EPJ Web of Conferences **260**, 11044 (2022)
NIC-XVI
https://doi.org/10.1051/epjconf/202226011044

SECAR: A recoil separator for nuclear astrophysics.

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

[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, 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. Proton- and alpha-capture reactions on unstable proton-rich nuclei power astrophysical explosions like novae and X-ray bursts. Direct measurements of these reactions are crucial for understanding the mechanisms behind these explosions and the nucleosynthesis at such sites. The recoil mass separator, SECAR (SEparator for CApture Reactions) at the National Superconducting Cyclotron Laboratory (NSCL) and the Facility for Rare Isotope Beams (FRIB), has been designed with the required sensitivity to study (p,γ) and (α,γ) reactions, directly at astrophysical energies in inverse kinematics, with radioactive beams of masses up to about A = 65. The complete SECAR system, including two Wien Filters for high mass resolution, has been installed at Michigan State University and is currently being commissioned. The present article introduces the SECAR concept, its scientific goals, and provides an update of the current status of the project.

1 Introduction

Exploding stars are laboratories for extreme physics, involving a complex interplay of high temperature thermonuclear burning and hydrodynamics. One of the interesting aspects of these systems are related to the processes by which the chemical elements are created and dispersed by these catastrophic events.

Nova explosions [1] and X-ray bursts [1] are two examples of such explosive astrophysical scenarios. They take place in the dense and hot atmosphere on the surfaces of accreting

---

[*] e-mail: tsint1p@cmich.edu

white dwarfs and neutron stars, respectively. The precise measurements of the reaction cross sections of radiative capture reactions of protons and alpha particles on unstable proton-rich nuclei can potentially address long standing questions associated with the energy generation and the nucleosynthesis occurring in these scenarios.

SECAR (SEparator for CApture Reactions) will allow direct measurements of many of the relevant reactions with proton-rich radioactive beams obtained from ReA3 and FRIB in inverse kinematics (*"i.e."* a heavy, proton-rich radioactive ion beam bombards a hydrogen or helium target). The recoil separation and detection capability enabled by SECAR provides the required sensitivity to detect astrophysical reactions with very low cross sections. SECAR will be used to improve our understanding of the evolution and element creation in these exotic astrophysical sites by enabling direct rate measurements for explosion studies.

2 The SECAR layout

The layout of the SECAR system [3], consisting of a total of 4 sections, is shown in Figure 1. The separator setup begins at the JENSA (Jet Experiments for Nuclear Structure and Astrophysics) chamber [4, 5], where the heavy ion beam enters the high density windowless gas jet target. JENSA is a recirculating gas jet target assembly, providing areal densities up to 10^{19} atoms/cm^2 of hydrogen or helium isotopes in a 4 – 5 mm diameter cylindrical jet.

Section 1 extends from the target to the focal plane 1 (FP1), and is comprised of two dipole magnets (B1–B2), five quadrupoles (Q1–Q5), and one hexapole magnet (Hex1) that allows flexible ion-optical settings and corrections for higher-order aberrations in the beam transport. This section accomplishes the selection of a single charge state, typically the most abundant, using magnetic analysis in B1-B2, and prepares the beam for optimal use of the Wien filter (WF1) in Section 2.

Section 2, between FP1 and FP2, includes two dipole magnets (B3-B4), two quadrupoles (Q6 and Q7), one Wien filter (WF1), two hexapole magnets (Hex2 and Hex3), and one octupole (Oct1). The heavy ion beam and the reaction products have essentially the same magnetic rigidity after the charge state selection and therefore cannot be separated solely by magnetic analysis. A combination of electric and magnetic dipoles is used for the separation of the beam from the reaction products based on their velocity difference. This is achieved with the use of a Wien filter that combines a magnetic and electric field in a ratio chosen such that only the particles with a velocity corresponding to the desired mass follow a straight line, while the rest are deflected off the ion-optical axis.

Following the mass separation of FP2, section 3 consists of two dipole magnets (B5-B6), four quadrupoles (Q8–Q11), and a second Wien filter (WF2), identical to WF1, which provides the required mass resolution at FP3. After a second velocity (mass) separation at FP3, a final momentum analysis is performed in section 4, using two dipole magnets (B7-B8), and four quadrupoles (Q12–Q15). This section enhances the rejection of the background of scattered beam particles and provides a clean environment for the recoil detection at the final focal plane.

