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Nuclear Astrophysical Reaction Studies Using Heavy Ion Storage Rings

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Introduction

Nuclear astrophysics is a fascinating field requiring exploration of nuclear reactions and properties of key importance for fundamental questions on the origin of the elements and the life cycle of stars. Performing such measurements represents a very challenging experimental endeavor, particularly when these reactions and properties involve unstable nuclei. These nuclei play a key role in hot stellar environments such as recurrent nova explosions taking place in binary systems, or cataclysmic supernovae and neutron star mergers. While significant progress was made over the decades since the rallying cry of Willy Fowler for such studies in his Nobel lecture of 1984, many stellar puzzles remain frustratingly unsolved. This is often due to our inability to determine accurately key reaction rates involving radioactive beam species in the astrophysical energy range for explosive burning (typically ~1-10 MeV/u). Daunting challenges arise in terms of luminosity and beam intensity, but also in terms of beam quality and beam and target purity. Development of appropriate new techniques and detection systems is required. Heavy ion storage rings offer a new arena to address these challenges.

Heavy ion rings have already been used extensively to study properties of exotic nuclei. These studies were pioneered at the Experimental Storage Ring (ESR) at the Society for Heavy Ion Research (GSI; Germany). A key discovery was the first observation of examples of bound-state beta-decay [1]. Studies of electron capture decay in hydrogen-like ions, mass measurements, and identification of long-lived isomeric states of exotic nuclei were also performed on the ESR [2]. Mass measurement programs are also presently being conducted at the heavy ion storage ring facilities, CSRe, Lanzhou, China [3] and the Rare RI-Ring, RIKEN, Japan [4].

Rings also offer several attractions for nuclear reaction studies. First, the unreacted beam is recycled and reaccelerated on the target approximately 10^5 times per second, resulting in a five orders-of-magnitude boost to the luminosity. Repeated passage through the ring magnets greatly purifies the isotopic composition of the stored beam, as only isotopes with charge over mass ratios within the acceptance of the magnets can remain stored. Finally, beam emittance is improved with the use of an electron cooler. These high-intensity, high-quality beams impinge on an ultra-thin (10^{10-14} atoms/cm^2) ultra-pure cryogenic jet target [5]. The ultra-thin target limits the effect of losses of recirculating ions in the ring and results in low energy loss for both the beam and charged particle reaction products induced in the target.

Pioneering experiments performed by the EXL collaboration on the ESR at GSI exploited thin gas jet targets to study low-energy target recoils detected using a ultra-high vacuum (UHV)–compatible Si array centered around 90 degrees in the laboratory frame. In Ref. [6], for example, a recirculating radioactive beam of 390 MeV/u ^{56}Ni ions injected into the ESR from the Fragment Recoil Separator (FRS) was used to study forward angle (in the Centre of Mass [CoM] frame, near 90 degrees in the lab) proton elastic (and inelastic) scattering and determine the matter radius of doubly magic ^{56}Ni. The EXL collaboration similarly studied near zero degree (CoM) inelastic scattering of ^{4}He target recoils for excitation of the Giant Monopole Resonance in ^{58}Ni (a similar reaction study was recently reported at CSRe [7]). Finally, still at the ESR, the ^{20}Ne(p,d)^{19}Ne transfer reaction was studied in inverse kinematics [8]. Silicon detectors were positioned at forward angles to detect coincidences between protons and ^{19}Ne/^{15}O ions as a prototype technique for branching ratio determinations of astrophysical resonances in X-ray burster reactions.

