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Compound-nuclear reaction cross sections via Surrogate measurements

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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. This is particularly true for many reactions of interest to astrophysics. An innovative indirect approach to compound-nuclear reactions has recently been used to obtain cross sections for neutron-induced fission for various actinide targets via "Surrogate" reactions [1 – 5]. In the present paper we will discuss the feasibility of using the Surrogate approach for neutron-capture reactions at low energies, relevant to the astrophysical s process. In particular, applications involving mass 90-100 nuclei will be discussed.

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1. Introduction

Cross sections for unstable nuclei are very difficult to measure, but they also play an important role for addressing some of the most compelling questions of basic science. Among the unanswered mysteries about the nature and evolution of our universe is the origin of the heavy elements [6]. Much effort is currently being devoted to exploring nuclear processes, such as the s and r processes ("slow" and "rapid" neutron-capture processes), and astrophysical environments that can produce the elements between iron and uranium. Of particular interest in the context of the s process are branch points, unstable nuclei that are produced in the s process with a life time long enough to allow the s process to proceed by either neutron capture or β decay [7]. A crucial ingredient for determining the probability of one path dominating over the other is the associated neutron-capture cross section. Calculated abundance patterns can be compared to data from stellar spectroscopy or analyses from presolar dust grains. Such comparisons impose stringent tests on available s-process models, including the nuclear physics input, and provide valuable information on the physical conditions under which the s process takes place. In addition, accurate and precise knowledge of the s process provides important constraints for the r process [8].

Direct cross section measurements for neutron-capture reactions on branch-point nuclei are difficult since they involve (by definition) unstable targets. Producing relevant isotopes for experiments in inverse kinematics will remain challenging for radioactive beam facilities. Moreover, cross section calculations are nontrivial since they require detailed knowledge of the nuclear structure (level densities, gamma strengths functions, etc.) involved. In this contribution, we will discuss an indirect method for determining cross sections for compound-nuclear reactions, the *Surrogate Nuclear Reactions* method. The next section gives a brief outline of the Surrogate approach. Different options for the utilization of experimental data from a Surrogate experiment are presented in Section 3, and the particular application of the method to neutron-capture reactions for astrophysics is presented in Section 4. Some concluding remarks follow in Section 5.

2. The Surrogate Approach

The "Surrogate Nuclear Reactions" method, originally presented in [9, 10], combines experiment with theory to obtain cross sections for compound-nuclear reactions, $a+A \rightarrow B^* \rightarrow c+C$, involving difficult-to-produce targets, A. In the Surrogate approach, B^* is produced by means of an alternative ("Surrogate") reaction, e.g. $d+D \rightarrow b+B^*$, and the desired decay channel ($B^* \rightarrow c+C$) is observed in coincidence with the outgoing particle b. 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 probabilities for this state [5, 11].

In the past, both inelastic scattering and transfer reactions have been employed to obtain Surrogate estimates for fission cross sections [4, 9, 10]. However, the present contribution focuses on (n,γ) reactions for spherical or near-spherical mass 90-100 targets. Many such reactions play an important role in the astrophysical s process. An example, that has been discussed recently in connection to the question of the mixing efficiency in AGB stars [12], is ^{95}Zr$(n,\gamma)^{96}$Zr. It will not be possible to measure the cross section for this reaction in the near future. However, a possible

Surrogate reaction that could be used to populate the intermediate ^{96}Zr state is $^{96}\mathrm{Zr}(\alpha,\alpha')^{96}\mathrm{Zr}$, which would allow for studying its subsequent gamma decay.

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

$$\sigma_{\alpha\chi}(E_\alpha) = \sum_{J,\pi} \sigma_\alpha^{CN}(E_{ex},J,\pi) \; G_\chi^{CN}(E_{ex},J,\pi) \; , \tag{2.1}$$

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 center-of-mass energy E_α via the energy needed for separating a from B: $E_\alpha = E_{ex} - S_a(B)$. In many cases the formation cross section $\sigma_\alpha^{CN} = \sigma(a+A \rightarrow B^*)$ can be calculated to a reasonable accuracy by using optical potentials, while the theoretical branching ratios 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. Under certain conditions, the branching ratios become approximately independent of the spin and parity of the decaying state. This limit is known as the Weisskopf-Ewing limit and is particularly relevant for the analysis of Surrogate experiments as we will discuss below.

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 $d+D$. We note that the population of the compound nucleus following the desired and the Surrogate reactions can be very different from each other. This is known as the J,π population mismatch. However, it is the quantity

$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_\delta^{CN}(E_{ex},J,\pi) \; G_\chi^{CN}(E_{ex},J,\pi) \; , \tag{2.2}$$

which gives the probability that the compound nucleus B^* was formed at an energy E_{ex} and decayed into channel χ, that can be obtained experimentally. This is the information that should be combined with theory to extract the desired cross section $\sigma_{\alpha\chi}(E_\alpha)$..

3. Theoretical analysis using decay data from a Surrogate experiment

The decay data from a Surrogate experiment can be utilized in several ways. Let us briefly discuss three different approaches:

1. Assuming that the Weisskopf-Ewing limit is valid for all energies and that consequently the J,π population mismatch is irrelevant.
2. Using direct reaction theory, possibly in combination with experimental signatures, to model the J,π distribution following the Surrogate reaction.
3. Normalizing calculated branching ratios to the measured decay probabilities in an energy region for which the Weisskopf-Ewing limit is valid.

