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# Determining neutron capture cross sections with the Surrogate Reaction Technique: Measuring decay probabilities with STARS

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Neutron-induced reaction cross sections are sometimes difficult to measure due to target or beam limitations. For two-step reactions proceeding through an equilibrated intermediate state, an alternate "surrogate reaction" technique [1–3] can be applicable, and is currently undergoing investigation at LLNL. Measured decay probabilities for the intermediate nucleus formed in a light-ion reaction can be combined with optical-model calculations for the formation of the same intermediate nucleus via the neutron-induced reaction. The result is an estimation for overall (n,$\gamma$/n/2n) cross sections. As a benchmark, the reaction $^{92}$Zr$(\alpha, \alpha')$, surrogate for n+$^{91}$Zr, was studied at the A.W. Wright Nuclear Structure Laboratory at Yale. Particles were detected in the silicon telescope STARS (Silicon Telescope Array for Reaction Studies) and $\gamma$-ray energies measured with germanium clover detectors from the YRAST (Yale Rochester Array for SpecTroscopy) ball. The experiment and preliminary observations will be discussed.

## 1. INTRODUCTION

Two-step reaction cross sections which are difficult to measure directly can be obtained via the Surrogate Reaction Technique [1–3]. The formation of the desired intermediate system is achieved through an alternate "surrogate" reaction. Decay probabilities are measured and combined with optical-model calculations [4,5] for the formation cross section via the n-induced reaction. The decay probabilities are determined from $\gamma$-ray intensities of the decay products for a given angle ($\theta$) and energy ($E$) of the exiting light particle:

$$P_\gamma(E_x, \theta) = \frac{N_\gamma(E_x, \theta)(1+\alpha)}{N_p(E_x, \theta)\epsilon_\gamma \tau_{live}}, \tag{1}$$

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where $N_\gamma$ is the number of detected $\gamma$-rays, $N_p$ is the number of exiting particles, $\epsilon_\gamma$ is the $\gamma$-ray efficiency, $\tau_{live}$ is the live time correction, and $\alpha$ is the conversion coefficient.

In the Weisskopf-Ewing limit, decay probabilities do not depend on the $J^\pi$ population of the compound nucleus, and the Bohr independence hypothesis applies. Otherwise, decay probabilities are not independent of the entrance channel, and the $J^\pi$ population of the intermediate state must be considered. In order to do this utilizing the measured quantities, the probabilities for a particular decay channel $\chi$ are separated from their formation via the surrogate reaction ($F_\delta$) in the theory. To briefly summarize Refs [4,5],

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

where $P_\chi(E)$ is the measured quantity. The final expression for the n-induced reaction cross section is,

$$\sigma_{n\chi}(E) = \sum_{J^\pi} \sigma_n^{cn}(E, J^\pi) G_\chi(E, J^\pi). \tag{3}$$

As an early step toward furthering the Surrogate Reaction Technique, scattering of $\alpha$ particles by $^{92}$Zr and $^{51}$V has been performed. The reactions $^{92}$Zr($\alpha, \alpha'/^3$He/t/d/p), and separately $^{51}$V($\alpha, \alpha'/^3$He/t/d/p), are being studied with a focus on the $^{92}$Zr$(\alpha, \alpha')^{92}$Zr (see for example, [7]) reactions which serve as surrogates for n+$^{91}$Zr.

## 2. EXPERIMENT

The experiment was performed at the A.W. Wright Nuclear Structure Laboratory at Yale University. $^4$He ions were produced in the duoplasmotron and accelerated to 51 MeV in the ESTU tandem Van de Graaff accelerator with approximately 17 MV on the carbon stripping foil at the terminal. The final average intensity of the beam was 8 enA, with an approximate diameter of 4 mm on target.

Scattered particles were detected in the silicon telescope STARS (Silicon Telescope Array for Reaction Studies). The array consists of double-sided silicon annular detectors segmented into 24 rings ($\theta$) on one side, and 8 sectors ($\phi$) on the reverse side. Each detector has an outer diameter of 70 mm with an inner diameter of 22 mm, and energy resolution of approximately 100 keV. Two detectors were used for this particular experiment with thicknesses of 138 $\mu$g and 985 $\mu$g and distances downstream of the target of 4.7 mm and 12.7 mm respectively. The angular acceptance for this configuration was 40-61° in $\theta$ and approximately 90% of $2\pi$ in $\phi$. In order to protect the silicon detectors from unwanted $\delta$-electrons and associated leakage current, a 0.25 mil Al shield was placed between the target and the thin detector and a 5 mil Al shield biased to +300 V was placed downstream of the thick detector. Gamma-rays were detected at 90° in 4 germanium clover detectors from the YRAST (Yale Rochester Array for SpecTroscopy) ball.

