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Neutron capture surrogate reaction on ^{75}As in inverse kinematics using (d,pγ)

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Abstract. The ^{75}As(d,pγ) reaction in inverse kinematics as a surrogate for neutron capture was performed at Oak Ridge National Laboratory using a deuterated plastic target. The intensity of the 165 keV γ-ray from ^{76}As in coincidence with ejected protons, from exciting ^{76}As above the neutron separation energy populating a compound state, was measured. A tight geometry of four segmented germanium clover γ-ray detectors together with eight ORRUBA-type silicon-strip charged-particle detectors was used to optimize geometric acceptance. The preliminary analysis of the ^{75}As experiment, and the efficacy and future plans of the (d,pγ) surrogate campaign in inverse kinematics, are discussed.

1 Introduction

Surrogate reactions are used to populate compound nuclear states through an alternate (and often easier to perform) process than the desired reaction of interest. This is especially true for neutron capture reactions on short-lived nuclei. Since a target of radioactive material leads to detector overload and high background, neutron capture experiments cannot currently be done for nuclei with a half life less than 100 days. Further complicating the issue is the inability to have a neutron target for use with rare isotope beams. Neutron capture measurements away from the valley of stability necessitate a surrogate approach in inverse kinematics.

Within the Hauser-Feshbach formalism [1], the cross section for the desired reaction is written as:

$$\sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi) \qquad (1)$$

where α and χ denote the entrance and exit channels, respectively. The energy in the center-of-mass of the entrance channel, E_a, determines the excitation energy, E_{ex}, of the compound nucleus. σ_{α}^{CN} is the cross section for forming the compound nucleus, and G_{χ}^{CN} is the decay probability to channel χ. Both are dependent on E_{ex}, J (spin), and π (parity).

Optical models can be used to reasonably calculate the formation cross section, σ_{α}^{CN}, while the decay probability to a specific channel requires knowledge of optical models, level density, and strength functions for several possible exit channels [2]. Experiments can attempt to measure the decay probability to channel χ by populating the same compound nucleus through a surrogate reaction. The experiment records the coincident probability of creating the compound nucleus through the alternate entrance channel (δ) together with the desired exit channel (χ):

$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi). \qquad (2)$$

Here, F_{δ}^{CN} is the probability that the compound nucleus was formed (with a given (E_{ex}, J, π)). With this method, $P_{\delta\chi}(E_{ex})$ can be measured, F_{δ}^{CN} is calculated, and then the result, $G_{\chi}^{CN}(E_{ex}, J, \pi)$, can be used in Equation 1.

Experimentally, other challenges arise when trying to populate the same compound nucleus in the surrogate reaction as in the desired reaction, with respect to spin, parity, and energy [3]. The Weisskopf-Ewing approximation [4,5] to Equation 1,

$$\sigma_{\alpha\chi}^{WE}(E_a) = \sigma_{\alpha}^{CN}(E_{ex}) G_{\chi}^{CN}(E_{ex}), \qquad (3)$$

is independent of spin and parity. It now follows that $P_{\delta\chi}(E_{ex})$, measured by the surrogate experiment, is equal to $G\chi^{CN}(E_{ex})$, and can be used to determine $\sigma_{\alpha\chi}^{WE}(E_a)$. In practice, the

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Weisskopf-Ewing approximation is not valid for many cases and substantial theoretic work is still required to account for the spin-party mismatch between the desired reaction and the surrogate.

2 Motivation

Arsenic has been used as a neutron fluence monitor, often called radiochemical detector, in underground nuclear tests to measure the amount of high-energy neutrons that induce (n,2n) reactions on stable ^{75}As. The products of these reactions are the neutron-deficient arsenic isotopes, ^{73}As($t_{1/2}$=80 d) and ^{74}As($t_{1/2}$=18 d) that are later retrieved and the ratio of ^{73}As/^{74}As is determined from $\beta - \gamma$ decay counting. To a first approximation, at low to moderate neutron fluences, the isotopic ratio is given by

$$^{73}\mathrm{As}/^{74}\mathrm{As} = (1/2)\sigma_{(\mathrm{n,2n})}\phi_{\mathrm{n}} \quad (4)$$

where $\sigma_{(\mathrm{n,2n})}$ is the cross section for the ^{74}As(n,2n) reaction at 14 MeV and ϕ_{n} is the 14-MeV neutron fluence (flux integrated over time). However, this simple interpretation is modified by neutron-capture reactions that are induced by fission spectrum neutrons (peaking at 1 MeV and falling off exponentially at higher energies) and by downscattered neutrons that extend down to low energies (keV or lower). Therefore, analogous to understanding isotopic abundances for nuclear astrophysics, a careful production and destruction reaction network calculation must be performed to obtain the correct neutron fluence.

