Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process

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1 Introduction

Most of the elements beyond iron are produced via neutron-induced reactions, mainly neutron captures. But there are about 35 proton rich nuclei between Se and Hg, which can neither be produced by the s process nor by the r process, see Figure 1. These nuclei are attributed to the p process, which requires high temperatures of about 2-3 GK. In such an environment the reaction flow is carried by photo-dissociation processes, i.e. by the (γ,n), (γ,p), and (γ,α) reactions. Since high temperatures are needed, the presently favored sites for the p process are the explosively burning O/Ne layers in Supernovae of type II, where temperatures of $2-3 \cdot 10^9$ K are maintained for about 1 s at densities of $\approx 10^6$g/cm^3 [1]. Under these conditions, especially the heavy proton-rich nuclei are produced by a sequence of (γ,n) reactions, while (p,γ) reactions are most likely dominating for lighter nuclei. When this sequence is halted after about five steps by the increasing neutron-separation energies, the further reaction flow is determined by (γ,p) and (γ,α) reactions. As the temperature decreases after the explosion, the reaction path moves back to the region of stable nuclei. This scenario involves about 2000 nuclei connected by more than 20000 reactions and requires correspondingly large reaction networks to describe the abundance distributions following from these scenarios, see Figure 2.

In view of the huge number of reactions, p-process studies will always have to rely on theoretical results obtained with a Hauser-Feshbach statistical model. Nevertheless, it is of utmost importance to base these calculations on a grid of experimental cross sections spread over the entire reaction network. Such data are crucial since the calculated cross sections exhibit uncertainties of several hundred percent even for stable isotopes. In case of the (n,γ) reactions, sufficient experimental data are available for constraining the model parameters close to stability so that theoretical uncertainties for stable nuclei can be reduced to a level of about 30%. These uncertainties are quickly

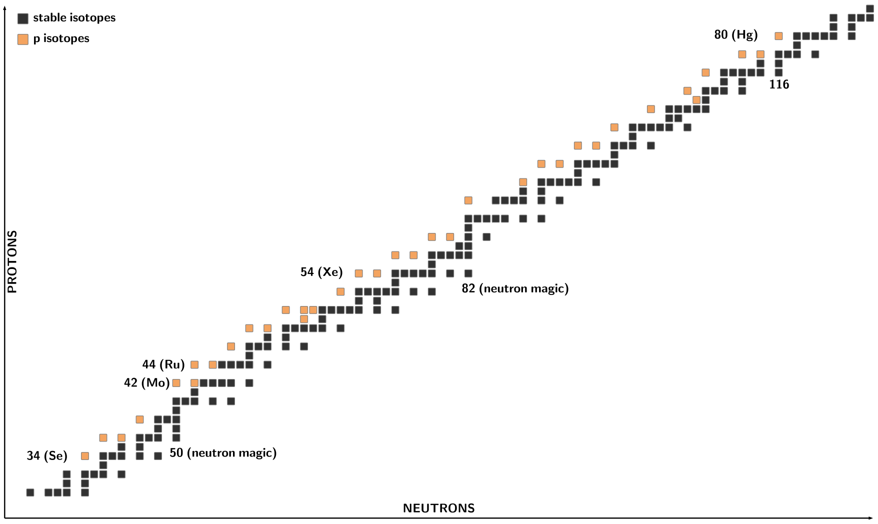

Figure 1: The p nuclei (bright) are on the proton-rich side of the valley of stability. ^{96,98}Ru marks the end of the mass range where proton capture reactions can contribute significantly to the element production. Gamma-induced reactions are therefore the main mechanism, which transforms matter originating from neutron-induced processes into proton-rich matter.

