Activation measurements of neutron capture cross sections at various temperatures

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Abstract. About 50% of the elements heavier than iron are produced during the slow neutron capture process. This process occurs in different stellar sites at various energies. To understand the ongoing nucleosynthesis, the probability of a neutron capture for different temperatures and therefore for different stellar sites is essential. Activation experiments using the ^{7}Li(p,n) reaction as neutron source were performed. At a temperature of $k_{\mathrm{B}}T = 25\,\mathrm{keV}$ the cross sections were determined for ^{27}Al, ^{37}Cl and ^{41}K. A new method was developed to perform activation experiments at even lower temperatures. For a proof of principle, the cross section for ^{64}Ni was measured at $k_{\mathrm{B}}T = 25\,\mathrm{keV}$ as well as for $k_{\mathrm{B}}T = 6\,\mathrm{keV}$. To study the impact of isomeric states at higher energies, activations of ^{181}Ta were performed using two different proton energies.

1 Introduction

The slow neutron capture process (s-process) synthesizes about 50% of the heavy elemental abundances. The s-process is divided into two components: main and weak component. The main component refers to thermally pulsing asymptotic giant branch (TP-AGB) stars during the advanced He burning stage. Two neutron sources acting temperature dependent: ^{13}C(α,n) at $k_{\mathrm{B}}T = 5\,\mathrm{keV}$ and ^{22}Ne(α,n) at $k_{\mathrm{B}}T = 30\,\mathrm{keV}$ [1]. The weak component of the s-process refers to He core burning with temperatures of $k_{\mathrm{B}}T = 25\,\mathrm{keV}$ and during the C shell burning at even higher temperatures of $k_{\mathrm{B}}T = 90\,\mathrm{keV}$ [1]. Therefore, depending on astrophysical sites the neutron capture cross sections for a broad energy range of temperatures are essential. The working horse for activation measurements at $k_{\mathrm{B}}T = 25\,\mathrm{keV}$ is the ^{7}Li(p,n) reaction as neutron source. At this temperature measurements for ^{27}Al to study the puzzle of active nucleosynthesis [2] as well as ^{37}Cl and ^{41}K, which act as neutron poisons [1] were performed. In order to investigate cross sections at lower temperatures, a new method for activation measurements at $k_{\mathrm{B}}T = 6\,\mathrm{keV}$ was developed. The principle was proven using a ^{64}Ni ring sample. Isomeric states can have a big impact at the nucleosynthesis path [3]. Many neutron capture measurements are only sensitive to the sum of the cross sections population of the isomeric and ground state. In order to study the neutron capture into the isomeric state at higher temperatures, a measurement of neutron capture on ^{181}Ta into the isomeric and ground state of ^{182}Ta was performed using higher proton energies.

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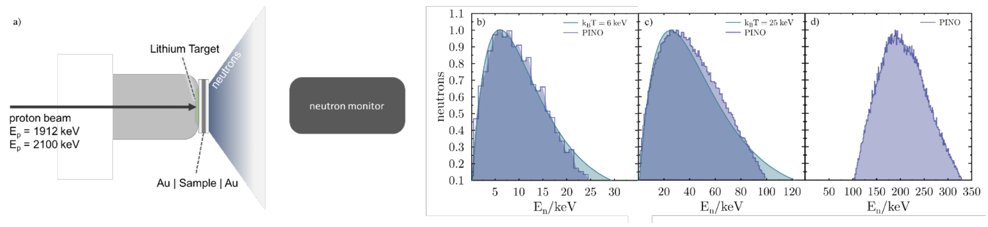

Figure 1. a) Setup for the activation measurements. b)-d) The MD (green) compared with simulated neutron spectrum (blue) for a sample b) ring-shaped. c) circular-shaped. d) circular-shaped with raised proton energy to 2100 keV.

