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The Surrogate Method; Past, Present and Future*

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The STARS/LiBerACE collaboration has been exploring the surrogate technique with success in the actinide region. This method uses a direct reaction to measure the decay probability of the same compound nucleus produced via a neutron-induced channel. This paper serves as an overview of these activities. Using the STARS array at 88-inch Cyclotron at Lawrence Berkeley National Laboratory we have explored the following surrogate reactions: ^{234}U$(\alpha, \alpha' f)$, ^{235}U(^{3}He,αf), ^{236}U$(\alpha, \alpha' f)$, ^{238}U$(\alpha, \alpha' f)$, ^{238}U(^{3}He,αf), ^{238}U(^{3}He,tf) surrogates for ^{233}U(n, f), ^{233}U(n, f), ^{235}U(n, f), ^{237}U(n, f), ^{236}U(n, f), and ^{237}Np(n, f), respectively.

Keywords: surrogate reactions, fission probability

1. Introduction

The Absolute Surrogate Technique was first suggested by Cramer and Britt in 1970[1] to overcome the problem associated with neutron induced experiments on short-lived targets. The main assertion of the Surrogate Technique is that the fission probability is independent of the direct reaction used to populate the compound nucleus of interest. If similar states are excited in the neutron capture and direct reactions, then the cross section for neutron fission can be estimated:

$$\sigma_{(n,f)}(E_n) \approx P_f(E_n - S_n) \times \sigma_{CN}(E_n) \tag{1}$$

where E_n is the equivalent neutron energy, S_n is the neutron separation energy and σ_{CN} is the energy dependent compound nucleus formation cross

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section. This equation depends on two factors (1) the σ_{CN} is known from a model or another source and (2) the decay probability is independent of the spin and parity.

In the following years, they had limited success with this method in the actinide region. This absolute surrogate method was limited to an excitation energy of around 11–12 MeV because of the maximum beam energy available and the introduction of the carbon and oxygen contaminants at high energies.

The external surrogate ratio method (ESRM) was introduced 35 years later by Plettner *et al.*[2] to overcome some problems of the absolute method. With the ESRM, the same direct reaction is used to produce two different compound nuclei, the exit channel probabilities are measured, and the ratio is used to infer one cross section if the other is well-known. In this paper, the probability of the $^{238}\mathrm{U}(d,d'f)/^{236}\mathrm{U}(d,d'f)$ ratio was used as a surrogate for the ratio of the $^{237}\mathrm{U}(n,f)/^{235}\mathrm{U}(n,f)$ cross section and $^{236}\mathrm{U}(d,pf)/^{238}\mathrm{U}(d,pf)$ ratio was used as a surrogate for the $^{236}\mathrm{U}(n,f)/^{238}\mathrm{U}(n,f)$. However, these experiments still suffered from a 15 – 20% uncertainty at low energies.

The STARS-LiBerACE collaboration is now exploring the techniques more thoroughly with experimental and theoretical work. This paper serves as an overview of the experimental work performed by the group in the actinide region. The theoretical work has been explained in great detail by Escher and Dietrich.[3]

2. Experimental

In the experiments summarized here, the targets were bombarded with the desired particle beam produced by the 88-inch Cyclotron at Lawrence Berkeley National Laboratory. The Silicon Telescope Array for Reaction Studies (STARS) was used to detect the scattered particles in coincidence with the outgoing fission fragments. The STARS array consisted of three to five Silicon Micron S2 detectors including a downstream ΔE - E particle telescope where the ΔE detector has a thickness of either 140 μm or 500 μm and the E detectors are in multiples of 1000 μm and an upstream “fission” detector (140 μm) as shown in Fig. 1. The S2 detectors can be set up with the full 48 rings and 16 sectors configuration or with a total of 24 rings and 8 sectors depending on the experiment and cover an angular range of $\theta_{polar} = 10^\circ - 66^\circ$ at one time with respect to the beam axis depending on the distance the telescope is placed from the target. Fission fragments were detected over an angular range of $\theta_{polar} = 106^\circ - 131^\circ$ upstream of

