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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Addendum to Proposal INTC-P-406 to the ISOLDE and Neutron Time-of-Flight Committee

Destruction of the cosmic γ-ray emitter ^{26}Al in massive stars by neutron induced reactions up to 600 keV

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Abstract: The cosmic γ-ray emitter ^{26}Al is of high interest in nuclear astrophysics, as its observation in our galaxy can provide unique insights into star formation, stellar evolution and stellar explosions. $^{26}\mathrm{Al}(n, \alpha)$ and $^{26}\mathrm{Al}(n, p)$ reactions have been identified as key uncertainties to predict ^{26}Al abundances in stars. Our collaboration recently published results for cross sections up to 150 keV measured at n_TOF EAR-2. However for massive stars, which are the dominant source of ^{26}Al in our galaxy, data at even higher neutron energy are essential. With this addendum, we propose a new

measurement of these important reactions, taking advantage of the new n_TOF spallation target resulting in a higher neutron flux and improved neutron energy resolution.

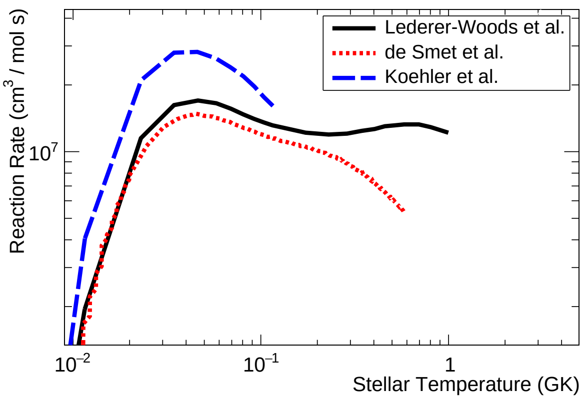
Requested protons: 6×10^{18} protons on target
Experimental Area: EAR2

1 Introduction

The radioactive isotope ^{26}Al ($T_{1/2} \approx 7 \times 10^5$ y) is a prominent cosmic γ-ray emitter. Its presence in our galaxy, which was confirmed by detection of its characteristic 1.8 MeV emission by space based telescopes, is proof of ongoing nucleosynthesis [1]. Detailed satellite observations of its abundance and velocity across the galaxy suggest that massive stars are the most likely sites of ^{26}Al [2]. However, accurate predictions of the ^{26}Al production in massive stars are hindered by uncertain nuclear reaction rates. In particular, a study by Iliadis et al. [3] concluded that uncertainties in the ^{26}Al(n,p) and ^{26}Al(n,α) reaction rates above 1 GK are most important.

Our collaboration recently determined precise ^{26}Al(n,p) and ^{26}Al(n,α) cross sections at n_TOF EAR-2 and JRC Geel, for neutron energies up to 150 keV [4, 5]. In this lower energy region, only 2 datasets for each reaction were previously available and results were discrepant [6, 7, 8, 9]. Figure 1 shows a comparison of our results (Lederer-Woods et al.) with these previous data for (n,α) in the left, and (n,p) in the right panel. For the (n,α) reaction, our results were in agreement within uncertainties with a measurement by de Smet et al. [9], while ruling out a measurement by Koehler et al. [8]. We also obtained a lower reaction rate than Koehler et al. for the (n,p) channel, but obtained higher reaction rates than activation data from Trautvetter et al. [6, 7].

In collaboration with leading stellar modellers, we have found that using our new reaction



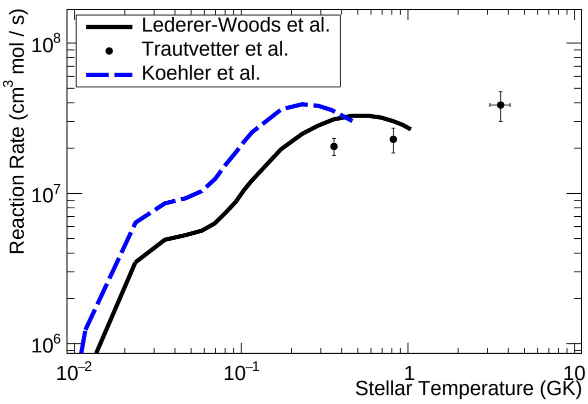


Figure 1: (Left) Comparison of the ^{26}Al(n,α) reaction rate obtained from a recent n_TOF measurement (Lederer-Woods et al.) with the only other experimental data. (Right) Same as left but for the ^{26}Al(n,p) reaction

rates, stellar models of low-mass Asymptotic Giant Branch stars can reproduce the full range of ^{26}Al/^{27}Al ratios measured in presolar grains which condensed in the circumstellar envelopes of these stars [10]. However, the dominant galactic source of ^{26}Al are massive stars, where the relevant stellar burning temperatures range from 1 to about 2.4 GK. As indicated in Fig. 1, our cross sections up to 150 keV do not allow to constrain the stellar reaction rate at these higher temperatures (this can also be seen by the decrease in the reaction rate at the higher temperature end which is an artefact due to missing cross section data above 150 keV). In fact, in our study [10] we found that depending on

