

ESR measurements of proton-induced reaction rates in the Gamow window of the astrophysical p process

M. Heil, I. Dillmann, F. Käppeler, and R. Plag, Forschungszentrum Karlsruhe
K. Beckert, P. Beller, F. Bosch, B. Franzke, H. Geissel, C. Kozhuharov, Yu. Litvinov, G. Münzenberg, F. Nolden, Ch. Scheidenberger, M. Steck, K. Sümmerer and Th. Stöhlker, GSI

spokesperson: Michael Heil, FZK; michael.heil@ik.fzk.de;
GSI contact person: Yuri Litvinov; Y.Litvinov@gsi.de

1. Motivation

The elements heavier than iron are predominantly produced via neutron capture and β^- -decays in the s and r processes, as first suggested by Burbidge *et al.* (B²FH) [1]. However, these processes do not account for the 32 stable isotopes on the proton rich side of the valley of stability between ⁷⁴Se and ¹⁹⁶Hg that are shielded from neutron captures by stable isobars. These so called p nuclei are typically 10 to 100 times less abundant than their neutron rich isotopes, but their abundance curve almost parallels those of the r and s nuclei. This leads to the conclusion that the p nuclei originate from an r - and s -process seed that is modified by either photo-disintegration or proton capture.

The presently favored sites for the p process are the explosively burning O/Ne layers in supernovae (SN) of type II, where temperatures of $T_9 = 2 - 3$ ($T_9 = 10^9$ K) are maintained for about 1 s at densities of $\approx 10^6$ g cm⁻³ [2, 3]. Under these conditions, proton rich nuclei are produced by a sequence of (γ, n) reactions. When this sequence is halted after about five steps by the increasing neutron separation energies, the further reaction flow is dominated by the (γ, p) and (γ, α) channels. As the temperature decreases during the explosion, the reaction path moves back to the region of stable nuclei. This scenario involves about 1500 nuclei and more than 10000 reactions and correspondingly large reaction networks to describe the abundance distributions following from these scenarios.

In view of the huge number of reactions required, p -process studies will always have to rely on theoretical data obtained with the Hauser-Feshbach statistical model. Nevertheless, it is of utmost importance to base these calculated data on a grid of experimental cross sections that should cover the entire reaction network. Such data are crucial since the calculated cross sections exhibit uncertainties of several hundred percent even for stable isotopes.

Contrary to neutron capture reactions, where sufficient experimental (n,γ) cross sections could be used to reduce the theoretical uncertainties to a level of about 30%, the situation for (p,γ) and (α,γ) reactions is completely inadequate since only a handful of experimental data has been determined in the Gamow window of the p process so far. Due to this lack of experimental information the corresponding reaction rates are typically uncertain by factors of 3.

Given this unsatisfactory situation with a rather uncertain nuclear physics input, 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]. Moreover, both scenarios do have problems in describing the light p -nuclei with $A < 100$ correctly. Since the p process in SN II is dominated by photodisintegrations from heavy seeds, this model does not account for the relatively large abundances of ^{92}Mo , ^{94}Mo , ^{96}Ru , and ^{98}Ru . An alternative origin of these nuclei could be via (p,γ)-reactions. High temperatures and proton densities are required for these reactions to proceed with significant rates, as is the case in novae or X-ray bursters [5], where hydrogen is burnt explosively under degenerate conditions.

Another possible site are SN Ia, where free protons are released via the $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ channel during explosive carbon burning in the core. Capture of these protons by the abundant neutron magic isotopes with $N = 82$ may then contribute to the missing p -process components of Mo and Ru. However, this effect is similarly felt by the lighter p nuclei ^{74}Se , ^{78}Kr , and ^{84}Sr , which are therefore systematically overproduced.

In the first place the present problems in describing the p abundances could be due to the yet very schematic treatment of the SN explosion, which has so far been assumed to be spherically symmetric at the position of the Ne/O layer. This assumption might be questionable in the light of current multi-dimensional SN calculations, which exhibit strong asymmetries [6]. There is also observational evidence that most SN are, indeed, asymmetric [7].

