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Low-energy nuclear reactions with stored ions: a new era of astrophysical experiments at heavy ion storage rings

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Abstract Heavy ion storage rings are powerful tools to store and observe key nuclear properties of rare radioactive isotopes. Recent developments in ring physics and enhanced beam intensities have now opened up the possibility to carry out low-energy investigations of nuclear reactions at rings. Pure, intense, exotic beams of isotopes that are otherwise challenging to access can be impinged on pure, ultra-thin targets, allowing the study of long-standing nuclear astrophysical puzzles in a variety of stellar sites that have so far resisted traditional approaches. In this review paper, we will describe pioneering studies with decelerated beams at the ESR storage ring at GSI (Germany), as well as future exciting prospects at the ESR and CRYRING at GSI/FAIR.

1 Introduction

Since their emergence in the late eighties and early nineties, heavy ion storage rings have been employed in a wide variety of ground-breaking investigations of nuclear properties involving both stable and radioactive heavy isotopes. In particular, unstable isotopes produced as secondary beams from a rare ion beam (RIB) facility were stored in pioneering experiments. Isotopes orbited the ring for ≈milliseconds to days, allowing unprecedentedly precise studies of their properties of interest [1]. Due to the limitations and challenges inherent to secondary beam production [2], the early focus was either on mass measurements of exotic nuclei by storing low-intensity fragment mixtures [3], or on investigations of exotic charge states revealing the interplay of atomic and nuclear physics [4,5]. These groundbreaking experiments were conducted at higher energies, i.e. around or above 100 MeV/u, for reasons of efficient beam production. Years later, the first direct nuclear reaction studies involving an internal target in the ring were conducted at the lower end of this energy range. Initially, high-intensity stable beams of ^{58}Ni were employed [6,7], but also a first run with a secondary beam of ^{56}Ni has been accomplished [8]. In the more recent past, significant experimental efforts facilitated an increasingly more efficient deceleration of stored radio-isotopes, which enabled beam intensities on the order of 10^6 stored exotic ions also in the low-energy realm of a few MeV/u. This short review will focus on reaction studies in this domain at the GSI storage rings ESR and CRYRING [9–11] and on the new era of ring experiments targeting low-energy nuclear reactions of key importance in nuclear astrophysics.

Experimental data constraining nuclear reaction rates involving short-lived radioactive nuclei at low center-of-mass energies are of vital importance [12] to improve our understanding of stellar evolution and the production of the elements. The latter is especially crucial for nucleosynthesis in explosive stellar scenarios like novae, supernovae or X-ray burst events [13–15]. Exotic, short-lived isotopes are created during and after the explosion, and their radioactive decay leads to the production of stable nuclei which we observe in the Solar System today. The most promising experimental approach, in many cases, is to utilize a RIB in an inverse-kinematic study since radioactive targets are exceedingly difficult to produce. In a few cases direct measurements of reaction cross sections using RIB have been successful, see e.g. [16–19] for related experiments.

However, most RIB experiments use a *single-pass* configuration, where the beam impinges on a solid or gaseous target, and is either lost in the target backing or is in any case dumped after interacting with the target once. In this case, the challenges of RIB production, i.e. finite intensities and often insufficient beam quality and isotopic purity, often result in severe experimental limitations. In a storage ring a *multi-pass* configuration can be achieved by letting the stored beam cross

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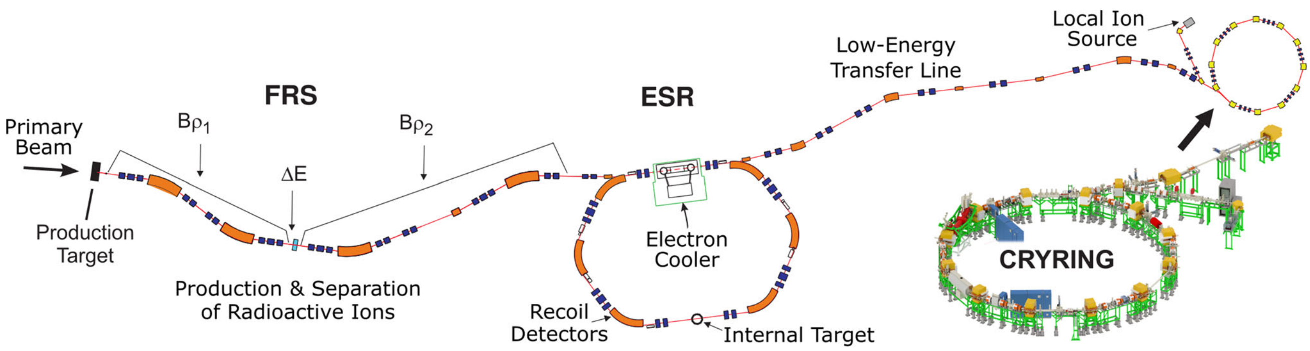

