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

B. Brückner$^{1,*}$, P. Erbacher$^1$, K. Göbel$^1$, T. Heftrich$^1$, K. Khasawneh$^1$, D. Kurtulgil$^1$, C. Langer$^3$, R. Nolte$^2$, M. Reich$^1$, R. Reifarth$^1$, M. Weigand$^1$, M. Wiescher$^3$ and M. Volknandt$^1$

$^1$ Goethe University Frankfurt, 60438 Frankfurt am Main, Germany
$^2$ Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany
$^3$ University of Notre Dame, 56556 Notre Dame, Indiana, USA

E-mail: *brueckner@iap.uni-frankfurt.de

October 2019

Abstract.

The neutron activation method has been proven to be a well-suited tool for the investigation of neutron capture cross sections relevant for the main component of the s-process. Neutrons produced via the $^7$Li(p,n)$^7$Be reaction at a proton energy of $E_p = 1912$ keV can be used to recreate a quasi-stellar neutron energy distribution mimicking the astrophysical s-process scenario at $k_BT = 25$ keV. For the weak s-process, which takes place in massive stars at temperatures between $k_BT = 25$ keV and $k_BT = 90$ keV, the activation method has not yet been successful in recreating quasi-stellar neutron spectra. However, simulations show that the activation method can be improved in order to recreate a quasi-stellar neutron spectrum at different energies by linear combination of different neutron spectra. In order to verify these simulations the neutron fields of the reaction have to be measured at different proton energies.

1. Introduction

The slow neutron capture process (s-process) is divided into the main- and weak-component. Differences lie in the neutron densities, the neutron-to-seed ratios and the temperature [1]. The main s-process component, which contributes mostly to nuclei with mass numbers above $A = 90$, takes place at $k_BT = 25$ keV in low mass asymptotic giant branch (AGB) stars. In contrast, the weak s-process takes place in massive stars with more than 8 solar masses during the core He burning at $k_BT = 25$ keV and the shell C burning phase at $k_BT = 90$ keV [3]. Nuclei in the mass number range between 60 and 90 are mostly created in this environment [4]. Since the neutron fluence in the weak
Investigation of the $^7\text{Li}(p,n)$ neutron fields at high energies

$s$-process is too low to achieve reaction flow equilibrium, a particular neutron capture cross section not only determines the abundance of the respective isotope, but affects the abundances of all heavier isotopes as well [4].

1.1. Neutron capture cross section

Nucleosynthesis simulations for the $s$-process depend on stellar decay half-lives and stellar neutron capture cross sections [4]. The Maxwellian-averaged Cross Section (MACS), which gives the cross sections averaged over the stellar neutron spectrum, can be written as [4]:

$$\langle \sigma \rangle_{\text{MACS}} = \frac{2}{\sqrt{\pi}} \frac{1}{(k_B T)^2} \int_0^\infty \sigma(E) E \exp \left( -\frac{E}{k_B T} \right) dE$$

(1)

This value is needed for temperatures $k_B T$ between 5 and 100 keV. The neutron capture cross sections for the investigation of the $s$-process are usually determined by two different techniques. While integral methods are based on the activation technique, the determination of energy-differential cross sections are based on the detection of capture $\gamma$-rays at time-of-flight (TOF) neutron sources [6].

1.2. The 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 spectrum corresponding to a temperature of $k_B T = 25$ keV can be obtained by bombarding a thick metallic lithium target with protons at an energy of 1912 keV. The neutrons are emitted in a forward cone of 120° opening angle [9]. Since only the angle integrated neutron spectrum mimics the quasi-stellar spectrum, the sample is placed directly on the backing of the lithium target [6]. In order to monitor the neutron flux through the sample, thin gold foils are used, since the stellar neutron capture cross section of $^{197}\text{Au}$ [7] and the parameters of the $^{198}\text{Au}$ [8] decay are well known. A typical activation experiment is shown in Fig. 1. After the irradiation of the sample and monitor foils, the decay radiation of the radioactive sample is measured by high purity germanium detectors (HPGe). The cross section is determined as an integral value over the neutron energy distribution. A big advantage of the activation method over the TOF method is the neutron flux, which is about 5 orders or magnitude higher. Also the detection setup can be placed in a low-background environment with sensitive equipment [6].