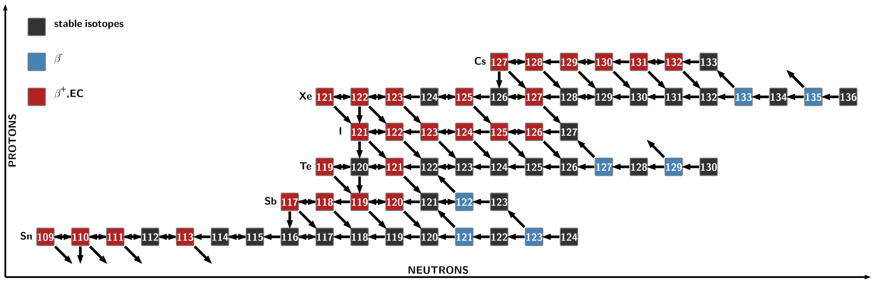

Figure 2: Reaction network during the p-process nucleosynthesis between Sn and Cs for $T_9 = 2.4$. The p-process network is dominated by (γ,n) reactions [2, 1].

increasing though, if one moves away from stability. Compared to this rather favorable situation, rate predictions for the (p,γ) and (α,γ) reactions are completely inadequate since only a handful of experimental data for stable isotopes has been determined in the Gamow window of the p process so far. Because of this lack of experimental information the corresponding reaction rates are typically uncertain by factors of two to three even for the stable isotopes.

Because of the uncertain nuclear physics input, p-process models for Supernovae of type II and Ia are capable of reproducing the p-abundances within a factor of about three [2]. Moreover, both scenarios do have problems in describing the light p-nuclei with $A < 100$ correctly. Since the p process in type II Supernovae is dominated by photo-disintegrations from heavy seeds, this model does not account for the relatively large abundances of ^{92,94}Mo and ^{96,98}Ru, see Figure 3. An alternative origin of these nuclei could be imagined via (p,γ)-reactions. The high temperatures and proton densities, which are required for these reactions to proceed with significant rates, are obtained in novae or X-ray bursters [3], where hydrogen is burnt explosively under degenerate conditions, but remixing of synthesized material to the interstellar medium is still in question for these scenarios.

Proton and alpha capture rates are, therefore, highly important in this context and can be directly used in p- and rp-process networks [2, 3]. They are also important indirectly for determining (γ,p) and (γ,α) rates via detailed balance.

Such measurements in the astrophysically interesting energy range are already very challenging on stable nuclei, especially for isotopes heavier than iron - the regime of the p process. Only a

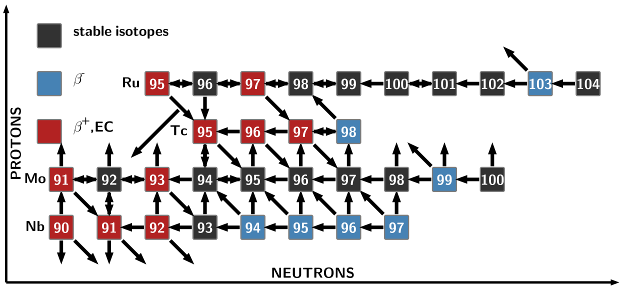

Figure 3: Reaction network during the p-process nucleosynthesis between Nb and Ru for $T_9 = 2.4$. The most important reactions are shown for $T_9 = 2.4$. The p-process network is dominated by (γ,n) reactions. Other reactions are shown, if they are dominating. See [2] for more details.

minute part of the nuclei involved in p-process networks, however, is stable. The majority of the isotopes crucial for the final p-process abundance are unstable.

The most promising approach to determine the desired reaction rates is to produce the isotopes in Radioactive Ion Beam (RIB) facilities and to investigate the reactions in inverse kinematics. Bombarding a hydrogen or helium target with the isotopes under investigation has the main advantage that no radioactive sample has to be produced. Since the reaction paths of the p process are relatively close and even in the valley of stability, the production of the relevant isotopes is significantly facilitated and can be achieved partly in the existing RIB facility at GSI with the in-flight fragment separator (FRS) and the storage/cooler ring ESR and with much improved intensity in the upcoming FAIR facility. At that stage RIBs will be available with unsurpassed intensities [4], enabling the investigation of charged particle induced reactions despite their extremely small cross sections.

