastic scattering, to unbound states. Modeling the compound-nuclear decay requires a proper description of structural properties of the reaction products (level densities, branching ratios, internal conversion rates), plus a fission model for cases which involve that decay mode. Furthermore, applications of the Surrogate technique outside the valley of stability will require microscopic approaches to optical models and level-density prescriptions which can be extrapolated to the region of interest.

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