96Ru(p,\gamma)\rightarrow 97Rh measurement at the GSI storage ring

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Abstract. A pioneering experiment was recently performed at the Experimental Storage Ring (ESR) at GSI. Fully stripped ions of 96Ru were injected into the storage ring and slowed down to a few MeV per nucleon. The 97Rh ions from the 96Ru(p,\gamma) reaction at a newly developed hydrogen jet target were detected with Double Sided Silicon Strip Detectors (DSSSD) mounted inside a pocket. The experiment and the status of the analysis at a beam energy of 11 MeV per nucleon will be presented.

1. Introduction
The nucleosynthesis of elements beyond iron is dominated by neutron captures in the s and r processes [1]. However, 32 stable, proton-rich nuclides between 74Se and 196Hg cannot be formed during those processes, because they are shielded from the s-process flow and r-process \beta-decay chains. These nuclei are thought to be produced in the p process, where proton-rich nuclei are made by sequences of photodisintegrations and proton captures reactions and following \beta+ decays on existing r- and s-seed nuclei. Rate predictions for the (p,\gamma) and (α,\gamma) reactions are very difficult since only a handful of experimental data for stable isotopes have been determined in the Gamow window of the p process so far. The presently favored sites for the p process are the explosively burning O/Ne layers in supernovae (SN) II and the explosive carbon burning in the core of SN Ia. The p-process models for SN II and for SN Ia are capable of reproducing the p abundances within a factor of three [2, 3, 4]. However, the light p nuclei 92,94Mo, and 96,98Ru are underproduced by more than a factor of 10 [3]. Cross-section measurements on (p,\gamma) and
\((\alpha,\gamma)\) reactions in the astrophysically interesting energy range are already very challenging on stable nuclei. Only a minute part of the nuclei involved in p-process networks, however, is stable. The majority of the isotopes crucial for the final p-abundance are unstable. The most promising approach to determine the desired reaction rates is to produce the isotopes at Radioactive Ion Beam facilities and to investigate the reactions in inverse kinematics.

In order to prove the principle of this approach, an experiment was performed at the Experimental Storage Ring (ESR) at the GSI Helmholtzzentrum für Schwerionenforschung GmbH. Fully stripped ions of \(^{96}\text{Ru}\) were injected into the ESR, slowed down to a few MeV per nucleon, interacted with a hydrogen target, and the reaction products were detected with particle detectors.

2. Experiment

The experiment was performed at the ESR with a circumference of 108.36 m, which has two 9.5 m long straight experimental sections, see Figure 1. In one of the experimental sections an electron cooler is installed while the other one hosts a gas target \([5, 6]\).

In order to produce fully stripped ions, \(^{96}\text{Ru}\) was first accelerated to 100 MeV/u and then stripped using a 11 mg/cm\(^2\) carbon foil. Afterwards the fully stripped ions were injected into the ESR, and slowed down to energies of 9, 10, and 11 MeV/u. Electron cooling was applied before and after the slowing down phase. After slowing down about \(5 \cdot 10^6 \) \(^{96}\text{Ru}^{44+}\) ions were stored in the ESR circulating at a frequency of \(\approx 500\) kHz. The thickness of the newly developed cryogenically cooled liquid microjet hydrogen target \([6]\) was \(\approx 10^{13}/\text{cm}^2\) resulting in a luminosity of \(2.5 \cdot 10^{25}/\text{cm}^2/\text{s}\).

The most important interactions of fully stripped \(^{96}\text{Ru}^{44+}\) ions with hydrogen are electron pick-up (atomic process) and proton-induced nuclear reactions like \((p,\gamma)\), \((p,\alpha)\), and \((p,n)\). Depending on the exact mechanism, the electron pick-up results in \(^{96}\text{Ru}^{43+}\) ions and possibly X-rays following the deexcitation of the atomic shell. Multi-Wire Proportional Counters (MWPC) were installed after the H\(_2\)-target on the outer side of the ESR in order to detect the \(^{96}\text{Ru}^{43+}\) ions. Germanium X-ray detectors were mounted close to the target at angles of 35\(^\circ\) and 90\(^\circ\) to detect the emitted X-rays.

The products of nuclear reactions, in particular the \(^{97}\text{Rh}^{45+}\) ions following the proton capture reaction under investigation, were detected with two Double Sided Silicon Strip Detectors.
(DSSSD) mounted in a pocket on the inside of the ESR. Each detector had 16 stripes in X- and Y-direction. The pocket had a stainless steel window of 25 µm. The thickness of this window restricted the possible energies of the $^{96}$Ru ions to energies above $\approx 9$ MeV, since the freshly produced $^{97}$Rh ions are otherwise not able to penetrate the window and could therefore not be detected with the DSSSDs. This means that we were not able to measure inside or close to the astrophysically interesting Gamow window around 3 MeV with this proof-of-principle experiment.

3. Preliminary result and discussion

The $(p,\gamma)$ cross section was measured relative to the well known electron recombination cross section at 9, 10, and 11 MeV per nucleon. The advantage of this approach is that the -otherwise difficult to determine- overlap between beam and target cancels out. The number of electron-pick-up events was determined using the X-ray detectors close to the target as well as the MWPC downstream of the target.

