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Abstract. The results from two surrogate reaction experiments using the STARS (Silicon Telescope Array for Reaction Studies) spectrometer are presented. The surrogate method involves measuring the particle and/or γ-ray decay probabilities of excited nuclei populated via a direct reaction. These probabilities can then be used to deduce neutron-induced reaction cross sections that lead to the same compound nuclei. In the first experiment STARS coupled to the GAMMASPHERE γ-ray spectrometer successfully reproduce surrogate (n,γ), (n,n'γ) and (n,2nγ) cross sections on ^{155,156}Gd using ^{3}He-induced reactions. In the second series of experiments an energetic deuteron beam from the ESTU tandem at the Wright Nuclear Structure Lab at Yale University was used to obtain the ratio of fission probabilities for ^{238}U/^{236}U and ^{237}U/^{239}U populated using the ^{236,238}U(d,d'f) and ^{236,238}U(d,pf) reactions. Results from these experiments are presented and the implications for the surrogate reaction technique are discussed.

INTRODUCTION

Reactions on unstable nuclei are at the core of nucleosynthesis in environments from stars to supernovae to the interior of nuclear weapons. However, the cross sections for many of these reactions are difficult to predict due to the influence of nuclear structure effects and unusual decay modes. Furthermore, these cross sections can be equally difficult to measure due to the short lifetimes and large backgrounds of the radioactive targets involved. The LLNL group is leading an effort to deduce neutron-induced reaction cross sections on unstable nuclei using a technique referred to as the surrogate reaction method. A surrogate reaction experiment involves measuring the decay probabilities of an intermediate nucleus populated using a light-ion induced reaction. The decay probability is determined through the coincident observation of the ejectile and a "tag" for a specific decay channel. Examples of tags include particles, γ-rays or fission fragments. The decay probability for channel x, P_x, would then be determined through the relation:

$$P_X(E_X) = \frac{N_X}{\varepsilon N_{ejectile}} \quad (1)$$

Where ε is the efficiency for detecting the residual nucleus tag, N_x is the number of residual nuclei tags observed for channel x and $N_{ejectile}$ are the number of coincident ejectiles observed The critical *ansatz* of the surrogate reaction method is that the intermediate nucleus formed in both the light-ion induced and the

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neutron induced reactions is compound . i.e. its decay probabilities are independent of its formation. Britt and Wilhelmy [1] pioneered the use of the surrogate technique to obtain (n,f) cross sections in the late 1960's and 1970's using light-ion induced direct reactions. Recent work by Younes and Britt [2] has combined these measured probabilities with the fission and optical model calculations to produce the surrogate neutron-induced fission cross section. Younes has also shown [3] that for excitation energies 2.5 MeV or more in excess of the neutron separation energy the decay probabilities become independent of spin (the Weisskopf-Ewing limit) In this limit the relationship between the measured decay probability and the desired neutron-induced reaction cross sections can be written as:

$$\sigma_{(n,f)} = P(E_x) \bullet \sigma_{reaction}(E_x) \quad (2)$$

Where $P(E_x)$ is the measured energy dependent decay probability, and $\sigma_{reaction}(E_x)$ is the neutron-absorbtion cross section from an optical model calculation.

Two large systematic errors uncertainties dominate surrogate measurements: the determination of $N_{ejectiles}$ (due to contamination of the particle-singles spectrum from reactions on light contaminants in the target such as Carbon and Oxygen), and the difference in angular momentum of the compound nucleus populated via the light-ion induced and the neutron-induced reactions

The first of the two experiments described in this paper involves the first use of surrogate reactions to probe channels other than fission. The particle-singles issue is bypassed in this experiment by utilizing ratios of γ-ray decay probabilities rather than the reaction channel probabilities themselves. The second of the experiments circumvents both the particle-singles and the angular momentum mismatch issues by measuring a ratio of fission probabilities for two very similar nuclei ($^{238}U/^{236}U$ and $^{237}U/^{239}U$). Although the STARS detector was utilized for both measurements the actual Silicon detectors used differed from one experiment to another. The details of the experiments are discussed in the following sections.

THE STARS+GAMMASPHERE EXPERIMENT

The first experiment was performed in April 2002 at the 88-Inch cyclotron at Lawrence Berkeley National Laboratory using the GAMMASHERE γ-ray spectrometer coupled to STARS. In this experiment the SiRi (Silicon RingSTARS. Four panels of SiRi detectors were arrayed in a partial "lampshade configuration designed to provide 8 equally spaced angle ranges between 30° and 60°. The thickness of the front ΔE and back E detectors was 140 μm and 1000 μm respectively. A beam of 45 MeV ^{3}He was used on a highly enriched ^{157}Gd target to produce compound nuclei of ^{156}Gd and ^{157}Gd through the ^{157}Gd(^{3}He,α)^{156}Gd and ^{157}Gd(^{3}He,^{3}He')^{157}Gd reactions. A total of 62 hours of particle-γ and particle-singles data were recorded at an average current of 0.2-0.3 particle-nanoamperes. A full set of γ-ray and particle calibration sources were used for calibration.

