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Opportunities for Nuclear Astrophysics at FRANZ

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Abstract: The 'Frankfurter Neutronenquelle am Stern–Gerlach–Zentrum' (FRANZ), which is currently under development, will be the strongest neutron source in the astrophysically interesting energy region in the world. It will be about three orders of magnitude more intense than the well-established neutron source at the Research Center Karlsruhe (FZK).

Keywords: nuclear reactions, nucleosynthesis, abundances

1 Introduction

About 50% of the element abundances beyond iron are produced via slow neutron-capture nucleosynthesis (*s* process). Starting at iron-peak seed, the *s*-process mass flow follows the neutron-rich side of the valley of stability. If different reaction rates are comparable, the *s*-process path branches and the branching ratio reflects the physical conditions in the interior of the star. Such nuclei are most interesting, because they provide the tools to effectively constrain modern models of the stars where the nucleosynthesis occurs. As soon as the β^- decay is faster than the typically competing neutron capture, no branching will take place. Therefore experimental neutron-capture data for the *s* process are only needed, if the respective neutron-capture time under stellar conditions is similar to or smaller than the β^- decay time, which includes all stable isotopes. Depending on the actual neutron density during the *s* process, the 'line of interest' is closer to or farther away from the valley of stability. In a recent estimate the neutron density within the classical *s*-process model (Käppeler et al. 1989) was estimated to be $n_\mathrm{n} = 4.94(+0.60, -0.50) \times 10^8\,\mathrm{cm}^{-3}$ (Reifarth et al. 2003). Figure 1 shows a summary of the neutron-capture and β^- decay times for radioactive isotopes on the neutron rich side of the valley of stability, under the condition that the classical neutron capture occurs than the terrestrial β^- decay. Obviously the vast majority of isotopes, where an experimental neutron capture cross-section is desirable, have β^- half-lives of at least hundreds of days.

The modern picture of the main *s*-process component refers to the He shell burning phase in AGB stars (Lugaro et al. 2003). The highest neutron densities in this model occur during the ^{22}Ne(α,n) phase and are up to $10^{11}\,\mathrm{cm}^{-3}$. Figure 2 shows the same as Figure 1, but for the higher neutron density. Now isotopes with half-lives down to

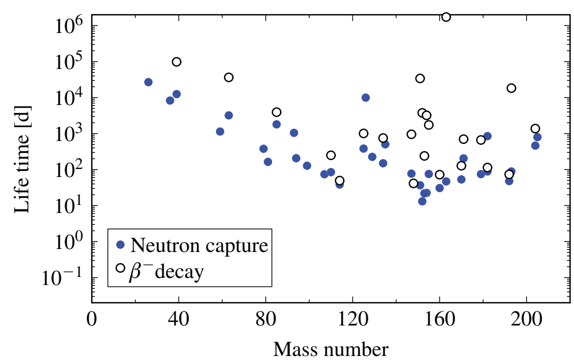

Figure 1 Neutron-capture live times (filled circles) for a neutron density of $5 \times 10^8\,\mathrm{cm}^{-3}$ and β^- live times (open circles) for unstable isotopes on the *s*-process path as a function of mass number. Shown are only isotopes where the neutron capture is faster than the (terrestrial) β^- decay. The neutron-capture cross-sections are taken from Bao et al. (2000).

a few days can be of interest for the *s*-process reaction network.

Improved experimental techniques, especially as far as the neutron source and sample preparation are concerned, are necessary to perform direct neutron-capture measurements on such isotopes (Reifarth et al. 2004).

In Section 2 a new approach currently realized at the Goethe University Frankfurt, Germany is described. The FRANZ facility will allow energy-dependent neutron-capture cross-section and activation experiments in the astrophysically interesting energy region with significantly higher neutron fluxes then currently available elsewhere (Koehler 2001).

In Section 2.1 the time-of-flight (TOF) method is described and a comparison of the new facility with existing facilities is given. In Section 2.2 the activation method is described and the opportunities and challenges at the

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new facility are discussed. In this approach the limited neutron flux is overcome by an extremely short distance between the sample and the neutron production target. The trade-off is then the very limited information about the energy-dependence of the measured cross-section.