In this context, the information contained in the p -abundance distribution may constitute an important source of information with respect to our understanding of the SN mechanisms. Such information can only be deduced, however, if it is not obscured by substantial uncertainties in the nuclear reaction rates, in particular in the more decisive parts of the reaction network on the proton-rich side of the stability valley.

As shown by Rapp [8] the p -process yields are sensitive to (p,γ) reactions mostly in the mass region $A < 160$, whereas the effect of (α,γ) reactions prevails at larger mass numbers. This is illustrated in Fig. 1, which shows part of the p -process network between Cd and Dy. The line thickness corresponds to the strength of the reaction flow. The strong importance of (p,γ) and (γ,p) reactions (vertical lines) in the lower part becomes weaker at the upper end, where the reaction flow starts to be governed by α -induced reactions.

For a substantial improvement of the yet uncertain reaction rates we propose a program for the measurement of (p,γ) and (α,γ) cross sections in the ESR, which aims at determining these data right in the Gamow window of the p process. Since the p -process temperatures are sufficiently high that thermal equilibrium is reached in the population of excited states, these cross sections can be converted via detailed balance into those of the inverse reactions, which are much more difficult to investigate.

The proposed program is unique since the GSI upgrade will provide sufficiently intense radioactive beams to perform these measurements on short-lived isotopes across the p -process network that are not accessible anywhere else. However, the proposed pilot experiments at the existing ESR using *stable* nuclei will test not only the capability of ion storage-cooler rings for this challenging but yet scarcely explored field of nucleosynthesis, but will also provide first substantial data.

2. The unique capability of the ESR for (p,γ) experiments

For inclusive (p,γ) experiments the ESR is ideally suited: Stored and cooled bare ions may pick-up a proton whenever they cross (with a frequency of about one MHz) the internal H_2 gas jet. This pick-up leads for medium-heavy ions ($A \approx 100$) to a change in the mass-over-charge ratio A/q of less than two percent. Hence, the reaction products still remain in the acceptance of the ESR (except the lightest ions with $A < 25$), but circulate on new orbits at the inner side of the aperture, and at a significantly altered revolution frequency. They can easily be recorded with a detection efficiency $\epsilon = 1$, and unambiguously identified either by their Schottky spectrum or, alternatively, by a position- and Z -sensitive detector moved into the aperture at the inner side of the ring. It should be emphasized that, for *bare* ions, an almost background-free spectrum can be expected in this detector, since there are none disturbing atomic processes, like electron stripping, that might lead to a comparable shift of the orbit onto the outer side of the ring.

The unrivalled combination of sharp ion energy, ultra-thin (as compared to solid-state targets) internal gas target, and simple energy variation by means of the electron cooler, enables precise, energy-differential scans of the (p,γ) cross section and possibly the detection of narrow resonances.

3. Experimental procedure

In this section the relevant technical aspects of ESR measurements related to p -process nucleosynthesis are discussed with particular emphasis on the cooling and decelerating of the beam, loss of intensity during deceleration, the particle density in the gas jet, and the actual measurement technique. It is understood that experimental tests will be carried out with stable beams first in order to demonstrate the feasibility of the method. The energy regime to be chosen for the pilot experiments with stable nuclei as well as for future experiments with unstable nuclei, is defined by the presumed Gamow window of the p process between 5 and 10 MeV/u depending on the different p -process scenarios. Since bare nuclei are preferred for the experiments,

the high-energy primary ions provided by SIS and fully stripped in a foil between SIS and ESR must be first decelerated in the ESR.

3.1 Scheme for cooling and deceleration:

The proposed (p, γ) experiment could be performed in repeated cycles according to the following scheme

- *injection energy 200 MeV/u*
- *first cooling step*
- *deceleration to 40 MeV/u*
- *second cooling step*
- *deceleration to the required energies between 5 and 10 MeV/u*
- *start of H₂ gas jet*
- *measurement during one life time of the beam (presumably 40 s at 10 MeV/u, see 3.4).*

At present, the overall time from injection to the start of the jet is about 45 s, but will be reduced to about 10 s in the near future. In principle, this implies that measurements can ultimately be performed on isotopes with half-lives of a few seconds. For technical reasons, two cooling steps are necessary for final energies below 15 MeV/u.

