PROCEEDINGS OF SCIENCE

Nuclear reaction studies using stored ions

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Reactions of astrophysical interest in explosive scenarios, e.g., with relevance for the γ- or rp-processes, often involve unstable isotopes that cannot be studied using traditional methods. In inverse kinematics, such isotopes are available making use of the Fragment Seperator (FRS) at GSI, Darmstadt, Germany. By using the ESR storage ring in combination with the internal microdroplet target (p,γ) and (α,γ) reactions can be studied. DSSSDs are employed to measure the spatial separation of reaction products after a dipole magnet. At energies between 9 and 11 MeV per nucleon, a proof-of-principle experiment was carried out investigating the reaction ^{96}Ru(p,γ). Details about the experiment, the ongoing analysis and recent developments are presented.

XIII Nuclei in the Cosmos,
7-11 July, 2014
Debrecen, Hungary

PoS(NIC XIII)096

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1. Introduction

The nucleosynthesis of the elements heavier than iron is mainly driven by neutron capture-reactions in the *s* and *r* processes [1, 2]. However, there are about 35 proton-rich isotopes between ^{74}Se and ^{196}Hg that cannot be produced by means of neutron capture [3]. These so-called *p* nuclei are usually of low relative abundance and their production is not well understood. According to the current understanding, the *p* nuclei are mainly produced by photo-disintegration of a heavy seed distribution. This network of photon-induced reactions, called the γ process, occurs in explosive scenarios like type II or type Ia supernovae at temperatures of 1-3 GK. Additionally, various mechanisms are considered to contribute significantly to the production of the lightest *p* nuclei up to ^{96}Ru. Two prominent candidates are the *rp* process being mainly composed of proton capture reactions and the νp process, which additionally involves neutrino interactions [4, 5].

For all these nucleosynthesis processes the modeling of reaction networks and the precision of the resulting isotopic yields strongly depend on the involved reaction rates and their uncertainties. Today, these nuclear uncertainties are still too large to allow strong constraints for the specific astrophysical site and its stellar conditions [6]. To improve the current situation and understanding of the *p*-nuclei origin, measurements of relevant cross sections and reaction rates are needed. On the one hand, such experimentally determined rates can be used in the models directly, on the other hand they can be analyzed to put constraints on nuclear theory predicting rates for uncharted regions of the table of nuclides [7, 8, 9].

All astrophysical processes related to the production of *p* nuclei involve reactions on unstable isotopes. Considering the target production and the small cross sections usually involved in the astrophysical energy range, such reactions are challenging or even impossible to study using traditional methods. However, Radioactive Ion Beam (RIB) facilities, e.g. at GSI, Germany, provide the unique possibility to investigate such reactions in inverse kinematics [10]. The isotopes of interest for *p*-process studies are relatively close to the valley of stability and their production is partly possible using the existing RIB facility at GSI, namely the fragment separator (FRS) and the storage/cooler ring ESR. Intensities of such beams will be greatly enhanced with the upcoming FAIR facility [11], allowing investigations of charged particle induced reactions on exotic nuclei despite their extremely small cross sections.

2. The pilot experiment

A test experiment was carried out at GSI by storing stable ^{96}Ru ions in the ESR. In order to obtain fully stripped ions the beam was accelerated to about 100 MeV per nucleon in the SIS18 and stripped using a carbon foil of 11 mg/cm^2. After injection into the ESR the ions were slowed down to energies of 9, 10, and 11 MeV per nucleon. Additionally, electron cooling was applied before and after deceleration. After this preparation phase about $5 \cdot 10^6$ ions were circulating at a frequency of about 500 kHz. To serve as a source of protons, the internal microdroplet target [12] was prepared to provide hydrogen at an area density of about 10^{13} particles per cm^2. With these settings a total luminosity of about $2.5 \cdot 10^{25}$ cm^{-2}s^{-1} was reached.

The reaction products of nuclear reactions like (p,γ), (p,n), or (p,α) taking place in the interaction zone of beam and target are bent to smaller radii in the dipole magnet after the target.

