Investigation of the ^{7}Li(p,n) neutron fields at high energies

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Abstract. The neutron activation method is well-suited to investigate neutron-capture cross sections relevant for the main s-process component. Neutrons can be produced via the ^{7}Li(p,n) reaction with proton energies of 1912 keV at e.g. Van de Graaff accelerators, which results in a quasi-Maxwellian spectrum of neutrons corresponding to a temperature of $k_\mathrm{B}T = 25$ keV. However, the weak s-process takes place in massive stars at temperatures between 25 and 90 keV. Simulations using the PINO code [2] suggest that a Maxwellian spectrum for higher energies, e.g. $k_\mathrm{B}T = 90$ keV, can be approximated by a linear combination of different neutron spectra. To validate the PINO code at proton energies $E_\mathrm{p} \neq 1912$ keV, neutron time-of-flight measurements were carried out at the PTB Ion Accelerator Facility (PIAF) at the Physikalisch-Technische Bundesanstalt in Braunschweig, Germany.

1 Introduction

The s-process is divided into the main and weak component. Differences lie in the neutron densities, neutron-to-seed ratios and the temperatures [1]. The main s-process component, which contributes mostly to nuclei with mass numbers above $A \approx 90$, takes place at $k_\mathrm{B}T = 25$ keV in thermal pulsing low mass asymptotic giant branch (TP-AGB) stars. In contrast, the weak s-process takes place in massive stars with more than 8 solar masses at temperatures between $k_\mathrm{B}T = 25$ keV and $k_\mathrm{B}T = 90$ keV. Nuclei in the mass number range between 60 and 90 are mostly created in this environment. Since the neutron fluence in the weak s-process is too low to achieve reaction flow equilibrium, a particular neutron-capture cross section not only influences the abundance of the respective isotope, but affects the abundances of all heavier isotopes as well [3].

1.1 Activation technique

The activation technique has been proven to be a well-suited tool to investigate neutron-capture cross sections relevant for the main s-process component: A quasi-stellar neutron

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spectrum corresponding to a temperature of $k_\mathrm{B}T = 25\,\mathrm{keV}$ can be obtained by bombarding a several µm thick metallic lithium target with protons at an energy of 1912 keV. The neutrons are emitted in a forward cone of 120° opening angle, which has to be covered by the sample [5]. The neutron capture cross section is determined as an integral value over the neutron energy distribution. A quasi-stellar neutron spectrum similar to a $k_\mathrm{B}T = 90\,\mathrm{keV}$ Maxwellian neutron energy spectrum cannot be reproduced by only one proton beam energy. However, simulations using PINO [2] suggest a linear combination of neutron distributions to approximate a quasi-stellar distribution with $k_\mathrm{B}T = 90\,\mathrm{keV}$ or other temperatures using the ^{7}Li(p,n)^{7}Be reaction. The results of the simulations are shown in Fig. 1. Hence, samples have to be activated with neutron distributions generated with various proton energies. The resulting spectrum-averaged cross sections (SACS) for each activation energy can be linearly combined to calculate the Maxwellian-averaged cross section (MACS).

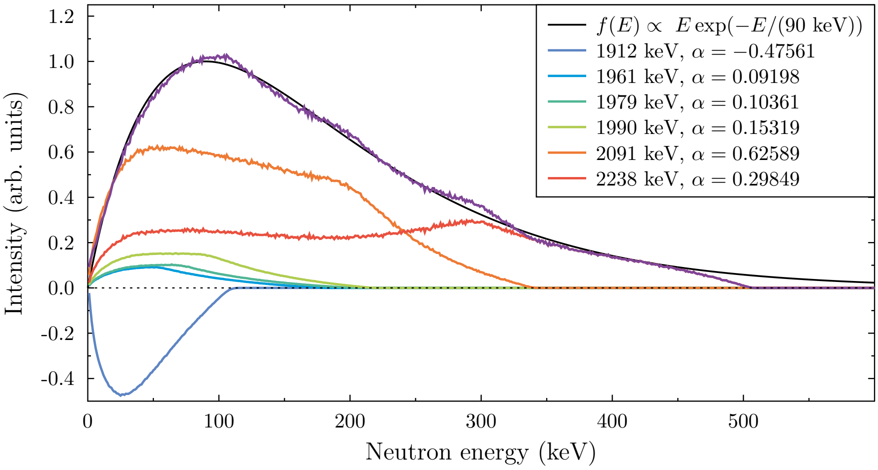

Figure 1. Simulated neutron energy distributions for the synthesis of an energy distribution with $k_\mathrm{B}T = 90\,\mathrm{keV}$.