Fig. 1 A schematic view of the typical beam injection scheme into the ESR and CRYRING storage rings. Secondary beam is produced in-flight and separated in the FRS, decelerated and stored in the ESR, and either used there or transferred to the CRYRING. The low-energy CRYRING also features a local ion source. Modified from [22]

an internal target region repeatedly. This has many advantages. The RIB intensity is effectively multiplied by the revolution frequency of the ions, which is usually on the order of a few 100 kHz at energies of astrophysical interest. This results in a remarkable luminosity boost of about 5 orders of magnitude compared to the single-pass setup. The ring environment also enables beam cooling and high resolving power in m/q, providing beams of high brilliance and unrivalled separation [20–22]. With the latest improvements in Schottky noise spectroscopy techniques a powerful, non-destructive method of beam monitoring is available [23], which facilitates complex beam manipulations including beam accumulation, local and global orbit manipulations, selective elimination of contaminants and many more [22,24,25]. Also, both ESR and CRYRING, have an internal gas jet available providing a variety of ultra-pure, ultra-thin target gases, most prominently hydrogen and helium which are central for the astrophysical studies discussed here [26].

Several exciting challenges related to this novel way to address astrophysical reaction studies in heavy ion storage rings remain to be faced. In particular, storage rings must operate in ultra-high or extreme-high vacuum conditions (UHV/XHV) to enable the measurement of a small nuclear cross section inside the Gamow window, i.e. with stored ions of a few MeV/u or below. In general, storage times of seconds or longer for highly charged ions require a vacuum pressure lower than 10^{-10} mbar, and the absence of high-Z elements in the residual gas. This becomes even more important at lower energies ($E < 10$ MeV/u), where the cross sections of the atomic processes that dominate beam losses become very large (> kilobarn) [27]. These vacuum requirements pose technical challenges to experimental setups located under vacuum. At higher energies this is usually accomplished using detectors in so called pockets, i.e. behind a stainless steel window acting as a vacuum barrier [28]. These windows can be as thin as 25 μm, nevertheless heavy ions well below 10 MeV/u will not be able to penetrate with detectable energies [29]. However, nowadays, sophisticated detection systems providing ion energy, hit timing, and position with good resolution and efficiency are commercially available for use in UHV environments. In particular, Double-sided Silicon Strip Detectors (DSSD) are commonly used for ion spectroscopy in low-energy nuclear physics and became available recently featuring low out-gassing materials and in situ bake-out above 100 °C [30]. Moreover, the development of solar cells and diamond semiconductor chips as heavy ion detectors is on-going and eventually envisioned for use in storage rings [31].

At GSI the RIB is produced in the FRagment Separator FRS using the in-flight technique with primary beams of several 100 MeV/u [2,32], and the typical in-flight beam injection scheme is shown in Fig. 1. Low-energy RIB studies in the rings are complicated by the requirement of post-deceleration of the secondary beam. While both rings at GSI provide this synchrotron feature by making use of an RF system enabling direct investigations inside the Gamow window, this technique has some disadvantages and more work remains to be done to optimise it. First, the speed of the simultaneous ramping of magnetic fields and RF frequency is limited and causes a reduction of the duty cycle for the experiment. Furthermore, low energy beams cover an increased phase-space volume due to intra-beam scattering. Combined with the reduced effective acceptance during ramping, this leads to beam losses. Both effects were first observed in the ESR and become more distinct for lower final energies [33].

Significant efforts are ongoing for the development of new storage ring features, vacuum-compatible setups, and detector technology, in order to face the challenges outlined above and improve the reach of these ground-breaking measurement techniques. In the following sections we will outline early pioneering experiments with stable and radioactive beam, as well as planned experiments and future prospects of this exciting new era of low-energy nuclear reaction experiments of astrophysical relevance.

