New experimental developments for s- and p-process research

R Reifarth, O Ershova, J Glorius, K Göbel, C Langer, O Meusel, 
R Plag, S Schmidt, K Sonnabend
Goethe Universität Frankfurt, 60438 Frankfurt, Germany

M Heil
GSI Helmholtzzentrum f. Schwerionenforschung GmbH, 64291 Darmstadt, Germany
E-mail: reifarth@physik.uni-frankfurt.de

Abstract. Almost all of the heavy elements are produced via neutron-induced processes in a multitude of stellar production sites. The remaining minor part is produced via photon- and proton-induced reactions. The predictive power of the underlying stellar models is currently limited because they contain poorly constrained physics components such as convection, rotation or magnetic fields. An important tool to determine such components is the comparison of observed with modeled abundance distributions based on improved nuclear physics input.

The FRANZ facility at the Goethe University Frankfurt, which is currently under construction will provide unprecedented neutron fluxes and proton currents available for nuclear astrophysics. It will be possible to investigate important branchpoint nuclei of the s-process nucleosynthesis path and proton-induced reactions important for p-process modeling.

At the GSI close to Darmstadt radioactive isotopes can be investigated in inverse kinematics. This allows experiments such as proton-induced cross section measurements using a heavy-ion storage ring or measurements of gamma-induced reactions using the Coulomb dissociation method. The future FAIR facility will allow similar experiments on very exotic nuclei, since orders of magnitude higher radioactive ions beams will be possible.

1. Introduction
Almost all of the heavy elements are produced via neutron capture reactions equally shared between s and r process [1, 2]. The remaining minor part is produced via photon- and proton-induced reactions during the p process, see Fig. 1. The predictive power of the underlying stellar models is limited because they contain poorly constrained physics components such as convection, rotation or magnetic fields. The crucial link between the observed abundances [3] and the desired parameters of the stellar interiors are nuclear reaction data. In contrast to the r process [4] the isotopes important for the p process [5] as well as for the s process [6] are stable or not to far off the valley of stability. The nuclear properties of those nuclei are therefore experimentally much easier to access. While indirect measurements, like the investigation of time-reversed reactions, are very often the only choice because of the short half-lives of the investigated isotopes [7, 8], this article is focussing on experimental developments aiming at a better understanding of the s and p processes by direct measurements of important capture reactions.
2. The s process

The modern picture of the main s-process component refers to the He shell burning phase in AGB stars [9]. Nuclei with masses between 90 and 209 are mainly produced during the main component. The highest neutron densities in this model occur during the $^{22}\text{Ne}(\alpha,n)$ phase and are up to $10^{12}\text{ cm}^{-3}$ with temperatures around $kT = 30$ keV. The other extreme can be found during the $^{13}\text{C}(\alpha,n)$ phase where neutron densities as low as $10^{7}\text{ cm}^{-3}$ and temperatures around $kT = 5$ keV are possible. Similarly to the main component, also the weak component referring to different evolutionary stages in massive stars has two phases [10, 11]. Nuclei with masses between 56 and 90 are mainly produced during the weak component. The first phase occurs during the helium core burning with neutron densities down to $10^{6}\text{ cm}^{-3}$ and temperatures around $kT = 25$ keV. The second phase happens during the carbon shell burning with neutron densities up to $10^{12}\text{ cm}^{-3}$ at temperatures around $kT = 90$ keV.

If the rates for neutron capture reactions are comparable to the rate of beta decay of particular nuclei, then the s-process path branches and some fraction of these nuclei are transformed via neutron capture, while another fraction undergoes beta decay. The branching ratio, or relative likelihood, for the different reactions depends on the physical conditions in the interior of the star, like temperature, neutron density, and electron density. Thus, the branching ratios deduced from the isotopic ratios observed in stellar material provide the tools to effectively constrain modern stellar models of the s-process, provided one knows the fundamental rates for neutron capture and beta decay under stellar conditions.