2 Experiment

Within this proposal we intend to further develop a (p,γ) program at the GSI/FAIR facility towards lower energies. We will show that it is possible to investigate radioactive isotopes, even if an isomeric exists. Given the very short beam time available in total and the fact that we need only 1 beam spill from the synchrotron every few minutes, we keep this proposal open to the primary beams available to other users (not ring experiments) and ask for parallel beam time. The number of interesting and feasible cases is huge. We will therefore only give a few examples of interesting cases in the following sections. It is very important to emphasize that we can use a large variety of primary beams for fragmentation into interesting p-isotopes. Even in the unlikely scenario that the FRS is overbooked, our moderate requirements on separation can be met because of possibility to scrape away unwanted contaminants directly in the ESR. We would then use a 2 cm ^{9}Be stripper foil in the TE-channel between SIS and ESR bypassing the FRS. The only real constraint is the atomic mass of the primary beam, which should be at least 70.

We propose to extend the successful series of proof-of-principle experiments (see Section 2.1) into the Gamow window of the p process. In particular from 2019 on, we will facilitate the CRYRING for the first time to perform nuclear 2-particle reaction experiments. In order to investigate the proton capture on the ground state as well as on the isomeric state, which is abundant in stars as well as in the freshly produced radioactive beam, we will vary the storage time at high energies. This variation of storage time allows the ratio of ground state and isomeric state to be changed. Since we always measure the capture on ground state and isomer at the same time, different ratios will allow us to disentangle the two components. The storage times can be varied at high energies in the ESR, where beam-life times are long because the interaction with the rest gas is negligible.

We will perform benchmark experiments for high-Z isotopes to show the potential of the described approach and prepare the experimental capabilities for FAIR. The beam will be prepared at the ESR. For energies close to the Gamow window, the experiment will be performed in the ESR. For the lowest energies, the beam will be transferred to the CRYRING.

Traditionally stable targets would be irradiated with protons of variable energies, but rare or short-lived radioactive isotopes can typically not be accumulated in amounts necessary to produce a target. Experiments in inverse kinematics are therefore necessary. Apart from the prospects offered by the FAIR facility, the existing CRYRING and ESR are ideally suited for inclusive (p,γ) experiments: Stored and cooled bare ions may pick-up a proton whenever they cross (with a frequency of about 0.1-1 MHz) the internal H_2.

The products of the (p,γ) can be detected with an efficiency close to 100%, and identified with a position-sensitive detector moved into the aperture at the inner side of the ring [5, 6]. It should be emphasized that for bare ions no atomic process, like electron stripping, will disturb the measurement. The products of electron pick up will be on orbits on the outer side of the primary beam.

The corresponding experimental equipment at CRYRING is currently under construction, funded by the BMBF Verbundforschung.

2.1 Previous (p,γ) experiments at the ESR

The method was successfully proven for the first time in 2009 during the experiment E062 at the example of ^{96}Ru(p,γ) [7] and the final publication got awarded with the "editors suggestion" [8]. In order to produce fully stripped ions, ^{96}Ru was first accelerated to 100 AMeV and then stripped using a 11 mg/cm^2 carbon foil. Afterwards the fully stripped ions were injected into the ESR (see Figure 4), and slowed down to energies of 9, 10, and 11 AMeV. Electron cooling was applied before and after the slowing down phase. The fairly high energy had to be chosen, because the ESR beam time schedule of 2009 did not allow such a measurement with enough preparation time to install the particle detectors in vacuum.