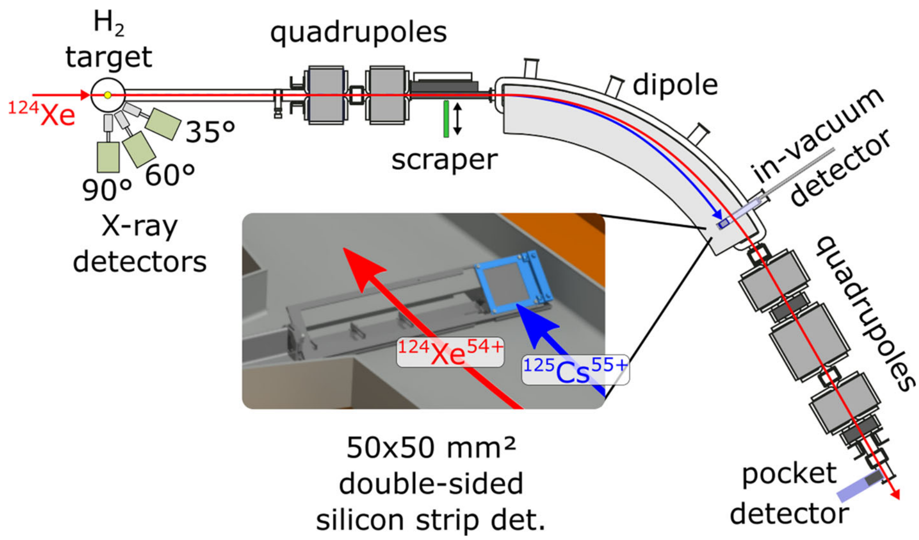

Fig. 2 The experimental setup for proton-capture measurements in the ESR and the beam and recoil trajectories relevant for the ^{124}Xe(p,γ)^{125}Cs reaction. Germanium X-ray detectors are placed around the target at different angles for a measurement relative to the K-REC process. The in-vacuum DSSD is positioned in the last quarter of the dipole magnet to intercept the ^{125}Cs recoils separated from the circulating ^{124}Xe beam due to a different magnetic rigidity. The position of the pocket DSSD used in the ^{96}Ru(p,γ) pilot experiment is indicated at the end of the beamline section depicted here. Moreover, the location of the new scraper system is given in front of the dipole magnet. The picture is modified from [30]

2 Direct measurements of proton-induced radioactive capture reactions at the ESR

The very first experiment with stored ions post-decelerated to about 10 MeV/u was carried out in the ESR in 2008 using a stable beam of ^{96}Ru^{44+} impinging on a hydrogen jet [34]. Conceptually the ring served as a luminosity booster and recoil separator for proton-capture reactions. The goal was an absolute measurement of the cross section of the ^{96}Ru(p,γ)^{97}Rh nuclear reaction, via detection of the ^{97}Rh recoils. Detection was facilitated by the negligible momentum carried away by the γ rays in radiative proton-capture reactions involving heavier ions. The recoil cone remained quite narrow and the beam-like ^{97}Rh^{45+} reaction product ejecta retained approximately the momentum of the stored beam, but had a lower rigidity $B\rho = p/q$ due to the higher charge state. This enabled separation of the reaction products from the stored beam in the first dipole magnet downstream of the target. DSSDs installed behind the dipole magnet (see Fig. 2) were used to implant the (p,γ) recoils with 100% efficiency providing excellent energy, time and position resolution.

In contrast to inverse kinematic experiments at dedicated low-energy recoil separators or spectrometers, the ions injected into ESR are bare, which is effectively a prerequisite for this measurement approach. The injection energy at about 100 MeV/u or higher enables efficient stripping usually using a carbon stripper foil ($\approx$ 10 mg/cm^2). In combination with the relatively thin target this strongly prevents having to deal with complex charge state distributions after the internal target interaction. For stored ions in lower charge states ionization in the target would have to be considered, and would result in beam-like products with very similar $B\rho$ to those ejecta formed by proton capture. Thus, since the atomic ionization cross sections are several orders of magnitude larger than any nuclear cross section, non-bare ions would render a (p,γ) measurement unfeasible due to the overwhelming atomic background.

In the pilot experiment no UHV detection system was available, instead a pair of common W1-type DSSDs (Micron Semiconductors Ltd. [35]), each 50 $\times$ 50 mm^2 in size, were employed inside the standard detector pockets at ESR (Fig. 2). A stainless steel entrance window of 25 µm thickness allowed ions as low as 9 MeV/u to be detected inside the helium filled pocket. Lower energies were not accessible. The measured horizontal position spectrum of ion hits at 11 MeV/u is shown in Fig. 3 against Monte-Carlo simulations. The rather complex background situation with regard to the (p,γ) signature is caused by the relatively high beam energies, which give rise to the competition of four different reaction channels. However, careful simulations of the ion optical system and apertures in ESR as well as the reaction kinematics enabled a disentanglement of the different distributions.

The entire proton-capture measurement is conducted relative to X-ray spectroscopy of the so-called K-REC process, i.e., the radiative component of the capture of a target electron into to the K-shell of the stored ion. For this basic atomic process, which is the inverse of the photo-effect, cross sec-

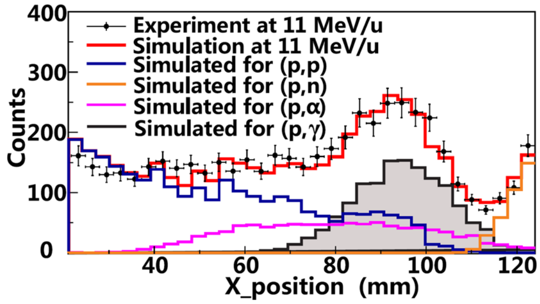

Fig. 3 The ion hit distribution measured by the pocket DSSD for ^{96}Ru(p,γ)^{97}Rh at 11 MeV/u in the ESR is shown. Distributions from four different reaction channels had to be considered by Monte-Carlo simulations in order to reproduce the spectrum and extract the proton-capture events. Taken from [34]

