Nuclear Reaction Data from Surrogate Measurements:
A Consideration of (n,f) Cross Sections

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A brief summary of the Surrogate reaction method, an indirect approach for determining compound-nuclear reaction cross sections, is presented. The possibilities for obtaining accurate (n,f) cross sections from Surrogate measurements that are analyzed in the Weisskopf-Ewing and Ratio approximations are considered. Theoretical studies and benchmark experiments that provide new insights into the validity and limitations of the Surrogate approach are discussed.

I. INTRODUCTION

Many reactions of interest to nuclear energy, national security, and nuclear astrophysics are compound-nuclear reactions, *i.e.* reactions that proceed through an equilibrated intermediate state, the compound nucleus. The associated cross sections, which are required for simulating various nuclear processes relevant to these applications, are typically obtained from data evaluations based on nuclear measurements. Often, the reactions of interest involve short-lived or highly radioactive target nuclei, which make direct measurements challenging or even impossible. In cases where measured cross sections are not available one has to rely on nuclear theory calculations, or on indirect experimental approaches. Calculations of compound-nuclear reaction cross sections require a thorough understanding of the underlying physical processes in order to be predictive. They are particularly challenging if only little information on the structure of the nuclei involved in the reaction is available – as is often the case for reactions proceeding near/through regions of instability in the isotopic chart. While indirect methods for determining cross sections have become an essential tool for experimental nuclear physics in recent years, most approaches currently under consideration focus on direct-reaction cross sections. The focus of the present contribution is an indirect method for determining compound-nuclear reaction cross sections – the Surrogate nuclear reaction approach.

The Surrogate technique aims at determining the cross section for a two-step ("desired") reaction that proceeds through a compound nuclear state by using a combination of experiment and theory. The compound nucleus is produced by means of an alternative ("Surrogate") reaction, and the desired cross section is obtained by combining a calculation of the compound-nucleus formation in the desired reaction with a measurement of the compound-nucleus decay in the Surrogate reaction (see Figure 1).

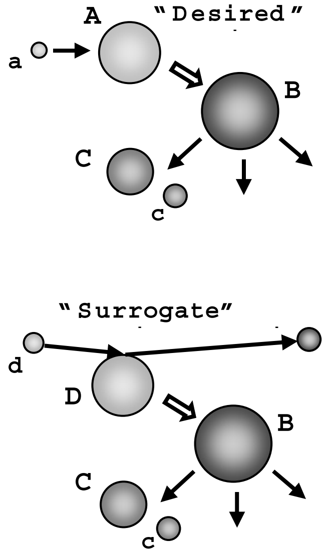

Figure 1. Schematic representation of the "desired" (top) and "Surrogate" (bottom) reaction mechanisms. The basic idea of the Surrogate approach is to replace the first step of the desired reaction, a+A, by an alternative ("Surrogate"") reaction, d+D → b+B*, that populates the same compound nucleus. The subsequent decay of the compound nucleus into the relevant channel, c+C, can then be measured and used to extract the desired cross section.

Originally introduced in the 1970s [1,2], the Surrogate approach has recently received renewed attention [3-20]. 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. Both the early and the more recent measurements have focused primarily on neutron-induced fission reactions for actinide targets, although a few experiments have been designed to obtain (n,γ) cross sections for some rare earth and actinide nuclei. The greatest potential value of the Surrogate approach lies in applications to reactions on unstable isotopes. The (n,f) cross sections for the short-lived ^{237}U ($t_{1/2}$ = 6.75d) and ^{233}Pa ($t_{1/2}$ = 26.96d) isotopes, for example, have recently been estimated with the Surrogate approach [5,6,8-10]. The latter reaction plays an important role in the thorium-uranium fuel cycle. In both cases there was very little cross section information available prior to the Surrogate measurements.

While the method has generated some very valuable cross section information, almost all applications so far have employed approximations that remain to be tested. The present contribution will review the Surrogate approach and discuss tests of the approximations commonly employed in Surrogate experiments that aim at extracting neutron-induced fission cross sections. Prospects for obtaining (n,γ) cross sections from Surrogate experiments have also been considered, for actinide nuclei [16,17], rare earth species [18-20], as well as A~90 nuclei [13]. This issue will be discussed in more detail elsewhere [17].