Scattered particles ("leaky beam") which are not eliminated by the electromagnetic separation may reach the final focal plane along with the recoils of interest. Two suitable detector systems, are installed at the end of section 4 and at the JENSA chamber, providing a high degree of discrimination between the capture reaction recoils of interest and the background ions. The SECAR detection system at FP4 consists of two microchannel plate detectors (MCP), serving as part of a local time-of-flight (ToF) system, and a hybrid system consisting of a gas ionization chamber (IC) and a double-sided silicon strip detector (DSSD), which provides ΔE-E energy particle identification. The auxiliary detection system at JENSA chamber comprises of a BGO scintillator detector array and two planar silicon detectors. The BGO array is used for the detection of γ-rays from the decay of the compound nucleus formed in the reaction. The two Si detectors, placed symmetrically on both sides of the beam axis, are used for monitoring the beam intensity and the beam-jet overlap by recording scattered target particles.

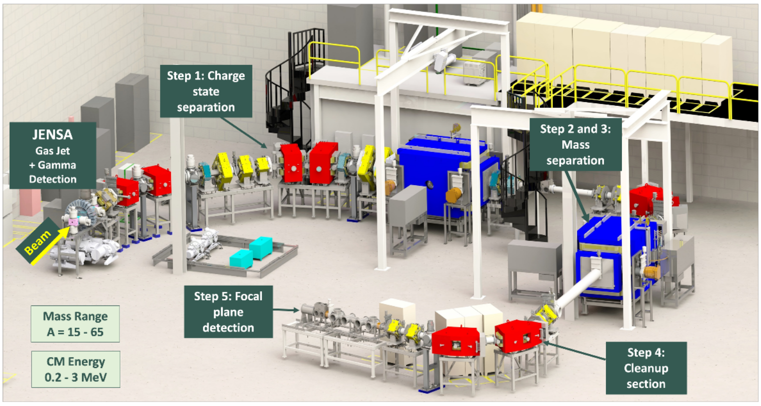

Figure 1. Beam enters SECAR through the JENSA gas jet target system (shown on the left of the picture), where the reaction takes place. γ-Rays, produced from the capture reaction, are detected at the JENSA chamber using an array of BGO detectors. Once a single charge state of the reaction recoils is selected (Step 1), it goes through a Wien Filter (WF1), where the unreacted beam ions are mass separated and eventually stopped using slits (Step 2). The remaining scattered beam particles are separated via the WF2 (Step 3), while the recoils go through a last "clean up" before reaching the detection system (Step 4) at the last focal plane.

Extensive ion-optical calculations and optimizations, using the computer code COSY Infinity [6], were performed to achieve all the design requirements of the SECAR system [3]. Figure 2 shows the ion optics of the SECAR layout that have been optimized and corrected up to the 4^{th} order to be used for (p,γ) and (α,γ) reaction measurements. The upper and lower panel show the characteristic rays in the horizontal and the vertical plane, respectively. The horizontal envelope is relatively large by design, as this is the dispersive plane of the system. The vertical envelope, however, never exceeds ± 6 cm to maximize transmission through the system. Also, a large horizontal envelope is required in the Wien filters to achieve a large mass separation. The system has an achromatic focus at FP2 and a zero energy dispersion focus at FP3. A left–right asymmetry of the envelope about the central ray, which is observed in Figure 2, is mainly due to the effect of the second and third order aberrations. Although more symmetric envelopes could be applied, the imposed reduction of the horizontal good-field region invariably resulted in a reduced mass resolution, therefore an asymmetric envelope was deemed more suitable for the maximization of the mass separation.

3 Commissioning results

A first successful direct measurement of the known strength of the 6.360 MeV resonance in the ^{16}O(α,γ)^{20}Ne reaction [7, 8] was recently attained in inverse kinematics using the full SECAR system. The measurement was obtained using an ^{16}O beam at four different energies, namely 1.986, 1.992, 1.996 and 2.003 MeV/u, at a typical beam intensity of 1.8x10^{8} pps, provided by ReA3. A helium gas jet target was used, with thicknesses of 3.4 and 5.2 x10^{18} at/cm^{2}, which corresponded to beam energy losses of 13 and 20 keV/u, respectively. To