3.2. Loss of ions during deceleration and cooling:

Deceleration in the ESR must be paid by significant beam losses, i.e. from an initial value of about $5 \cdot 10^8$ stored bare ions right after injection of two bunches to about $5 \cdot 10^7$ at 10 MeV/u and about 10^7 at 5 MeV/u. These values refer the mass $A = 100$ region.

3.3. Particle densities in the gas jet:

As shown by Krämer [9], densities of $1 \cdot 10^{13}$ atoms/cm² have been reached for the liquid N₂ cooled H₂ gas jet of the ESR. This density could be maintained for 1-2 days, but was later significantly reduced due to frozen skimmers. At present, undisturbed operation of the gas jet throughout an entire week is safely guaranteed for a density of $4 \cdot 10^{12}$ H₂ atoms/cm². For a helium jet, no reliable densities are available so far.

3.4. Life time of the ion beam during operation of the H₂ gas jet

Life times of 120 s have been measured for bare ions with $A = 70$, $Z = 30$ and 10 MeV/u in the ESR, when the gas jet was operated with $4 \cdot 10^{12}$ H₂ atoms/cm² [10]. At this energy, ions are mainly lost due to radiative electron capture (REC) in the gas jet and - to a lesser extent - in the electron cooler. This life time is in very good agreement with calculations based on the eikonal approximation for electron capture. By an appropriate Z^2 -scaling of the measured capture cross sections, a life time of at least

40 s can be safely presumed for $Z = 50$ nuclei under the experimental conditions of the pilot experiments proposed in next paragraph. For 5 MeV/u, where no data are yet available, electron capture is already dominated by the non-radiative electron capture (NREC)-process. Therefore, one has to anticipate significantly shorter life times of 15 s or even less.

3. 5. Proposed pilot experiments at the ESR

We propose to demonstrate the experimental technique for (p, γ) measurements in the ESR with a test beam time using stable ^{112}Sn and ^{124}Sn ions. The half-lives of the corresponding (p, γ)-products are 6.8 min (^{113}Sb) and 2.7 yr (^{125}Sb) so that they can be considered stable within our short measuring cycle. Since both isotopes are of low natural abundance (1% for ^{112}Sn , 6% for ^{124}Sn), enriched ion-source material would be of advantage for obtaining the required 10^9 primary ions per spill.

3.6. Measurement technique:

We intend to measure the energy-differential (p, γ) cross sections for bare $^{112}\text{Sn}^{50+}$ and $^{124}\text{Sn}^{50+}$ ions at some 20-30 energy steps within the Gamow window of about 5-10 MeV/u. Schottky analysis can be used, because the reaction products are kept in the ring. Due to the change in A/q of about two percent, the bare (p, γ)-products appear in the Schottky spectrum as well-resolved and widely separated lines to the right of the mother ions. Hydrogen-like product ions that have picked-up an electron in the gas jet or the electron cooler remain also in the acceptance of the ring, but appear to the left of the mother ion in the Schottky spectrum (Fig. 2). After calibration of the frequency scale in A/q , the bare as well as the H-like products can be unambiguously identified. The total (p, γ)-yield is contained in the corresponding Schottky lines. Therefore, the (p, γ)-cross section can be extracted by integration after conversion of the intensity into particle number. An independent way of recording the number of (p, γ)-products could be achieved by inserting a position- and Z-sensitive detector [11] into the inner part of the ring aperture at an appropriate position near the scraper in the northern part of the ESR.

As suggested above a typical experimental cycle consists a beam preparation phase following injection into the ESR that lasts for about 45 s and a measurement phase with the hydrogen jet. During the second phase, which is expected to last for about 40 to 60 s, the reaction products are recording in the Schottky spectrum (or using the particle detector). This cycles is repeated every 120-180 s.