A brief outline of the Surrogate concept is given in Section II, and the approximations typically used in Surrogate analyses are presented in Section III, along with representative examples. In Section IV, efforts to test the validity of these approximations and to establish the limitations of the Surrogate approach are discussed. Both experimental and theoretical studies are considered. A brief summary and outlook is given in Section V.

II. THE SURROGATE METHOD

Surrogate reaction methods are based on the assumption that the formation and decay of a compound nucleus (CN) are independent of each other (for each angular momentum and parity value). The relevant CN is formed in a “Surrogate” reaction (d+D → b+B*) rather than in the “desired” reaction (a+A → B* → c+C) and the desired reaction cross section is obtained via a combination of experimental observation and modeling, using statistical Hauser-Feshbach theory.

In the Hauser-Feshbach formalism [21,22], the cross section for this “desired” reaction takes the form:

$$\sigma_{\alpha\chi}(E) = \Sigma_{J\pi}\, \sigma^{CN}{}_{\alpha}(E,J,\pi)\, G^{CN}{}_{\chi}(E,J,\pi), \qquad (1)$$

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

In the Surrogate approach, the compound nucleus B* is produced by means of an alternative, direct (“Surrogate”) reaction, d+D → b+B*, and the desired decay channel χ (B* → c+C) is observed in coincidence with the outgoing particle b. The coincidence measurement provides

$$P_{\delta\chi}(E) = \Sigma_{J\pi}\, F_{\delta}^{CN}(E,J,\pi)\, G_{\chi}^{CN}(E,J,\pi), \qquad (2)$$

the probability that the compound nucleus was formed in the Surrogate reaction with spin-parity distribution $F_{\delta}^{CN}(E,J,\pi)$ and subsequently decayed into the channel χ. The spin-parity distributions $F_{\delta}^{CN}(E,J,\pi)$, which may be very different from the compound-nuclear spin-parity populations following the absorption of the projectile a in the desired reaction, have to be determined theoretically, so that the branching ratios $G_{\chi}^{CN}(E,J,\pi)$ can be extracted from the measurements.

In practice, the decay of the compound nucleus is modeled and the $G_{\chi}^{CN}(E,J,\pi)$ are obtained by fitting the calculations to reproduce the measured decay probabilities and subsequently inserted in Equation 1 to yield the desired cross section [3,4].

Alternatively, approximations to the full Surrogate formalism outlined here can be employed. These will be discussed next.

III. APPROXIMATION SCHEMES EMPLOYED IN SURROGATE ANALYSES

Almost all applications of the Surrogate method to date have relied on approximations to the full Hauser-Feshbach treatment of the problem. Here, we provide a brief outline of the Weisskopf-Ewing and Surrogate Ratio approaches and mention some experiments that were analyzed in the framework of these approximation schemes. The validity of the underlying assumptions will be considered in Section IV.

III.A. Weisskopf-Ewing Approximation

In the Weisskopf-Ewing approximation [23], the compound-nuclear decay probabilities are treated as independent of J and π, and the cross section for the desired reaction takes the simple product form:

$$\sigma^{WE}_{\alpha\chi}(E) = \sigma^{CN}_{\alpha}(E)\, G^{CN}_{\chi}(E) \ , \qquad (3)$$

where $\sigma^{CN}_{\alpha}(E) = \Sigma_{J\pi}\ \sigma^{CN}_{\alpha}(E,J,\pi)$ is the reaction cross section describing the formation of the compound nucleus in the desired reaction and $G^{CN}_{\chi}(E)$ denotes the (J,π)-independent decay probability for the exit channel χ. In the context of Surrogate reactions, this approximation greatly simplifies the application of the method: It becomes straightforward to obtain the (J,π)-independent branching ratios $G^{CN}_{\chi}(E)$ from measurements of $P_{\delta\chi}(E)$ [$=G^{CN}_{\chi}(E)$ since $\Sigma_{J\pi}\ F_{\delta}^{CN}(E,J,\pi)=1$] and to calculate the desired reaction cross section. Calculating the direct-reaction probabilities $F_{\delta}^{CN}(E,J,\pi)$ and modeling the decay of the compound nucleus are no longer required.