Particle-identification was determined by sorting the off-line data into ΔE- vs. E matrices. Figure 1 shows one of these matrices. The α-γ and ^{3}He-γ coincident data was then sorted into total energy vs. γ-ray matrices. The intensity of the most important γ-ray transitions in $^{154-156}$Gd as a function of ejectile energy was determined by slicing on this matrix. A sum of non-coincident γ-rays, $\Gamma_x(E_x)$, was then formed for the strongest transitions observed in the (^{3}He,αxn) and the (^{3}He,^{3}He'xn) channels following the approach discussed in ref. [4]:

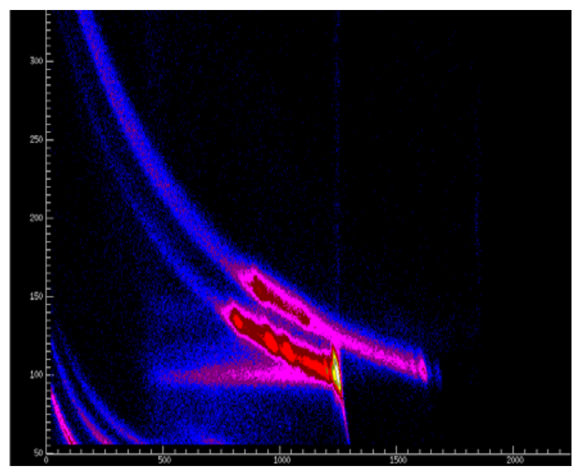

FIGURE 1. The ΔE-E matrix of the STARS+GAMMASPHERE experiment. The α and ^{3}He particles are clearly separated.

$$\Gamma_y(E_x) = \sum_{i=non-coincident} I_\gamma^i(^3He,\alpha yn\gamma_i) \quad (3)$$

Where I_y^i are the efficiency and electron-conversion corrected intensities of the strongest non-coincidence

γ-ray transitions γ_i. The ratio of the $\Gamma_x(E_x)$ for a given channel was then divided by the sum over all open channels on order to determine the decay probability of the compound nucleus into that channel, i.e.:

$$P_y(E_x) = \frac{\Gamma_y(E_x)}{\sum_{i=0}^{2} \Gamma_i(E_x)} \quad (4)$$

Reaction modeling

We used the statistical model code STAPRE (STAatistical-PREequilibrium) to model the γ-ray decay cross sections for comparison to our data [5]. STAPRE includes a Hauser-Feshbach treatment of statistical decay and a simple exciton model of pre-equilibrium decay. STAPRE models the γ-ray decay of the residual nuclei using a statistical level density and γ-ray strength function at high energies that maps to the measured γ-ray cascade at a low enough energy where complete level spectroscopy is known.

The ratios from eq. [4] allow direct comparison between the decay of the nuclei formed using the ^{3}He-induced direct reactions and neutron-induced reactions on different targets. Figure 2 shows a comparison between the ratios for the ^{157}Gd(^{3}He,α2nγ)^{154}Gd and the ^{157}Gd(^{3}He,$\alpha\gamma$)^{156}Gd channels from the STARS data and STAPRE calculations for the ^{155}Gd(n,2n)^{154}Gd and ^{155}Gd(n,γ)^{156}Gd reactions.

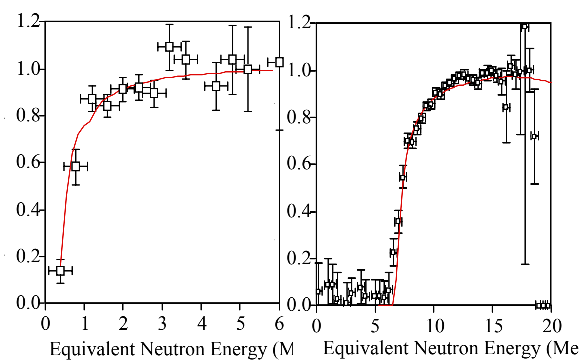

FIGURE 2. Decay probabilities for the (^{3}He,^{3}He nγ) (left) and the (^{3}He,$\alpha\gamma$ (right) respectively from the STARS+GAMMASPHERE experiment (data points) compared to the same quantity from the STAPRE calculations for ^{156}Gd(n,n'γ) and ^{155}Gd(n,2nγ) reactions. The STARS at Yale Experiment

The agreement between experiment and theory is remarkably good. It should be noted that the poor resolution of the particle data (FWHM=360 keV) make direct comparison between the data and the STAPRE calculations particularly difficult at low energies. Nonetheless, the agreement between the data and the model is particularly compelling at low energies where the angular momentum mismatch between the direct and the neutron-induced reactions are maximal. Similar agreement is seen for the ^{157}Gd(^{3}He,^{3}He'xnγ) STARS data and the ^{156}Gd(n,γ) calculations using STAPRE.