In this review we will focus in particular on recent developments and exciting new opportunities at the ESR and the new CRYRING [5] low-energy storage ring at GSI/FAIR (Figure 1). Over the last decade, significant advances in post-deceleration of in-flight ions down to astrophysical energies

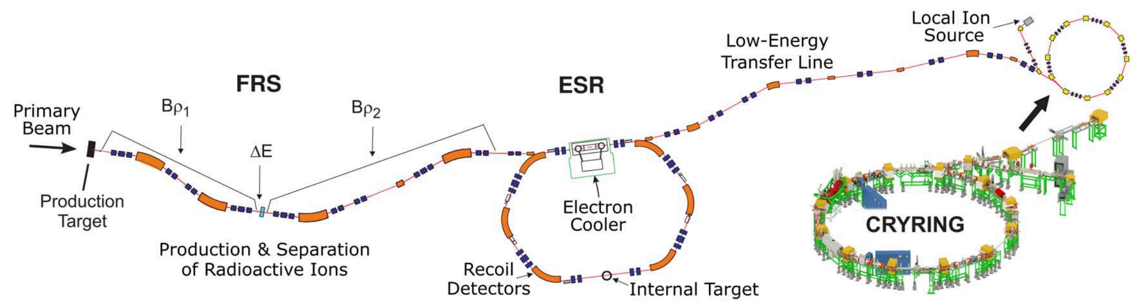

Figure 1. *The extended storage ring complex at GSI with the FRS and the combination of ESR and CRYRING. Stable or radioactive ions can be stored, cooled, and decelerated for experiments in the energy range between 400 AMeV and ~100 AkeV. Taken from [2].*

have opened the path to investigation of nuclear reactions directly at the energies at which they occur in stars at these two rings. Paired with a radioactive beam facility, this offers world-unique and unprecedented possibilities for direct and indirect measurements of stellar cross-sections of pivotal importance to solve long-standing stellar puzzles.

Proton-Induced Reactions at the ESR

Knowledge of proton-induced reactions (or their inverse) at E_{cm}~ few MeV is key to understand explosive nucleosynthesis of the so-called *p*-nuclei [9]. This group of stable, rare, neutron-deficient isotopes is not produced by neutron-capture synthesis. Instead, the bulk of *p*-nuclei is believed to originate from an uncertain network of nuclear processes in supernovae or similarly violent scenarios. Due to the lack of experimental data, rates are taken from the Hauser-Feshbach theory, which carries sizeable and poorly known uncertainties [9]. This translates in uncertain model predictions and prevents definitive conclusions on the origin of the solar *p*-nuclei. Key reactions involving heavy radioactive isotopes need to be studied experimentally to shed light on this long-standing issue.

With a novel experimental approach established at the ESR, such measurements are now possible using stored, exotic ions revolving in the ring. After ion beam production and preseparation in the FRS, the hot fragment beam is stripped bare, injected into ESR and precooled by stochastic cooling to about $\Delta p/p \sim 10^{-4}$ within a few seconds. Low fragment yields can be compensated via beam accumulation. Once a sufficient amount of ions is stored, the radio frequency system of the ring can decelerate the bunched beam. This procedure also purifies the beam, usually to 100% isotopic purity. When the final energy is reached, continuous electron cooling is applied in order to reach $\Delta p/p \sim 10^{-6}$ and to compensate for the small energy loss suffered when the gas target is switched on. For the detection of nuclear reactions, the ESR is used as a recoil separator for the heavy beam-like products of (p,γ) and (p,n) reactions, which have a different p/q ratio versus the stored beam. A UHV-compatible Si detector is positioned at the end of the dipole magnet to intercept these recoils and deliver energy and position information.

Cross-sections for atomic electron capture are typically ~ kilobarn, and are the main contributors to beam losses in the ring. In particular, low-energy ions are rapidly (~few seconds) lost due to interactions with the residual gas, the electron cooler, and the target. However, nuclear cross-section measurements can take advantage of these large atomic cross-sections and use them for normalization. For this purpose, the characteristic X-ray emission at the target can be detected using high-purity germanium detectors at different emission angles. This process is well understood and can be described theoretically with uncertainties of the order of 1%.