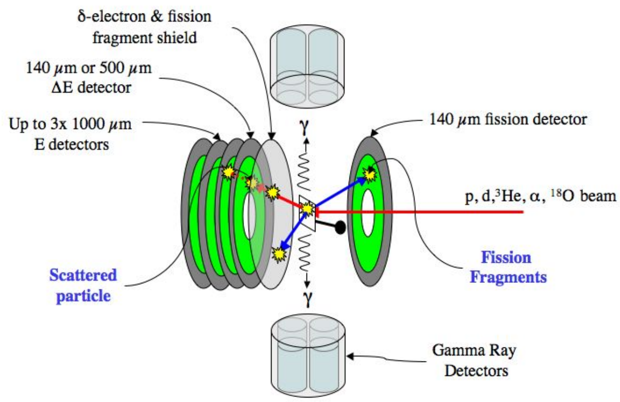

Fig. 1. (color on-line) A drawing of the STARS telescope array shown with the GeHP detectors LiBerACe.

the target. One of the master triggers (MT) set for the data acquisition can require a coincidence between the ΔE and E detectors. Fission detector energies were recorded if they came typically within 4 μs of the trigger. In addition, the relative time difference between the ΔE - E detectors and the fission detector were recorded reducing the prompt window down to ∼200 – 300 ns. The setup is explained in more detail in Ref.[4,5]

In subsequent off line analysis, charged particles (p, d, t, ^{3}He, ^{4}He, ^{16}O) were identified by plotting the energy loss measured in the ΔE detector against the total energy, ΔE + E. A 2-d gate was employed to select the particle events of interest. The scattered particle energy was used, on an event by event basis, to determine the excitation energy of the uranium nucleus by correcting for the angular-dependent recoil energy of the target nucleus, for the energy losses in the target layers, and the thin (4 mg/cm^2) aluminum fission fragment shield and the dead layers of the silicon detectors.

3. Results

An overview of the experiments conducted by the Livermore group and collaborators include three completed analysis and three experiments in various stages of completion in the actinide region.

In one of the first experiments, ^{236}U (184 μg/cm^2) and ^{238}U (585 μg/cm^2) targets were bombarded with a 55 MeV α beam. ^{236}U$(\alpha, \alpha' f)$ is the surrogate for ^{235}U(n, f) and ^{238}U$(\alpha, \alpha' f)$ is the surrogate for ^{237}U(n, f). The cross section for neutrons on ^{235}U is well known but neutrons on ^{237}U was difficult to measure given the short half-life of the target ($\tau_{1/2} = 6.75$ days). To overcome this difficulty, the External Surrogate Ratio was used to find the ^{237}U(n, f) cross section over an equivalent neutron energy range of 0 – 20 MeV.[4]

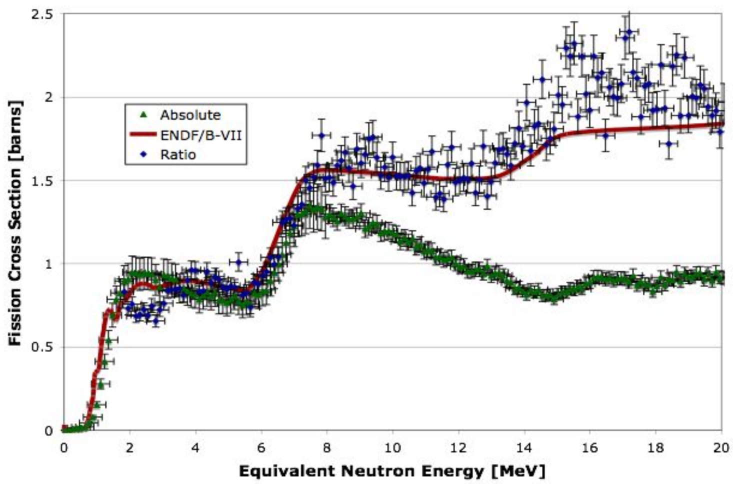

Fig. 2. (color on-line) The ^{236}U(n, f) cross section is plotted in three different ways. The solid line is from the ENDF/B-VII[6] database, the green triangle points are from the absolute surrogate method while the blue diamonds are from the surrogate ratio method, both taken from Ref.[5]

