EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Neutron capture cross sections of ^{69,71}Ga at n_TOF EAR1

May 31, 2016

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Abstract: We propose to measure the neutron capture cross sections of the stable gallium isotopes ^{69}Ga and ^{71}Ga. These reactions are important during the astrophysical slow neutron capture process (s-process) which produces about half of the elements heavier than iron. The neutron capture cross sections of the two gallium isotopes not only determine the abundances of gallium, but also affect the abundances of the elements up to zirconium. The data from cross section measurements of Ga(n,γ) is scarce, and no data is available for the relevant energy range during the s-process. The Ga(n,γ) cross sections will be measured in the full energy range from 25 meV to about 500 keV at n_TOF EAR-1.

Requested protons: 4.0×10^{18} protons on target
Experimental Area: EAR1

1 Motivation

The origin of heavy elements in the Universe is a fascinating and interdisciplinary challenge. The quest starts with an inventory: In our Solar System, the solar photosphere, the Earth, and meteorites reflect the chemical signature of the gas cloud in which the Sun formed. These abundances show the combined results of different nucleosynthesis contributions and the imprints of nuclear physics. Astrophysicists aim at reproducing the observed abundances by measuring nuclear reaction cross sections and by performing stellar simulations and nucleosynthesis calculations.

Most of the elements heavier than iron are produced by the slow (s) and the rapid (r) neutron capture processes. The **s-process** takes place during stellar He and C burning phases with neutron densities between 10^8 and 10^{10} cm^{-3}. The reaction path closely follows the valley of stability since neutron capture times of typically ten years are much slower than most of the β-decay times of the involved nuclei (Figure 1) [1].

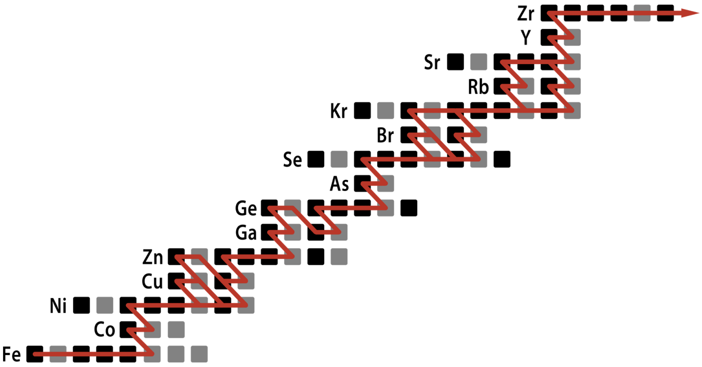

Figure 1: The s-process path closely follows the valley of stability (black squares, stable isotopes in the chart of nuclei) since neutron capture time scales (typically ten years) are much slower than most of the β-decay time scales of the involved nuclei.

The s-process is composed of the weak and the main component [2]. The main differences lie in the neutron-to-seed ratios, the temperatures as well as the neutron densities. The main component of the s-process takes place at about 5 to 25 keV in low-mass asymptotic giant branch (AGB) stars and produces the nuclei with mass numbers above $A \approx 90$ [2]. The **weak component of the s-process** takes place at about 90 keV in massive stars with $M_{\rm star} > 8\ M_{\odot}$. The time-integrated neutron flux is lower compared to the main component producing nuclei with mass numbers $A \leq 90$.

1.1 Neutron capture cross sections for the s-process

Nucleosynthesis simulations for the s-process depend on stellar decay half-lives and stellar neutron capture cross sections. The Maxwellian Averaged Cross Section (MACS) gives the cross section averaged over the stellar neutron spectrum and is defined as

$$< \sigma >= \frac{2}{\sqrt{\pi}} \frac{1}{(k_{\rm B}T)^2} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_{\rm B}T}\right) {\rm d}E$$

where E is the neutron energy, $k_{\rm B}$ is the Boltzmann constant and T is the temperature in the star. The MACS needs to be known for an energy range of 5 to 90 keV for the main and the weak s-processes. Hence, the excitation function has to be determined up to neutron energies of a few hundred keV by a time-of-flight measurement.

1.2 The weak s-process

The weak s-process produces most of the s-process isotopes between iron and strontium. The neutron fluence in the weak s-process is too low to achieve reaction flow equilibrium, in contrast to the main s-process component. Therefore, **a particular neutron capture cross section not only determines the abundance of the respective isotope** (as in the case of the main component), **but affects the abundances of all heavier isotopes as well**.

The uncertainties of the neutron capture cross sections of the weak s-process nuclei ($60 \leq A \leq 90$) are higher than the uncertainties of the main s-proces nuclei (A $\geq$ 90). Following the weak s-process path, the cumulated uncertainties affect all isotopes of the weak s-process, up to krypton and strontium, with possible minor contributions to the yttrium and zirconium abundances [3, 1]. Accurate predictions require the cross sections to be known with an accuracy of at least 5% for all involved nuclei in the weak s-process [4]. In the past years, new measurements of neutron capture cross sections of isotopes beyond iron significantly changed the predicted weak s-process distribution due to the propagation to heavier isotopes on the s-process path. Recent nucleosynthesis calculations showed an increase of s-process yields from nickel up to selenium. New cross sections of the nuclei ^{74}Ge, ^{75}As and ^{78}Se resulted in a higher production of germanium, arsenic, and selenium, thereby reducing the s-process yields of heavier elements by propagation [3].

