https://doi.org/10.1051/epjconf/202327913005

A technique for studying (n,p) reactions of astrophysical interest using radioactive beams with SECAR

Pelagia Tsintari[1,9,*], *Georg P. A.* Berg[3,10], *Jeff* Blackmon[6], *Kelly* Chipps[5], *Manoel* Couder[3,10], *Catherine* Deibel[6], *Nikolaos* Dimitrakopoulos[1,9], *Ruchi* Garg[2,8,9], *Uwe* Greife[7], *Kirby* Hermansen[2,8,9], *Ashley* Hood[6], *Rahul* Jain[2,8,9], *Cavan* Maher[2,8,9], *Caleb* Marshall[4,9], *Zach* Meisel[4,9], *Sara* Miskovich[2,8,9], *Fernando* Montes[2,9], *Georgios* Perdikakis[1,2,9], *Jorge* Pereira[2,9], *Thomas* Ruland[6], *Hendrik* Schatz[2,8,9], *Kiana* Setoodehnia[2], *Michael* Smith[5], *Louis* Wagner[2,9], and *Remco G. T.* Zegers[2,8,9]

[1]Department of Physics, Central Michigan University, Mt. Pleasant, MI 48859, USA
[2]Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA
[3]Department of Physics and Astronomy, University of Notre Dame, Notre Dame, IN 46556, USA
[4]Department of Physics & Astronomy, Ohio University, Athens, OH 45701, USA
[5]Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[6]Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA
[7]Department of Physics, Colorado School of Mines, Golden, CO 80401, USA
[8]Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[9]The Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements, Michigan State University, East Lansing, MI 48824, USA
[10]The Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements, University of Notre Dame, Notre Dame, IN 46556, USA

Abstract. The formation of nuclei in slightly proton-rich regions of the neutrino-driven wind of core-collapse supernovae could be attributed to the neutrino-p process (νp-process). As it proceeds via a sequence of (p,γ) and (n,p) reactions, it may produce elements in the range of Ni and Sn, considering adequate conditions. Recent studies identify a number of decisive (n,p) reactions that control the efficiency of the νp-process. The study of one such (n,p) reaction via the measurement of the reverse (p,n) in inverse kinematics was performed with SECAR at NSCL/FRIB. Proton-induced reaction measurements, especially at the mass region of interest, are notably difficult since the recoils have nearly identical masses as the unreacted projectiles. Such measurements are feasible with the adequate separation level achieved with SECAR, and the in-coincidence neutron detection. Adjustments of the SECAR system for the first (p,n) reaction measurement included the development of new ion beam optics, and the installation of the neutron detection system. The aforementioned developments along with a discussion on the preliminary results of the p(^{58}Fe,n)^{58}Co reaction measurement are presented.

1 Introduction

Advances in the the modeling of the core collapse of supernovae have demonstrated that neutrino-driven winds may be proton-rich immediately after the collapse [1]. As such, a

*e-mail: tsint1p@cmich.edu

neutrino-p (νp) process [2] has been inferred as a possible formation mechanism of neutron deficient isotopes close to the valley of stability. The strong neutrino fluxes allow for electron anti-neutrino absorption on protons to yield a small residual neutron density. These neutrons are then used in (n,p) reactions to overcome the typical reaction-flow delay caused by the nuclei with relatively long β-decay half-lives (such as the ^{56}Ni and ^{64}Ge) [3, 4].

Research efforts for the development of a suitable technique to study and experimentally constrain the (n,p) and (p,n) reaction rates of short-lived nuclei [5] are ongoing 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 the most recent experimental effort towards this direction.

2 The SECAR system

The SEparator for CApture Reactions at NSCL/FRIB, is a sequence of a total of 8 dipole (B1-B8), 15 quadrupole (Q1-Q15), 3 hexapole (Hex1-Hex3), 1 octupole (Oct1) magnets, and 2 velocity filters (WF1 and WF2). It has been designed with the appropriate sensitivity to study capture reactions in inverse kinematics of astrophysical interest [6]. A first direct measurement of the known ^{58}Fe$(p,n)^{58}$Co reaction [7] in inverse kinematics with SECAR demonstrates the capability of the system to accommodate such cross section measurements.