The very first applications of the Surrogate approach made use of the Weisskopf-Ewing approximation: In the 1970s transfer reactions with triton and ^{3}He projectiles were employed to estimate neutron-induced fission cross sections for various actinide targets [1,2]. While the resulting (n,f) cross section estimates agreed with direct measurements (where available) to about 10-20% for incident neutron energies above about 1 MeV, there were serious discrepancies below 1 MeV. These discrepancies were attributed to large uncertainties in the low-energy optical-model calculations employed, and the use of the Weisskopf-Ewing approximation in the analysis of the experiments.

More recently, Surrogate experiments analyzed in the Weisskopf-Ewing approximation were used to determine cross sections for neutron-induced reactions on several minor actinide nuclei relevant to the thorium-uranium fuel cycle [5,6,15]. At the IPN Orsay**,** the transfer reactions ^{232}Th(^{3}He,x) with x=α,t,d,p, were employed to obtain (n,f) and (n,γ) cross sections for Th and Pa targets [5,6]. The procedure was tested by comparing the resulting ^{230}Th(n,f) and ^{231}Pa(n,f) cross sections to earlier, direct measurements. Special emphasis was placed on the isotope ^{233}Pa, which plays a key role in the production of the fissile isotope ^{233}U and for which very little cross section data existed prior to the Surrogate measurements. The ^{233}Pa(n,f) and ^{233}Pa(n,γ) cross sections were extracted for neutron energies up to 10 MeV and 1 MeV, respectively.

In a very recent experiment at LBNL, the charge-exchange reaction ^{238}U(^{3}He,t) was employed to determine the ^{237}Np(n,f) cross section for neutron energies between 10 and 20 MeV [15]. The result was found to be in good agreement with direct measurements and evaluated cross sections. Furthermore, the ratio σ[^{237}Np(n,f)]/ σ[^{235}U(n,f)], with the ^{237}Np(n,f) cross section obtained from the Surrogate experiment and the ^{235}U(n,f) cross section taken from the ENDF/B-VII evaluation, was found to be in very close agreement with a recent direct measurement of this ratio by Tovesson and Hill [24].

III.B. The Surrogate Ratio Approach

The recently introduced Surrogate Ratio approach [8,10-12,14] is an approximation that makes use of the Surrogate idea and requires the (approximate) 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 the total number of d+D → b+B* reaction events, which has been the source of the largest uncertainty in Surrogate experiments performed recently.

In the Surrogate Ratio approach, the ratio R(E) $= \sigma_{\alpha1\chi1}/\ \sigma_{\alpha2\chi2}$ of the cross sections of two compound-nuclear reactions $a_1+A_1 \rightarrow B_1^* \rightarrow c_1+C_1$ and $a_2+A_2 \rightarrow B_2^* \rightarrow c_2+C_2$ is measured, using two Surrogate experiments. Typically, the Surrogate experiments 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. An independent determination of the cross section $\sigma_{\alpha1\chi1}$ can then be used to deduce $\sigma_{\alpha2\chi2}$. There are indications that small to moderate deviations from the Weisskopf-Ewing assumption might cancel in this approach (see Refs. [12,16] and Section IV below). Furthermore, employing the Ratio approach to indirectly determine fission cross sections can, under the proper circumstances, reduce or remove dependence on the angular distribution of fission fragments, which is not well characterized in the present experiments.

The Surrogate Ratio Method has been employed to estimate cross sections for several neutron-induced reactions on the unstable nucleus ^{237}U. Inelastic deuteron [8] and α [10] scattering experiments on ^{238}U and ^{236}U were carried out to obtain the fission probabilities for ^{238}U relative to those for ^{236}U. The measured ratio of fission probabilities was then related to the ratio σ[^{237}U(n,f)]/ σ[^{235}U(n,f)] and the desired ^{237}U(n,f) cross section was determined with the help of the known ^{235}U(n,f) cross section. The analysis [10] resulted in a cross section for the ^{237}U(n,f) reaction that was found to be in good agreement with an earlier theoretical estimate by Younes *et al.* [25].