2 Activation setup

Protons were accelerated and impinged on a Li target. Via ^{7}Li(p,n) neutrons are emitted in a cone (Figure 1a). Each sample was positioned between gold foils, which act as monitors for the neutron flux. Neutron flux fluctuations were determined with a Li glass detector. There are two options to perform measurements at different energies: Variation of the impinging proton energy or different sample shapes. For incoming beam energy of 1912 keV, the resulting neutron spectrum for a sample which covers the hole neutron cone follows a Maxwell distribution (MD) at $k_{\mathrm{B}}T = 25\,\mathrm{keV}$. Figure 1 shows the simulated neutron spectra using PINO [4] which passes different shaped samples (blue) compared to MDs (green). Recently a new method was developed to measure cross sections at lower energies. If the sample is ring-shaped, the angular coverage of the neutron cone represents a MD at various energies depending on the outer and inner radius of the ring and the distance to the Li target. To perform an activation at $k_{\mathrm{B}}T = 6\,\mathrm{keV}$, an outer radius of 10 mm, an inner radius of 6 mm and a distance to the Li target of 3.2 mm was chosen (Figure 1b). If the proton energy is raised up to E_P= 2100 keV, the resulting neutrons which pass the sample are shown in Figure 1d.

3 Analysis

The freshly produced radioactive nuclei were observed by their characteristic γ-rays. A setup consisting of two Broad Energy Germanium Detectors (BEGe) was built up at Goethe University, allowing γ-spectroscopy with high efficiency. The detectors are cylindrical Ge crystals (70x31) mm mounted head to head. The efficiency was determined by measurements and compared with simulations using GEANT. The γ-intensity is included in the simulations as well as the absorption of the γs in the specific samples. The sample is placed in the middle of both detectors. The produced activity is given by: $A = \lambda\left(\frac{C_\gamma}{\epsilon_\gamma f_{\mathrm{m}} f_{\mathrm{dt}}}\right)$, where λ is the decay constant, C_γ are the detected events (Counts), ϵ_γ the efficiency, $f_{\mathrm{m}} = 1 - \exp(-\lambda t_{\mathrm{m}})$ the correction for the decay after the measurement and f_{dt} is the correction for the deadtime of the detection system. The neutron flux was determined by using the gold samples surrounded the target as monitors by: $\Phi_n = \frac{N(^{198}Au)}{N(^{197}Au)\sigma(^{197}Au)}$, where $N(^{198}Au)$ are the gold nuclei which captured a neutron, $N(^{197}Au)$ are the stable gold nuclei of the samples and $\sigma(^{197}Au)$ is spectrum averaged cross section (SACS) for the neutron capture on gold. The activities of produced radioactive gold nuclei were determined using the BEGe setup. The spectrum average cross section for gold were determined using PINO [4] (Table 1). Using the evaluated neutron flux and the activity of the product nuclei and the non-activated nuclei N_{sample}, the cross section is

Table 1. The SACS of gold, measured and literature cross sections.

		this work		literature
reaction	$k_\mathrm{B}T$ [keV]	σ(Au) [mb]	σ [mb]	σ [mb]
^{64}Ni(n,γ)^{65}Ni	6	1958±35	12±2 [5]	11.8 [8, 9]
^{64}Ni(n,γ)^{65}Ni	25	655±12	4.3±0.3 [5]	9.0[8, 9]
^{27}Al(n,γ)^{28}Al	25	648±9	3.9±0.2 [6]	4.1[8, 10]
^{37}Cl(n,γ)^{38}Cl	25	650±10	2.8±0.2 [7]	2.47[8, 11]
^{41}K(n,γ)^{42}K	25	652±10	19±2 [7]	24.7[8, 12]
^{181}Ta(n,γ)^{182}Ta	25	652±10	771**	863 [8, 13]
^{181}Ta(n,γ)^{182}Ta^m	25	652±10	0.8**	
^{181}Ta(n,γ)^{182}Ta	200*	252±8	197**	
^{181}Ta(n,γ)^{182}Ta^m	200*	252±8	0.51**	

*non MD
** expected uncertainties in the range of 10 %

given by:

$$\sigma = \frac{A}{\lambda N_\mathrm{sample}\Phi_n}. \tag{1}$$

4 Summary

Using the standard reaction with a proton energy of 1912 keV and disc-shaped samples, the cross section of ^{27}Al, ^{37}Cl and ^{41}K were measured at $k_\mathrm{B}T = 25$ keV. Recently, using a new method to measure cross sections at $k_\mathrm{B}T = 6$ keV was developed. The samples were prepared as a ring and therefore the angular-coverage of the neutron cone by the samples refers to to a MD of the neutrons at $k_\mathrm{B}T = 6$ keV. At much higher temperatures of 200 keV it was studied the temperature dependency of neutron capture cross section into the isomeric state for the isotope ^{181}Ta. This work has received funding from the Helmholtz International Center for FAIR. We thank M. Dworak, S. Schöffler and P. Ziel for providing excellent beam conditions during these experiments.

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