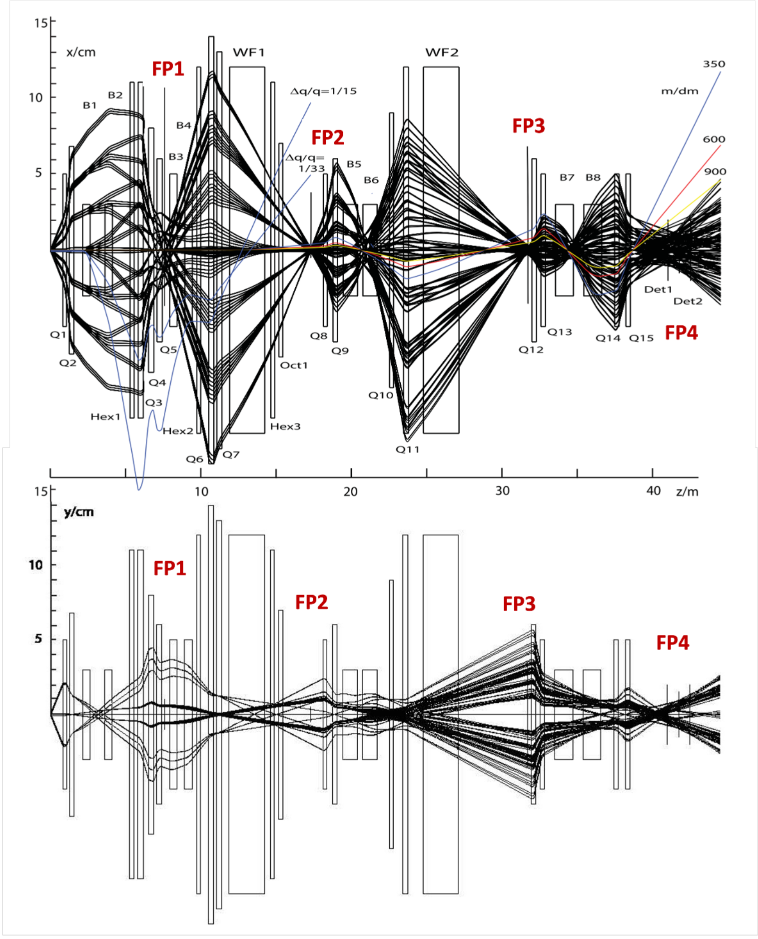

Figure 2. The ion optics of SECAR for the layout shown in Figure 1 is corrected up to the 4^{th} order. The characteristic rays in the horizontal and vertical plane are shown in the upper and lower panel, respectively. The mass resolution in the horizontal plane at FP2 is m/Δm = 510 and at FP3, m/Δm = 780. The picture was obtained from G.P.A. Berg et al., Nuclear Inst. and Meth. in Phys. Res. A, 877, 87–103 (2018).

ensure charge state equilibrium of the ^{20}Ne recoils of interest, a 54 μg/cm^2 C stripper foil was used immediately after the target.

Figure 3 (left) shows all the ions detected at the IC and DSSD detectors at FP4 with SECAR tuned to the 8^+ charge state of the ^{20}Ne recoils. This particle ID plot shows three distinct groups. The reaction recoils were identified as the top right group, while the other two were confirmed as being "leaky beam" particles. The recoil identification was verified by selecting the ions that had a coincident gamma-ray detection at the target location within a 3.2±0.2 μs window in the BGO - Si Time of Flight spectrum. Figure 3 (right) shows the particle ID plot gated on the BGO - Si ToF peak. The γ-ray energy spectrum of these coincident events is shown in Figure 4, where the three peaks corresponding to the decay cascade of the ^{20}Ne 11.09 MeV level can be clearly seen at 1.633, 2.613, and 6.841 MeV.

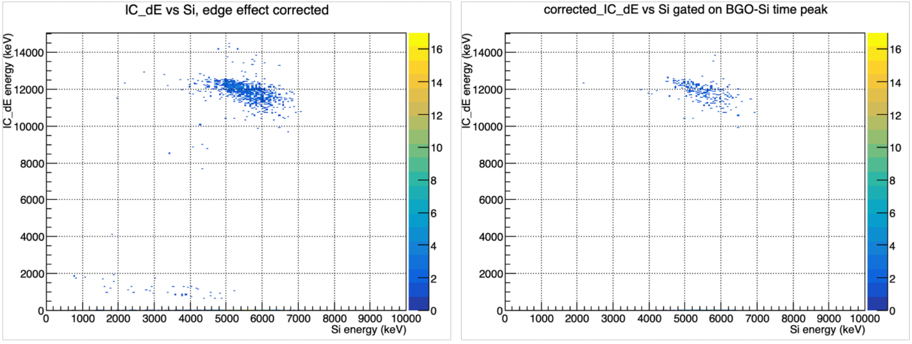

Figure 3. Left: All ions reaching the final focal plane measured with the IC and DSSD detectors (ΔE-E) when SECAR was tuned to the 8^+ charge state of the ^{20}Ne recoils. Three distinctive groups of ions are observed corresponding to recoils and "leaky beam" particles. Right: Same as the left plot, but with the events gated on the BGO - Si time difference peak corresponding to the recoil ToF between the target and the FP4.