While Hauser-Feshbach codes, such as GNASH [6], can often calculate (n,2n) cross sections reasonably accurately (to the 10-20% level), neutron capture cross sections are notoriously difficult to estimate (with common uncertainties in the 100-200% range) due to their strong optical model and level density dependencies.

At Los Alamos National Laboratory, new neutron capture cross section measurements on ^{75}As have been recently performed [7] using DANCE (Detector for Advanced Neutron Capture Experiments) [8]. The only possible way to get a measurement of the ^{74}As(n,γ) cross section, and perhaps for ^{73}As(n,γ) as well, is to use a surrogate reaction, such as (d,pγ). This first experiment was done with the stable ^{75}As to gauge the viability of the experimental technique and the application of the Weisskopf-Ewing formula before applying it to radioactive nuclei. We chose to use the (d,p) reaction to populate the compound nucleus ^{76}As because it is expected to bring in less angular momentum than other reactions, similar to the desired neutron capture reaction. Furthermore, if the technique proves viable, this method is ideal for inverse kinematic studies of other nuclei far from stability that are important for the r-process and stockpile stewardship science.

Recent work [9] indicates that the (d,pγ) reaction can be used as a surrogate for (n,γ) by measuring the ^{171,173}Yb(d,pγ) reactions (in normal kinematics) and comparing the ratio of cross sections with measurements of the actual (n,γ) cross section ratios [10]. Preliminary results are consistent with the deduced (n,γ) cross sections of no greater than 15% for neutron energies above 150 keV.

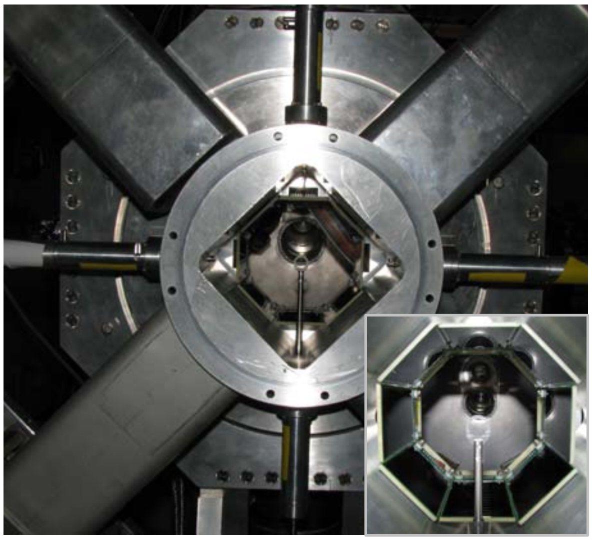

Fig. 1. Picture of experimental setup for the ^{75}As(d,pγ) experiment showing the tight geometry of the square target chamber surrounded by four germanium clovers covering the four sides. The inset shows a close-up view of the 8 silicon-strip detectors inside the 5 inch square target chamber.

3 Experimental details

The experiment was performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL) in Tennessee. A stable beam of ^{75}As was accelerated through the 25 MV tandem with a total energy of 530 MeV. A beam of 10^7 pps impinged on a deuterated plastic target (CD_2) 400 μg/cm^2 thick. Charged particles were detected at backward angles between 90 and 140 degrees using ORRUBA-type resistive-strip silicon detectors [11]. These detectors measured the energy and position of the ejected protons. The coincident γ-rays were detected by four segmented high-purity germanium clover detectors (part of the CLARION array [12]) for a total of sixteen segmented crystals, in a close-packed geometry.

Figure 1 is a photograph of the setup with four germanium clovers outside of a central target chamber (5 inches square). Inside the chamber, eight ORRUBA-type silicon detectors formed an octagon centered around the target. They were placed at backward angles to select only ejected protons from the (d,p) reaction and to avoid any elastically scattered deuterons or carbon atoms.

The proton angles were calculated from the position of the hit on the strip with a resolution ranging from 3° near 90° to 1.5° at more backward angles near 135°. The efficiency of all the γ-ray detectors was 10.4% at the 165 keV energy of interest. One week of beam time yielded over 10^6 proton events in each strip of ORRUBA detector to compare to γ coincidences.

