Prospects for surrogate neutron capture measurements with radioactive ion beams and GODDESS

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Abstract. Neutron capture reactions are responsible for the synthesis of almost all of the elements heavier than iron through s-process and r-process nucleosynthesis. Uncertainties in (n,γ) rates on neutron-rich nuclei can have significant impact on the predictions of observed r-process abundances for different astrophysical scenarios. The (d,pγ) reaction has recently been demonstrated to be a valid surrogate for (n,γ). This reaction has been measured in inverse kinematics with Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) where the Gammasphere array of Compton-suppressed HPGe detectors is coupled to the Oak Ridge Rutgers University Barrel Array (ORRUBA) of position-sensitive silicon-strip detectors. Preliminary results from the (d,pγ) measurement with ^{134}Xe beams are reported.

Keywords: Neutron-transfer reactions, radioactive-ion beams, neutron capture.

1 Introduction

The neutron capture (n,γ) reaction is responsible for the synthesis of almost all of the elements heavier than iron. The slow s-process proceeds close to the line of nuclear stability. In contrast, waiting points for the rapid neutron capture r-process are very neutron-rich isotopes far from stability. Reproducing the observed r-process abundance pattern is a sensitive measure of the astrophysical r-process site(s) and requires knowledge of the properties of and (n,γ) reaction rates on isotopes near the waiting points, nuclei far from stability and with very short half lives [Mum16].

Understanding (n,γ) rates near the r-process path is especially challenging because this reaction can not be measured directly, because short-lived ($t_{1/2}$<<100 days) targets cannot be manufactured and the lack of a pure neutron target for studies with radioactive ion beams. Near the N=82 shell closure at ^{132}Sn, neutron capture is dominated by direct-semi-direct (DSD) capture that depends sensitively on the excitation energies and spectroscopic factors of the $3p_{1/2}$ and $3p_{3/2}$ neutron configurations. These properties have been measured [Jon10,Koz10,Man19] in (d,p) reactions with radioactive ion beams of ^{132,130,128,126}Sn and the DSD capture cross sections as a function of neutron energy have been deduced [Koz10,Man19]. While the $^{132}Sn(n,\gamma)$ cross section is expected to be dominated by DSD capture, for N<82 isotopes the contribution from statistical capture, modeled in a Hauser-Feshbach formalism, is expected to dominate over DSD processes [e.g., Chi08]. Therefore a validated surrogate for neutron capture is required to deduce the (n,γ) rate.

The neutron transfer (d,pγ) reaction has recently been demonstrated to be a valid surrogate for neutron capture [Rat19]. The (d,p) reaction can also inform DSD capture. To deduce the (n,γ) cross section, the γ-decay probabilities as a function of excitation energy of several discrete gamma-ray transitions are measured. The measured decay probabilities are fit with level density and gamma-ray strength function models [Esc18] with (d,p)-induced compound nucleus formation and spin-parity weights calculated from non-elastic breakup of the deuteron [Pot16]. Surrogate (d,pγ) measurements require a radioactive ion beam of intensity $>10^4$ pps, a large solid angle, segmented array of charged particle detectors, and a high-efficiency gamma-ray detector array.

2 GODDESS and ^{135}Xe

Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies (GODDESS) [Pai17] was commissioned in 2015 at Argonne National Laboratory. Gamma radiation was measured with the 110-detector Gammasphere array of Compton-suppressed HPGe detectors coupled to the Oak Ridge Rutgers University Barrel Array (ORRUBA) of position-sensitive silicon-strip detectors [Pai07]. Accelerated beams of ^{134}Xe and ^{95}Mo from the ATLAS accelerator interacted with CD_2 targets. Both charged-particle singles and particle-gamma coincidence events were recorded. The rectangular position-sensitive silicon-strip SX3 detectors of the ORRUBA barrel were supplemented with pie-shaped, highly-segmented QQQ5 detectors that formed annular arrays mounted at angles upstream and downstream of the ORRUBA barrel. At forward angles both the QQQ5 and many of the SX3 detectors were mounted in a ΔE-E telescope to enable particle identification.