Neutron capture measurements on radioactive isotopes for neutron energies in the keV region represent a stringent challenge for further improvements of experimental techniques. This holds true for the neutron sources, the detection systems and the technology to handle radioactive
material. Though the activation method or accelerator mass spectroscopy of the reaction products could be applied in a limited number of cases, experimental facilities like DANCE at LANL (USA) [12], n-TOF at CERN (Switzerland) [13] and the upcoming facility FRANZ in Frankfurt (Germany) [14] are addressing the need for such measurements on the basis of the more universal method of detecting the prompt capture $\gamma$-rays, which is required for the application of the neutron time-of-flight (TOF) technique. In particular the FRANZ facility, which will be located close to the new FAIR facility might allow the investigation of radioactive isotopes with half-lives down to tens of days, while present facilities require half-lives of a few hundred days.

In addition to the uncertainties affecting the neutron capture rates [15], weak interaction properties also face severe theoretical problems. Although all the $\beta$-decay and EC rates of relevance in the s-process are known under terrestrial conditions, the contribution of thermally populated excited states, as well as atomic effects in the strongly ionized stellar plasma can drastically modify the laboratory values [16]. The calculated $\beta$-rates in stellar environments are subject to nuclear uncertainties, which remain difficult to estimate. The uncertainties in the stellar $\beta$-decay and EC rates strongly depend on the relevance of the experimentally unknown transitions at a given temperature and density. So far, the stellar decay rates have been estimated in a systematic study [16]. In order to illustrate the effect of the remaining nuclear uncertainties the calculations have been re-iterated modifying the unknown transition rates by an error value of $\log ft = \pm 0.5$ [17]. For a typical s-process temperature of $T_8 = 3$ K and electron density of $N_e = 10^{27}$ cm$^{-3}$ the final rate was then altered by a maximum value of 3.16. This maximum variation is obtained for many rates.

Under stellar conditions, ground state and low-lying excited states are in thermal equilibrium. The combined $\beta$-decay rates of these states determine, therefore, the $\beta$-decay probability of the species. Hence, both rates need to be determined in order to understand the important branchings in the reaction path of the s-process. But only in the case of isomeric excited states with sufficiently long half-lives one may attempt to determine their weak-decay rate experimentally.

3. The p process

The most intensively studied astrophysical site of the p-process is the O-Ne layer of a massive star passed by the shock wave of a type II supernova [18]. Here, the p nuclei are produced in a series of photodisintegration reactions, such as ($\gamma$,n), ($\gamma$,p), and ($\gamma$,α) reactions, from a given seed abundance. This picture is often referred to as $\gamma$-process [5]. The reaction network to describe this scenario includes a huge number of reaction rates, which are generally calculated in the framework of the Hauser-Feshbach statistical model. In the last decade, different experimental studies have been carried out to test the reliability of these predictions and their sensitivity to the nuclear physics input parameters, such as $\gamma$-ray strength functions and particle-nucleus optical potentials (OP). Radiative capture reactions were observed with in-beam and activation methods to understand the influence of different particle-nucleus OPs and to learn about the inverse reactions being involved in p-process nucleosynthesis. This approach was followed for protons [19, 20, 21], α particles [22, 23, 24] and neutrons [25, 26] at various facilities.

Two major problems in modelling the production of the p nuclei in the $\gamma$-process remain unresolved, even though the sometimes huge discrepancies between theoretical prediction and experimental results are taken into account [5]. First, the light and abundant p nuclei ($^{92,94}$Mo and $^{96,98}$Ru) are largely underproduced compared to the solar p-nuclei abundance distribution. This holds true even for the relative overproduction factors of the light isotopes only, see left part of Fig. 2. Second, considering the entire galactic chemical evolution type II supernovae do not contribute sufficiently to the production of the p nuclei [27]. Therefore, additional sites and processes like proton captures in combination with $\gamma$-process in type Ia supernovae have to be
Figure 2. Left: Overproduction factors of the light, most abundant p nuclei during the $\gamma$-process normalized to $^{92}$Mo [5]. Right: Production mechanisms for the most abundant p nucleus $^{92}$Mo. The green and red arrows indicate ($\gamma$,n) and ($\gamma$,\alpha) reactions. They occur in the $\gamma$ process. The situation is illustrated exemplary for a typical temperature of $T_9 = 2.5$ K as predicted by [30]. The blue arrows indicate the production via a chain of radiative proton capture reactions as suggested in [27, 29].