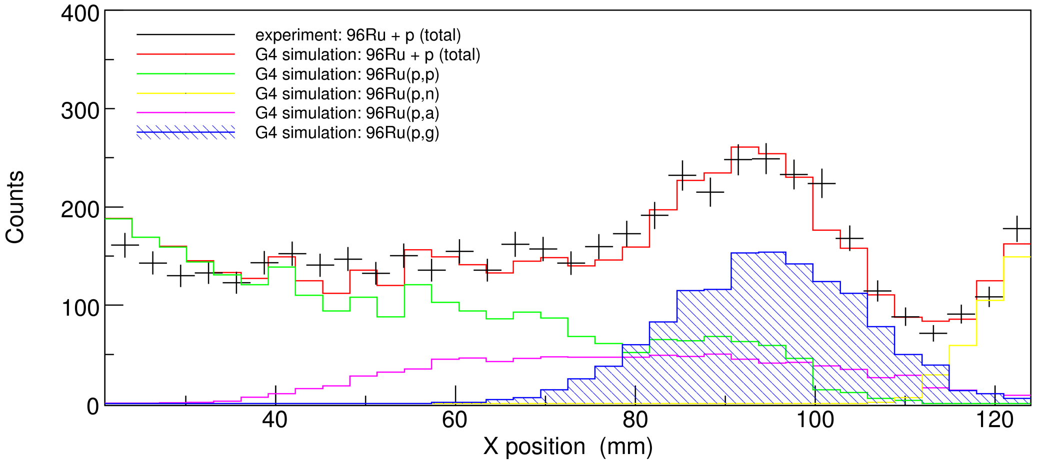

Figure 1: X position spectrum of the DSSSDs for ^{96}Ru at 11 MeV per nucleon. The black data points represent the experimental spectrum. Additionally, the contributions from (p,γ) [blue], (p,n) [yellow], (p,α) [purple] and (p,p) [green] reactions according to the GEANT4 simulation are shown after a simultaneous fit of the sum contribution [red] to the experimental data.

This magnetic separation allows the direct and background-free detection of the reaction products, provided the ion beam is fully stripped. In case of an incompletely stripped beam, particles can be ionized and would subsequently lie on tracks similar to the ones of the nuclear reaction products. For the particle detection two double-sided silicon strip detectors (DSSSDs) were used, which were positioned to cover the inner tracks of ions approximately 5 meters downstream of the dipole magnet. These DSSSDs are segmented in 16 x- and 16 y-strips and cover 5×5 cm^2 each, allowing for a spatial resolution of about 3.1 mm in both dimensions. The two particle detectors were situated in a detector pocket, separated from the ultra-high vacuum (UHV) of the ring by a stainless steel window 25 μm in thickness.

The entrance window of the pocket allows to use devices that do not meet the strict UHV requirements of the ring itself, still the ions need to have a sufficiently high energy to penetrate the window and reach the detector. The 25 μm of stainless steel introduce an energy threshold of about 7.3 MeV per nucleon for ^{96}Ru not including the energy loss in the air-filled pocket and in the dead layer of the detector itself. In practice, particle detection below 9 MeV per nucleon was not possible with this setup.

In view of this limitation in beam energy, the pilot experiment covered three energies of 9, 10, and 11 MeV per nucleon. According to the predictions of the reaction code TALYS [13, 14] the (p,γ) cross section is expected to be the smallest of the four proton-induced reactions considered here [(p,γ), (p,n), (p,α), (p,p)]. Therefore, one expects significant background from the competing nuclear reactions detected by the DSSSDs. To disentangle the four components, each reaction has been simulated using the GEANT4 framework [15]. A simultaneous fit of the simulated DSSSD response components to the data is shown in Fig. 1, which allows one to determine the (p,γ) contribution quantitatively.

For an absolute measurement of the nuclear cross section, one needs to know the absolute beam intensity, the density of the target stream, as well as the overlap of target and beam. The

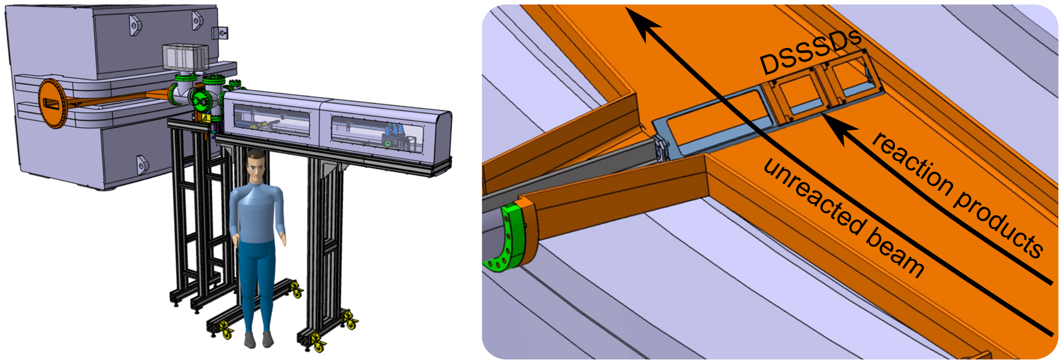

Figure 2: The newly installed setup for particle detection on inner tracks. Left panel: Shown is a part of the dipole and the detector manipulator, which moves the DSSSDs from the outside to a position on the inner ion tracks. Right panel: Interior of the dipole chamber showing the two DSSSDs in the most extended position. The circulating primary beam can pass the device through an open window, whereas the products of nuclear reactions are detected on the inner tracks.