This complex experimental approach was established and refined step-by-step in recent years, starting with stable beams of $^{96}Ru^{44+}$ and $^{124}Xe^{54+}$, both of which are *p*-nuclei. The ^{96}Ru(p,γ) reaction cross-sections were measured in a pilot experiment at CoM energies between 9 and 11 MeV. The detection setup was located behind a steel window that stopped ions at beam energies lower than 9 MeV/u [10]. After an upgrade to a UHV-compatible setup the ^{124}Xe(p,γ) reaction was successfully measured at several energies as low as 5.5 MeV in the CoM frame [11], shown in Figure 2. Both experiments delivered important new constraints for the physics underpinning the Hauser-Feshbach reaction theory, as well as the synthesis of *p*-nuclei. Finally, with the most recent upgrade of this technique the only remaining source of background on the Si detector, Rutherford scattering on the target, was eliminated [12]. A dedicated fast scraping system was installed in front of the first dipole magnet after the target in order to block the wide Ruther-

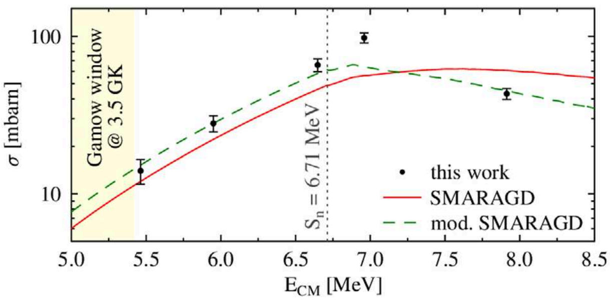

Figure 2. *Experimental cross-sections of ^{124}Xe(p,γ) as measured in the ESR in comparison to theory, representing the first measurement of an absolute cross-section in the Gamow window energy range using stored ions. Taken from [11].*

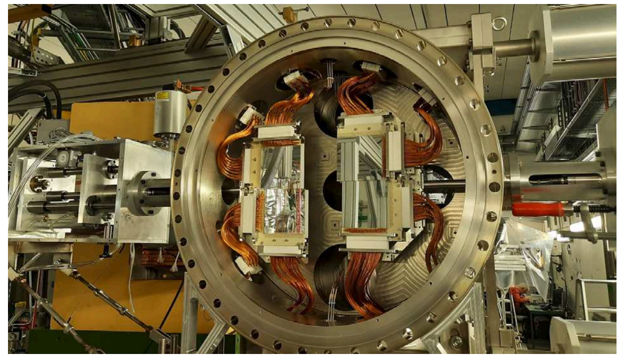

Figure 3. *A photo of the section of CARME where the four moving DSSDs are installed. The beam would travel (entering the page) via the hole in the middle of CARME, partly covered by the right-hand DSSDs.*

ford scattering cone at a position where the nuclear recoil cone is still narrow and overlaps with the stored beam. This approach was successfully tested in a second experiment using ^{124}Xe^{54+} which saw a factor 8 improvement in the signal-to-background ratio. The (p,n) reaction channel was successfully analyzed for the first time, extending the potential range of reaction studies in the ring, and results will soon be published.

This latest refinement facilitated the first in-ring proton-capture measurement using a radioactive beam of ^{118}Te^{52+} with six days of half-life produced in the FRS by means of in-flight fragmentation of primary ^{124}Xe. After careful optimization of the entire FRS–ESR cycle, a pure beam of up to 10^6 fragments could be stored at energies of 6 and 7 MeV/u. The observed spectra showed a clear proton-capture signature, currently under analysis. This long-awaited breakthrough marks a new era of astrophysical experiments at the ESR, bringing milestone measurements for explosive nucleosynthesis within reach. Prominent examples are the ^{59}Cu(p,γ) reaction, which acts as a bottleneck of the *rp*-process in the X-ray burst scenario (see Ref. [11] and references therein) and the ^{91}Nb(p,γ) reaction, which would shed light on the puzzling nucleosynthesis of ^{92}Mo in the *γ*-process and provide an improved calibration of the ^{92}Nb/^{92}Mo cosmic clock [9].