By combining the jet density of $4 \cdot 10^{12}$ H_2 atoms/ cm^2 and a beam intensity of $5 \cdot 10^7$ cooled, decelerated ions with 10 MeV/u at the start of the measurement, we expect a mean luminosity $L \approx 4 \cdot 10^{25}$ cm^{-2} s^{-1} within the measuring phase of each cycle. (At this energy the revolution frequency is 0.39 MHz). Assuming a typical (p, γ) cross section

of 10 mb in the Gamow window and a measuring time of 40 s per cycle, this translates into an expected rate of about 16 events per cycle, or about 300 events/h for a total cycle length of three minutes. At 5 MeV/u, the lower revolution frequency of

0.27 MHz, the reduced ion intensity, and the shorter measuring time per cycle results in an expected rate of about 30 events/h. Both estimates confirm that the proposed measurements can be performed in sufficiently fine energy steps and with acceptable statistics.

4. Long-term program

A main advantage of (p,γ) cross section measurements in the ESR is the universality of the technique. Most of the few existing data in the Gamow window of the p process have been obtained in activation measurements. This method is straightforward and can be pursued even with limited resources. However, it is restricted to few reactions on stable isotopes, because it requires radioactive product nuclei within a certain range of suitable half-lives and with well known γ -decay properties.

No such limits exist for the proposed ESR experiments since the reaction products are identified by mass, regardless whether they are stable or radioactive. The only important condition is the required beam intensity in the ring, which can presently be met only for stable isotopes. Accordingly, a representative data set along the valley of stability can be established in the near future as an important bench mark test of theoretical data. With this information, the statistical model extrapolation into the proton-rich region could already be greatly improved.

As soon as the GSI upgrade provides sufficiently high RIB intensities, the technique *can be applied to practically all* radioactive isotopes in the entire reaction network of the p process. By then, the cooling and deceleration times will be short enough that a grid of experimental reaction rates across the entire p -process network can be established with the ultimate goal to remove the nuclear physics uncertainties from the problem of characterizing the astrophysical site of the p process.

5. Beam time request

According to our experience, the preparation of stable, periodically repeated cycles of storing, cooling, and deceleration, the synchronization with the gas jet, as well as the optimisation of the overlap between ion beam and gas jet requires at least 2 days (6 shifts). For the 'pure' measuring time with two ion species and about 25 energy steps for each of them we calculate an additional request of at least 5 days (15 shifts) assuming an average time of 2.5 hours per step.

We ask, therefore, for **21 shifts (7 days) of beam time** with (enriched) ^{112}Sn and ^{124}Sn ions at an energy (SIS extraction) of **200 MeV/u**.