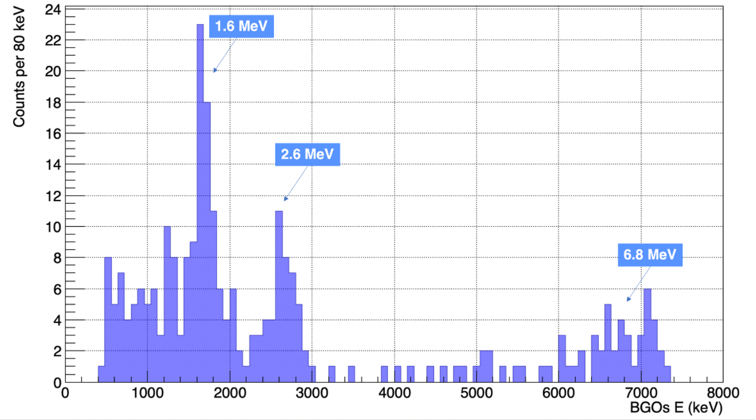

Figure 4. BGO spectrum gated on the events of the BGO - Si time difference peak corresponding to the recoil ToF. The γ-rays of the ^{20}Ne 11.09 MeV level decay cascade can be clearly seen at 1.633, 2.613, and 6.841 MeV.

4 Summary

The new recoil separator, SECAR, at NSCL-FRIB is optimized for measurements of radiative capture reactions (p,γ) and (α,γ) at very low energies of astrophysical interest in inverse kinematics for high intensity short-lived radioactive ion beams, for which such capture reaction measurements in normal kinematics are not feasible. The system is designed to have high transmission of capture reaction recoils and high rejection of scattered unreacted beam particles. With unstable beams from the FRIB facility, it is anticipated that SECAR will enable measurements of thermonuclear reactions critical for our understanding of stellar explosions.

The separation of the beam and reaction products is accomplished by initially selecting one charge state and then transmitting the beam and recoil products having almost identical momenta. Specially designed Wien filters are subsequently used for a high degree (approximately 10-13) of rejection of unreacted scattered beam particles, which is needed to measure the weakest resonances in certain capture reactions. Further background reduction is accomplished in the detector system at the end of the recoil separator.

The successful first direct measurement of the strength of the known 6.360 MeV resonance of the ^{16}O(α,γ)^{20}Ne reaction, demonstrated that all components of SECAR are operational. Also, the detection of the in-coincidence γ-rays at the target were used to confirm the detection of the recoils of interest, at the end of SECAR system. These results indicate that the construction phase is completed, and that the system is ready for further commissioning and measurements with radioactive beams.

References

[1] J. José, M. Hernanz, C. Iliadis, Nuclear Phys. A, **777**, 550-578 (2006)

[2] H. Schatz, K.E. Rehm, Nuclear Phys. A, **777**, 601-622 (2006)

[3] G.P.A. Berg, M. Couder, M.T. Moran, K. Smith, M. Wiescher, H. Schatz, U. Hager, C. Wrede, F. Montes, G. Perdikakis, X. Wu, A. Zeller, M.S. Smith, D.W. Bardayan, K.A. Chipps, S.D. Pain, J. Blackmon, U. Greife, K.E. Rehm, R.V.F. Janssens, Nucl. Inst. Meth. Phys. Res. A, **877**, 87–103 (2018)

[4] K.A. Chipps, U. Greife, D.W. Bardayan, J.C. Blackmon, A. Kontos, L.E. Linhardt, M. Matos, S.D. Pain, S.T. Pittman, A. Sachs, H. Schatz, K.T. Schmitt, M.S. Smith, P. Thompson, Nucl. Inst. Meth. Phys. Res. A, **763**, 553–564 (2014)

[5] K. Schmidt, K.A. Chipps, S. Ahn, D.W. Bardayan, J. Browne, U. Greife, Z. Meisel, F. Montes, P.D. O'Malley, W-J. Ong, S.D. Pain, H. Schatz, K. Smith, M.S. Smith, P.J. Thompson, Nucl. Inst. Meth. Phys. Res. A, **911**, 1-9 (2018)

[6] M. Berz, COSY Infinity, $http://www.bt.pa.msu.edu/index_files/cosy.html$

[7] D. J. Steck, Phys. Rev. C, **17**, 1034-1050 (1978)

[8] L. K. Fifield, et al., Nuclear Physics A, **334**, 109-126 (1980)