Nuclear Reaction Measurement at CRYRING

In order to access typical temperatures in nova explosions (T~1 GK) or quiescent burning stars (T~10–100 MK), even lower stored beam energies ($E \ll 10$ MeV/u) are required. Ions at these energies would be extremely challenging or just impossible to keep circulating in the ESR. The newly commissioned CRYRING is an ultra-low-energy heavy ion storage ring that is capable of storing ions down to 100 keV/A and even lower. Paired with the FAIR facility, this offers the world-unique and unprecedented opportunity to study nuclear reactions involving radioactive heavy isotopes at energies relevant for astrophysical scenarios (i.e., inside the Gamow window). At these low energies, the primary challenge to keep a stored beam recirculating is to maintain an extremely good level of vacuum. For this reason, CRYRING is operated in extreme high vacuum conditions (10^{-12}~mbar) that are quite challenging to achieve and maintain, and that require sophisticated pumping systems and technical design solutions.

The cutting-edge CRYRING Array for Reactions MEasurement (CARME) [13], funded by Science and Technologies Facilities Council (STFC UK), was specifically designed and mounted on the CRYRING in order to carry out nuclear physics investigations in these challenging conditions. CARME is a charged-particle detection system featuring several Double-sided Silicon Strip Detectors (DSSD) designed to be compatible with the stringent requirements of the CRYRING XHV (eXtreme High Vacuum) environment. Uniquely, some of these detectors shown in Figure 3 are capable of frequently moving in and out of the beam axis under vacuum. The need for motion under vacuum is due to the fact that the beam injected in a storage ring is usually rather broad and has poor emittance, especially if it is produced in-flight. The beam emittance improves after a few turns, thanks to the electron cooler [5]. Therefore, detectors have to be far from the beam axis when the beam is first injected, and then move in very close in order to both maximize the solid angle observed, and measure at very small angles that are often crucial in transfer reactions in inverse kinematics. These highly segmented (128 x 128 strips) DSSDs afford a resolution of approximately 0.1° in the center of mass for typical conditions in inverse kinematics.

CARME was commissioned in March 2022 using a deuterium beam on a nitrogen target produced by the CRYRING internal jet target system [5]. Results are currently being analyzed, and will display the excellent performance of this cutting-edge detection system. Looking at the future, the ELDAR (burning questions on the origin of the Elements in the Lives and Deaths of stARs) UKRI ERC grant will exploit CARME for a range of investigations. Using both direct and indirect techniques, ELDAR will probe a range of stellar scenarios, including, for example, nova explosions, making use of low-emittance, high-quality recirculating beams produced in-flight impinging on ultra-pure internal jet targets. An extremely exciting opportunity should present itself in the next years when the Fast Ions Slow Ions Collisions transverse ion source will also be mounted on the CRYRING. This source was designed to investigate ion–ion collision for atomic physics research. As part of the ELDAR project, this ion source will be exploited to cross fully ionized ion beams in order to carry out the first ever measurement of cross-sections free of electron screening at energies of astrophysical interest. This has long been a dream of the nuclear astrophysics community, and will be a decisive step forward to understand whether and how our models of electron screening are failing to describe experimental data, a crucial and very long-standing issue in all quiescent burning scenarios, including in particular our own Sun.

Future Prospects and Summary

New rings specifically designed to carry out nuclear reaction measurements are being considered (among others) at the European Council for Nuclear Research, TRIUMF (Canada), and Los Alamos (USA). A future challenge will be to carry out neutron capture reaction studies using short-lived stored radioactive ions impinging on neutron "targets" [14]. These reactions are of critical importance to understand the synthesis of heavy elements. Surrogate reactions are another approach to study neutron-induced reaction employing indirect techniques. This approach also greatly benefits from heavy ion rings and first measurements are being carried out at the ESR in the context of the NECTAR ERC project [15].

Heavy ion storage rings are powerful tools to carry out a wide variety of studies tackling long-standing problems in nuclear astrophysics, from quiescent burning stars to heavy element production in cataclysmic stellar explosions. New measurements planned at rings around the world will decisively improve our knowledge of key nuclear reactions taking place in these fascinating stellar scenarios. In particular, in the next few years, the proton capture measurement program at the ESR ring will shed light on p-nuclei and the *rp*-process while the program at CRYRING will investigate nova explosions and electron screening effects in quiescent scenarios.

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