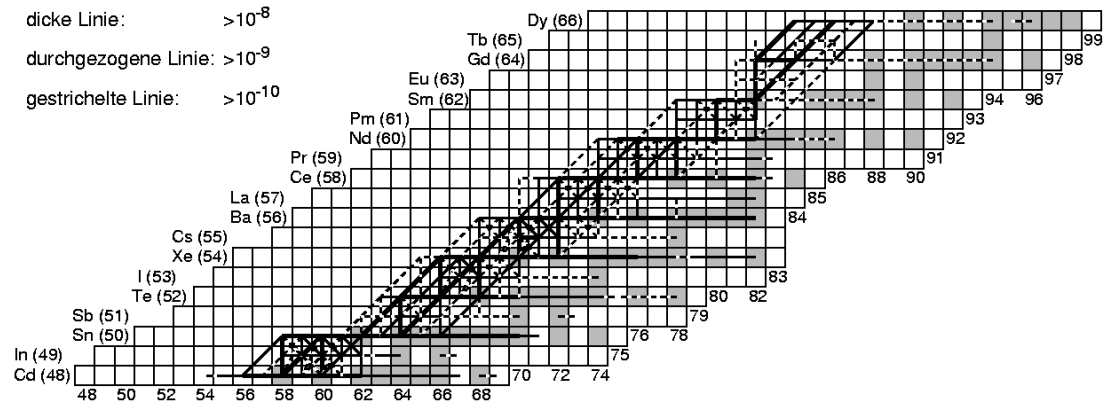


Fig. 1. The reaction flow between Cd and Dy in a typical p -process scenario. The strength of the various reactions is indicated by the line thickness. The dominance of p -induced reactions (vertical lines) becomes weaker at the upper end, where the reaction flow is mostly carried by α -induced reactions.

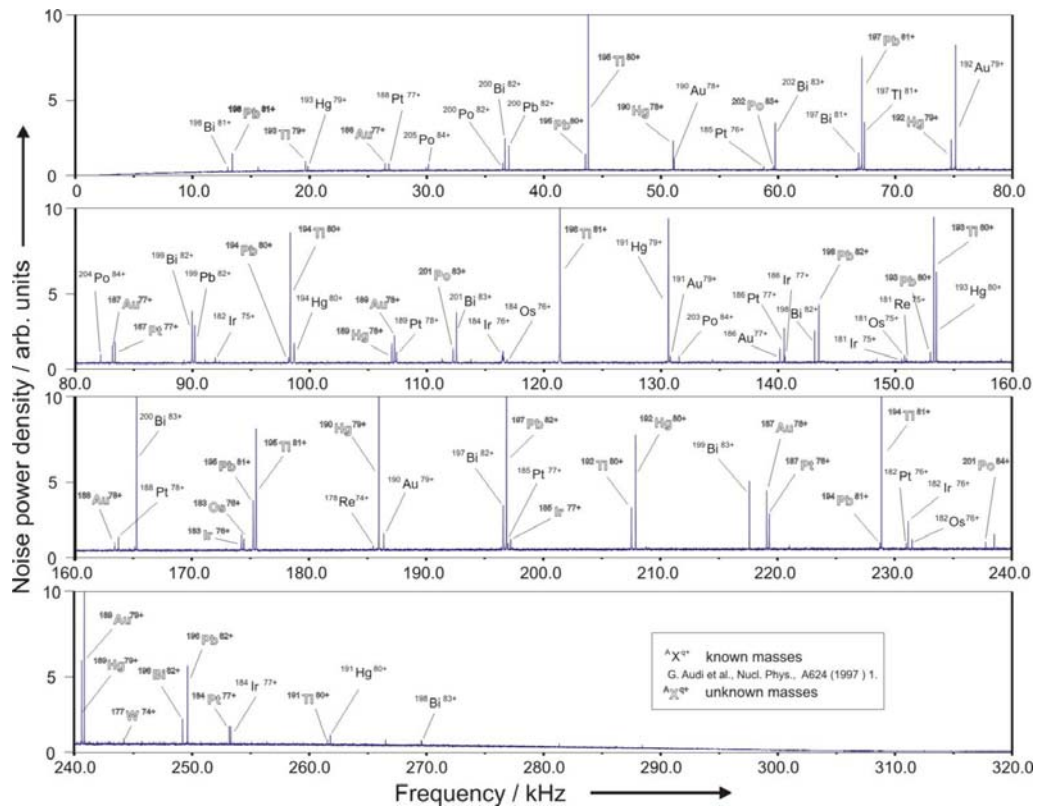


Fig. 2 Schottky spectrum of stored and electron-cooled fragments, filling almost the whole ring acceptance. In a similar relative revolution-frequency scale the Schottky line of $^{125}\text{Sb}^{51+}$, the bare (p,γ)- daughter of bare $^{124}\text{Sn}^{50+}$, would appear at about 100 kHz to the right of the mother ion. Product ions that have picked-up an electron, e.g. H-like $^{125}\text{Sb}^{50+}$, are also kept in the ring and would appear at about 40 kHz to the left. In this Z-regime the signals are strong enough to allow even the detection of one single stored ion.

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