First Measurement of $^{72}\mathrm{Ge}(n,\gamma)$ at n_TOF

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Abstract. The slow neutron capture process (s-process) is responsible for producing about half of the elemental abundances heavier than iron in the universe. Neutron capture cross sections on stable isotopes are a key nuclear physics input for s-process studies. The ^{72}Ge(n,γ) cross section has an important influence on production of isotopes between Ge and Zr during s-process in massive stars and therefore experimental data are urgently required. ^{72}Ge(n,γ) was measured at the neutron time-of-flight facility n_TOF (CERN) for the first time at stellar energies. The measurement was performed using an enriched ^{72}GeO$_2$ sample at a flight path of 185 m with a set of liquid scintillation detectors (C$_6$D$_6$). The motivation, experiment and current status of the data analysis are reported.

1 Introduction

The main ideas of stellar nucleosynthesis were proposed around 60 years ago by Cameron [1] and Burbidge, Burbidge, Fowler and Hoyle [2], who introduced two neutron-driven processes for the formation of heavy elements between Fe and Bi. Half of these abundances are formed in the slow neutron capture process (**s-process**), which happens at low neutron density n_n of up to $10^{11}\ \frac{\mathrm{n}}{\mathrm{cm}^3}$, in which case faster radioactive β-decays guide the reaction path along the valley of stability. Neutrons are provided mainly by two source reactions: $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$. With understanding the abundance pattern, different components of the s-process were introduced.
The **main** component contributes to all abundances from Fe to Bi, but mainly isotopes between Zr and Bi. It occurs in low - and intermediate mass TP-AGB (thermally pulsing asymptotic giant branch) stars at temperatures of $(0.1-0.3)\cdot 10^9$ K. A sufficient neutron exposure establishes a reaction flow

equilibrium, which means that the product of cross section times abundance is constant (details can be found in Ref. [3]).

The **weak** component of the s-process, which dominantly contributes to abundances of isotopes up to $A = 90$ takes place in massive stars ($M > 8M_{\odot}$). The s-process occurs during convective helium-core burning around $T = 0.3 \cdot 10^9$ K and in subsequent convective carbon-shell burning around $T = 1.0 \cdot 10^9$ K.

Neutrons are thermalised in these hot stellar environments and follow a Maxwell-Boltzmann velocity distribution. The effective stellar neutron capture cross section for the s-process is therefore a Maxwellian Average Cross Section (MACS), at the corresponding neutron energies of $kT \approx 8, 25$ and 90 keV.

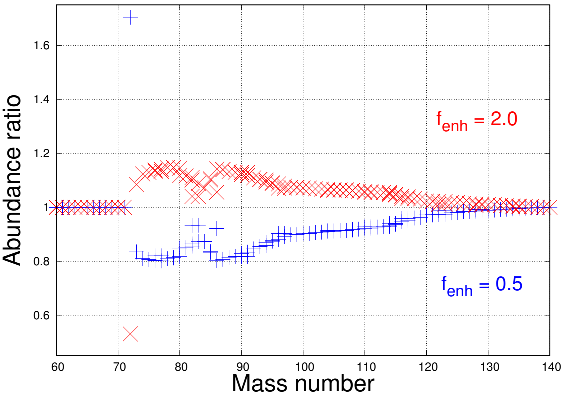


Figure 1: NETZ-calculation [4] shows that only the change of one single MACS of ^{72}Ge by an enhancement factor f_{enh} of 2 or $\frac{1}{2}$ produces a change up to 50 to 70% for the isotope itself, but as well up to 20% changes for heavier isotopes up to $A = 125$.

In the weak s-process neutron exposures are not high enough to establish a reaction flow equilibrium. Therefore, an indivual MACS has influence not only on the abundance of its isotope, but also on abundances of isotopes following the reaction chain as well [5]. This propagation effect is shown for the case of ^{72}Ge in Fig. 1. Changes in the abundances up to ± 20% for heavier isotopes up to Te ($A = 125$) are observed for enhancement of the ^{72}Ge(n, γ)-MACS by factors of 2 and $\frac{1}{2}$, respectively. For ^{72}Ge(n, γ) only one measurement above thermal neutron energies exists [6], covering energies up to a few keV, while no experimental data [7] are available for the astrophysically important higher keV region. Therefore, experimental data are required for neutron energies up to about 200 keV to determine MACSs for the entire energy range of interest.