2 FRANZ

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 (Uberseder et al. 2009) 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. Our approach 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 last setup at FZK for ToF measurements had a flight path of about 80 cm and about 10^4 neutrons s^{-1} cm^{-2} at the sample position with proton currents of $\approx$2 µA (Wisshak et al. 1990; Reifarth et al. 2002). During activation measurements (DC) 10^9 s^{-1} at proton currents of $\approx$100 µA are typically produced (Reifarth et al. 2003).

The Stern–Gerlach–Zentrum SGZ recently founded at the University of 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 150 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 1.9 and 2.1 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 keV and $\approx$500 keV by the primary proton beam energy (see Figure 3).

2.1 *Time-of-Flight Experiments*

In a first step, the use of the accelerator mentioned above and established lithium target technology, average beam

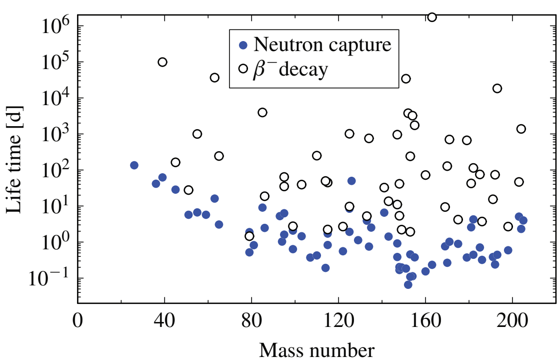

Figure 2 Neutron-capture live times (filled circles) for a neutron of density 10^{11} cm^{-3} and β^- live times (open circles) for unstable isotopes on the *s*-process path as a function of mass number. Shown are only isotopes where the neutron capture is faster than the terrestrial β^- decay. The neutron-capture cross-sections are taken from Bao et al. (2000).

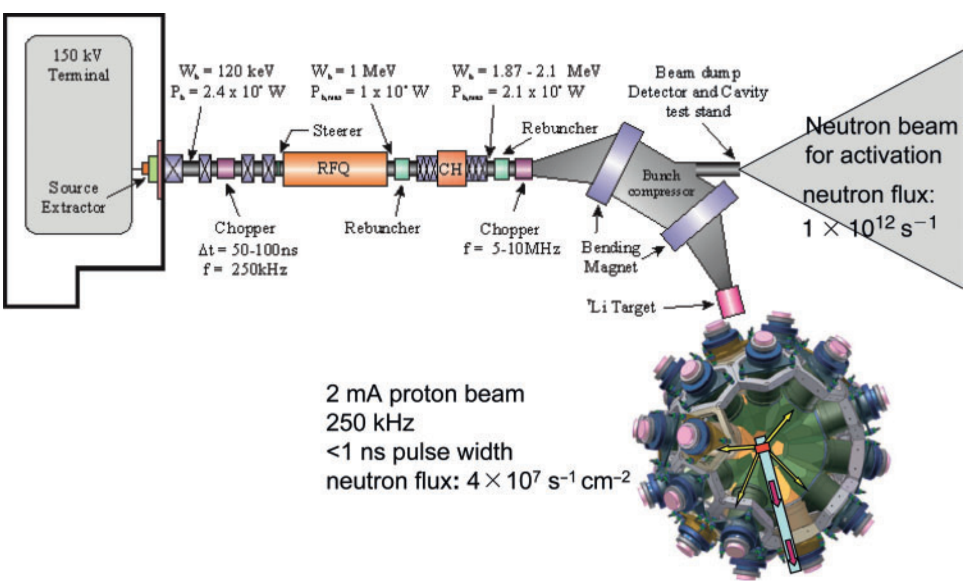

Figure 3 Schematic layout of the Frankfurter Neutron Source FRANZ.

currents of 0.1 mA are possible with a repetition rate between 250 kHz.

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.

Important contributions to our understanding of the nucleosynthesis can then be made by measurements of extremely small capture cross-sections on light elements, which are important since the respective isotopes are very abundant in the stars. Examples for this category of measurements are ^{1}H(n,γ), which is important for Big Bang nucleosynthesis, and ^{12}C(n,γ), ^{16}O(n,γ), ^{22}Ne(n,γ), which act as neutron poisons for the *s*-process.