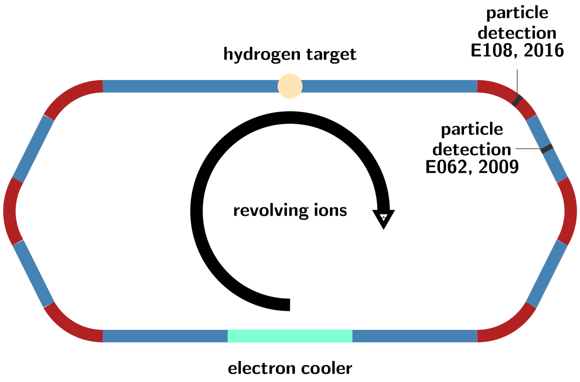

Figure 4: Schematic layout of the experimental storage ring at GSI. It contains an hydrogen jet target and an electron cooler device. The ring has a circumference of 108 m and a maximum magnetic rigidity of 10 Tm.

The products of nuclear reactions, in particular the ^{97}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 past the first dipole following the hydrogen target. Each detector had 16 strips 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 AMeV, 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 (center of mass energy) with this first proof-of-principle experiment.

The experiment E108 performed in the summer of 2016 at the ESR closed this gap. We investigated the important p-nucleus ^{124}Xe in inverse kinematics. The silicon detectors were mounted under UHV conditions inside the first dipole following the hydrogen target (see Figs. 4 and 5). Within this experiment we were able to measure proton captures at energies as low as 5.5 AMeV.

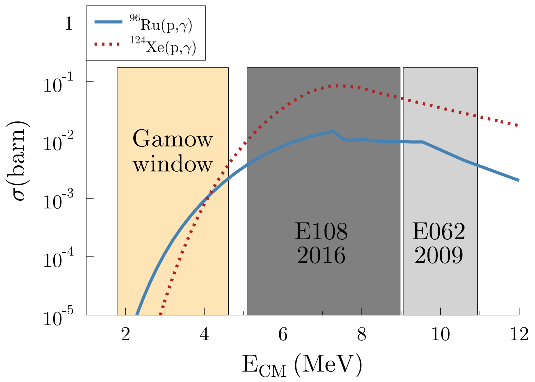

Figure 5: Energy ranges and corresponding cross sections of the worldwide only proton capture experiments in inverse kinematics performed so far. With the current proposal, we intend to measure inside the Gamow window of the astrophysical p-process.

The detection efficiency for (p,γ) events using the DSSSDs is approximately 100%, because virtually all ions hit the detectors. Not only events from proton capture occur in the DSSSDs. Depending on the energy and reaction under investigation, the important components in the position spectrum of the DSSSDs are (p,γ), (p,α), (p,n) and (p,p) reactions. The different components result in different position distributions on the DSSSDs and can therefore be disentangled, Figs. 6.

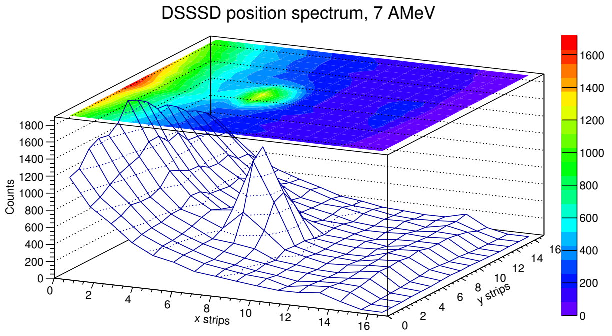

Figure 6: Spectrum taken during the E108 experiment corresponding to a ^{124}Xe beam at 7 AMeV on hydrogen. The x-y plane corresponds to the strip number, hence position on the DSSSD (3 mm/strip). The unreacted beam circulates to the left of the histogram. The relatively sharp peak in the center originates from proton captures, while the large structure at the edge of the detector results from ^{124}Xe ions elastically scattered on protons at the target.

2.2 Proposed experiment

The unrivaled combination of sharp ion energy, ultra-thin (as compared to solid-state targets) internal gas target, and the possibility of in-ring energy adjustments enables precise, energy-differential scans of the (p,γ) cross sections. The Gamow window for proton capture reactions on a nucleus with Z=50, A=112, T_9=2–3 (typical p-process temperature) is at E_{Gamow} = 1.8–4.5 MeV for proton-induced reactions. We propose to perform 2 steps:

- Inject a **radioactive species** of astrophysical interest into the ESR, condition the beam and measure (p,γ) reactions to energies as low as possible.