Subsequently, a variant of the Ratio approach described above was explored by Bernstein *et al.* [11] for determining the ^{237}U(n,γ) and ^{237}U(n,2n) cross sections. Rather than comparing the decay of two compound nuclei, B_1^* and B_2^*, formed with the same type of Surrogate reaction, the authors determined the ratio of decay probabilities for two *different exit channels*, χ_1= c_1+C_1 and χ_2= c_2+C_2, of *one particular compound nucleus*, $B_1^*= B_2^* = B^*$. Specifically, the compound nucleus of interest, ^{238}U*, was populated via inelastic scattering by 55-MeV α projectiles. The relative fission and neutron-evaporation decay probabilities were measured and related to ratios of cross sections for various n-induced reactions on a ^{237}U target. Employing the ^{237}U(n,f) cross section determined in an earlier Surrogate experiment allowed the authors to extract the ^{237}U(n,γ) and ^{237}U(n,2n) cross sections.

IV. VALIDITY OF THE APPROXIMATIONS

While most applications of the Surrogate method include some validation of the approach and the approximations used via a comparison of an extracted cross section with an independent measurement or evaluation, it is essential that studies be carried out which specifically test various aspects of Surrogate approaches. Here we discuss some benchmark experiments and theoretical studies that shed light on the applicability and limitations of the Surrogate method.

IV.A. Theoretical Simulations

Theoretical studies can provide useful insights that complement the experimental findings. In particular, it is possible to carry out calculations to predict the behavior of the branching ratios $G^{CN}_{\chi}(E,J,\pi)$ as a function of energy, angular momentum, and spin, and to draw some conclusions about the limitations of the Weisskopf-Ewing approximation. Such calculations have been carried out for the decay of the CN ^{236}U by fission and γ emission [12,16]. The relevant branching ratios were extracted 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. For more details see Ref. [12]. The calculated branching ratios $G^{CN}_{fission}(E,J,\pi)$ for fission proceeding through positive parity states in the compound nucleus ^{236}U are shown in Figure 2. The top panel shows the $G^{CN}_{fission}(E,J,\pi)$ for J=0, 5, 10, 15, 20 for neutron energies E_n = 0 - 20 MeV ($E_n = E(^{236}U) - S_n(^{236}U)$). The branching ratios exhibit a significant angular-momentum dependence, in particular for low neutron energies, E_n = 0 - 5 MeV. 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 negative parity states (not shown) are very similar.

If one considers a narrower range of angular-momentum values, e.g. J=0–5, see Figure 2 (bottom), one finds that the associated branching ratios are very similar to each other for all but the lowest energies. This observation 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. While the Weisskopf-Ewing approximation may break down for a reaction that populates a wide range of (J,π) states, it may provide a valid description for a reaction that populates a narrow range of angular-momentum values. Thus, it becomes important to obtain information on the spin-parity distributions of the decaying CN.