1.3 The case of gallium

Gallium is mostly produced by the weak s-process in massive stars. Recent simulations [3] show that gallium is the most abundant s-element at the end of shell carbon burning. So far, there is only a time-of-flight measurement with a sample of natural gallium [5]. Other nuclei (^{81}Br, ^{75}As, ^{74}Ge) measured within the same experimental campaign show large deviations from more recent results [6]. For ^{71}Ga two discrepant results from integral measurements at 25 keV are published [7, 8]. The cross sections should be remeasured to solve the discrepancies. Data for carbon shell burning in massive stars at 90 keV are highly desired.

Figure 2 shows the sensitivities to the propagation effect of cross section uncertainties of ^{69}Ga and ^{71}Ga during the weak s-process. Changing the stellar neutron capture cross section of one gallium isotope by 50% leads to changes of up to 20% for the s-abundances of all following isotopes. The abundances of ^{69}Ga and ^{71}Ga are changed by a factor of two. Accurate cross section data for neutron energies from 25 meV up to 500 keV are needed to provide a reliable prediction of the gallium and weak s-nuclei abundances.

2 Experimental Setup and Beam Time Request

We propose to measure the neutron capture cross sections of ^{69}Ga and ^{71}Ga at Experimental Area 1 (EAR1) of the n_TOF facility for the full neutron energy range from 25 meV up to a few hundred keV. We will use the C_6D_6 detection setup at n_TOF to detect the prompt γ-radiation of neutron capture events. The C_6D_6 detectors show a very low sensitivity to scattered neutrons, an important background component.

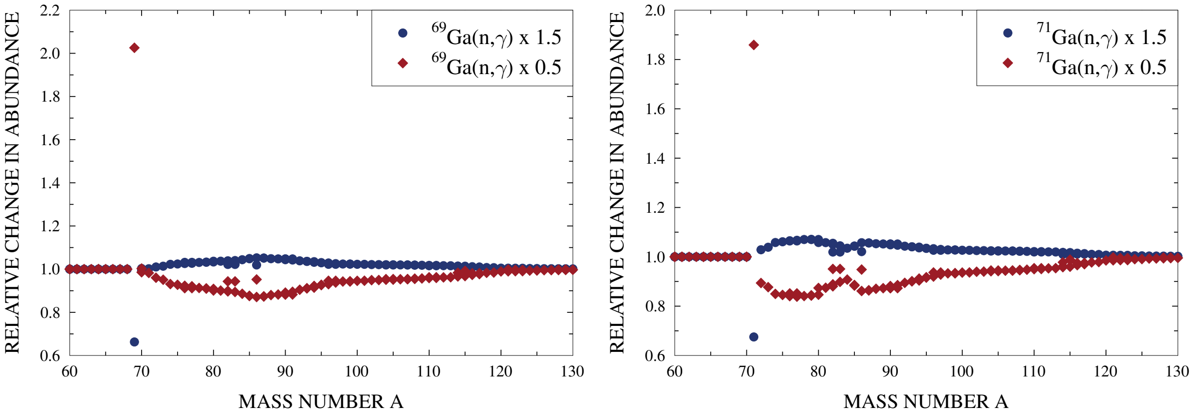

Figure 2: Impact of the cross section uncertainties of the reactions ^{69}Ga(n,γ) (left panel) and ^{71}Ga(n,γ) (right panel) on the abundances of the weak s-process elements.

Each of the samples will consist of 1 gram, with an isotopic enrichment of 99.6% for ^{69}Ga and 99.8% for ^{71}Ga. We will provide cylindrical samples with a diameter of 2 cm. Figures 3 and 4 show the expected count rate for the C_6D_6 detection setup for the ^{69}Ga and ^{71}Ga samples with 1.6×10^{18} protons on the spallation target. We used the evaluated neutron capture cross sections of ENDF/B-VII [9] for the calculations. The results are shown for a resolution of 5000 bins per energy decade, which is needed to perform a resonance shape analysis. We compare the results to the background level obtained from the germanium measurements performed at n_TOF in 2015 [10]. We expect the background level to be lower in the case of gallium since the ratio of the neutron scattering cross section and the neutron capture cross section is lower than in the case of germanium.

We will normalize the cross section using the saturated resonance technique with a gold sample of the same size as the gallium samples. We will study the background by recording runs without a sample in the beam. We will measure the background due to sample scattered neutrons with a carbon sample, which has a very high neutron scattering to capture ratio. The background and normalization measurements require 0.8×10^{18} protons. Sample specifications and the requested number of protons are listed in Table 1.