The second category where significant contributions can be expected are ToF measurements on radioactive branch point nuclei. Some prominent examples of such measurements are (n,γ) experiments on ^{60}Fe, ^{85}Kr, ^{95}Zr, ^{147}Pm, ^{154}Eu, ^{155}Eu, ^{153}Gd, and ^{185}W (Couture & Reifarth 2007).

The TOF experiments performed at the Research Center Karlsruhe had typically a flight path of ≈80 cm. The few exceptions, where a shorter flight path was used were carried out with Moxon Rae detectors (Jaag & Käppeler 1996). This setup allowed extremely short flight paths of only 2 cm. For this particular setup, the gain in neutron flux resulting from the short flight path was partly compensated by the significant loss in γ-ray detection efficiency compared to the BaF_2 array. In principle both ideas — ultra-short flight path and 4π BaF_2 array — could be combined, but then the challenge is the enormous γ-flash immediately after the interaction of the proton pulse with the lithium target (Reifarth et al. 2004; Walter et al. 2006). Figure 6 shows an example of the time distribution of a possible realization. This approach is in particular interesting, if the activation method, which intrinsically has a much higher sensitivity, is not applicable. Prominent examples of such isotopes are (n,γ) experiments on ^{60}Co, ^{65}Zn, ^{86}Rb, ^{89,90}Sr, ^{127,127m}Te, ^{134,137}Cs (Couture & Reifarth 2007).

2.2 Activation Experiments

While the detection efficiency of the (n,γ) products can be improved by up to one order of magnitude (the typical γ-ray efficiency of the currently mostly used 4π Ge setup is 10%), a real quantum leap is possible by improvements in the lithium target technology. Figure 7 shows the typical activation setup used at the Research Center Karlsruhe allowing a measurement relative to the well known ^{197}Au(n,γ)^{198}Au cross-section (Ratynski & Käppeler 1988). Following the neutron irradiation, the activity of the gold foils can be determined via the 412 keV γ-ray from the ^{198}Au decay ($t_{1/2} = 2.69$ d).

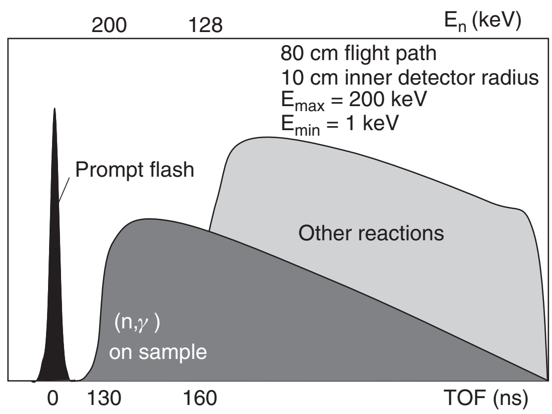

Figure 4 Schematic TOF spectrum of the setup shown in Figure 3 for a maximum neutron energy of 200 keV. The TOF region corresponding to neutron energies between 130 and 200 keV is basically free of beam-related background.

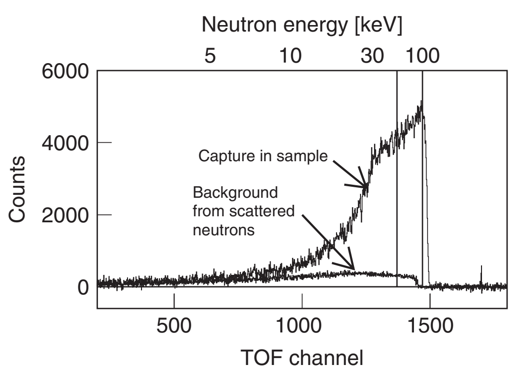

Figure 5 TOF spectrum measured with the ^{129}Xe for 100 keV maximum neutron energy. The background from neutrons scattered at the sample is shown separately.