2 Experiment

We want to verify and improve the accuracy of the PINO simulations for energies other than $E_\mathrm{p} = 1912\,\mathrm{keV}$. Therefore, we investigated the angular energy distribution of the neutrons from the ^{7}Li(p,n)^{7}Be reaction for different proton energies at the PTB Ion Accelerator Facility (PIAF) at the Physikalisch-Technische Bundesanstalt in Braunschweig. The unique experimental setup of the low-scatter facility allows the production of neutron reference fields in open geometry [4]. The neutron energy was determined by the time-of-flight method, which relies on the periodical production of neutrons at a well-defined frequency [3], given by the fast pulsed proton beam which was delivered by a 2 MV Tandem accelerator with a maximum repetition rate of 2.5 MHz. The proton beam had a nominal pulse width of about 1.5 – 2 ns and a frequency of 1.25 MHz. The beam impinged on a metallic lithium target on tantalum backing with a thickness of 5 µm, assuming a nominal density of 0.534 g/cm^3. By measuring the neutron time-of-flight t for a certain length of flight path L the neutron energy E_n can be determined by the classic approximation:

$$E_\mathrm{n} = \frac{1}{2} m_\mathrm{n} \left(\frac{L}{t}\right)^2 \tag{1}$$

Since the neutron-energy resolution can be enhanced by an increased flight path, but at the expense of neutron flux at the detector position, a flight path of $L = 0.7$ m was selected as a compromise. Ten different proton energies were measured: 1.887 MeV, 1.897 MeV, 1.907 MeV, 1.912 MeV, 2 MeV, 2.1 MeV, 2.2 MeV, 2.3 MeV, 2.5 MeV and 2.8 MeV. Measurements below 1.912 MeV were conducted for the energy calibration of the accelerator and to investigate the neutron production threshold. Neutron spectra were recorded using three ^{6}Li-Glass scintillation detectors mounted on movable arms. The neutron flux was monitored with two long counters positioned at 16° and 98° relative to the ion beam.

3 Results and Outlook

For each proton beam energy time-of-flight spectra were acquired at angles between 0° and 95° in 5° steps. The measurement durations varied between 15 and 60 min depending on the proton current and neutron yield of the reaction. During the measurements the proton current on target was 0.7-1.5 μA. The time-of-flight spectra were background corrected and the neutron yield was normalized using the recorded number of protons on the lithium target.

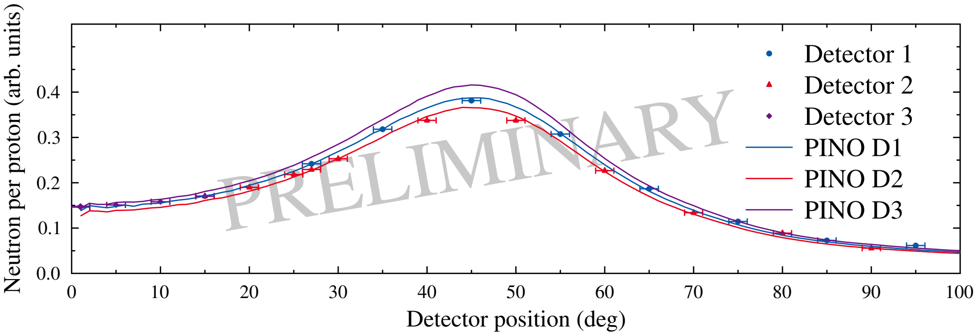

Figure 2. Neutron-per-Proton distribution over the measured angles. Each detector was simulated individually due to unique specifications and minor differences in target-detector distance.

For proton energies smaller than 2.3 MeV the resulting spectra as shown in Fig. 2 are in very good agreement with the PINO simulation. Above this energy, however, larger deviations are observable. Their origin is probably the uncertain description of the second neutron production channel ^{7}Li(p,n)^{7}Be^m. As soon as the reason for the deviations becomes clear the PINO code will be adjusted.

References

[1] P. A. Seeger, W. A. Fowler and D. D. Clayton, The Astrophysical Journal **11** 121 (1965)
[2] R. Reifarth, M. Heil, F. Käppeler and R. Plag, Nuclear Instruments and Methods in Physics Research A **608** 139 - 143 (2009)
[3] R. Reifarth, C. Lederer and F. Käppeler, Journal of Physics G **41** 053101 (2014)
[4] S. Roettger, R. Boettger, F. D. Brooks, A. Buffler, J. P. Meulders, R. Nolte, F. D. Smit and F. Wissmann, AIP Conference Proceedings **1175** 375 - 381 (2009)
[5] W. Ratynski and F. Käppeler, Physical Review C **37** 595 (1988)