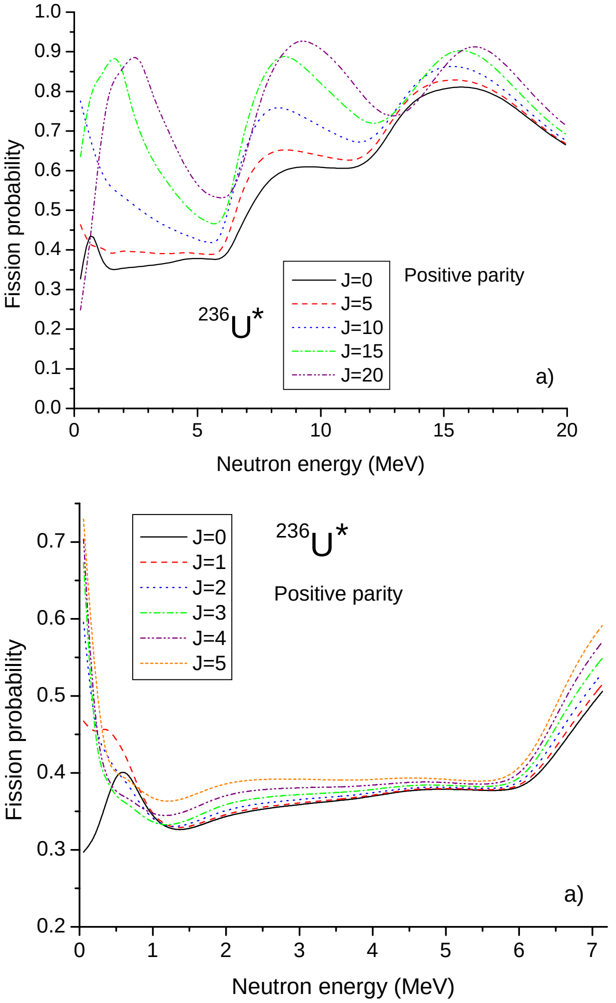

Figure 2. Calculated branching ratios $G_{\chi}^{CN}(E,J,\pi)$ for fission of ^{236}U*, as a function of the laboratory neutron energy in the ^{235}U + n system. (top) Results are shown for the decay of positive parity states with total angular momenta J = 0, 5, 10, 15, 20. (bottom) Results for positive parity states with small total angular momenta, J = 0,1,2,3,4,5.

Given the dependence of the branching ratios $G^{CN}_{\chi}(E,J,\pi)$ on the spin of the decaying CN, illustrated above, it is relevant to consider the impact of neglecting this dependence on cross sections extracted from Surrogate experiments. Assuming some Surrogate (J,π) distributions $F_{\delta}^{CN}(E,J,\pi)$, such as those shown in Figure 3, and combining these with the fission probabilities $G_{fission}^{CN}(E,J,\pi)$ of Figure 2, one can simulate observables that are measured in a Surrogate experiment and carry out an analysis of the simulated result invoking the Weisskopf-Ewing approximation.

The resulting (n,f) cross sections are found to depend on the (J,π) distribution selected in the analysis: For the ^{235}U(n,f) case, e.g., the cross sections extracted from the simulated experiments differ from the expected results by as much as 40% for neutron energies above 5 MeV, and up to a factor of 2.5 for smaller energies, as can be seen in Figure 4 (top). The deduced cross sections clearly depend on the (J,π) distribution considered for the compound nucleus. This reflects the fact that the Weisskopf-Ewing limit is not strictly valid in this case. The uncertainties are particularly large for energies below 3 MeV, as expected from the discussion of the fission probabilities shown in Figure 2. However, the agreement between the deduced and extracted cross sections is noticeably better for distribution d: The extracted cross section closely tracks the expected result for energies up to about 8 MeV, and deviates from it no more than about 15% for higher energies. The reason for this good agreement is the similarity of distribution d and the angular-momentum distribution of ^{236}U following the absorption of a neutron in the desired reaction (for details, see Ref. [12]). Identifying a Surrogate reaction that produces a compound nucleus similar to the one produced in the desired reaction obviously yields the best results for the extracted cross section.

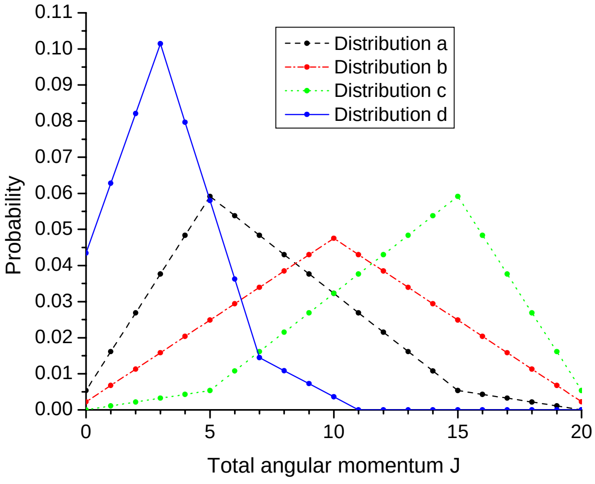

Figure 3: Schematic distributions of total angular momentum for ^{236}U*, as studied in Ref. [16]. Distribution d was considered based on insights from related experiments [27].