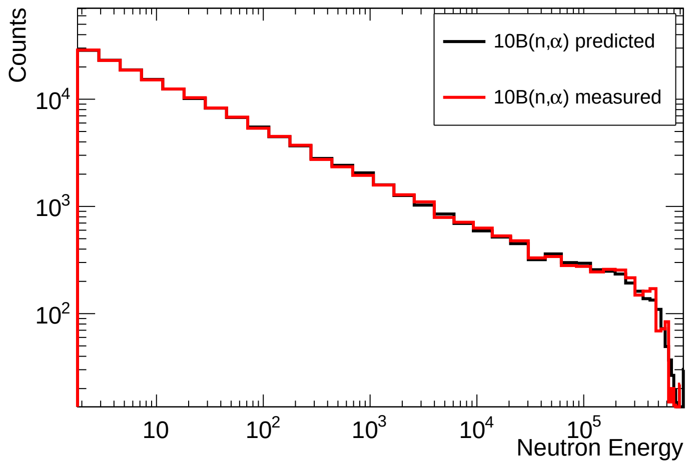


Figure 2: Counts in the ΔE detector from the test beam time measured with a ^{10}B sample. The data are compared to a calculation taking into account the EAR-2 neutron flux and resolution function. The data are normalised in the region from 2-10 eV.

the stellar model, the uncertainty in ^{26}Al production in massive stars can be as high as a factor 2.4.

The previous experiment at n_TOF had to be performed with a large beam collimator to maximise counting statistics. This resulted in a large prompt signal in the detectors, induced by the proton beam hitting the spallation target (called γ-flash) and ultimately lead to the upper neutron energy limit of 150 keV. During the recent long shutdown at CERN, a new spallation target has been installed at n_TOF which resulted in a 50% higher neutron flux in EAR-2. This means that a measurement can now by performed using the smaller beam collimator, while maintaining similar counting statistics. We have recently tested our setup during these new conditions to investigate which upper energy limit is now possible. Figure 2 shows results of measurement of the $^{10}\mathrm{B}(n,\alpha)$ reaction. In the figure, the measured counts per bin are compared to the prediction (based on neutron flux shape and energy resolution). The spectra are normalised to the 2-5 eV region. The expected excitation function is reproduced very well by our data up to about 600 keV. This demonstrates, that our system can be used for measuring the cross section at higher neutron energies, and thus will allow us to determine stellar reaction rates at massive star temperatures ($\geq$70% of the $^{26}\mathrm{Al}(n,\alpha)/^{26}\mathrm{Al}(n,p)$ reaction rates can be constrained for the highest relevant temperatures of 2.4 GK based on calculations using the EMPIRE nuclear reaction code [11]).

2 Method

We plan to use the same ^{26}Al sample [12] as in the previous measurement, which is owned by JRC Geel. The (n,p) and (n,α) reactions will be detected using a silicon detection setup arranged in a ΔE-E configuration, similar to what we already used in the previous

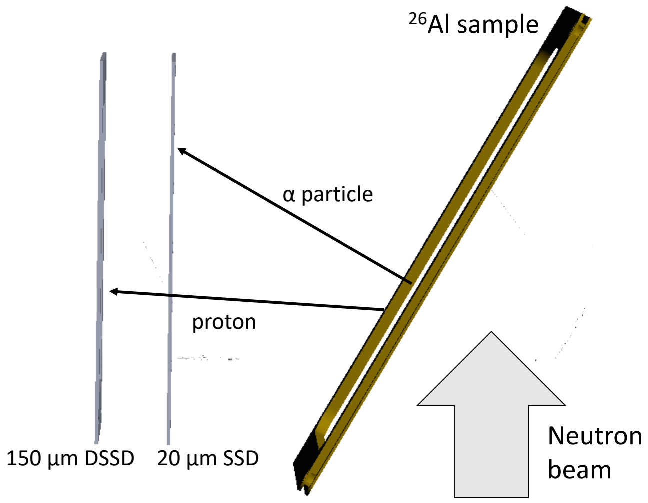


Figure 3: Proposed setup: The ^{26}Al sample is facing a ΔE-E silicon telescope setup of 20μm and 150μm thickness, respectively.