If $K$-REC is the radiative electron-capture process to the K-Shell, $N_{(p,\gamma)}$ and $N_{K-REC}$ the number of detected $(p,\gamma)$ and $K$-REC events, $\varepsilon_{(p,\gamma)}$ and $\varepsilon_{K-REC}$ the respective detection efficiencies, $\sigma_{(p,\gamma)}$ and $\sigma_{K-REC}$ the respective cross sections, one finds:

$$\sigma_{(p,\gamma)} = \sigma_{K-REC} \frac{\varepsilon_{K-REC}}{\varepsilon_{(p,\gamma)}} \frac{N_{(p,\gamma)}}{N_{K-REC}}.$$  \hspace{1cm} (1)

The cross section $\sigma_{K-REC}$ can be calculated based on theory with an uncertainty in the range of 5\% [7]. K-REC is detected using the X-ray detectors and their efficiencies were calibrated using a standard X-ray source.

The detection efficiency for $(p,\gamma)$ events using the DSSSDs is approximately 100\%, because all ions hit the detectors. Since the measurement had to be performed above 9 MeV in the CM-frame, not only events from proton capture occur in the DSSSDs. The important components in the position spectrum of the DSSSDs are $(p,\gamma)$, $(p,\alpha)$, and $(p,n)$ reactions. An additional background component is caused by elastic scattering of $^{96}$Ru$^{44+}$ ions on protons, see Figure 2. Figure 2 does not consider all details of the acceptance of the storage ring, which will modify the distribution in the DSSSDs.

Figure 2. The x-distribution at the position of the DSSSD particle detectors as expected from elastic scattering of $^{96}$Ru$^{44+}$ ions on protons predicted using the Monte Carlo code MOCADI [8]. The position of the primary beam is at -40 mm.

The shape of the different nuclear components can be predicted using the code LISE++ [9], see left part of Figure 3. The right part of Figure 3 shows a fit, where besides $(p,\gamma)$ only $(p,\alpha)$ and the elastic scattering were considered. The $(p,n)$ component was neglected for this preliminary analysis, because the exact shape depends strongly on the exact geometry of the beam line components and its contribution to the $(p,\gamma)$ peak is expected to be small. The final analysis will contain all components. Because of this assumption, we report here an upper limit
of the \((p,\gamma)\) cross section. So far only first results at 11 MeV per nucleon are available. The derived upper limit of the \(^{96}\text{Ru}(p,\gamma)^{97}\text{Rh}\) cross section is 4.0 mb, which is comparable to the predictions from the NON-SMOKER code [10].

![Graph](image1)

**Figure 3.** The left part shows the LISE++ [9] shape predictions of the different nuclear components. The right part shows a fit of the experimental data neglecting the \((p,n)\) component. The position of the primary beam is at -40 mm.

4. Summary and outlook
A pioneering experiment was performed at the Experimental Storage Ring (ESR) at GSI. Fully stripped ions of \(^{96}\text{Ru}\) were injected into the storage ring and slowed down to 9-11 MeV per nucleon. The \(^{97}\text{Rh}\) ions following the \(^{96}\text{Ru}(p,\gamma)\) reaction at a cryogenically cooled liquid microjet hydrogen target were detected with Double Sided Silicon Strip Detectors (DSSSD) mounted inside a pocket. We could prove the feasibility of this approach and clearly detected events originating from proton captures on \(^{96}\text{Ru}\). The analysis is still in progress and we could therefore only report an upper limit on the cross section at 11 MeV, which is slightly above the prediction from the NON-SMOKER code. The detailed analysis will eventually include a simulation of all beam line components and reaction channels. It will also be extended down to 10 and 9 MeV. In the future, such experiments have to be performed with particle detectors inside the ultra-high vacuum of the ESR in order to measure in the Gamov window. Additionally a demonstration experiment for \((\alpha,\gamma)\) reactions is planned.

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References
[1] Burbidge E, Burbidge G, Fowler W and Hoyle F 1957 *Rev. Mod. Phys.* 29 547
[2] Prantzos N, Hashimoto M, Rayet M and Arnould M 1990 *Astron. Astrophys.* 238 455
[3] Rayet M, Arnould M, Hashimoto M, Prantzos N and Nomoto K 1995 *Astron. Astrophys.* 298 517 – 527
[4] Howard W, Meyer B and Woosley S 1991 *Ap. J.* 373 L5
[5] Reich H, Bourgeois W, Franzke B, Kritzer A and Varentsov V 1997 *Nuclear Physics A* 126 417
[6] Kühnel M, Petridis N, Winters D, Popp U, Dörner R, Stöhlker T and Griest T 2009 *NIM A* 602 311
[7] Eichler J and Stöhlker T 2007 *Physics Reports* 439 1–99
[8] Iwasa N, Geissel H, Münzenberg G, Scheidenberger C, Schwab T and Wollnik H 1997 *NIM B* 126 284
[9] Tarasov O and Bazin D 2008 *Nucl. Inst. Meth.* B 266 4657
[10] Rauscher T and Thielemann F K 2000 *Atomic Data Nucl. Data Tables* 75 1