A quasi-stellar neutron spectrum recreating a $k_B T = 90$ keV Maxwellian neutron energy spectrum can not be reproduced by only one proton beam energy. Therefore $k_B T = 90$ keV activation experiments were unsuccessfull previously.
Investigation of the $^7\text{Li}(p,n)$ neutron fields at high energies

Figure 1: Schematic of a typical neutron activation setup. The proton beam is hitting the metallic lithium layer (blue). The produced neutrons irradiate the neutron flux monitors (red) and the sample (black). During the activation the neutron flux is additionally monitored by $^6\text{Li}$Glass-detectors. Depending on the proton energy, the neutrons are emitted in a forward cone indicated by the black lines or in all directions.

1.3. Activation technique for high energies

In order to reproduce a quasi-stellar neutron spectrum for $k_B T = 90\,\text{keV}$, various simulations using PINO (Protons In Neutrons Out) [2] were performed. The simulations show a reproduction using the $^7\text{Li}(p,n)^7\text{Be}$ reaction is possible, by activating samples of the same composition at various proton beam energies. The results of the simulations are shown in Fig. 2. After the determination of the spectrum averaged cross sections (SACS) for each activation energy the values can be linearly combined to calculate the MACS.

Figure 2: Simulated neutron energy distribution for the synthesis of an energy distribution with $k_B T = 90\,\text{keV}$.
Investigation of the $^7\text{Li}(p,n)$ neutron fields at high energies

2. Experimental verification of PINO[2]

In order to determine the degree of accuracy of the simulations using PINO [2] at energies higher than $E_p = 1912\text{keV}$ the angular energy distribution of the neutrons had to be verified. This was done 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 [5]. The neutron energy was determined by the time-of-flight method. The time-of-flight method relies on the periodical production of neutrons at a well defined frequency [4], given by the fast pulsed proton beam which was delivered by a 2MV Tandem accelerator with a maximum repetition rate of 2.5MHz. The proton beam had a nominal pulse width of about $1.5 - 2\text{ns}$ and a frequency of 1.25MHz. The beam was impinging on a metallic lithium target on tantalum backing with a thickness of $5\mu\text{m}$, assuming a nominal density of $0.534 \text{g/cm}^3$. By measuring the neutron flight time $t$ for a certain length of flight path $L$ the neutron energy $E_n$ can be determined by:

$$E_n = m_n c^2 (\gamma - 1) \quad (2)$$

where $m_n$ denotes the neutron mass and $c$ the speed of light. For neutron energies relevant in nucleosynthesis studies the relativistic factor $\gamma = \left(\sqrt{1 - (L/t)^2/c^2}\right)$ can be neglected and eq. (2) reduces to:

$$E_n = \frac{1}{2} m_n \left(\frac{L}{t}\right)^2 \quad (3)$$

The energy resolution of the neutron energy spectrum which is derived from eq. (3) can be written as:

$$\frac{\Delta E_n}{E_n} = 2 \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}} \quad (4)$$

[4][6]. As shown in eq. 4 the neutron-energy resolution can be enhanced by increasing the flight path, however, at the expense of neutron flux at the detector position. Simulations prior to the experiment recommended to select a flight path of $L = 0.7\text{m}$, in order to achieve a good compromise between neutron-energy resolution and neutron flux.