3 Summary

The neutron capture cross sections of the stable gallium isotopes ^{69}Ga and ^{71}Ga determine the abundances of the elements up to zirconium, which are produced during the weak s-process. So far, only data from integral measurements is available for ^{71}Ga for the energy range of the main s-process. Data for the weak s-process is highly desired.

We propose to measure the neutron capture cross sections for ^{69}Ga and ^{71}Ga at n_TOF EAR-1. We will use the C_6D_6 detection setup at n_TOF to detect the prompt γ-radiation of neutron capture events. We request 4.0×10^{18} protons to measure the neutron capture cross sections in an energy range from 25 meV to 500 keV.

Summary of requested protons: $\mathbf{4.0\times10^{18}}$

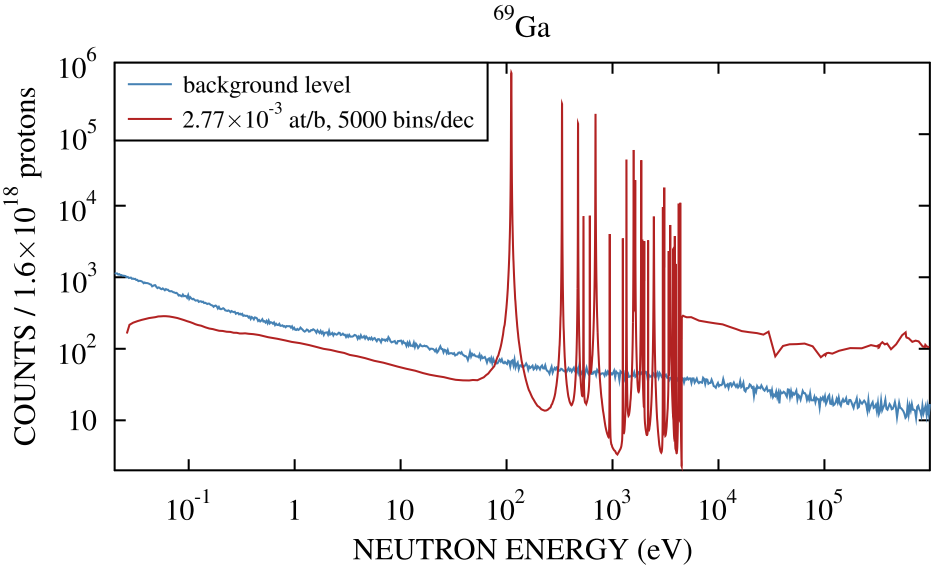

Figure 3: Count rate estimates (red line) for ^{69}Ga. The sample characteristics are described in Table 1. The blue line shows the background level obtained from the germanium measurements performed at n_TOF in 2015 [10].

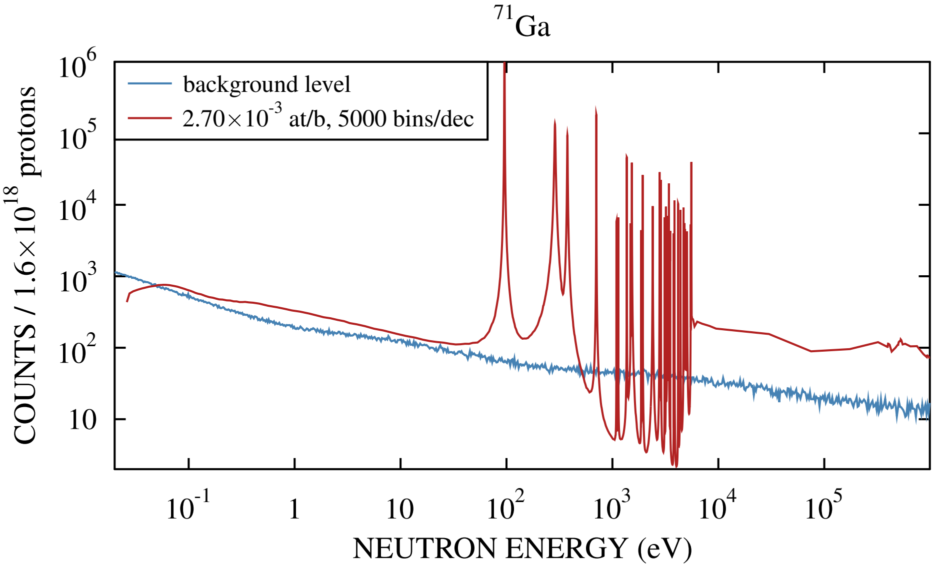

Figure 4: Count rate estimates (red line) for ^{71}Ga. The sample characteristics are described in Table 1. The blue line shows the background level obtained from the germanium measurements performed at n_TOF in 2015 [10].

Sample	Mass (g)	Enrichment (%)	Thickness (at/b)	No. of Protons ($\times 10^{18}$)
^{69}Ga	1	99.6	2.77×10^{-3}	1.6
^{71}Ga	1	99.8	2.70×10^{-3}	1.6
Au				0.2
C				0.2
Empty frame				0.4
Total				**4.0**

Table 1: Summary of samples and corresponding requested number of protons. Isotopic enrichment as quoted by ISOFLEX [11].

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