Note that the first approach will give you the desired cross section directly from the measured decay probability with the single theoretical input being the formation cross section $\sigma_\alpha^{CN}(E_{ex})$. This approach was used in the original version of the method [9, 10], and is still being used for some applications [3]. It is also implicit in approximations to the full Surrogate formalism such as the Ratio Method [4, 5]. However, it relies heavily on the applicability of the Weisskopf-Ewing

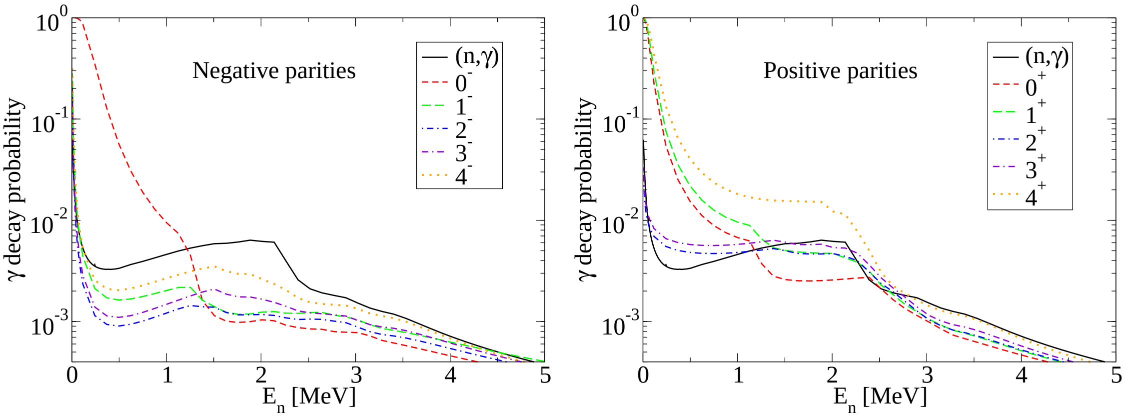

Figure 1: Gamma decay probabilities of ^{92}Zr* as a function of J, π and equivalent neutron energy E_n. The total gamma decay probability following neutron absorption is also shown.

limit and can not be used, e.g., for low-energy neutron capture as will be seen in the discussion of Fig. 1.

The latter two approaches require more theoretical input since a statistical reaction calculation must be performed; and the experimental data is used to constrain the associated nuclear models. In approach (2) 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. These branching ratios are then inserted in Eq. (2.1) to yield the desired cross section. This procedure requires a reliable theory for the population of continuum states in direct reactions, and their subsequent damping into equilibrated compound nuclear states. Efforts to develop such a theory are underway, and the first attempts at employing this approach have already been performed [1, 2]. We note that supplemental experimental information such as measurements at several ejectile angles, gamma multiplicities, and individual gamma intensities are very useful to check the predicted populations.

In applications where the decay probabilities are very sensitive to the J, π population one can try to exploit the fact that Surrogate experiments can give decay probabilities over a very wide energy range. By studying an energy region in which the Weisskopf-Ewing limit is valid, one can normalize calculated branching ratios to the measured decay probabilities. The deduced normalization factor can subsequently be used in the statistical reaction calculation of the cross section in the desired energy range. As we will discuss next, this seems to be the method of choice for extracting low-energy (n, γ) cross sections for spherical or near-spherical targets.

4. Surrogate approach to neutron-capture reactions

The gamma decay probabilities of compound-nuclear states just above the neutron separation threshold can be very sensitive to the J, π of the decaying state. The reason is the small number of open decay channels, usually not more than one or a few neutron channels plus the gamma channel, and the fact that the neutron transmission coefficients will be very large for s wave, and possibly p wave, channels while they are small for all other channels. This is clearly demonstrated in Fig. 1, which shows the gamma decay probabilities of ^{92}Zr* compound-nuclear states as a function of their

J,π and the equivalent neutron energy $E_n = E_{ex} - S_n$. These results are obtained from a statistical reaction calculation with nuclear model parameters from recently developed regional systematics for nuclei spanning the range $34 \leq Z \leq 46$ [13]. It is clear from studying Fig. 1 that we are far from the Weisskopf-Ewing limit at small energies. Approach (1) outlined above can therefore not be used. In addition, the sensitivity to the J,π population is so strong that approach (2) would be extremely difficult to apply with good accuracy since it would require a very precise prediction of the J,π population mismatch. Instead, approach (3) seems to be the best choice for extracting low-energy neutron capture cross sections from Surrogate experiments. In the case shown here, the Weisskopf-Ewing limit sets in at around $E_n \geq 2.5$ MeV, and experimental data at high energies could therefore be used for a normalization of the decay model. We note that neutron capture cross sections modeled with the Hauser-Feshbach formula are most sensitive to the photon transmission coefficients and nuclear level densities. Preliminary simulations of this approach show that the normalization of the decay model at high energies result in a very accurate, and almost model independent, prediction at the relevant low energies [14].

5. Summary and outlook

In this paper we have discussed different options for utilizing decay data from Surrogate experiments. Our main focus has been on the particular application of the method to extract low-energy neutron capture cross sections for spherical or near-spherical targets. This turns out to be a particularly difficult application, but the idea outlined in this presentation is very promising. More detailed studies will require further simulations and benchmark experiments.

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