- Transfer the pre-conditioned beam of radioactive species to the CRYRING, condition the beam and measure (p,γ) reactions down to energies **inside the Gamow window**.

2.2.1 Radioactive isotopes and isomers at the ESR

For the first phase of the experiment we propose to inject a radioactive species of interest for the p-process into the ESR and slow it down into the energy range of the 2016 experiment. This will be the first time that a (p,γ) reaction is measured on a radioactive nucleus in inverse kinematics. It has been shown already that stable beams can be investigated at the ESR down to 5.5 AMeV and we will use the very same equipment as during the last run in 2016.

Aside from the worse emittance of the freshly produced radioactive beam compared to stable beam, isomeric states pose a new challenge and an interesting opportunity at the same time. Because of the hot environment during the stellar nucleosynthesis, excited states above the ground state are constantly populated and will contribute to the total reaction rate of a given isotope. Proton capture reactions on isomers have not been measured yet. If the the half-life times of isomeric and ground state are not too long, but different, the ratio of the two can be varied by storing the beam in the order of the shorter half-life time. Very interesting examples are ^{103}Ag or ^{109}In. The (p,γ) rates of both isotopes are important to understand the p-process nucleosynthesis, as was shown recently in large-scale Monte-Carlo studies [9, 10]. The ground state of both isotopes has a half-life time of at least one our, while the isomer lives for 6 s in the case of ^{103m}Ag and 80 s in the case of ^{109m}In. Both isomers decay almost exclusively to the ground state. This means, if the freshly produced radioactive beam is stored for a few minutes at high energies where the interaction with the rest gas in the storage ring can be neglected, all nuclei in the isomeric state are decayed and the beam consists of isotopes in the ground state only. If the cross section is measured twice, once with and once without the additional waiting time, both cross sections can be disentangled. The amount of isotopes in the isomeric state right after the production can be determined via an activation measurement of implanted beam.

As mentioned above, we are very flexible in terms of the specific primary beam. Other astrophysically interesting examples are ^{77m,gs}Br, ^{73}As, ^{83}Rb, ^{91m,gs}Nb, and ^{93m,gs}Tc.

2.2.2 Reaching the Gamow window using the CRYRING

The second phase consists of actually measuring proton capture cross sections for the first time inside the Gamow window in inverse kinematics. The ideal tool for such a measurement is the CRYRING@FAIR, see Fig. 7. The CRYRING was used to investigate atomic interactions in the past and is optimized for low beam energies. Funded by the BMBF Verbundforschung, experimental equipment is currently being installed to measure atomic as well as nuclear interactions. The CRYRING will probably be available in 2019. We propose to used the same isotope as investigated during the first phase. The knowledge how to prepare the beam at the ESR will then be already available, which saves beam development time. The beam will be transfered to the CRYRING at about 10 AMeV and then slowed down as far as possible. We anticipate that 3 AMeV will be possible, which is in the position of the Gamow peak, the maximum reaction rate inside the Gamow window.

