SEparator for CApture Reactions (SECAR) Pre-Conceptual Design Report

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Abstract: This documents presents the preliminary scientific and technical proposal by the Separator for Capture Reactions (SECAR) Collaboration for the SECAR project at the ReA3 reaccelerated beam facility at Michigan State University. SECAR will form an experimental endstation at ReA3 optimized for the direct detection of the recoils produced by proton- and alpha-capture reactions on proton-rich unstable nuclei. The reactions measured at SECAR will be those critical for the energy generation and element synthesis in stellar explosions. This Report presents an overview of the SECAR project, the scientific motivation, and the Pre-Conceptual Design of the system.

1. Introduction

The SEparator for CApture Reactions (SECAR) Collaboration is proposing an equipment project for the Department of Energy (DOE) Office of Science, Office of Nuclear Physics. The project involves the fabrication of a recoil separator system optimized for nuclear astrophysics measurements at the ReA3 reaccelerated beam facility at National Superconducting Cyclotron Facility (NSCL) at Michigan State University. This document is the pre-conceptual design proposal for this project. Following this introduction, we will present the scientific motivation for the project and the essential features of the conceptual design. The project cost, schedule, and management approach will be described in separate documents.

1.1. FRIB, ReA3, and the SECAR Collaboration

The Facility for Rare Isotope Beams (FRIB) will be the premiere low energy nuclear science facility in the world when it becomes operational in 2022. Currently under construction on the campus of Michigan State University (MSU), FRIB will utilize a unique approach that combines the advantages of beams produced by fast fragmentation with those of beams accelerated from rest. Specifically, FRIB will use a new 200 MeV/u LINAC to produce very short-lived species via fast fragmentation, stop these in a gas, and reaccelerate them from rest in a new postacceleration LINAC to give superlative beam characteristics. FRIB is the highest priority for the low energy nuclear science community, and has endorsements from the NSAC Long Range Plan, the RISAC task force, and numerous other review panels and reports.

NSCL has recently been reconfigured so that its existing heavy ion accelerators provide fast fragments that are routed to a new gas stopper and the first 3 MeV/u phase of the postacceleration LINAC. Dubbed the ReAccelerated beam (ReA3) facility, ReA3 is now operational at MSU NSCL and has already delivered low-intensity radioactive beams to the low-energy hall for a number of experiments. Once FRIB is completed, the system will stop and reaccelerate the intense fast fragments produced by FRIB.

There is a strong overlap of the beam species anticipated at FRIB with the unstable nuclei whose thermonuclear capture reactions power novae, X-ray bursts (XRB), and other stellar explosions. For this reason, the direct measurement of such capture reactions is a critical component of the science program planned at FRIB. The Separator for Capture Reactions (SECAR) will be a dedicated experimental endstation that is optimized for these measurements.

The SECAR Collaboration had its genesis in an earlier group formed in 2004 with the goal of constructing a recoil separator for astrophysics measurements at the Rare Isotope Accelerator (RIA). When RIA was transformed into FRIB, the SECAR collaboration was formed to reaffirm the science need, plan experiments, and design a device that will improve our understanding of stellar explosions via measurements with radioactive beams from FRIB. The SECAR collaboration submitted a proposal in 2008 in response to a DOE call for experimental equipment at FRIB.

The proposal was accepted for funding in 2009, but budget limitations prevented that work from proceeding. The SECAR Collaboration has since worked with the DOE Office of Nuclear Physics, the Joint Institute for Nuclear Astrophysics, Oak Ridge National Lab, Michigan State University, and Notre Dame University to sponsor a refinement of the design, the development of a novel simulation approach to characterize the anticipated system performance, the assembly of a project management team, and the completion of a pre-conceptual system design.

In 2010 and 2013, the FRIB Scientific Advisory Committee (SAC) reviewed the status of plans of the Working Groups for equipment at FRIB. In both reviews, SECAR received the highest rating from the SAC in terms of potential scientific impact and overall readiness. The collaboration currently consists of 27 members from 13 institutions in the US and Canada, and includes faculty, senior and junior researchers, postdocs, and graduate students.

1.2. SECAR at ReA3 and FRIB

SECAR will form an experimental endstation in the low-energy hall at ReA3 and FRIB optimized for the direct detection of the recoils produced by proton- and alpha-capture reactions on proton-rich unstable nuclei. It will take advantage of the unique production capabilities of low energy radioactive beams at NSCL/ReA3 and FRIB that are complementary to other rare isotope facilities. Unlike other facilities, NSCL/ReA3 and FRIB will use projectile fragmentation in connection with a gas stopping and reacceleration approach to produce beams not available elsewhere. The reactions measured at SECAR will be those critical for the energy generation and element synthesis in nova explosions and X-ray bursts.

SECAR will be utilized for measurements in inverse kinematics, wherein a heavy, proton-rich radioactive ion beam bombards protons or alphas from a gas target system. SECAR will be located immediately after the target system along the ion-optical axis (i.e., at zero degrees) and will accept all of the heavy nuclear products – the “recoils” – resulting from proton- or alpha-capture reactions between the beam and target. SECAR will also accept all of the unreacted beam particles, which have intensities typically 10^{11} – 10^{15} times higher than the recoils but nearly the same momentum.