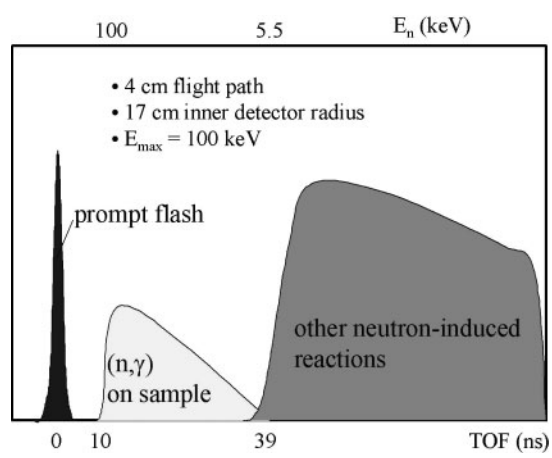

Figure 6 Schematic TOF spectrum of the setup shown in Figure 3 similar to the one shown in Figure 4. In this case a very short flight path of only 4 cm was assumed. The intrinsic time resolution of the BaF_2 array and the proton accelerator would be sufficient to disentangle neutron-capture events from neutron-induced background as well as from the γ-flash based on their time relative to the proton pulse.

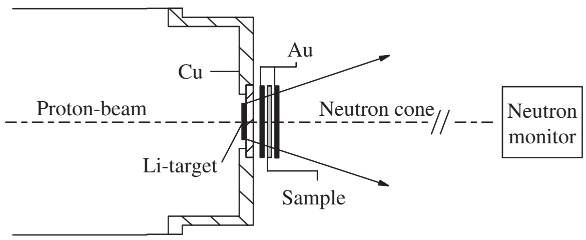

Figure 7 Sketch of the activation setup at the Van de Graaff accelerator.

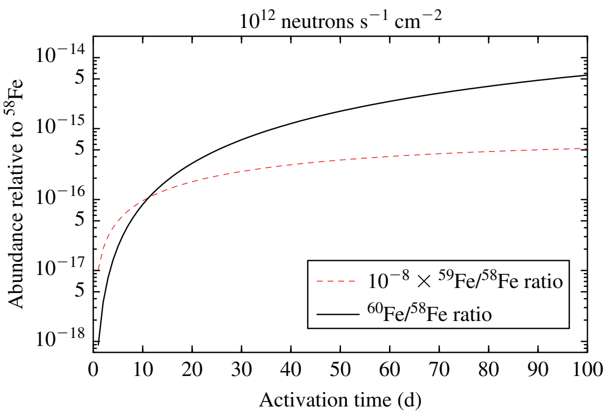

Figure 8 Time dependence of the ^{59}Fe and ^{60}Fe content in a ^{58}Fe sample during irradiation with 10^{12} s^{-1} cm^{-2} at FRANZ.

Possible improvements of the target technique include rotating wheels as well as liquid lithium targets. If the target is able to handle the above mentioned ≈60 mA proton beam, neutron fluxes of about 10^{12} s^{-1} cm^{-2} were available. Not only would that increase the sensitivity of the well established experimental techniques like cyclic activation (Beer 1991) by three orders of magnitude, it would also allow to do activations via double neutron capture. This 'advanced activation' would for instance allow the measurement of the unstable ^{59}Fe ($t_{1/2} = 45$ d) by activating a stable sample of ^{58}Fe. The desired ^{59}Fe(n,γ) cross-section could then be extracted by determining the ^{60}Fe/^{58}Fe ratio via AMS (Knie et al. 2004). This approach would provide a certain independence from the availability of radioactive samples (see Figure 8).

3 Summary

Neutron-induced experiments have been successfully performed over the last 30 years at the Research Center Karlsruhe. The basic ideas of the two well-established techniques, time of flight and activation, will be applied at the FRANZ facility, which is currently under construction at the University of Frankfurt. Taking advantage of the latest developments in accelerator design, it will be possible to increase the sensitivity of both techniques by about three orders of magnitude. This will open a new era in experimental nuclear astrophysics, since it will then be possible to investigate radioactive isotopes, which act as important branch points in the *s* process, on a routinely basis.

Acknowledgments

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