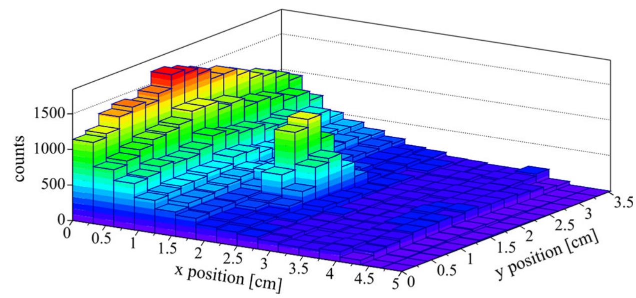

Fig. 5 Recoil hit distribution of the in-vacuum DSSD for ^{124}Xe^{54+} incident on a hydrogen jet at 7 MeV/u in the ESR. The narrow cluster of ^{125}Cs ions from proton-capture sits on a broad background of events from Rutherford scattering at the target. Taken from [30]

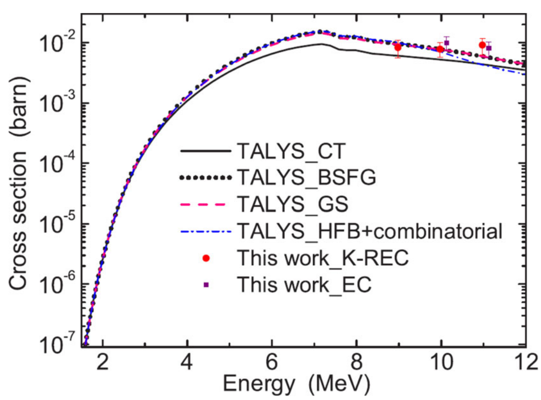

Fig. 4 The final cross section results of the ^{96}Ru(p,γ) pilot experiment compared to different cross section predictions are shown. Three data points between 9 and 11 MeV provided new constraints for theory. Note, that the normalization based on different measurements of atomic electron capture are compared here. Taken from [34]

tions can be calculated with high precision for few electron systems [36,37]. As shown in Fig. 4 cross sections for the ^{96}Ru(p,γ) reaction at 9, 10 and 11 MeV/u could be extracted, providing additional constraints for the production of the p nucleus ^{96}Ru in the γ process, for further details see [34]. Perhaps most importantly, the successful proof-of-concept for this novel low-energy approach led to further developments towards storage ring investigations at even lower energies and with the final goal of an application to RIBs.

The focus in the following years was on upgrading of the detection system to facilitate barrier-free ion implantation in the active material of a detector. This was achieved in 2016, when a new in-vacuum setup was installed at the end of the dipole magnet after the target in ESR (see Fig. 2). It consisted of a single W1 DSSD, for which a UHV package became commercially available a few years earlier [35].

This detector upgrade facilitated the following experiment within the campaign, which focused on the ^{124}Xe(p,γ)^{125}Cs reaction using a stable ion beam of ^{124}Xe^{54+}, investigating a proton-capture cross section relevant for the production of this p nucleus in the γ process. This novel, cutting-edge detection system enabled to measure for the first time the absolute (p,γ) cross section at five energies between 5.5 MeV/u and 8 MeV/u, which covers the high energy tail of the Gamow peak for this reaction [38]. At these energies a beam lifetime on the order of a few seconds and intensities of about 10^7 ions could be achieved. The results of the study are shown in Fig. 6 and provide the first experimental constraints for theory models in this realm, for details see [30].

The study also showed that in this relatively low energy domain, in particular for $E_{\mathrm{CM}} < |Q_{(\mathrm{p,n})}|$, nuclear reaction channels other than (p,γ) are negligible. Rutherford scattering at the target, however, causes an intense and broad background distribution (Fig. 5). In fact the signal-to-background ratio for proton-capture becomes worse with decreasing beam energy, as one would expect from the divergent behaviour of the declining nuclear and increasing Rutherford cross sections. To anticipate this sensitivity limit of the experimental technique, which is critical for applications inside the Gamow window, an improved method was developed [39,40]. It is based on blocking part of the Rutherford distribution directly in front of the dipole magnet, where the scattering cone is already quite extended while the beam-like (p,γ) products remain on the storage orbit. For this purpose a dedicated scraping system was installed, which can be rapidly moved into a position close to the beam with sub-millimeter precision (Fig. 2).

In a recent beamtime in 2021 this device was taken into operation with an otherwise unmodified setup using again a ^{124}Xe^{54+} beam. The comparison of (p,γ) data taken with and without the scraper in position revealed a tremendous increase of the signal-to-background ratio by approximately a factor of 10. As will be shown in a forthcoming publication [41], this upgrade leads to an increased sensitivity for the (p,γ) measurement and additionally enables the straightforward extraction of a cross section for the (p,n) reaction channel for $E_{\mathrm{CM}} > |Q_{(\mathrm{p,n})}|$.