2 Measurement and Data Analysis

The measurement of the ^{72}Ge(n, γ) cross section [8] was performed at the neutron time-of-flight facility n_TOF, located at CERN. Details of n_TOF are described here [9]. At n_TOF, neutrons over a large energy range (25 meV to several GeV) are produced by spallation reactions of a highly energetic (20 GeV/c), pulsed proton beam (from the CERN Proton Synchrotron) impinging on a massive Pb target, yielding in an instantaneous neutron intensity of $\sim 2 \times 10^{15}$ neutrons per pulse.

The capture measurement was performed using a 96.59 %-enriched ^{72}GeO$_2$ sample at a distance of $L \approx 185$ m from the spallation target at Experimental Area 1 (EAR-1). The prompt γ rays, following a neutron capture event, were detected by a set of four liquid scintillation C$_6$D$_6$ detectors, which are optimized to have an extremely low sensitivity to neutrons scattered from the sample [10, 11]. A photograph of the setup is shown in Fig. 2a. For each capture event, the neutron energy is determined by measuring the time-of-flight t_n, i.e. the time difference between production of the neutron and detection of the capture events, using Eq. 1:

$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1-\beta^2}} - 1\right) \quad \text{with } \beta = \frac{L}{t_n c} \tag{1}$$

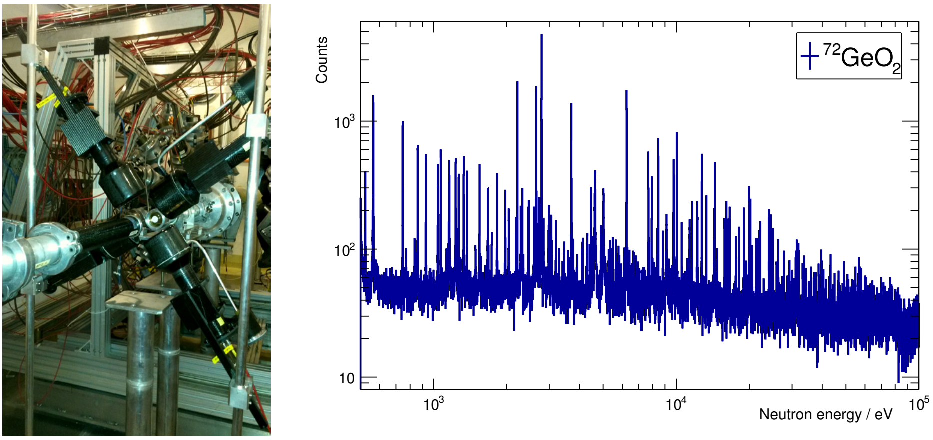
The counting spectrum can be transformed to the neutron capture yield using

$$\mathbf{Y} = f_N \frac{(\mathbf{C} - \mathbf{B})}{\Phi \cdot \varepsilon}, \tag{2}$$

where **C** is the number of counts measured with the ^{72}GeO$_2$ sample and **B** is the background, which is measured with no sample in the beam. The detection efficiency ε depends on the de-excitation path of the compound nucleus. A detection efficiency independent of the latter can be achieved by applying the Pulse Height Weighting Technique [12], which requires detailed Monte-Carlo simulations of the detector response functions, taking into account the experimental geometry. The neutron flux spectrum Φ is measured with different detector arrays, e.g. a set of silicone detectors measuring alphas and tritons after neutron capture on a thin ^{6}Li-target. Finally a normalisation f_N to the 4.9 eV resonance in ^{197}Au(n, γ), which is saturated in the capture yield [13], is applied to determine the yield **Y**.
In the following, a preliminary counting spectrum is plotted for ^{72}Ge(n, γ) in Fig. 2b, showing a number of neutron resonances in the stellar energy range. In further analysis, resonances will be analysed from the neutron capture yield and used to determine the MACS.

3 Summary

The ^{72}Ge(n, γ) was measured for the first time at stellar energies at n_TOF (EAR-1). This cross section is of importance to determine abundances produced in the s-process in massive stars.



(a) (b)

Figure 2: (a) Neutron capture setup at EAR-1 shows four C_6D_6 detectors with the ^{72}GeO$_2$ sample in the middle. The neutron beam is coming from the left. (b) Preliminary unweighted counting spectrum of neutron capture on ^{72}GeO$_2$ is plotted in the neutron energy region of interest.

The experiment was performed using an enriched ^{72}GeO$_2$ sample and a set of liquid scintillation detectors (C_6D_6) to detect prompt γ rays emitted after neutron capture. The analysis procedure has been shortly introduced and preliminary counting spectrum was shown. The data are still under analysis and first experimental results at stellar energies can be expected soon.

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