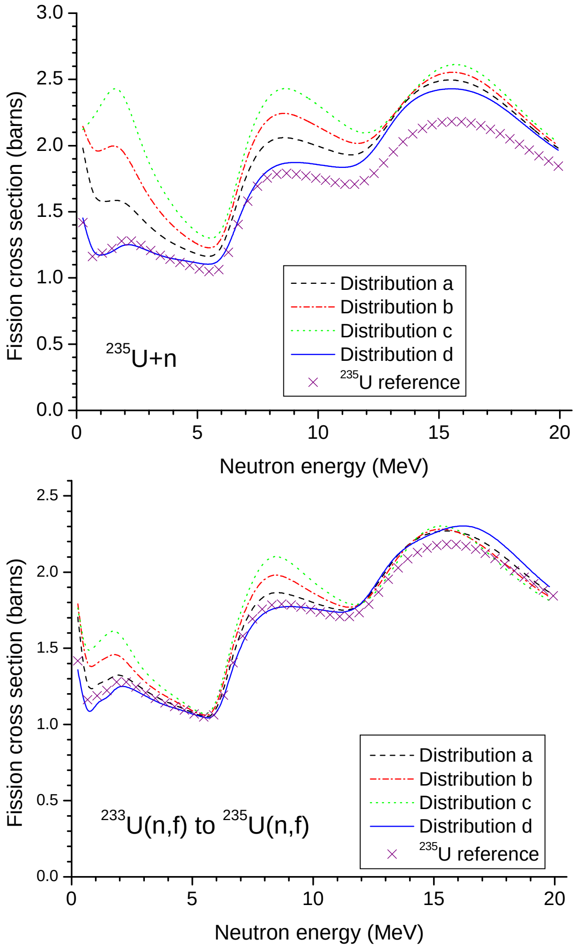

Figure 4. (top): Weisskopf-Ewing estimates for the ^{235}U(n,f) cross section, using the schematic angular-momentum distributions a-d shown in Figure 3, compared to the expected cross section. (bottom): Estimates of the ^{235}U(n,f) cross section obtained from the Ratio method, using the (J,π) distributions a-d.

In analogy to the study of the Weisskopf-Ewing approximation, one can carry out a theoretical investigation of the Surrogate Ratio method. In this case, fission probabilities $G^{CN}_{\chi}(E,J,\pi)$ are calculated for two compound nuclei, e.g. ^{234}U and ^{236}U, and combined with (J,π) distributions, such as those in Figure 3. Carrying out a Ratio analysis for the simulated Surrogate Ratio experiment yields the cross sections shown in Figure 4 (bottom), which are found to be in better agreement with the expected result than those obtained from the Weisskopf-Ewing analysis. Although the Ratio method is based on the assumption that the Weisskopf-Ewing approximation is valid, the simulations indicate that small to moderate deviations from this assumption might cancel in this approach, thus improving the agreement with the expected results under certain circumstances.

IV.B. Experimental Tests

Unfortunately, it is not feasible to determine the $G^{CN}_{\chi}(E,J,\pi)$ for individual (J,π) values experimentally and thus test under which conditions the Weisskopf-Ewing approximation is justified. The validity of the approximation is typically established by comparing cross sections obtained from Surrogate experiments that were analyzed in the Weisskopf-Ewing limit or in the Surrogate Ratio framework with independent direct measurements or cross section evaluations. Such *a posteriori* verifications provide important tests of the assumptions underlying the experiments and their analysis.

An experimental investigation of the Surrogate Ratio method was carried out by Lesher *et al.* [26]. Two Surrogate reactions, $^{234}U(\alpha,\alpha')$ and $^{236}U(\alpha,\alpha')$ were employed to produce the compound nuclei $^{234}U^*$ and $^{236}U^*$, respectively, and to measure their decay by fission. The ratio of the fission probabilities was extracted from the experiment and used to determine $R(E)=\sigma[^{233}U(n,f)]/\sigma[^{235}U(n,f)]$, the ratio of the cross sections for neutron-induced fission for ^{233}U and ^{235}U targets. The quantity R(E) was found to be in good agreement with the analogous cross section ratio obtained from the ENDF/B-VII evaluation, for neutron energies between about 0.6 and 18 MeV. Some deviations were found for energies below 0.6 MeV. Overall, the experimental findings are in agreement with the results of the theoretical study discussed above.