THE STARS AT YALE EXPERIMENTS

The second series of experiments were carried out in April and May of 2004 at the A.W. Wright Nuclear Structure Laboratory at Yale University. **T**wo "S2" annular double-sided Silicon detectors from Micron Semiconductor were used in STARS for this run. The S2 detectors consist of 48 rings on the ground plane and 16 sectors on the Junction side. However, adjacent rings and sectors were electrical connected producing a total of 24 azimuthal and 8 polar angles with respect to the beam. 24 MeV and 32 MeV deuteron beams were used on two Uranium Nitrate targets (^{236}U and ^{238}U) and a single Ammonium Nitrate target "stippled" on a 200 μg/cm^2 Carbon backing. The140 μm thick front detector was used to as both the ΔE component of the particle telescope and as a coincident fission fragment detector. Two 1000 μm thick "back" detectors were used to provide additional stopping power for the Hydrogen isotope ejectiles. The front detector and the complete telescope covered an angular range of 36.2°-66.8° and 36.2°-56.3° each with respect to the beam. The YRAST ball (Yale-Rochester Array for Spectroscopy) array, consisting of 8 "clover" Ge detectors was used for γ-ray detection, but is not used in this analysis. Although the ΔE separation between the isotopes of Hydrogen is not as clear as the ^{3}He and α ejectiles in the GAMMASPHERE + STARS data it is still sufficient to assure good particle identifications.

The ratio of the number of fission events in coincidence with deuterons for the ^{236}U and the ^{238}U targets was used to obtain the relative fission probability for the excited nuclei formed via (d,d') and (d,p) reactions in order to avoid the large systematics uncertainties arising from the Carbon, Nitrogen and Oxygen in the target. The ratios were corrected for the differing amount of target material (determined using the number of counts in the elastically scattered peaks), different running times (determined by the master trigger rate), and at low energy for the different particle-fission fragment angular correlation for the two different compound nuclei. The ratios of fission probability are inherently more robust than the fission probability since systematics uncertainties in the detector efficiencies and the particle singles spectrum cancel out. However, in comparing these ratios to the ratios for neutron-induced reactions the assumption is made that the direct reactions on the ^{236}U and the ^{238}U targets are essentially identical.

Figures 4 above shows the ^{236}U(d,pf)/^{238}U(d,pf) and the ^{238}U(d,d'f)/^{236}U(d,d'f) ratios respectively. Detector "punch through" and the Coulomb barrier of the ejectiles determine the energy limits of the meausrement. The good agreement between the measured ^{236}U(d,pf)/^{238}U(d,pf) ratio and the ^{236}U(n,f)/^{238}U(n,f) from ENDF-B6 lends confidence in using equating the ^{238}U(d,d'f)/^{236}U(d,d'f) ratio to the ^{237}U(n,f)/^{235}U(n,f) ratio. Also shown in Figure 4 are the ratio of the predictions of Younes [7] for the ^{237}U(n,f) over the ^{235}U(n,f) cross section from ENDF-B6. The agreement between the (d,d'f) ratios and the prediction of Younes is remarkably good over the energy range covered in these experiment.

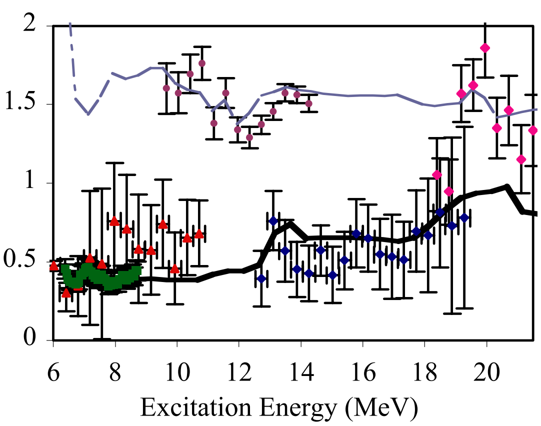

FIGURE 3. Fission probability ratios for STARS for 24 (red and purple points) and 32 MeV (pink and blue points) deuteron beam energies. The lower two ratios are for ^{238}U(d,d'f)/^{236}U(d,d'f). The solid curve and the green data points are from [7] and [3] respectively. The upper two ratios are for ^{236}U(d,pf)/^{238}U(d,pf) . The top curve is the ratio of ^{236}U(n,f)/^{238}U(n,f) from ENDF-B6.

CONCLUSIONS

The results of two surrogate reactions measurements have been presented. In the first case, excellent agreement is observed between neutron decay probabilities inferred from discrete γ-ray yields for ^{3}He-induced reactions and statistical model calculations of neutron-induced reactions leading to the same intermediate nucleus. In the second case, the ^{236}U(d,pf)/^{238}U(d,pf) ratio matched the evaluated ^{236}U(n,f)/^{238}U(n,f) ratio over a wide range of energy. We have then used the ^{238}U(d,d'f)/^{236}U(d,d'f) ratio to deduce the ^{237}U(n,f)/^{235}U(n,f) fission cross section over an unprecedented range of surrogate energy. These results indicate that the that the surrogate reaction technique holds significant promise as a tool to deduce neutron-induced cross sections for reactions that are difficult to quantitatively predict or measure. However, additional theoretical and experimental work is needed to determine the limits of the surrogate reaction approach.

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