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Surrogate nuclear reactions – an indirect method for determining reaction cross sections

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Abstract. An indirect method for determining cross sections of reactions proceeding through a compound nucleus is presented. Some applications of the Surrogate nuclear reaction approach are considered and challenges that need to be addressed are outlined.

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1. The Surrogate concept

Determining cross sections for reactions on short-lived nuclear species is a major challenge for nuclear physics and nuclear astrophysics. Many of these nuclei are too difficult to produce with currently available experimental techniques or too short-lived to serve as targets in present-day set-ups. Some nuclear reactions will not even be measurable at upcoming and planned radioactive-beam facilities. It is therefore important to explore alternative methods for determining reaction cross sections involving unstable nuclei.

Figure 1. Schematic representation of the Surrogate reaction mechanism.

The Surrogate nuclear reaction technique is an indirect method for determining the cross section for a particular type of “desired” reaction, namely a two-step reaction, $a + A \rightarrow B^* \rightarrow c + C$, that proceeds through a compound nuclear state B^* , see Figure 1. The Surrogate idea is based on the assumption that the formation and decay of a

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compound nucleus (CN) are independent of each other (for each angular momentum and parity value). In such situations, the cross section for the “desired” reaction can be (somewhat schematically) expressed as

$$\sigma_{\alpha\chi}(E) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E, J, \pi) G_{\chi}^{CN}(E, J, \pi). \quad (1)$$

Here α denotes the entrance channel $a + A$ and χ represents the relevant exit channel $c + C$. 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 decay probabilities G_{χ}^{CN} for the different channels χ are often quite uncertain. The objective of the Surrogate method is to determine these decay probabilities experimentally.

In a Surrogate experiment, the compound nucleus B^* is produced via an alternative (“Surrogate”), direct reaction $d + D \rightarrow b + B^*$ and the decay of B^* is observed in coincidence with the outgoing particle b . The probability for forming B^* in the Surrogate reaction (with specific values for the excitation energy E , angular momentum J , and parity π) is $F_{\delta}^{CN}(E, J, \pi)$, where δ refers to the entrance channel $d + D$. The quantity

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

which gives the probability that the compound nucleus B^* was formed with energy E and decayed into channel χ , can be obtained experimentally. The direct-reaction probabilities $F_{\delta}^{CN}(E, J, \pi)$ have to be determined theoretically, so that the decay probabilities $G_{\chi}^{CN}(E, J, \pi)$ can be extracted from the measurements and, subsequently, inserted in equation (1) to yield the desired reaction cross section.

2. Applications of the Surrogate method

The Surrogate approach was used in the 1970s, albeit in a very simplistic manner, to extract (n, f) cross sections from t -induced or ^3He -induced transfer reactions [1]. Measured fission probabilities, P_f , were simply multiplied by an estimated cross section for the formation of the compound nucleus in the neutron-induced reaction of interest: $\sigma_{(n,f)} \approx \sigma_n^{CN} P_f$. 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, it resulted in serious discrepancies below 1 MeV, which were attributed to i) large uncertainties in the low-energy optical-model calculations employed, and ii) the neglect of the difference in the angular-momentum populations of the compound nucleus in the Surrogate (direct) and “desired” (neutron-induced) reactions (see Section 3).

Recently, Younes and Britt [2] revisited the Surrogate (t, pf) , $(^3\text{He}, df)$, and $(^3\text{He}, tf)$ fission-correlation measurements from the 1970s. They employed a simple direct-reaction model to compensate for the angular-momentum population difference between neutron-induced and direct reactions and used improved optical-model calculations to obtain (n, f) cross sections for various Th, U, Np, Pu, and Am isotopes. For the benchmark case ^{235}U , they obtained significant improvements over the early Surrogate work. In addition to reproducing the fission cross section for the $J^{\pi} = 7/2^{-}$

ground state of ^{235}U , Younes and Britt were able to estimate the fission cross section for the isomeric $1/2^+$ state at 77eV, 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 $\pm 10\%$ for $E_n \gtrsim 1$ MeV [$E_n \gtrsim 2$ MeV] when obtained from Surrogate (t,pf) [$(^3\text{He}, xf)$] data; at lower energies the discrepancies are about 20%.