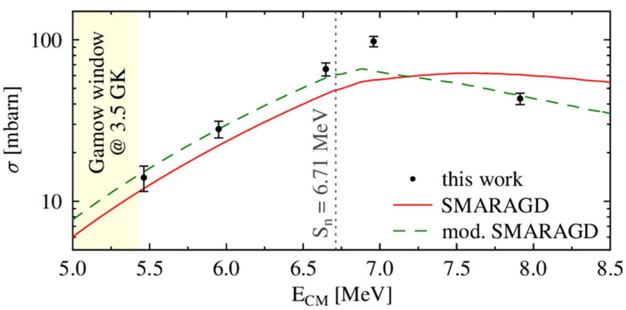

Fig. 6 Results of the ^{124}Xe(p,γ) measurement in the ESR. Five absolute cross section values on the high-energy tail of the Gamow window could be extracted. The experimental data set is compared to theory calculations based on different nuclear model input. Taken from [30]

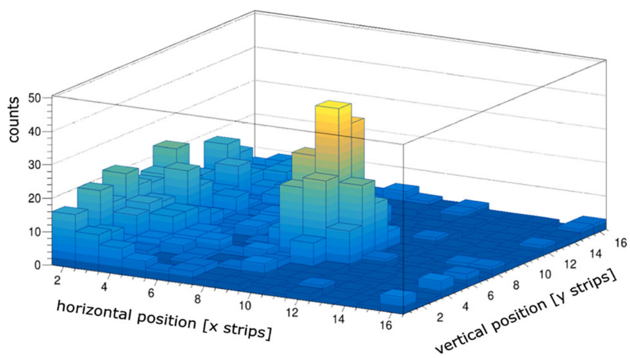

Fig. 7 Recoil distribution measured with the DSSD for radioactive $^{118}Te^{52+}$ stored in the ESR at 7 MeV/u. A few hundred events in the narrow central distribution can be attributed to the proton-capture channel. The Rutherford background is strongly suppressed by blocking the relevant part before the dipole. Taken from [42]

In the same experiment, the ^{124}Xe primary beam was also used to produce a fragment beam of radioactive $^{118}Te^{54+}$ ($T_{1/2}$ = 6.0 d) with the goal to measure the reaction ^{118}Te(p,γ)^{119}I. Analysis of this set of data is ongoing, but we report here on the performance of the ESR in combination with a hot and intense fragment beam from FRS.

Primary beam intensities of about 3.5×10^9 could be converted in-flight to fragment injections of about 3.5×10^5 pre-separated ions. A production target of ^{9}Be was employed, and the FRS setup was optimized to arrive at 400 MeV/u injection energy to facilitate rapid stochastic cooling of the hot fragment beam [21]. By accumulating up to 20 injections in the ESR the stored intensity reached peak values of 7×10^6. Subsequently the fragments were decelerated to about 7 MeV/u and subject to permanent electron cooling [20]. At this final stage an isotopically pure beam with an intensity of about 1×10^6 $^{118}Te^{52+}$ ions and a lifetime of roughly 2 s could be achieved.

With this complex beam setup it was possible for the first time to detect a (p,γ) recoil signature from stored, radioactive ions in the low energy domain. For ^{118}Te(p,γ)^{119}I two energies have been covered at 6 and 7 MeV/u with each measurement yielding a few hundred counts on top of a strongly suppressed background [42].

These recent achievements represent a milestone for the proton-capture campaign and low-energy reaction studies with stored, rare ion beams in general. The future plans of the campaign involve to address challenging measurements of key reactions in explosive nucleosynthesis. An outstanding example is ^{91}Nb(p,γ)^{92}Mo, which has strong impact and the potential to shed a new light on the mysterious synthesis of ^{92}Mo in supernovae [43,44]. This measurement would deliver an improved calibration of the ^{92}Nb-^{92}Mo cosmic chronometer that could be used to benchmark different nucleosynthesis contributions to the p-nuclei composition of the solar system [45,46].

3 Direct and indirect measurements of nuclear properties at CRYRING

The recently commissioned low-energy CRYRING heavy ion storage ring opens up the world-unique and unprecedented possibility to carry out measurements with intense, high-purity radioactive beams produced in-flight, decelerated to a few hundred of keV/u, and possibly lower [11]. This allows investigations of a wide range of lower energy astrophysical sites, such as novae, the Big Bang, and quiescent stellar burning, directly at Gamow energies. Studying nuclear reactions and observables of interest in these scenarios requires a somewhat different detection solution compared to the setup mounted at the ESR.

The new CRYRING Array for Reaction MEasurement (CARME) [47] was the first nuclear detection array designed and constructed specifically to be used at the CRYRING. CARME was recently mounted at the low-energy ring and is a modular detection system for charged particles located next to the internal target, without any magnet selecting and separating the reaction products between the interaction point and the detectors. Instead, highly-segmented DSSDs (128x128 channels, 100 x 100 mm), moving under the Extreme High Vacuum conditions of the ring (Fig. 8), allow CARME to detect reaction products with excellent angular resolution (typically better than 1 degree) and solid angle coverage down to around 1 degree from the beam axis. When mounted downstream of the internal target, this allows CARME to detect charged particles produced by direct reactions, e.g. (p,α) or (α,p), with negligible energy losses or straggling due to the ultra-thin internal target, and high efficiency. If mounted upstream of the target instead, CARME can be used for ultra-high resolution investigations of angular distributions of indirect nuclear reactions such as e.g. (d,p) at angles close to the beam axis, which are key to extract nuclear properties of interest for astrophysics.

