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First (p,n) reaction measurement in inverse kinematics with SECAR

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Abstract. Nucleosynthesis in the νp-process occurs in regions of slightly proton-rich nuclei in the neutrino-driven wind of core-collapse supernovae. The process proceeds via a sequence of (p,γ) and (n,p) reactions, and depending on the conditions, may produce elements between Ni and Sn. Recent studies show that a few key (n,p) reactions regulate the efficiency of the neutrino-p process (νp-process). We performed a study of one of such (n,p) reactions via the measurement of the reverse (p,n) in inverse kinematics with SECAR at NSCL/FRIB. Such proton-induced reaction measurements are particularly challenging, as the recoils and the unreacted projectiles have nearly identical masses. An appropriate separation level can be achieved with SECAR, and along with the in-coincidence detection of neutrons these measurements become attainable. The preparation of the SECAR system for accommodating its first (p,n) reaction measurement, including the development of alternative ion beam optics, and the setup of the in-coincidence neutron detection, along with discussion on preliminary results from the p(^{58}Fe,n)^{58}Co reaction measurement are presented and discussed.

1 Introduction

Production of most of the stable neutron deficient isotopes has traditionally been attributed to the p-process [1]. Advances in the the modeling of the core collapse of Supernovae have

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shown that neutrino-driven winds immediately after the collapse may be proton-rich [2]. As such, a neutrino (νp) process [3] has been postulated as a possible source of abundances of those isotopes. The strong neutrino fluxes allow for electron anti-neutrino absorption on protons to produce a small residual neutron density. These neutrons are then captured via (n,p) reactions bypassing the typical reaction-flow slow-down due to the decay of nuclei with relatively long β-decay half-lives (such as the ^{56}Ni and ^{64}Ge) [4, 5]. Research efforts to develop a suitable technique to experimental constrain (n,p) and (p,n) reaction rates of short-lived nuclei [6] are underway at FRIB (Facility for Rare Isotope Beams). The measurement of the ^{58}Fe(p,n)^{58}Co reaction in inverse kinematics at SECAR (SEparator for CApture Reactions) described in this work is a recent effort in that direction.

2 The SEparator for CApture Reactions - SECAR

SECAR at NSCL/FRIB, consists of 8 dipole (B1-B8), 15 quadrupole (Q1-Q15), 3 hexapole (Hex1-Hex3), 1 (Oct1) octupole magnets, and 2 Wien filters (WF1-WF2). It has been designed with the required sensitivity to study (p,γ), and (a,γ) reactions, directly at astrophysical energies in inverse kinematics [7]. A first direct measurement of the known ^{58}Fe(p,n)^{58}Co reaction [8] was recently attained in inverse kinematics with SECAR and demonstrates that (p,n) cross section measurements are also possible with SECAR.

The ^{58}Fe beam delivered by ReA3/NSCL [9] at 3.8 MeV/u energy, with a charge state of 21^{+}, and an average intensity of 3.0E6 pps impinged on a polyethylene foil located at the SECAR target location [10, 11]. The delivered beam contained ^{58}Ni as a contaminant, estimated at around 20%. A C foil target was also used for background characterization. After a reaction in the target foil, the heavy ion recoils enter the SECAR system, along with the unreacted beam particles. The selection of a single charge state occurs using magnetic analysis in the first couple of dipoles (B1-B2). Two sets of a combination of a dipole pair and a velocity filter follow (B3-B4 and WF1, B5-B6 and WF2, respectively), providing the separation of the recoils from the unreacted projectiles for capture reactions. The final momentum analysis is performed with the last pair of dipole magnets (B7-B8) enhancing the rejection of scattered beam particles ("leaky beam"). The nearly identical masses between recoils and unreacted beam particles in the (p,n) reaction, pose a particular challenge and limit their separation solely to their energy difference. The energy difference between ^{58}Fe and ^{58}Co (as well as with the ^{58}Ni contaminant), mainly due to the reaction threshold, kinematics, and the stopping power effects (e.g. from target), is the only available dissimilarity to exploit via magnetic separation with SECAR.

3 Key components of the (p,n) technique development

Extensive ion-optical calculations were performed, using the COSY Infinity code [12] in multi-objective optimization routines to develop suitable ion optics for (p,n) measurements. The left and right panel at Figure 1 show the characteristic rays in the horizontal and the vertical plane, respectively. The heavy ions exiting the target foil have reached charge state equilibrium therefore, the most abundant charge state of ^{58}Co^{22+} recoils are shown in red, while the unreacted ^{58}Fe^{22+} particles are in blue (both set at the expected energy after the target). The key difference to the standard SECAR beam optics for the study of capture reactions (see Figure 3 in [7]) is the shift of the focal planes further downstream. This method enabled us to achieve sufficient magnetic separation at the position of the mass separation slits. Moreover, the Wien filters were inactive during the (p,n) measurement due to the fact that the difference in the magnetic rigidity of the beam and recoil ions was deemed adequate for their separation.

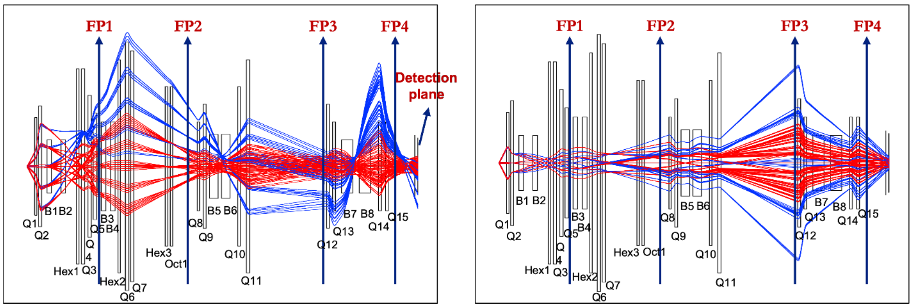

Figure 1. The ion optics of SECAR. The characteristic rays in the horizontal and vertical planes are shown in the left and right panel, respectively. The red lines represent the $^{58}Co^{22+}$ recoils, while the blue ones the unreacted $^{58}Fe^{22+}$ ions. The mass slits at every focal plane were used to cut down the majority of the unreacted beam.

As it can be observed in Figure 1, a small part of the unreacted beam particle distribution (blue lines) is not eliminated from reaching the final focal plane by the magnetic separation and the use of mass slits, yet it could still be discriminated with the use of in-coincidence detection systems. A gas ionization chamber (IC) and a double-sided silicon strip detector (DSSD), installed at the detection plane at the end of SECAR beam-line, provided a ΔE-E particle identification. A new installation of a neutron detection system, at the start of the SECAR beam-line, close to the target location, included four organic liquid scintillators (EJ-301, cylindrical 2x2 inches active volume) in a ring configuration, and 21 LENDA bars (Low-Energy Neutron Detection Array) [13]. These neutron detectors provide crucial neutron-tagging and permit the event-by-event in-coincidence detection between neutrons emitted at the target location and recoils reaching the SECAR final focal plane. The two planar silicon surface barrier detectors of 75 μm thickness and 300 mm^2 active area, located inside the target chamber were used for monitoring beam intensity, via the detection of scattered target particles.

4 Discussion

A preliminary analysis demonstrates that the percentage of the unreacted beam particles and "leaky beam" reaching the detection plane of SECAR does not exceed 0.01%. Therefore, this performance is expected to be sufficient for separating the beam and recoil ions using in-coincidence the neutron and focal plane detection systems. As the analysis is still ongoing, correction factors such as neutron efficiency, transmission, rejection and acceptance of the system, are yet to be determined. The completed work is expected to be presented in a future publication.

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