The influence of the compound-nuclear spin-parity distribution on the fission cross section extracted from a Surrogate experiment were investigated in some detail by Lyles *et al.* [14]. Since the angular-momentum transfer between projectile and target in a direct (Surrogate) reaction $d+D \rightarrow b+B^*$ depends on the angle of the outgoing particle b, the measured coincidence probabilities $P_{\chi}(E)$ should depend on that angle if the Weisskopf-Ewing approximation is not valid. Lyles *et al.* observed such angular dependence in an experiment carried out at the 88-inch Cyclotron at Lawrence Berkeley National Laboratory: A 42-MeV ^{3}He beam was used to create the CN ^{237}U via the $^{238}U(^{3}He,\alpha)$ Surrogate reaction. The α-fission coincidence probabilities were measured and the $^{236}U(n,f)$ cross section was determined, using the Weisskopf-Ewing approximation. Restricting the analysis to α-fission coincidence events for which the outgoing α particle was observed at angles between 36° and 45° relative to the beam axis led to a cross section that is different from the cross section obtained for α particles observed in the 57° to 62° range, for neutron energies below about 1.5 MeV. This is illustrated in Figure 5, where the cross sections extracted for the two angular ranges are compared to each other and to the cross section that is obtained by averaging over the full angular range.

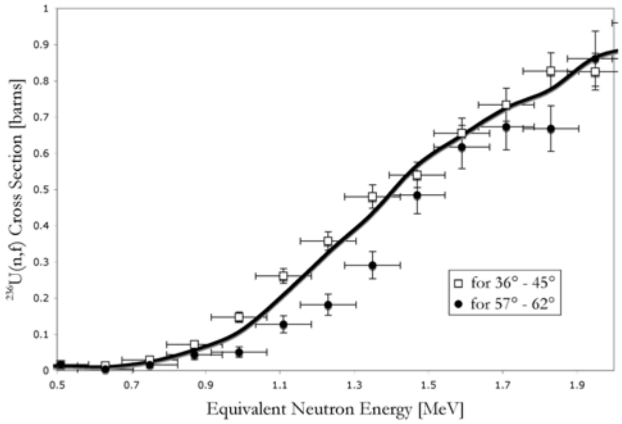

Figure 5: $^{236}U(n,f)$ cross section obtained from a Weisskopf-Ewing analysis of Surrogate $^{238}U(^{3}He,\alpha)$ measurements. Data represented by open squares correspond to events for which the outgoing α particle was observed at 36° to 45°, while filled circles correspond to an angular range of 57° to 62°. The solid line is the cross section that results from averaging over all experimentally accessible angles, 36° to 62°.

The findings demonstrate that more theoretical and experimental work is required to fully understand the population and decay of compound nuclear systems and to improve the accuracy and reliability of cross sections extracted from Surrogate experiments, in particular for low energies (below about 2 MeV).

IV.C. Moving Beyond Current Approximations

The importance of moving beyond the Weisskopf-Ewing approximation was also illustrated by Younes and Britt [3,4], who revisited the Surrogate (t,pf), (^{3}He,df), and (^{3}He,tf) fission-correlation measurements from the 1970s. They employed a simple direct-reaction model to compensate for the spin-parity population difference between neutron-induced and Surrogate reactions and used improved optical-model calculations to obtain (n,f) cross sections for various actinides. For the benchmark case ^{235}U, they obtained significant improvements over the early Surrogate work by Cramer *et al.* [1]. In addition to reproducing the fission cross section for the $J^p = 7/2^-$ ground state of ^{235}U, Younes and Britt were able to estimate the fission cross section for the isomeric $1/2^+$ state at 77eV ($t_{1/2}$ = 26 min), which to date has not been measured directly. In general, the (n,f) cross sections deduced by Younes and Britt for various actinide nuclei agree with direct measurements to within 10% for $E_n \geq 1$ MeV [$E_n \geq 2$ MeV] when obtained from Surrogate (t,pf) [^{3}He,xf] data; at lower energies the discrepancies are up to about 20%.