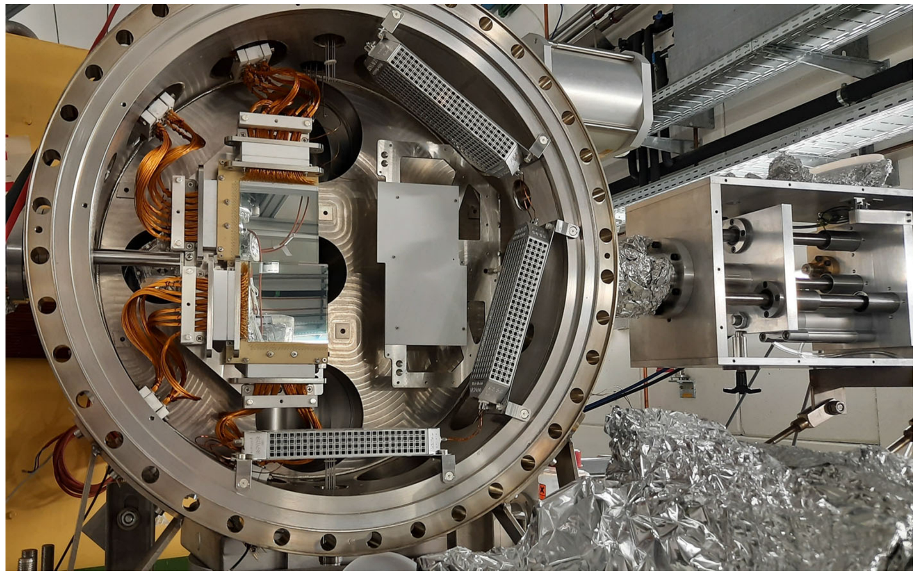

Fig. 8 A photo of the inside of CARME, showing two of the four moving DSSD mounted. The beam passes through the hole in the middle, partly covered by the detectors in the photo. Note the arm to actuate the motion on the right-hand side of the photo

The scientific programme of CARME will be supported by the ELDAR UKRI ERC StG (PI CG Bruno) going forward. ELDAR will aim at developing novel measurement techniques and approaches using CARME at CRYRING, many of which are world-unique and unprecedented. At present CARME is mounted downstream of the internal target of the CRYRING and in the near future its science programme will focus mostly on direct measurements of nuclear reactions and properties of interest for astrophysics. In particular, the first approved investigation will be the ^{15}O(α,α)^{15}O nuclear reaction. This is a direct way to measure the alpha widths of the ^{19}Ne nucleus that is formed by the ^{18}F(p,α)^{15}N reaction which plays a central role in novae explosions [48]. Precise knowledge of the alpha widths is crucial to reduce reaction rate uncertainties [49], but limitations in energy resolutions have hampered investigations. Using electron-cooled radioactive beams at CRYRING (ΔE/E $\simeq 10^{-4}$) impinging on the ultra-thin internal target is expected to result in an exceptional energy resolution for this scattering reaction of the order of 1 keV FWHM in the centre-of-mass frame, more than an order of magnitude better than current values [50].

Beam can be injected in the CRYRING from a local ion source independently of the main GSI/FAIR accelerators. This off-line ion source will be used to carry out both commissioning tests and a wide range of scientific investigations for nuclear and atomic physics. While at present the source can only provide stable isotopes there are plans to upgrade it to an EBIT source capable of providing beam of relatively long-lived radioactive isotopes such as e.g. ^{44}Ti ($t_{1/2}$=63y) [51]. This radioisotope plays a central role in our understanding of supernova remnants [52], i.e. the radioactive ashes left behind by core-collapse supernovae [53]. Significant uncertainties remain in the destruction rate of ^{44}Ti via the ^{44}Ti(α,p)^{47}V reaction during the supernova runaway, preventing us from making full use of astronomical observations to constrain our models. Experimental investigations are hampered by the difficulty of producing sufficiently intense ^{44}Ti beams. There are only two datasets available: an upper limit in the supernova Gamow window [54], and a set of data at higher energies [55] for which a re-analysis of published uncertainties was later carried out [56]. Tensions remain between the two datasets [56] and the situation is far from satisfactory. Exploiting the luminosity enhancement thanks to beam recirculation at CRYRING will allow an investigation of this reaction at Gamow energies. Reaction products will be detected with nearly 100% geometric efficiency using the CARME array, thanks to strong kinematic forward focusing.

Indirect studies using techniques such as (d,p) transfer are also planned to be performed at CARME once it will be moved upstream of the internal target. Note that moving CARME requires breaking the vacuum of the CRYRING and returning to XHV, which can take weeks to months [47]. Transfer reactions are very powerful tools [57] to investigate nuclear properties that cannot be otherwise accessed due to e.g. lack of intense radioactive beams, but also properties relating to sub-threshold states or angular distributions that can be difficult to access even with intense beams available. The possibility to use high-quality, high-purity in-flight beams at CRYRING and detect reaction products at extremely small angles with high efficiency, energy and angular resolution using CARME is unprecedented and will open the path to exciting new possibilities. Potentially, a 0 degree system similar to the one described above for the ESR could be used in conjunction with CARME to detect both ejectiles and recoil nuclei, allowing coincidence measurements to be performed.