In a second experiment, a 42 MeV ^{3}He beam was used on a 720 μg/cm^2 ^{235}U target and a 761 μg/cm^2 ^{238}U target. The ^{235}U(^{3}He,αf) and ^{238}U(^{3}He,αf) were surrogates for ^{233}U(n, f) and ^{236}U(n, f), respectively. Using the alpha exit channel, the external ratio and the absolute surrogate techniques were used to examine the ^{236}U(n, f) cross section over an equivalent neutron energy range of 0 to 20 MeV[5] and the sensitivity to the spin and parity population distribution between the two entrance channels was explored. The results can be seen in Fig. 2. The data from the absolute surrogate technique agreed well with the direct measurement until the ^{3}He gate becomes mixed with the α gate and the denominator is affected. Significant deviations between the ESRM and the ENDF data are noticeable below about 3.3 MeV and may indicate the breakdown of the Weisskoph-Ewing assumption or a need to remeasure the ^{233}U(n, f) cross section in this region. Between the absolute surrogate technique, below 3.3 MeV and the ESRM, above 3.3 MeV we are able to reproduce the ENDF data curve.

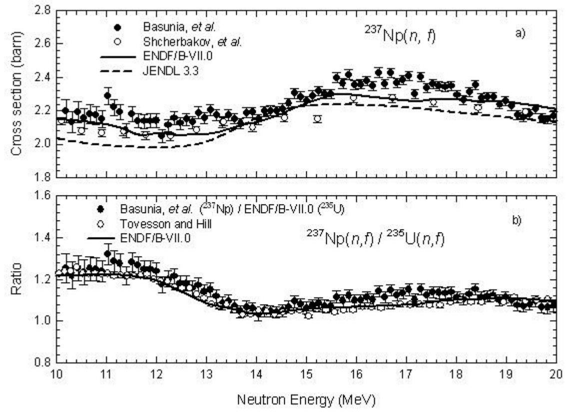

Fig. 3. (color on-line) a) The ^{237}Np(n, f) cross section is plotted as an absolute surrogate and b) as a ratio to ^{235}U(n, f). Reproduced from Ref.[7]

From the same experiment, but using the ^{238}U(^{3}He,tf) reaction channel, ^{237}Np(n, f) was examined using the absolute surrogate technique for an energy range between 10 – 20 MeV by Basunia *et al.*[7] Fig. 3a) shows the results in comparison with the STARS data and the ENDF/B-VII.0 database and direct measurement data from Shcherbakov *et al.*[8] These results agree within 6%. In Fig. 3b), the STARS data is taken in ratio with the ^{235}U data from ENDF/B-VII.0 to compare with a recent direct measurement of the same cross section[9] with good agreement. This work benchmarks the use of the (^{3}He,tf) reaction for the absolute surrogate (n, f) cross section in the 10–20 MeV range.

Currently there are three experiments under analysis in the actinide region. First, ^{234}U$(\alpha, \alpha' f)$ and ^{236}U$(\alpha, \alpha' f)$ serves as a benchmark for the ESRM since both of the surrogate reactions, ^{233}U(n, f) and ^{235}U(n, f), respectively have been measured directly. This will also confirm the result found in Burke *et al.*[4,10]

The next experiment involves bombarding a ^{238}U target with ^{18}O and observing the ^{16}O exit channel, to determine the ^{239}U(n, f) and $(n, 2n)$ cross section as a test of the two-neutron transfer mechanism.[11]

Finally, a benchmark of the (n,γ), $(n, 2n)$ using 21 MeV and 29 MeV deuterons on ^{235}U will test the Internal Surrogate Ratio Method (ISRM). In this technique, one compound nucleus is made and two exit channels are examined. As in the ESRM, if one of the exit channels is known, the other can be compared and cross section can be inferred. The ^{235}U(d, px) reaction is the surrogate for ^{235}U(n, x), where $x = f, \gamma, 2n$, etc.[12]

4. Conclusions

The STARS/LiBerACE collaboration has performed a variety of experiments to test the surrogate technique and benchmark the surrogate ratio method. The technique has been benchmarked for the (α, α') and (^{3}He,t) reactions in different energy ranges. The ^{237}U(n, f) cross section was extracted from 0–20 MeV equivalent neutron energy with less than 10% uncertainty. We have explored the spin distribution probability between the direct and neutron induced reactions to test one of the major ansatz of the method. Other experiments are in various stages of analysis to determine new cross-sections in the actinide region and also benchmark different reactions.

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