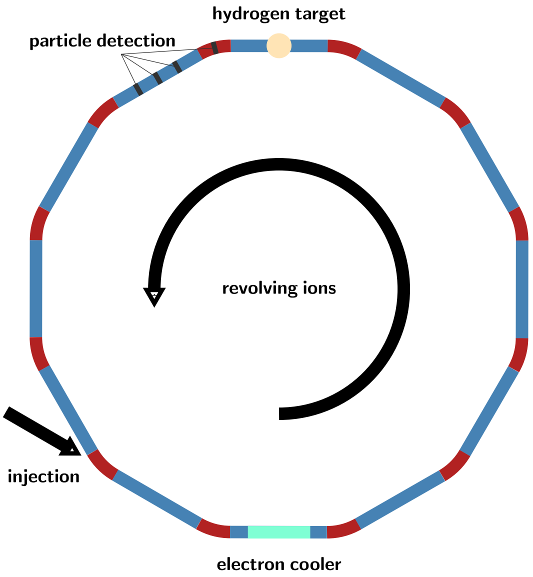

Figure 7: Schematic layout of the CRYRING at FAIR. It contains an hydrogen jet target and an electron cooler device. The ring has a circumference of 54 m and a maximum magnetic rigidity of 1.44 Tm for heavy ions. It consists of 12 dipoles, each bending the beam by 30°. Six of the 12 straight sections are equipped with beam optical elements, e.g. quadrupoles, while the other 6 are equipped with special tools like electron cooler, gas target, or RF.

2.3 Secondary beam production and count rate estimate

The production of selected radioactive species in the FRS was estimated using LISE++ [11]. A summary of the production estimates for several isotopes assuming an injection energy into the ESR of 400 AMeV and the stacking technique is given in Table 1. Beam stacking in the ESR results in an increase of the amount of stored particles by more than one order of magnitude unless the space charge limit is reached [12].

In the case of ^{109}In not only the ground state (9/2+) can be produced via the in-flight fragmentation but also the isomeric state (1/2-) at 649.79 keV. Predictions based on the ABRABLA code [13] show a high isomeric fraction of about 90%. This allows the proton-capture measurement at different isomeric ratios based on different waiting times as mentioned earlier.

Table 1: Production of radioactive ions for ESR.

secondary beam	primary beam	primary intensity	energy [MeV/u]	^{9}Be target [g/cm^2]	production xs [mbarn]	stored intensity
^{109}In	^{112}Sn	$5 \cdot 10^8$	555	3.0	58.5	$7.2 \cdot 10^5$
^{109}In	^{124}Xe	$2 \cdot 10^9$	515	2.0	17.0	$2.7 \cdot 10^5$
^{103}Ag	^{112}Sn	$5 \cdot 10^8$	525	2.5	30.5	$1.8 \cdot 10^5$
^{103}Ag	^{124}Xe	$2 \cdot 10^9$	525	2.5	12.1	$2.2 \cdot 10^5$
^{93}Tc	^{96}Ru	$5 \cdot 10^8$	555	3.5	64.5	$7.4 \cdot 10^5$
^{91}Nb	^{94}Mo	$1 \cdot 10^9$	555	3.5	56.5	$1.2 \cdot 10^6$
^{83}Rb	^{86}Sr	$5 \cdot 10^8$	545	3.5	47.2	$5.1 \cdot 10^5$
^{77}Br	^{80}Kr	$1 \cdot 10^9$	545	4.0	59.1	$1.2 \cdot 10^6$

The resulting (p,γ) count rates for the ESR were calculated using TALYS [14]. Between 10^3 and 10^4 counts/day are expected for all isotopes mentoined in Table 1.

Table 2: Proposed usage of beam time. Each shift corresponds to 8 h.

#	item	E_{beam} (AMeV)	shifts
1	setting up FRS & ESR	7	6
2	(p,γ)	7	3
3	setting up ESR	5	1
4	(p,γ)	5	5
	subtotal		**15**
5	Setting up ESR & CRYRING	5	6
6	(p,γ)	5	6
7	setting up CRYRING	4	2
8	(p,γ)	4	6
9	setting up CRYRING	3	2
10	(p,γ)	3	8
	subtotal		**30**
	total		**45**

2.4 Plan for beam time usage

Our proposal is to perform a proof of principle experiment for (p,γ) reactions of a radioactive isotope in two phases. The first phase builds on the experience gained so far at the ESR while the CRYRING will be utilized for the first time for proton capture experiments during the second phase. The total requested beam time is 15 days, see Table 2.

3 Publications of the spokesperson

The most important project-related publications of the spokesperson are [1, 6, 8, 15, 16].

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