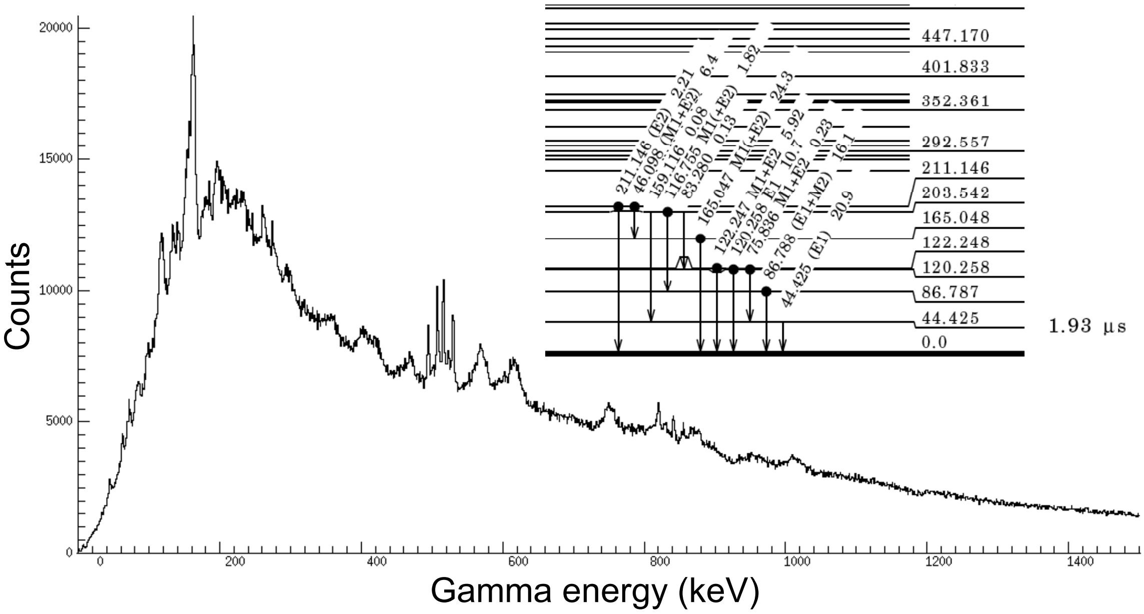

Fig. 2. Doppler corrected γ-ray spectrum in coincidence with charged particle events detected in the silicon detector array. The inset shows the evaluated gamma-cascade intensities for gamma transitions following thermal neutron capture on ^{75}As [13] above the neutron separation energy of 7.33 MeV in ^{76}As.

4 Preliminary analysis

Earlier measurements [13] of the thermal neutron capture on ^{75}As reveal that 24% of the γ-ray cascade flows through the 165 keV transition to the ^{76}As ground state. We use this transition to tag our γ-ray coincident data. The sixteen segmented germanium crystals each recorded about 10^6 counts. Each crystal is segmented into two halves, symmetric about the target position. Doppler correction was done on each crystal, and the final resolution of the γ-ray spectrum was 6 keV (FWHM) at 165 keV. Since the event trigger originated from the charged-particle detectors, every Ge detector event is coincident with a detected particle in the ORRUBA-type detectors. The γ-ray spectrum is shown in Figure 2 with a prominent 165 keV peak. The inset shows the evaluated intensities to various levels in ^{76}As following thermal neutron capture on ^{75}As [13].

4.1 Background subtraction

Proton energy as a function of laboratory angle histograms, shown in Figure 3, display a clear onset of the distinctive kinematic curve where the (d,p) channel opens up (less proton energy at a given angle corresponds to higher excitation energy). The background events above this curve most likely come from evaporated protons following fusion reactions of the beam with carbon present in the target. The compound nucleus following fusion is ^{87}Y at 50 MeV. Fusion-evaporation simulations [14] predict that, on average, about 2 neutrons and one proton are evaporated, with sizeable cross sections for protons at back angles. Since the cross section for fusion is much greater than for (d,p), a separate experiment with a natural carbon target was measured. A faint horizontal line is seen due to 5.8 MeV alphas from a ^{244}Cm-alpha source contamination inside the target chamber. The carbon-target data, shown in Figure 4, illustrates the overlap of these evaporated protons with the desired (d,p) protons.