The measurements by Lyles *et al.* and the results by Younes and Britt, discussed above, illustrate the most significant limitation of the Surrogate method at this time: the fact that the compound-nuclear spin-parity distributions in the desired and Surrogate reactions differ from each other in a manner that is poorly understood. While optical-model calculations provide fairly reliable spin-parity information for the desired reaction, no tools are currently available for formulating accurate predictions of the spin-parity distributions for compound nuclei produced in Surrogate reactions. This situation does not merely reflect an absence of useful reaction codes, but points to an incomplete picture of the reaction mechanisms that produce the compound nucleus in a Surrogate reaction. A significantly improved (qualitative and quantitative) understanding of the underlying processes is required. This includes a description of direct reactions that populate highly-excited, unbound states, the damping of these doorway states into more complicated configurations that lead to a compound nucleus (or non-equilibrium particle emission), the dependence and influence of these processes on angular momentum, parity, and energy, and possible width fluctuation corrections to the standard Hauser-Feshbach-type formalism.

V. SUMMARY AND OUTLOOK

We have briefly reviewed the Surrogate nuclear reactions approach, with a particular focus on the possibilities for obtaining accurate (n,f) cross sections from Surrogate measurements that are analyzed in the Weisskopf-Ewing or Ratio approximation. We discussed theoretical studies as well as benchmark experiments that provide new insights regarding the applicability and limitations of the Surrogate method.

We have demonstrated that it is not *a priori* clear whether the Weisskopf-Ewing limit applies to a given reaction. The validity of this approximation depends not only on the energy of the decaying compound nucleus, but also on the range of (J,π) states populated in the reaction under consideration. Using the Weisskopf-Ewing approximation in the analysis of simulated Surrogate experiments yields (n,f) cross sections that depend on the compound-nuclear spin-parity distribution, but agree roughly with the expected results, for the schematic (J,π) populations selected in the study. The Ratio approach was found to be useful in reducing errors in certain cases when the conditions for validity of the Weisskopf-Ewing approximation are not well satisfied.

The experiments discussed here indicate that for neutron energies above 1 or 2 MeV, the Weisskopf-Ewing and Ratio approximations may be satisfactory for extracting (n,f) cross sections for actinde nuclei from Surrogate experiments. For lower energies, the effects of the spin-parity mismatch between the desired and Surrogate reactions become visible. These findings are in agreement with the insights gained from the theoretical studies summarized here.

The findings presented here underscore the need to take into account the spin-parity mismatch between desired and Surrogate reactions with the help of appropriate calculations and/or to identify Surrogate reactions that minimize this mismatch. For both strategies, it becomes important to obtain information on the spin-parity distributions of the compound nucleus. In principle, the compound-nuclear (J,π) populations can be supplied by suitable direct-reaction calculations leading to the excitation of high-lying final states. However, developing reliable calculations for the wide variety of applicable direct reactions (stripping, pickup, inelastic scattering, and charge exchange) is a challenge for the theorists.

Moving beyond the Weisskopf-Ewing approximation will be especially important for Surrogate applications to (n,γ) reaction cross sections, as these exhibit more sensitivity to the spin-parity distributions than the fission cross sections [13,16,17,18]. Recent theoretical studies [16,17] indicate that yields of low-lying gammas following gamma cascades de-exciting high-lying compound states can give useful information on (J,π) distributions to supplement the results of direct-reaction calculations. This needs to be exploited experimentally.

Many applications in the areas of nuclear energy, national security, and nuclear astrophysics require cross sections for compound-nuclear reactions involving unstable targets. In some situations, using the Surrogate approach might be the only alternative to a very difficult direct measurement. The last few years have led to significant improvements in our understanding of this approach, but more theoretical and experimental work is required to fully develop the method.

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