Preliminary particle-energy as a function of laboratory angle data with the ^{134}Xe beam are displayed in Figure 1. At the largest laboratory angles (that correspond to the most forward center of mass (c.m.) angles for the (d,p) reaction), only (d,p)-reaction protons are expected to be observed. Forward of 90° in the laboratory, the spectrum is dominated by elastic scattering on the CD_2 target. Angular distributions of reaction protons at smaller lab (larger c.m.) angles can be deduced from proton particle identification with ΔE-E telescopes. The red dotted lines are kinematic curves expected for ground and new $E_x>2.0$ MeV states. The gap in counts between the ground and $E_x>2.0$ MeV states in ^{135}Xe corresponds to the gap in excitations below and above the N=82 shell closure.

A preliminary, partial level scheme of ^{135}Xe is displayed in Figure 1. The states at 2.04 and 2.40 MeV are likely $7/2^-$ and $3/2^-$ states with significant $2f_{7/2}$ and $3p_{3/2}$ strength, respectively. These assignments are consistent with their decay patterns, preliminary angular distributions of the proton data, and systematics of the N=81 isotone ^{131}Sn. The states at 2.83 and 3.11 MeV have highly tentative $1/2^-$ and $5/2^-$ assignments based on systematics and the decay pattern. Gamma rays in ^{134}Xe, the surrogate (n,n'γ) nucleus, are observed for proton gates above the neutron separation energy.

Analysis of the ^{134}Xe(d,pγ) reaction is ongoing and will include proton angular distribution analysis to support the tentative J^{π} assignments. It is unlikely that there will be sufficient statistics in this commissioning experiment to deduce a surrogate (n,γ) cross section. We anticipate that there will be sufficient statistics in the subsequent measurement with ^{95}Mo beams for a surrogate (n,γ) analysis, as well as an extension of the ^{96}Mo level scheme.

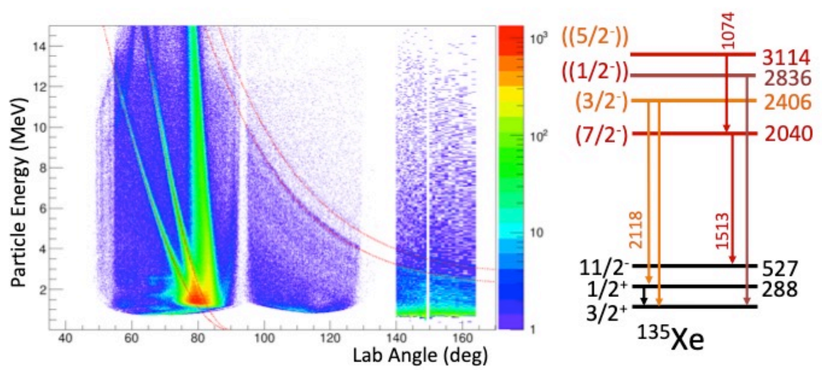

Figure 1. (Left) Histogram of particle energy vs lab angle for the ^{134}Xe + CD_2 measurement. Kinematic curves (red dotted) for the ground and ≈2 MeV states in ^{135}Xe (angles >80°) and deuteron and proton elastic scattering (angles <90°) are indicated. (Right) Preliminary partial level scheme for ^{135}Xe with transitions measured with Gammasphere and deduced from particle-gamma coincidences. Only the $3/2^+$ ground and $1/2^+$ 288-keV states and $t_{1/2}$ 15-min $11/2^-$ 527-keV isomer were known. The states at 2040 and 2406 keV are likely $(7/2^-)$ and $(3/2^-)$ states, respectively, based on the preliminary analysis. The states at 2836 and 3114 keV are assigned highly tentative $((1/2^-))$ and $((5/2^-))$ J^{π} values, respectively, based on systematics and the decay pattern. Additional analysis is required before more definite spin-parity values can be assigned.

3 Summary and Future Prospects

Techniques to measure the (d,pγ) reaction with radioactive ion beams have been developed with GODDESS: the coupling of ORRUBA to a high-efficiency gamma-ray detector array. Preliminary results from the commissioning experiment with ^{134}Xe beams identify for the first time excitations in ^{135}Xe above the N=82 shell gap. The analysis of the ^{95}Mo(d,pγ) reaction is proceeding. We are approved to measure the (d,pγ) reaction as a surrogate for (n,γ) with ORRUBA coupled to the GRETINA [Fal16] gamma-ray detector array. Fission fragment ^{143}Ba and ^{80}Ge beams would be deployed, the latter to inform neutron capture for (weak) r-process nucleosynthesis.

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