We are in the process of subtracting the protons from the carbon target from the data with the CD_2 target to extract background-subtracted (d,p) proton spectra. Next, the γ-ray spectra in coincidence with (d,p) protons for excitation energies in ^{76}As above the neutron separation energy will be extracted. The intensity of the proton-gated 165-keV transition as a function of excitation energy, corresponding to effective neutron energies, will be used to deduce the decay probabilities of the compound nucleus. These decay probabilities will be combined with Hauser-Feshbach calculations of the compound nucleus formation cross section to deduce a (n,γ) cross section as a function of neutron energy that can be compared to previous measurements [13] and with a recent measurement [7].

5 Future experiments

Given the difficulties in measuring decay probabilities in an odd-odd nucleus and the importance of benchmarking the effectiveness of the (d,pγ) reaction as a surrogate for (n,γ), additional experiments have been approved to run at ORNL next year. The (d,pγ) measurements with beams of ^{57}Fe and ^{95}Mo are planned; these beams were chosen because the final nuclei are even-even and the (n,γ) cross sections up to $\approx$200 keV have been measured [13]. In addition to measuring the intensity collected in the $2^+ \rightarrow 0^+$

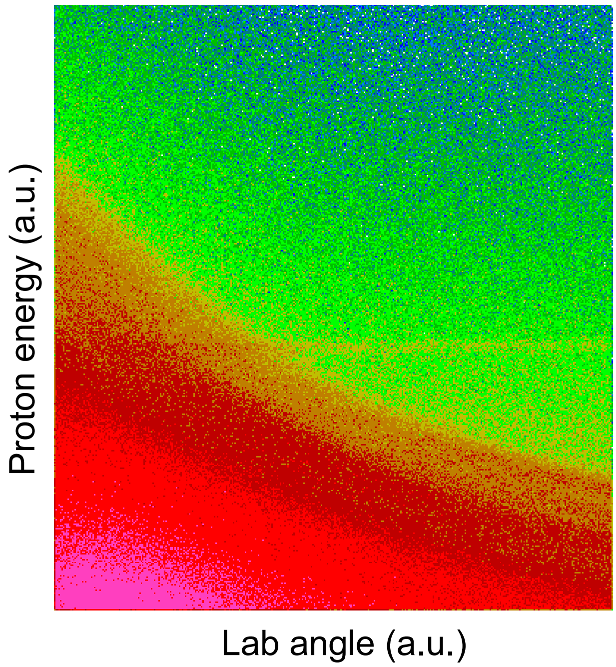

Fig. 3. Energy versus angle of ejected protons from the CD_2 target. Angular range is between 97° and 135°.

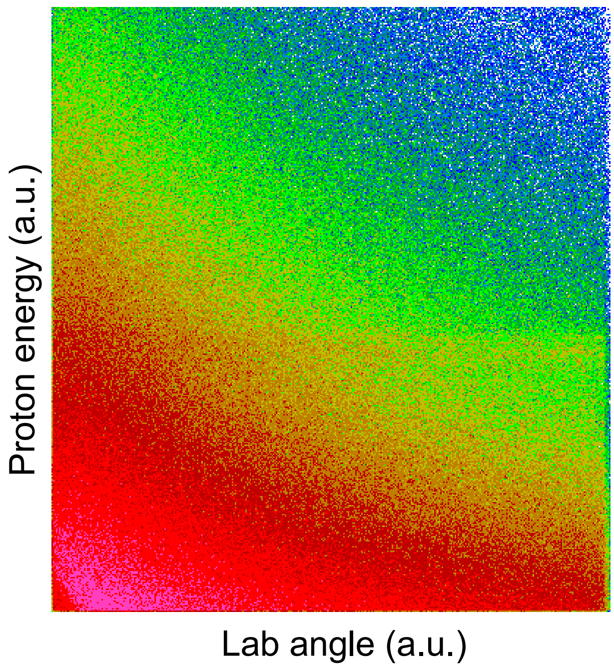

Fig. 4. Energy versus angle of ejected protons for the carbon target. Angular range is between 97° and 135°.

ground state transition, we plan to measure the decay from the 6^+ and 4^+ states to determine the angular momentum distributions in the (d,p) reaction, which would be compared to the angular momentum distributions expected for (n,γ) reactions. This will be used to investigate the angular momentum mismatch issue in the entrance channel of the compound nucleus.

Experimental enhancements are also planned. In particular, recoils from the (d,p) reaction will be identified either via time of flight, by using a gas-filled ion chamber, or with a recoil spectrometer.

Finally, the analysis of this ^{76}As experiment, as well as the upcoming ^{57}Fe and ^{95}Mo (d,pγ) experiments, will serve as benchmarks and address some of the yet unresolved issues of the (d,pγ) surrogate technique in inverse kinematics.

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