Finally, the CRYRING is expected to benefit from the installation of a transverse low-energy beamline from the the FISIC project [58]. This will open up a world-unique opportunity for CARME at CRYRING to approach the electron screening problem. Electron screening is a long-standing puzzle [59] that affects all nuclear reactions taking place in quiescent scenarios, including in particular our own Sun. Briefly, nuclear reactions in a laboratory are induced by impinging a beam ion (that can be fully ionised in principle) on an atomic target nuclei, which always has electrons attached. Electrons surrounding target nuclei shield the Coulomb repulsion between the projectile and the target, enhancing the cross-section. A reliable formalism to model this process is still outside of our grasp [59]. Crossing a fully ionised beam stored in the ring with the fully ionised beam produced by FISIC, will allow the first ever attempt to measure nuclear reactions free of electron screening directly at energies of astrophysical interest. This ground-breaking measurement is expected to take place in the next few years.

4 Neutron induced reactions and the surrogate method with stored ions

Neutron-induced reactions on radioactive nuclei are of crucial importance in nuclear astrophysics. Key nuclear reactions with a strong impact on the element synthesis have been identified for s, r and p processes [13,60,61]. The main challenge in measuring these reactions experimentally is the unavailability of a free neutron target, which excludes similar experimental schemes as described in Sects. 2 and 3, as well as most traditional single-pass experiments. The application of RIB techniques to this topical challenge is still at an early stage, in particular with respect to exploiting the advantages of heavy ion storage rings.

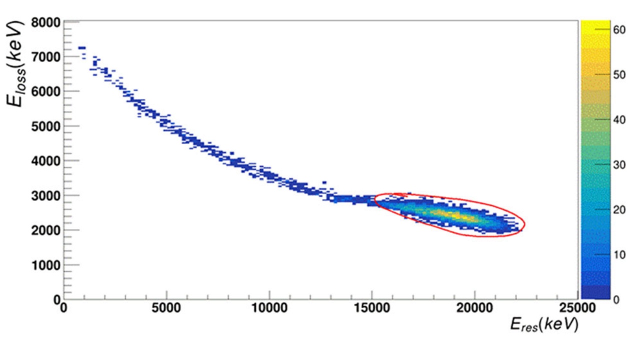

Fig. 9 The ΔE-E measurement for scattered protons at the target is shown for a single strip (64.5°) of the telescope DSSD. The banana shape of the inelastic distribution culminates in an intense peak from the elastic channel. The red contour selects elastic scattering events to infer the experimental resolution. Taken from [66]

Supported by the ERC advanced grant NECTAR, a new project for an experimental campaign aiming to solve this long-standing issue was started at the GSI/FAIR storage rings, with the goal to apply the indirect surrogate technique to infer cross sections of neutron capture and neutron-induced fission [62]. According to the compound nucleus model, the formation and decay of the compound nucleus (CN) system can be treated separately [63], i.e. the exit channel is independent of the entrance one. The experimental approach is to produce the CN state of interest using an alternative nuclear reactions, which does not require a neutron target, in order to study its decay behaviour and improve the predictions of theoretical cross section calculations. The surrogate technique using transfer reactions or inelastic scattering is already established for light beams incident on a heavy target [64,65]. However, the possibility to study a wide range of astrophysically relevant reactions involving radioactive nuclei becomes available only when employing RIBs.

The vision of this new experimental campaign is to establish surrogate measurements in inverse kinematics using stored, rare and highly-charged ions. It requires a detection scheme that enables the identification of all decay channels of the CN in coincidence with the preceding excitation process. For this purpose the heavy decay products of the CN are implanted in particle detectors positioned according to the reaction kinematics, i.e. in different locations downstream the target. Similar to the proton-capture experiments, this requires bare ions to exclude ionization of beam particles in the target to avoid an overwhelming atomic background. In parallel, the particle ID of light recoil ions from the exciting reaction is extracted from telescope detectors directly at the target.

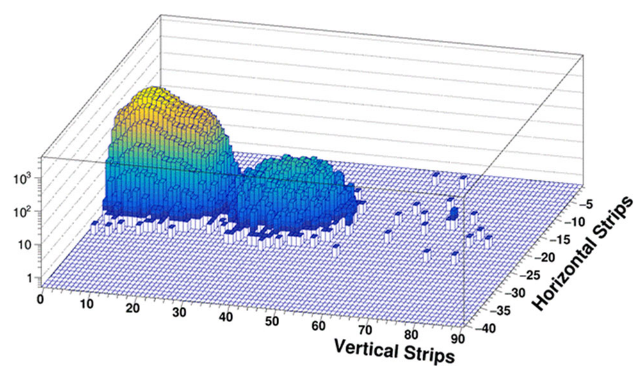

Fig. 10 Heavy ion hit map of the DSSD downstream of the target and dipole magnet in ESR, when in position close to the stored beam. The coincidence condition to scattered protons detected by the telescope at the target is applied and filters events not related the decay of the nuclear compound system. Recoils from the γ decay channel are located close to the detector edge (left bump), the neutron emission signature is clearly separated further away from the beam orbit (central bump). Taken from [66]