While the Surrogate method can (in principle) be used to determine cross sections for reactions on a large variety of nuclei, its greatest potential value lies in applications that involve unstable isotopes. Cross sections for unstable nuclei are not only very difficult to measure, 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 [3]. Much effort is currently being devoted to exploring nuclear processes, such as the s and r 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. A crucial ingredient for determining the probability of one path dominating over the other is the associated neutron-capture cross section. It is therefore worthwhile to investigate whether the Surrogate method can be employed to obtain low-energy ($\lesssim 30$ keV) neutron-capture cross sections.

3. Challenges for the Surrogate approach

In order to assess whether the Surrogate technique can be used to reliably determine low-energy (n, γ) cross sections, various theoretical and experimental challenges have to be addressed. The most obvious issue that needs to be studied is the so-called “ J^π population mismatch”: A compound nucleus is, by definition, a quantum-mechanical system in statistical equilibrium, and as such has no memory of its formation process. Nevertheless, constants of motion, such as angular momentum and parity, are conserved throughout the reaction. In general, the Surrogate reaction populates the states in the intermediate nucleus differently than the desired $a + A$ channel, i.e. the weights $F_\delta^{CN}(E, J, \pi)$ by which the decay probabilities $G_\chi^{CN}(E, J, \pi)$ are multiplied in equation (2), are different from the relative formation cross sections $\sigma_\alpha^{CN}(E, J, \pi) / \sum_{J', \pi'} \sigma_\alpha^{CN}(E, J', \pi')$ of equation (1), and depend on the direct reaction under consideration. In the early work it was assumed that the experimental conditions were such that the Weisskopf-Ewing limit applied, i.e. the decay probabilities were independent of J^π and the cross section of the reaction could be written as a simple product $\sigma_{\alpha\chi}(E) \approx \sigma_\alpha^{CN}(E) G_\chi^{CN}(E)$. The more recent work by Younes and Britt demonstrates the importance of accounting for the “ J^π population mismatch”.

In order to identify reactions that can possibly serve as Surrogates for a particular desired reaction, it is important to know the J^π populations that are obtained in various direct reactions (stripping, pick-up, inelastic scattering), as well as the dependence of these populations on projectile, target, excitation energy, angle of outgoing particle, etc. This is a nontrivial task since a proper treatment of direct reactions leading to highly excited states in the intermediate nucleus involves a description of particle transfers, and inelastic scattering, to unbound states.

It is furthermore important to study how the J^π populations that can be obtained in the various reactions affect the *decay of a compound nucleus*. More specifically, if

there is a significant “ J^π population mismatch” between the Surrogate and “desired” reactions, one has to investigate whether the Surrogate measurement can provide meaningful constraints for the cross section of the “desired” reaction.

To obtain the experimental decay probabilities $P_\chi(E)$ for a particular exit channel $\chi = C + c$, it is essential to *identify the final reaction product(s)* in that channel. For some applications of the Surrogate technique, this identification involves detecting fission fragments. In other cases, the identification involves measuring characteristic γ rays from the de-excitation of the desired reaction product C . In order to convert the measured γ -ray intensities to channel probabilities $P_\chi(E)$, a model for the de-excitation process is needed, which, in turn, requires a proper description of structural properties of the remnant C , such as level densities, branching ratios between discrete levels, and internal conversion rates.

Another important issue to be investigated in the context of Surrogate reactions is the *role of pre-equilibrium reactions*: Central to the Surrogate method is the assumption that the formation and decay of the intermediate nuclear state – in both the “desired” and the Surrogate reaction – are independent of each other (apart from conserving constants of motion). This is only valid if the intermediate nucleus equilibrates (becomes a “compound” nucleus) before it decays into the final reaction products. Rapid (“pre-equilibrium”) decay of the intermediate configuration before a compound nucleus can be formed would invalidate the Surrogate analysis. The probability that a compound nucleus is actually formed in a particular reaction needs to be estimated and the effects of pre-equilibrium decays on energy balances and J^π populations have to be studied.

Finally, to establish the validity of the Surrogate approach, it is necessary to carry out experiments that provide appropriate benchmarks. Planning for such a benchmark experiment is underway: the reaction $\alpha + {}^{102}\text{Ru} \rightarrow \alpha' + {}^{102}\text{Ru}^*$ will be used as a Surrogate for $n + {}^{101}\text{Ru} \rightarrow {}^{102}\text{Ru}^*$. Observing the decay ${}^{102}\text{Ru}^* \rightarrow {}^{102}\text{Ru}$, by γ -ray emission, in coincidence with the outgoing α particle allows one to infer the cross section for $n + {}^{101}\text{Ru} \rightarrow \gamma + {}^{102}\text{Ru}$, which can then be compared to direct measurements.

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