measurement. The ^{26}Al sample will be placed at an angle of 50 degrees wrt the neutron beam with the silicon telescope perpendicular and about 5 cm from the neutron beam center (see Fig. 3). The telescope will consist of a 5×5 cm^2 single sided silicon strip detector of 20μm thickness (16 strips) as ΔE detector, followed by a thick double sided silicon strip detector with a thickness of 150 μm (16×16 strips) as E-detector. This combination will completely stop p_1 and p_2 proton emission (emission to first and second excited state of ^{26}Mg) and most of the p_0 events; the range of p_0 protons (≈4.6 MeV) in silicon is about 190μm, due to the different incident angles most protons will travel further than the 20+150 μm thickness of the telescope. The fraction of events that is not stopped can be separated and identified easily due to their large deposited energy of above 4 MeV. The α-particles produced in the reaction will already be completely stopped in the ΔE detector.
The cross sections will be normalised to the well known ^{10}B(n, α) reaction cross section, using a ^{10}B sample of the same geometry as the ^{26}Al sample. In addition we will perform measurements of the ^{6}Li(n, t) reaction using an enriched ^{6}LiF target to determine the efficiency of detecting coincident events between ΔE and E detectors. This is the same procedure we already applied in the last measurement [4, 5]. We will also perform measurements with an empty sample holder to confirm the absence of any significant background, similar to the last campaign.
We expect uncertainties due to systematic effects to be about 10%. The largest sources of uncertainty will be the areal density of the ^{26}Al and ^{10}B targets (5%). In addition, we expect the uncertainty in the neutron fluence shape and the neutron fluence normalisation to be about below 5% each (based on the previous measurement).

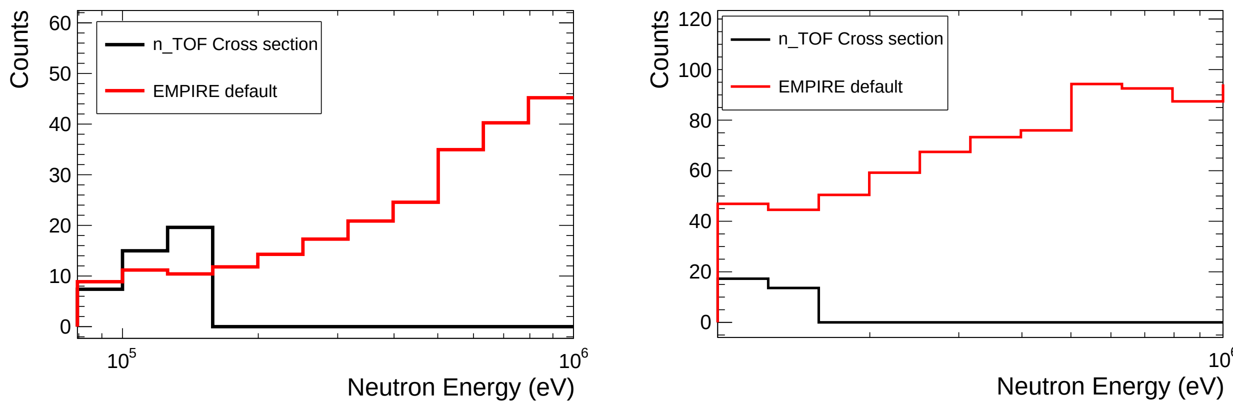


Figure 4: (*Left*) Counts per bin expected for the ^{26}Al(n, α) reaction, for 5×10^{18} protons. The prediction is made using cross sections below 150 keV measured previously at n_TOF (black), and a theoretical calculation using default settings in the EMPIRE code. (*Right*) Same as left panel, but for the ^{26}Al(n, p) reaction

3 Beam Time Estimate

Our beam time estimate is based on the preliminary evaluation of the neutron flux at EAR-2, the areal density of the ^{26}Al target, efficiency of the detection system (≈5%) and the respective reaction cross sections. For the energy region below 150 keV, we have estimated the number of expected counts using our previous results, while for higher energies we have calculated the cross section using the EMPIRE code with default settings.

The main aim of this proposal is to measure the cross section at neutron energies higher than 150 keV: The two panels in Figure 4 show the expected number of counts per bin for 5×10^{18} protons, using the cross section determined at n_TOF (which stops at about 150 keV), and the EMPIRE calculation for higher energies. We expect good counting statistics over the entire energy range. While our data suggest that the ^{26}Al(n, p) cross section (right panel in Fig. 4) may be over estimated by EMPIRE, even a 2 times lower cross section would result in enough statistics of at least ≈ 10 counts per bin. Thus, the statistical uncertainty in the stellar rate will be kept well below 10% since the cross section data will be averaged over the stellar neutron spectrum. Alongside the cross sections at high energy, we also expect data of similar quality than the previous run at lower neutron energies.

In addition to the 5×10^{18} protons for runs on the ^{26}Al target, we request 1×10^{18} protons for commissioning the detection setup in beam (e.g. alignment, noise reduction etc.), performing reference runs on ^{10}B and ^{6}Li, and background runs with an empty sample holder.

Summary of requested protons: 6×10^{18} protons

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using [SiTe-EDI : Silicon Telescope setup used in P-406 (present at CERN)]	☒ To be used without any modification ☐ To be modified
If relevant, write here the name of the fixed installation you will be using [SiMon-2]	☒ To be used without any modification ☐ To be modified
If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute [^{26}Al target]	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
Small spare parts, such as detector holders, cabling, spare detectors etc.	☒ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]	

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	[pressure] [bar], [volume][l]
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☐	[voltage] [V]
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]

	Dangerous for the environment	☐	[fluid], [quantity]
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards			