Neutron capture on short-lived nuclei via the surrogate (d,pγ) reaction

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Abstract. Rapid *r*-process nucleosynthesis is responsible for the creation of about half of the elements heavier than iron. Neutron capture on short-lived nuclei in cold processes or during freeze out from hot processes can have a significant impact on the final observed *r*-process abundances. We are validating the (d,pγ) reaction as a surrogate for neutron capture with measurements on ^{95}Mo targets and a focus on discrete transitions. The experimental results have been analyzed within the Hauser-Feshbach approach with non-elastic breakup of the deuteron providing a neutron to be captured. Preliminary results support the (d,pγ) reaction as a valid surrogate for neutron capture. We are poised to measure the (d,pγ) reaction in inverse kinematics with unstable beams following the development of the experimental techniques.

1 Introduction

Neutron capture is responsible for the synthesis of almost all of the elements heavier than iron. While the slow, *s* process proceeds close to stability, the rapid, *r* process occurs on nuclei far from stability. Studies by Surman and her coworkers [1,2] have demonstrated how unknown (n,γ) rates on nuclei near the *r*-process path, and in particular near closed neutron shells, could have significant impact on predicting abundances with *r*-process network calculations. Constraining (n,γ) rates could also serve to inform our knowledge of the site of the *r* process. This is especially important for synthesis of A≈80 elements [2] where both neutrino-driven winds from core-collapse supernovae and neutron-star mergers could be sites for nucleosynthesis.

Neutron capture reactions have been studied for decades. The importance of these studies has been highlighted in the long series of (Neutron) Capture Gamma-Ray Spectroscopy symposia over the past 38 years. More recently, the techniques [e.g., 3] have been developed to measure (n,γ) reactions on rare isotopes with relatively long half lives (>100 days) where the need to suppress the decay radiation is critical. However, all of the *r*-process waiting point isotopes have very short half lives, and for many are not even known

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to exist. The *r*-process path is characterized by isotopes where (n,γ) and (γ,n) reactions are in equilibrium and the neutron separation energies are typically ≈3.5 MeV. Most *r*-process scenario environments are hot, with temperatures of $T>10^9$ K and high neutron densities, $>10^{20}$ n/cm^3. However, in cold scenarios, and especially in freeze out from hot scenarios, the environments are no longer characterized by (n,γ) ⇔ (γ,n) equilibrium. These are conditions where (n,γ) on daughters of the *r*-process waiting points become important. Unknown (n,γ) rates on specific nuclei, especially near neutron shell closures, have been shown by Surman and colleagues to significantly impact the final observed *r*-process abundances [1,2]. Measurements of (n,γ) reactions on scores of unstable nuclei near the r-process path are required to constrain models of *r*-process nucleosynthesis, including freeze out from hot processes.

The neutron is unstable – therefore it will probably always be impossible to measure (n,γ) reactions directly on key nuclei that live for << 100 days. The only way to deduce (n,γ) cross sections will be via a validated surrogate for these reactions and with accelerated radioactive ion beams. The present manuscript outlines the status of the validation of a very promising surrogate for neutron capture: the (d,pγ) reaction.

2 (d,pγ) as (n,γ) surrogate

Neutron capture can be modelled by using an optical model to calculate the entrance n+A system that forms the compound nucleus at a given excitation energy and spin-parity and a Hauser-Feshbach (HF) approach to model the decay. The (n,γ) cross section can then be written as [4]:

$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E_{ex},J,\pi) G_\gamma^{CN}(E_{ex},J,\pi) \qquad (1)$$

The formation of the n+A compound nucleus (CN), σ_n^{CN}, and decay of the compound nucleus, $G_\gamma^{CN}(E_{ex},J,\pi)$, need to be determined. While the optical model used to calculate σ_n^{CN} is robust, the level density and gamma-ray strength function models needed to calculate the HF decay are on less solid footing, especially away from stability and as the nucleus becomes less bound. A surrogate reaction is chosen to form the same compound nucleus, with character as close as possible to the desired n+A system. The reaction framework must compensate for the differences between the desired and surrogate reactions. The measured gamma-ray decay of the surrogate CN then provides the information needed to calculate the level density (LD) and gamma-ray strength function (GSF) that reproduce the surrogate data and provide input to calculate G_γ^{CN} in equation 1.

Gregory Potel and coworkers [5] have recently demonstrated that the (d,p) reaction is an excellent candidate for forming a compound nucleus that is a surrogate for the n+A system. Because the deuteron is weakly bound, it can readily break up via both non-elastic and elastic processes. The non-elastic breakup provides a neutron that can be captured by the "target" nucleus with a specific orbital angular momentum transferred. The Potel framework predicts as a function of excitation energy the balance between non-elastic and elastic breakup, as well as the distribution of transferred angular momentum. The (d,p) reaction at ≈7-10 MeV/u (14 to 20 MeV deuteron energy) brings in relatively little angular momentum, typically no more than about ℓ=3, reducing the angular momentum mismatch between the surrogate and desired (n,γ) reaction which is dominated by low ℓ (e.g., ℓ=0,1) capture.

Jutta Escher and coworkers [4] have been developing the protocol for using surrogate discrete gamma-ray spectroscopy as a function of excitation energy to deduce the level density and γ-ray strength function parameters needed to extract (n,γ) cross sections. In the surrogate approach, the LD and GSF formulations needed to calculate the (n,γ) cross section are deduced from the measured gamma-decay probabilities as a function of excitation energy and angular momentum [4]:

$$P_{dp\gamma}(E_x) = \sum_{J,\pi} F_{dp}^{CN}(E_{ex}, J, \pi) G_{\gamma}^{CN}(E_{ex}, J, \pi) \qquad (2)$$

$$P_{dp\gamma_i}(E_x) = {N_{dp\gamma_i}}\Big/{\varepsilon_\gamma N_p} \qquad (3)$$

The left-hand side of eq. 2 is the measured surrogate gamma-ray decay probability deduced from eq. 3 for each transition, the ratio of measured (d,pγ) coincidence to singles proton data as a function of excitation energy, corrected for appropriate efficiencies in the system. Several discrete transitions, from states with different initial angular momenta are used as input. The Potel model [5] is used to calculate the formation of the surrogate compound nucleus, *F*, through non-elastic deuteron breakup; the angular momentum decomposition as a function of excitation energy is taken into account. In the Escher framework, a Bayesian approach is used to deduce the level density and strength function parameters that best fit the data and hence the gamma-decay *G* of the surrogate compound nucleus. This deduced *G* as a function of excitation energy and angular momentum is then used as input into equation 1 to calculate the surrogate (n,γ) cross section, with an optical model used to provide the formation of the (n,γ) CN.

3 Status of (d,pγ) surrogate validation: the ^{95}Mo(d,pγ) reaction

Our collaboration measured the (d,pγ) reaction at the Texas A&M cyclotron with stable ^{95}Mo targets and an array of annular silicon strip detectors and clover Compton-suppressed HPGe detectors, the STARLiTeR system [6]. ^{95}Mo was chosen because the final nucleus is even-even (and therefore a relatively simple gamma-ray spectrum at low excitation energies) and the ^{95}Mo(n,γ) cross section had been measured to ≈200 keV [7,8]. A schematic of the ^{96}Mo level scheme and preliminary spectra from both ^{95}Mo (d,pγ) at TAMU and (n,γ) at LANSCE reaction measurements are presented in Figure 1. In both the (d,pγ) and (n,γ) studies, transitions depopulating low-lying levels (up to 4^+) are dominant with relatively little population of the 6^+ yrast state, and no observation of the 8^+ to 6^+ yrast transition in the (n,γ) reaction. Note that for the $5/2^+$ ^{95}Mo ground state, ℓ=0 capture populates 2^+,3^+ compound nuclear states.

Figure 2 displays preliminary gamma-ray decay probabilities for six states in ^{96}Mo and two states in ^{95}Mo, the (n,n'γ) surrogate that becomes important above the neutron separation energy. The decay probabilities of these ^{96}Mo states are being used by Escher to deduce (n,γ) cross sections, combined with Potel predictions of the non-elastic breakup, and optical model predictions of the n+A compound nucleus formation. Preliminary results reproduce the previously measured and evaluated cross sections [7,8]. The excitation function of the transitions in ^{95}Mo have a similar shape to (n,n'γ) excitation functions measured with E>175 keV neutrons at LANSCE with the GEANIE array [12].

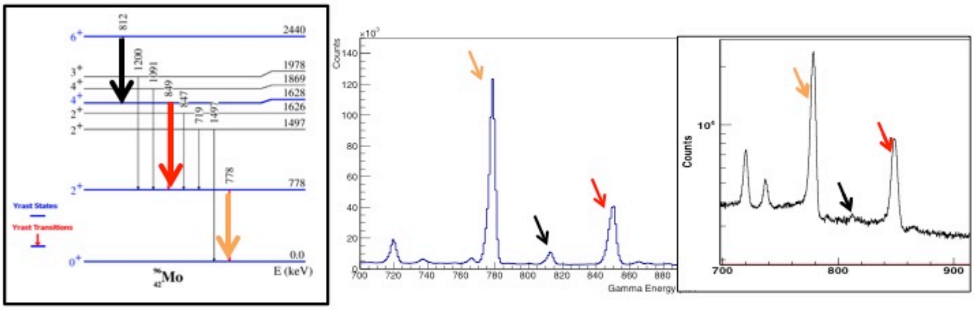

Figure 1. (Left) Schematic of the level scheme of ^{96}Mo. (Center) Preliminary ^{95}Mo(d,pγ) spectrum measured with STARLiTeR. (Right) Preliminary ^{95}Mo(n,γ) spectrum for the 3^+ resonance at 45 eV [9,10] measured on FP12 at LANSCE.

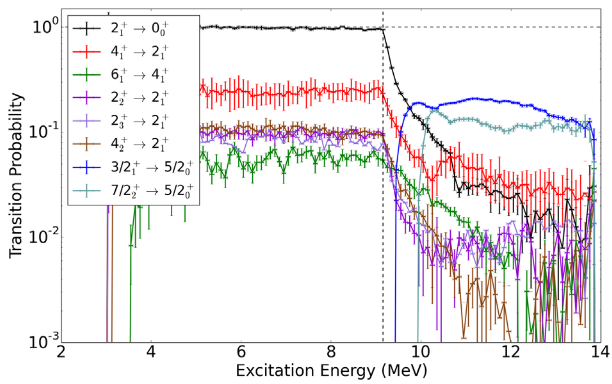

Figure 2. Preliminary gamma-decay probabilities for six states in ^{96}Mo and two states in ^{95}Mo measured with the STARLiTeR system at TAMU. Adopted from [11].

4 Developing techniques to measure (d,pγ) reactions with RIBs

We are part of the Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) collaboration [13] that has developed the techniques to couple the Oak Ridge Rutgers University Barrel Array (ORRUBA) of position-sensitive silicon strip detectors [14] to the Gammasphere array of up to 110 Compton-suppressed HPGe detectors at the ATLAS accelerator at Argonne National Laboratory. The commissioning experiment exploited ^{134}Xe beams with ≈1 mg/cm^2 CD_2 targets to measure excitations in ^{135}Xe including candidates for 2f7/2 and 3p3/2 excitations above the N=82 shell gap. Preliminary results have been reported [13] and show gamma-ray events in coincidence with protons well above the neutron separation energy, the surrogate (n,n'γ) excitation region. ORRUBA can also be coupled to GRETINA [15] and a new LaBr3(Ce)-based Hybrid Array of Gamma-Ray Detectors (HAGRiD) currently being developed under the leadership of the University of Tennessee [16].

5 Summary and conclusions

In summary, we are demonstrating that the (d,pγ) reaction is a valid surrogate for the (n,γ) reaction important in understanding observed abundances in *r*-process nucleosynthesis. The Potel theoretical framework has shown how non-elastic breakup of the deuteron provides a neutron to be captured in the (d,p) reaction and predicts the decomposition of the transferred angular momentum as a function of excitation energy. The framework developed by Escher [4] is used to take extracted gamma-ray decay probabilities for several discrete transitions as a function of excitation energy to model level density and gamma-ray strength functions needed as input to predict gamma decay of the n+A compound nucleus calculated with an optical model. The techniques to measure (d,pγ) reactions with RIBs have been developed. First experiments with N≈82 nuclei near the *r*-process path of nucleosynthesis are being planned.

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