combination of these three parameters is very difficult to measure and is subject to large uncertainties. For that reason a relative measurement was carried out making use of the well-known atomic electron capture (EC) cross sections and its radiative component (REC) [16]. These atomic processes are measured simultaneously with the nuclear reactions and can, hence, be used for normalization. The measurement of the total EC is done by using direct particle detection inside the dipole magnet downstream of the internal target. A multi-wire proportional counter in a pocket covering the outer ion tracks is used for this purpose [17]. Additionally, the REC is measured by means of x-ray spectroscopy at the target. Both methods of normalization are independent and agreed within the uncertainties.

3. A new setup for low-energy measurements

While the experimental method was successfully employed in the pilot experiment, it was not possible to measure (p,γ) reactions at astrophysically relevant energies inside the Gamow window (1 - 6 MeV per nucleon) with the presented setup, because the entrance window of the DSSSD pocket had to be penetrated. This problem can be avoided by placing the particle detectors into the UHV directly. To be able to do this, new silicon detectors have been developed that are compatible with the strict UHV requirements of the ESR vacuum ($< 10^{-10}$ mbar). These detectors are designed for performance equal to that of standard DSSSDs, but exhibit special features like enduring a bake-out procedure at a low outgassing rate.

Apart from the new design of the DSSSDs, the entire setup was moved to a position inside the first dipole magnet after the target. This position exhibits a smaller dispersion and therefore a larger angular acceptance than the former location of the DSSSDs. Since the chamber inside the C-shaped dipole is only accessible from the outside of the storage ring, a detector manipulator had to be designed to move the DSSSDs from the outside to a position covering the inner ion tracks. This problem was solved by an open window in the detector holder to let the primary beam pass, as can be seen on the right hand side of Fig. 2.

This new setup has already been installed and is ready to be used at the ESR. An experiment is planned using an ^{124}Xe beam and a hydrogen microdroplet stream to study the reaction ^{124}Xe(p,γ).

The astrophysical impact of such low-energy data will be greatly enhanced compared to the previously accessible energy range. Of course, the cross section (e.g. of a (p,γ) reaction) is likely to be smaller at lower energies making the measurement more challenging. But in fact, the ratio of the (p,γ) cross section to all competing reaction channels can be improved significantly compared to the situation at higher energies. For instance, for ^{124}Xe at or below 7 MeV per nucleon the contribution from the (p,α) and (p,n) channels is negligible or even nonexistent due to the reaction threshold. This fact can make the disentanglement of different components straightforward and certainly reduces the dependency on simulations.

4. Conclusion and outlook

The ^{96}Ru(p,γ) pilot experiment at GSI demonstrated the feasibility of low-energy nuclear reaction measurements using cooled, stored ions. The analysis of this experiment is currently in progress and results are expected to be published soon. With the new setup the threshold for particle detection below ≈ 10 MeV per nucleon can be overcome and a measurement inside the Gamow window is now possible.

The future development of the setup will include, among other things, an updated particle detection system for EC reactions, which currently is still subject to the energy limitation introduced by the detector pocket. This will allow an improved normalization of nuclear cross sections. Furthermore, the study of α-induced reactions using a helium target is of great interest for, e.g., *p*-process investigations. Finally, with the upcoming FAIR facilities, especially the Super-FRS, the intensities of radioactive beams will be enhanced to a level that allows similar reaction studies using a large variety of unstable isotopes.

In the near future, the installation of CRYRING at GSI [18] and TSR at HIE-ISOLDE [19] will ideally complement the astrophysical program at the ESR. Both projects are particularly suitable for low-energy nuclear reaction measurements and therefore represent promising extensions of the astrophysical spectrum of applications at storage rings in general [10].

Acknowledgments

This work was supported by the European Research Council [NAUTILUS 615126], by the German Federal Ministry for Education and Research [contract number 06GI7127/05P12R6FAN] and by the Alliance Program of the Helmholtz Association (HA216/EMMI).

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