taken into account. This was already proposed in Ref. [28] and, just recently, it was found in two different approaches [27, 29] that it might solve both of the mentioned problems. The conditions during type Ia supernovae as derived in these works are suitable to allow the production of the light p nuclei by a series of radiative proton-capture reactions in addition to the $\gamma$-process as illustrated in the right part of Fig. 2. The production via proton-capture reactions (blue arrows) is compared to a selection of photon-induced reactions occurring in the $\gamma$-process (red and green arrows). The experimental database in the astrophysical relevant energy range, the Gamow window, is scarce, since the amount of available sample material is usually limited. In addition, the cross sections are small in the Gamow window because of the Coulomb barrier between the charged reaction partners. Therefore, the signature of the reaction exceeds the background only if the intensity of the projectiles is high enough.

4. (n,$\gamma$) reactions

As already discussed in section 1, it is desirable to improve the currently available experimental possibilities for neutron capture experiments. Spallation or photo-neutron sources require large accelerators, but a small accelerator as used for the recent $^{60}$Fe activation at FZK [31] is best suited for neutron experiments in a university environment. This solution has the additional advantage that the neutron spectrum can be tailored to the specific energy range of interest.

Among the different options for producing neutrons in the keV region, the $^7$Li(p,n)$^7$Be reaction with a threshold of 1.881 MeV is by far the most prolific. Near the threshold one can also take advantage of the fact that kinematically collimated neutrons can be produced in the energy range up to 100 keV. The current approach at FRANZ is therefore to use the existing experience with this method to produce neutrons by upgrading the proton source as well as high current lithium targets. The well-known setup for ToF measurements at the former Forschungszentrum Karlsruhe had a flight path of about 80 cm and about $10^8$ neutrons/s/cm$^2$
at the sample position with proton currents of \( \approx 2 \mu A \) [32, 33]. During activation measurements (DC) \( 10^9 \) neutrons/s at proton currents of \( \approx 100 \mu A \) are typically produced [34].

The Stern-Gerlach-Zentrum recently founded at the Goethe University Frankfurt allows to build and operate larger experiments now in accelerator physics, astrophysics and material science research. It was decided to develop an intense neutron generator within the next years. The proton driver LINAC consists of a high voltage terminal already under construction to provide primary proton beam energies of up to 120 keV. A volume type ion source will deliver a DC beam current of 100-250 mA at a proton fraction of 90%. A low energy beam transport using four solenoids will inject the proton beam into a RFQ while a chopper at the entrance of the RFQ will create pulse lengths in the range of 100 ns at a repetition rate of up to 250 kHz. A drift tube cavity, witch delivers variable end energies between 1.8 and 2.2 MeV will be installed downstream of the RFQ. Finally a bunch compressor of the Mobley type forms a proton pulse length of 1 ns at the Li target. The maximum energies of the neutrons will be adjustable between \( \approx 50 \text{ keV} \) and \( \approx 500 \text{ keV} \) by the primary proton beam energy (see Fig. 3).

In a first step average beam currents of 0.1 mA are possible with a repetition rate of 250 kHz. Those conditions are very well suited for time-of-flight measurements in the astrophysically interesting keV-regime, as illustrated in the left part of Fig. 4. The second step would be to focus on improvements of the lithium target technology with the goal to increase the proton beam on target and hence the neutron flux. Improved cooling technologies allow targets with stable lithium layers that can handle up to 2 mA. This implies that without any major changes of the experimental setup compared to FZK (apart from the neutron production) an increase in neutron flux by a factor of 1000 can be achieved.