The function of SECAR is to direct the low-intensity recoils to a detector system for identification and counting, while simultaneously eliminating the high-intensity background from unreacted beam particles. Recoil counting enables us to make an absolute cross section determination of the capture reaction, which is the empirical basis for the subsequently calculated thermonuclear capture reaction rate.

SECAR is designed to be a next-generation device, with specifications to match the beam production capabilities of FRIB and the scientific needs of the community. These specifications will significantly exceed the two major separators in the field, the Detectors of Recoils And Gammas of Nuclear reactions (DRAGON) at TRIUMF ISAC and the Daresbury Recoil Separator (DRS) at ORNL. Specifically, the energy and angular acceptances, the mass resolution, the transmission, and the estimated suppression of unreacted beam particles will be unsurpassed in SECAR. This level of performance is required to enable statistically significant measurements of the most important thermonuclear capture reactions on unstable nuclei that power novae and X-ray bursts. To establish that the pre-conceptual design described in this document satisfies the necessary performance goals, it was necessary to develop a novel simulation approach to characterize the anticipated performance of the system.

1.3. Overview of SECAR Proposal

Following this introduction, we will present the scientific motivation for the project, general considerations for inverse kinematics measurements and recoil separators, the performance goals, a technical description of our conceptual design, a detailed discussion of our simulations of the system performance, and specifications of the system components. We will also detail the target and detector systems needed for our capture reaction measurements. We briefly outline the components of the separator system here, and provide more detail on each in Section 3 below.

To simultaneously achieve a high transmission of capture reaction recoils and a high rejection of unreacted beam particles, SECAR has been designed with four sections. The first section captures the particles exiting the target with diverging trajectories by focusing them back towards the axis, as well as selects a single charge state, eliminating about half of the beam particles (projectiles) that have not undergone a reaction in the target. Due to their nearly identical momenta but slightly different masses, the recoils and unreacted projectiles have different velocities. The second section therefore uses a crossed-field device, a velocity filter, to pass particles with the recoil velocity along the axis. The filter steers away any particles with higher velocity, specifically the unreacted projectiles. It also steers away the lower velocity particles, specifically projectiles that have scattered off a slit, chamber wall, or other internal components of the separator. The velocity filter is used in combination with a dipole magnet to form a mass focus. The third section has a second combination of dipole magnet and velocity filter, needed to further enhance the rejection of projectiles. The fourth section consists of a dipole magnet and a drift section to give a final rejection of any scattered beam particles that have made it to this point in the device. At the final focus, we utilize a variety of detectors designed to identify and count the particles transmitted by the separator, including a final discrimination against projectiles that have been scattered into the detector. We have designed these four sections using 8 dipole magnets, 15 quadrupole magnets, 3 hexapole magnets, an octupole magnet, and two velocity filters. The system is shown in Figure 1.1.

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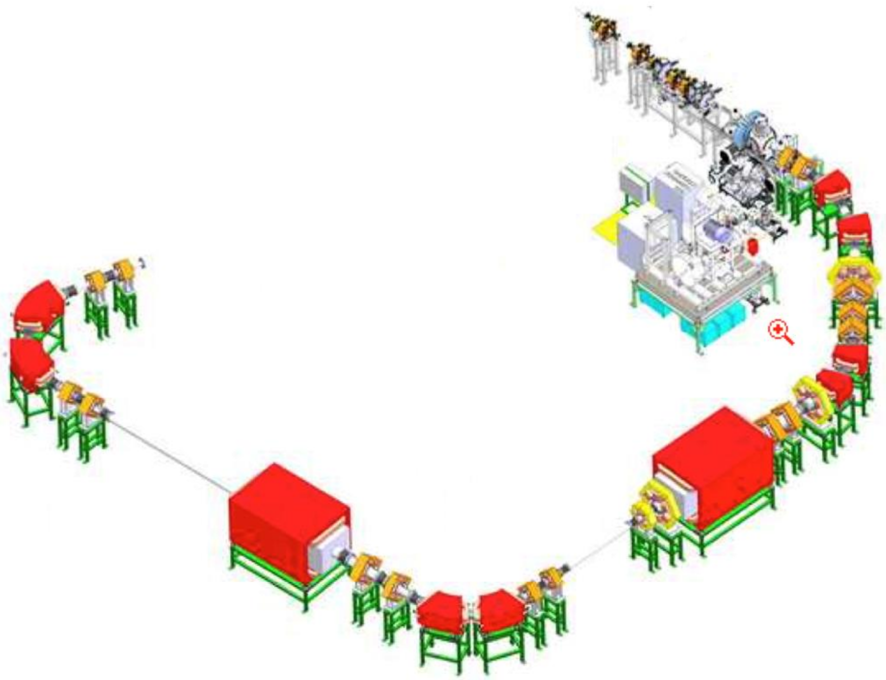

Figure 1.1. Layout of the SECAR system.

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