A polyethylene foil placed at the beginning of the SECAR beam-line was irradiated with a $^{58}Fe^{21+}$ beam at 3.8 MeV/u energy, and an average intensity of 3.0x10^6 pps, that was delivered by ReA3/NSCL [8]. It also included a 30%, on average, contamination of $^{58}Ni^{21+}$ ions. In addition, a carbon target foil was used for background characterization.

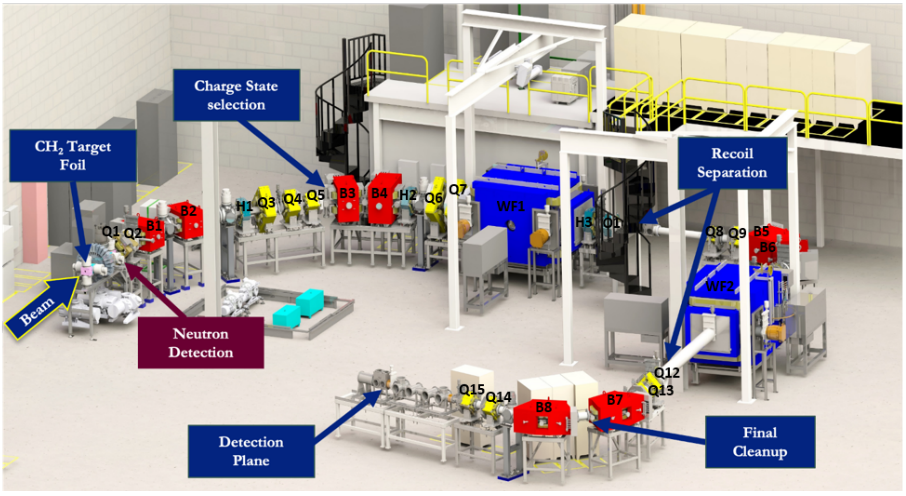


Figure 1. The SECAR layout. Beam enters SECAR at the target location, shown on the left of the picture. A neutron detection system surrounds the target. It is constituted of four liquid scintillators (EJ-301, 2x2 inch) in a ring configuration, and 21 LENDA bars (Low-Energy Neutron Detection Array) [10]. Thereafter, the consecutive sequence of dipole pairs, focusing magnetic elements, and velocity (Wien) filters follows, aiming to separate the recoils from the unreacted projectiles. Note that the Wien filters fields were not used for this measurement as the difference in magnetic rigidity was deemed adequate for separation. Refer to Section 2 for a detailed description of the system.

As the $^{58}Fe^{21+}$ ions impinge the target foil, both the heavy-ion recoils and the unreacted beam particles enter SECAR shown in Figure 1. Since all the ions going through the target

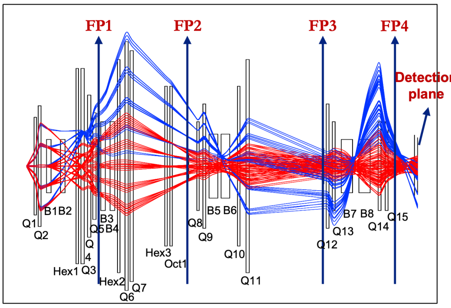
 https://doi.org/10.1051/epjconf/202327913005

reach charge-state equilibrium, the selection of a single charge state occurs using magnetic analysis in the first couple of dipoles (B1-B2). Thereafter, a consecutive sequence of two dipole pairs and velocity (Wien) filters follow (B3-B4 and WF1, B5-B6 and WF2, respectively), separating the recoils from the unreacted projectiles. An additional pair of dipole magnets (B7-B8) performs a final momentum analysis for the rejection of scattered beam particles ("leaky beam"), near the end of the SECAR beam-line. Although the Wien filters provide the necessary separation for radiative capture reaction studies, the magnetic rigidity difference between the beam and recoils for the (p,n) measurement was sufficient and the Wien filters fields were set to zero.

3 Experimental details

The separation between the recoils and unreacted beam particles from a (p,n) reaction, is limited solely to their energy difference as they have nearly identical masses. More specifically, the energy difference between the ^{58}Fe and ^{58}Co ions (as well as with the ^{58}Ni contaminant), originates from the reaction threshold, kinematics, and energy-loss effects from target.