An interesting branching of the s-process is the region around \( ^{85}\text{Kr} \), see right part of Fig. 4. On the one hand, the \(^{84}\text{Kr}/^{86}\text{Kr} \) ratio can be determined in presolar SiC grains originating from T-AGB stars [35, 36]. The competition between \( \beta^- \)-decay and neutron capture at \(^{85}\text{Kr} \) is reflected in the observed \(^{84}\text{Kr}/^{86}\text{Kr} \) ratio. The interpretation of the observed ratio as a measure of stellar parameters is currently hampered by the only very poorly known \(^{85}\text{Kr}(n,\gamma) \) cross section [37, 15]. On the other hand, the decay of the long-lived \(^{87}\text{Rb} \) (48 Gyr) reflects the abundance ratio of the otherwise s-only isotopes \(^{86},^{87}\text{Sr} \). A detailed understanding of the s- and r-contribution to \(^{87}\text{Rb} \) would allow the determination of the onset of the s- and r-process in the history of our universe [38]. Also here, the biggest remaining uncertainty is the \(^{86}\text{Kr}(n,\gamma) \) cross section. While some attempts have been made to investigate s-process branchings indirectly investigating the time-reversed reaction [39], this method is very difficult to apply in the case of \(^{86}\text{Kr}(\gamma,n) \) because of the unfavourable decay properties of \(^{85}\text{Kr} \).
Figure 4. Left: Schematic TOF spectrum of the setup shown in Figure 3 for a maximum neutron energy of 200 keV. The TOF region corresponding to neutron energies between 130 and 200 keV is basically free of beam-related background. Right: Reaction network during s-process nucleosynthesis around the important branch point $^{85}$Kr. The green arrows correspond to the situation, where no neutron capture occurs at $^{85}$Kr, while the red arrows denote the neutron capture branch.

A direct measurement of the neutron capture cross section of $^{85}$Kr using the time-of-flight method is therefore highly desirable. The FRANZ facility will be able to provide sufficient neutron flux for a measurement using a 4π-array to calorimetrically detect the γ-rays following the neutron capture [40]. One of the big challenges of such experiments is the production of the sample. In this particular case, the sample could be produced via α-irradiation of stable, metallic $^{82}$Se. Since the $^{82}$Se(α, γ)$^{86}$Kr channel is suppressed at high energies, the $^{82}$Se(α, n)$^{85}$Kr reaction is by far dominating at high energies. The second highest cross section at high energies, $^{82}$Se(α, p)$^{85}$Br, also leads to $^{85}$Kr via $β^−$-decay with $t_{1/2}$ ≈ 3 min, thus $^{85}$Kr can be produced almost isotopically pure. Krypton stays trapped inside selenium until heated [41]. The temperature during the irradiation has to stay below ≈ 50° C. After the transport of the irradiated sample to a sample preparation site, the freshly produced krypton can be released by heating the selenium sample to the melting point. The amount of $^{85}$Kr required for an experiment at FRANZ is ≈ 10$^{18}$ atoms. This corresponds to a maximum number of 2.5 × 10$^{19}$ $^4$He ions on target.

5. (p,γ) reactions

New experiments concerning direct (p,γ) reactions are currently under development at the experimental storage ring at GSI, where reaction measurements in inverse kinematics are possible close to the Gamow window of the p-process [42]. In addition, it seems feasible to facilitate FRANZ for proton-induced reactions at low energies. As already shown in Fig. 3, one beam line is foreseen to use the proton beam directly for proton-induced reactions. In the current layout, the FRANZ facility provides protons in an energy range of 1.8 MeV to 2.2 MeV. Thus, it covers the low-energy part of the Gamow window at typical temperatures for p-process nucleosynthesis. For the measurement of proton-induced reactions the accelerator will be operated in cw mode using the RFQ and IH structure. The time structure of the beam is determined by the intrinsic repetition rate of 175 MHz. This translates into a time of 5.7 ns between two bunches of 1 ns width. It is possible to distinguish between events in coincidence to beam pulses and the breaks in between for a detector system providing time resolutions in the sub-ns range, thus, providing a tool for background suppression.
The proton beam current in cw mode reaches up to 20 mA in the current design of FRANZ. Compared to Van-de-Graaff accelerators the current is enhanced by a factor of 100 to 1000. Therefore, measurements of very small reaction cross sections and/or with very little sample material can be realized. However, the sample has to be designed in a way that the corresponding high areal power densities resulting in high heat loads can be withstood and sputtering of the sample is avoided. It is planned to investigate \((p,\gamma)\) reaction in the region around the neutron shell closure at \(N = 50\), which includes the production chain of \(^{152}\)Mo via proton captures (Fig. 2).

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