Nine different proton energies were measured: $1887\text{keV}, 1897\text{keV}, 1907\text{keV}, 1912\text{keV}, 2000\text{keV}, 2100\text{keV}, 2200\text{keV}, 2300\text{keV}, 2500\text{keV}$ and $2800\text{keV}$. The measurements below $1912\text{keV}$ were conducted for the energy calibration of the accelerator and to investigate the neutron production threshold. The neutron spectra were recorded using three $^6\text{Li}$Glass scintillation detectors mounted on movable arms. The neutron flux was monitored with two long counters positioned at $16^\circ$ and $98^\circ$ relative to the ion beam (Fig. 3).
Investigation of the $^{7}\text{Li}(p,n)$ neutron fields at high energies

Figure 3: Schematic setup of the time-of-flight experiment at the PTB Ion Accelerator Facility (PIAF). The long counters used as flux monitors are labeled LC.

3. Time-of-flight results and outlook

For each proton beam energy, time-of-flight spectra were acquired at angles between $0^\circ$ and $95^\circ$ in $5^\circ$ steps. The duration for each measurement varied between 15 and 60 min depending on the accelerator current and neutron yield of the reaction. During the measurements the average current on target was $0.7 - 1.5 \mu\text{A}$.

The recorded TOF spectra (Fig. 4) show the advantages of the PIAF facility. The induced background mostly created by scattered neutrons and photons is very low. This ensures a clear conversion into an energy spectrum after background subtraction. The neutron energy spectrum shown in Fig. 5 was created by converting a TOF spectrum, obtained at a proton energy of $2.3\text{MeV}$, into the respective energy spectrum using eq. 3. However no corrections of ambient or beam induced background as well as efficiency have been taken into account.

4. Outlook

After the successful background and detector-efficiency correction of the recorded TOF spectra, the results will be compared to PINO [2] simulations. In case of deviations
Investigation of the $^7$Li(p,n) neutron fields at high energies

Figure 4: The time-of-flight spectrum for neutrons produced by a 2.8 MeV proton beam. The red and blue histograms show data taken with the detector at 0° and 45°, respectively. Clearly visible is the so called γ-flash which results from the prompt reaction at the target. The two other visible peaks correspond to the neutrons created by the reaction $^7$Li(p,n)$^7$Be and $^7$Li(p,n)$^7$Be$^*$. 

Figure 5: Neutron energy raw spectrum at 0° for proton energy of 2.3 MeV. The step-like peak form is a result of the finite binning of the time-of-flight measurement.

From PINO [2] the code will be adjusted. This will be necessary in order to successfully repeat the simulations for the reproduction of a $k_B T = 90$ keV quasi-stellar neutron spectrum.
Investigation of the $^7$Li(p,n) neutron fields at high energies

Acknowledgments

This work was funded by the German Research Foundation (DFG), project GAIN (GAllium In the slow Neutron capture process) project number: 386246739.

References

[1] P. A. Seeger, W. A. Fowler and D. D. Clayton The Astrophysical Journal. 11 (1965) 121
[2] R. Reifarth, M. Heil, F. Käppeler and R. Plag Nuclear Instruments and Methods in Physics Research A. 608 (2009) 139 - 143.
[3] F. Käppeler, R. Gallino, S. Bisterzo and Wako Aoki Reviews of Modern Physics. 83 (2011) 157 - 193.
[4] R. Reifarth, C Lederer and F. Käppeler Journal of Physics G. 41 (2014) 053101.
[5] S. Roettger, R. Boettger, F. D. Brooks, A. Buffler, J. P. Meulders, R. Nolte, F. D. Smit and F. Wissmann AIP Conference Proceedings. 1175 (2009) 375-381.
[6] R. Reifarth, P. Erbacher, S. Fiebiger, K. Göbel, T. Heftrich, M. Heil, F. Käppeler, et al. The European Physics Journal Plus 133 (2018) 424.
[7] W. Ratynski and F. Käppeler Physical Review C 37 (1988) 595.
[8] R. Auble Nuclear Data Sheets 40 (1983) 301.
[9] Z. Y. Bao, H. Beer, F. Käppeler, F. Voss, K. Wisshak and T. Rauscher Atomic Data and Nuclear Data Tables 76 (200) 70.