## 3. PRELIMINARY OBSERVATIONS

In order to obtain the decay probabilities for the intermediate nucleus, the exiting particle and its energy are identified to tag the reaction, and gamma-rays are counted in coincidence with the exiting particle for identification of the decay product (see Eqn

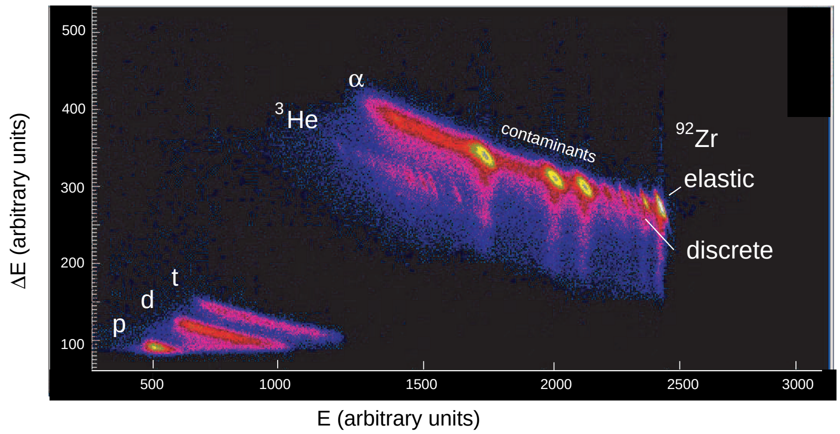


Figure 1. Energy lost in the thin detector is plotted against energy lost in the thick detector (ΔE vs. E). Helium ions, ($\alpha$, $^{3}$He), tritons (t), deuterons (d) and protons (p) are labelled. Elastic scattering by the target $^{92}$Zr nuclei as well as contaminants in the target are visible. Alpha particles with energies corresponding to discrete states in $^{92}$Zr are also present in the spectrum. This is a preliminary spectrum.

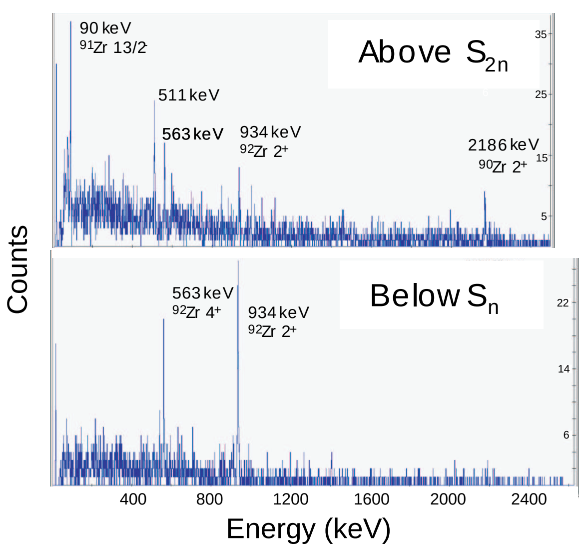


Figure 2. Gamma-ray energies after gating on particles above $S_{2n}$ in $^{92}$Zr are presented in the top panel, and below $S_n$ in $^{92}$Zr in the bottom panel. The states in $^{90,91,92}$Zr visible in the spectrum gated above $S_{2n}$, and in $^{92}$Zr in the spectrum gated below $S_n$ are labelled. These are preliminary spectra.

1). Due to the angular segmentation in the silicon, decay products can be identified for a particular angle and energy of the exiting particle. This is accomplished initially by placing gates on energy lost in the thin detector (ΔE) vs. energy lost in the thick detector (E) for each scattering angle over the detector. Particle-gated $\gamma$-ray energies are then used to determine the decay probabilities at a desired energy and scattering angle of the exiting light particle. Figure 1 presents the ΔE vs. E plot for a scattering angle of 47°. Alpha particles, $^3$He ions, tritons, deuterons and protons are all distinguishable in the spectrum. Elastic scattering of the $\alpha$ particles is also evident as indicated, from both the $^{92}$Zr as well as contaminants in the target. The scattering by the contaminants is lower in energy due to recoil. Alpha energies corresponding to discrete peaks in $^{92}$Zr are also noticeable. Preliminary gamma-ray spectra after gating on particles above the two neutron separation energy and below $S_n$ in $^{92}$Zr are also shown (Figure 2).

Because the trigger was an AND of the thin and thick detectors, the experiment was limited energetically by the energy required to exit the thin detector and the subsequent stopping range in the thick detector. For the $(\alpha, \alpha')$ reaction, $Q = 0$ and $S_n = 8.635$ MeV for $^{92}$Zr. Within the limitations, exiting $\alpha$ particles with energies from 18 MeV to 50 MeV were detected. This corresponds to energies in the equilibrated intermediate nucleus of 33 MeV to 1 MeV respectively, and equivalent neutron energies in the neutron-induced desired reaction, of 24 MeV to -7.6 MeV respectively. The equivalent neutron energy is determined by $E_n = Q - K_{p'} + K_p - Sn = E^* - S_n$, where $K_{p'}$ and $K_p$ are the kinetic energies of the exiting and incident particles, and $E^*$ is the energy in the intermediate nucleus.

## 4. OUTLOOK

Plans for the ongoing development of the Surrogate Reaction Technique aim toward benchmarking the method. The current analysis of the $^{92}$Zr$(\alpha, \alpha')$ data will address experimental limitations. Other pertinent issues [6] include the difference in $J^\pi$ population between the desired and surrogate reaction, $\gamma$-ray feeding in the decay products, and competition between pre-equilibrium and equilibrium states. In addition to these benchmarking tasks, $^{85}$Kr(n,$\gamma$) and $^{151}$Sm(n,$\gamma$) are good candidates for the technique, and have been identified as important goals for the Surrogate program at LLNL.

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