Recently, a proof-of-principle experiment for this technique was conducted at the ESR investigating the ^{207}Pb(n,γ)^{208}Pb reaction via the surrogate reaction ^{208}Pb(p,p') to produce ^{208}Pb* and study its probability to decay by neutron vs. γ emission. A primary beam of $^{208}Pb^{82+}$ at 270 MeV/u was stored in ESR and decelerated down to 30 MeV/u. About 5×10^7 ions were impinged on the hydrogen target (6×10^{13} atoms/cm^2), which resulted in a beam lifetime of approximately 25–30 s. A silicon telescope was aligned to 60° at the target, it consisted of a DSSD front layer followed by six 1 mm layers of single-sided, single-area Si detectors with an active area of about 20 mm^2. Additionally, a DSSD with a size of 122×44 mm^2 covered inner ring orbits behind the dipole magnet downstream of the target. Thanks to the relatively high beam energies, all particle detectors could be operated in the standard detector pockets of ESR. See [66] for a detailed description of the experiment.

The ΔE-E measurement of the proton recoils at the target is shown in Fig. 9 for a single strip of the front DSSD at 64.5°. The expected banana shape of the inelastic scattering distribution overlaps with the intense peak from the elastic channel at high residual energy. The heavy residues of the CN decay were measured by the downstream DSSD, but would usually be concealed by the heavy beam-like partner from elastic scattering. They were revealed by applying the coincidence condition with the inelastic component of the proton distribution at the target. The two extended ion clusters were detected with nearly 100% efficiency, and could be clearly identified and separated, as shown in Fig. 10. The excitation energy of the CN can be reconstructed by making use of the angular resolution of the telescope. This enables a determination of the energy-dependent decay probabilities P_n and P_γ with a resolution of a few 100 keV. In the current setup this resolution is limited by the target diameter $D \approx 5$ mm.

While the analysis of the data set is ongoing, this proof-of-principle test can be considered accomplished based on the preliminary data analysis presented in [66]. Further development of the technique will focus on an extension to include the detection of the fission channel as well as on a reduced target diameter to improve the energy resolution. The next experiment within NECTAR will use a $^{238}U^{92+}$ beam and a deuterium jet target in order to excite the compound systems of ^{238}U* and ^{239}U* via (d,d') and (d,p), respectively, and study all open decay channels.

5 Conclusion

The study of nuclear cross-sections using low-energy stored beams at heavy ion storage rings is an exciting emerging field in experimental nuclear astrophysics. Modern technologies are now enabling sophisticated, high-precision experiments and novel approaches investigating long standing nuclear puzzles of key importance in a wide variety of astrophysical sites and scenarios. GSI/FAIR has been playing the lead role in pioneering this ground-breaking approach. Direct measurements of nuclear cross sections have been established for proton-induced reactions and RIBs in the ESR, and a number of key reactions for explosive nucleosynthesis are now within reach. CARME is now in operation at the new CRYRING facility with access to the lowest energies needed to cover the Gamow window, and first experiments with stable beams are expected to run soon. Radioactive beam studies will be following soon, and a large variety of topical nuclear reactions will be in focus in the near future. The FISIC project will for the first time enable crossed beam experiments to investigate electron screening effects. Finally, the power of the surrogate technique at storage rings has now been demonstrated experimentally at the ESR with stable beams, and further experiments applying it to radioactive heavy isotopes are planned for the future.

The possibility to carry out these exciting cross-section measurements relies heavily on the availability of intense beams at rings. The performance of the rings themselves, and the possibility to carry out complex beam manipulation operations, such as *e.g.* beam cooling, are absolutely critical for the success of these experiments and for the delivery of the science programme. Further development of ring capabilities is now required, especially for what concerns the challenges linked to efficient storage of radioactive, short-lived secondary beams.

The remarkable success of storage ring experiments has attracted significant attention at an international level leading to several major international ring projects e.g. at FAIR [67] and HIAF (China) [68]. The interest is particularly high in the low-energy nuclear astrophysics community, where several dedicated low-energy ring projects have been proposed and are in varying states of planning, e.g. at ISOLDE (CERN) and TRIUMF (Canada). In the context, the idea of pairing a free neutron target to a storage ring [69] is being actively pursued in Canada and in the USA [70]. Different approaches are being considered to obtain the necessary neutrons e.g. either from a reactor, or a spallation source, or a commercial neutron generator. The success of this initiative will open up the possibility to directly measure neutron-induced reactions on radioactive isotopes at energies of interest, an extremely significant step forward in the quest of understanding the origin of heavy elements in our Universe.

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