The standard SECAR ion optics, specifically designed for radiative capture studies [6], was modified to accommodate for the requirements for the (p,n) measurement. The code COSY Infinity [9] with multi-objective optimization routines was used to find the best SECAR tune. In Figure 2 characteristic rays in the horizontal and the vertical plane, are shown in the left and right graph, respectively. The red lines represent the ^{58}Co^{22+} recoils, while the unreacted ^{58}Fe^{22+} particles are in blue (both ions were assumed to have a charge-state distribution that is in equilibrium and mean calculated energy after the target). The notable difference compared to the standard SECAR beam optics (see Figure 3 in [6]) is the deflection of the beam observed at the four focal planes (FP1-FP4 in Figure 2). This shift provided a sufficient magnetic separation at the original positions of the focal planes (FP1-FP4) and enabled us to use the existing slits at those focal planes to achieve an adequate beam rejection.



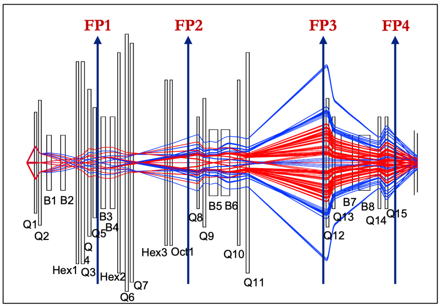


Figure 2. The ion optics of SECAR for the (p,n) measurement. The characteristic rays in the horizontal and vertical planes are shown in the left and right panel, respectively. The red lines represent the ^{58}Co^{22+} recoils, and the blue ones the unreacted ^{58}Fe^{22+} ions. The arrows show the focal plane positions where the existing mass slits were used to cut down the majority of the unreacted beam.

Although, the unreacted beam-particle distribution (central blue lines Figure 2) is not completely rejected, and the "tail" of the distribution may still reach the detection plane, it could still be eliminated with the use of neutron (at the target) - recoil (at FP4) coincidence. A neutron detection system at the start of the SECAR beam-line is installed. It includes four organic liquid scintillators (EJ-301, 2x2 inch) in a ring configuration around the target, and 21 LENDA bars (Low-Energy Neutron Detection Array) [10]. This system was used in-coincidence with the SECAR detection plane that consists of a gas ionization chamber (IC) and a double-sided silicon strip detector (DSSD) acting as a ΔE-E particle identification. The two detection systems allow for an event-by-event in-coincidence detection between neutrons emitted at the target location and recoils reaching the end of SECAR beam-line.

Lastly, the beam intensity was monitored with two fully depleted planar silicon surface barrier detectors of 75 μm thickness and 300 mm^2 active area located inside the target chamber, via the detection of scattered target particles.

4 Discussion

The analysis of the experimental data is still ongoing however, preliminary results show that the unreacted beam particles and "leaky beam" reaching the SECAR detection plane do not exceed 0.01% of the average beam intensity. While this performance is adequate, the essential separation of the recoil ions will emerge from the neutron detection in coincidence with the focal plane detection system.

As the analysis is still progressing, multiple crucial factors are yet to be determined (e.g. neutron efficiency, transmission, rejection and acceptance of the system) for the reaction cross-section calculation to be completed. The complete cross-section calculation along with a detailed description of the method developed of (p,n) measurements with SECAR will be be presented in a future publication.

5 Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Award Number DE-SC0014285. This work was supported by the National Science Foundation through grant no. PHY-2209429. The SECAR project is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-SC0014384 and by the National Science Foundation under grant No. PHY-1624942.

References

[1] T. Fischer, et al., Astronomy and Astrophysics, **517**, A80+, (2010)
[2] C. Froehlich, et al., Phys. Rev. Lett., **96**, 142507, (2006)
[3] S. Wanajo, et al., APJ, **729**, 46, (2011)
[4] A. Arcones, et al., APJ, **750**, 18, (2012)
[5] P. Gastis, et al., Nucl. Inst. Meth. Phys. Res. A, **985**, 164603, (2021)
[6] G. P. A. Berg, et al., Nucl. Inst. Meth. Phys. Res. A, **877**, 87–103 (2018)
[7] S.G. Tims, et al., Nucl. Inst. Meth. Phys. Res. A, **563**, 473-493, (1993)
[8] D. Leitner, Nucl. Inst. Meth. Phys. Res. B., **317**, 235-241, (2013)
[9] M. Berz, COSY Infinity, $http : //www.bt.pa.msu.edu/index_files/cosy.html$
[10] G. Perdikakis, et al., Nucl. Inst. Meth. Phys. Res. A, **686**, 117-124, (2012)