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Determination of ^{118}Sn$(p,\gamma)^{119}$Sb cross-section at astrophysical energies from X-ray emission yields

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1. Abstract

Proton capture reactions at sub-barrier energies have significant contributions in explosive nucleosynthesis environments. In particular, they are crucial to determine the reaction rate of the inverse (γ, p) reaction and describing the production of the stable p-nuclei, a set of 35 naturally occurring nuclei from Se to Hg that cannot be produced in neutron capture processes like the s-process or the r-process. In this work, we present the measurement for the first time of the radiative proton capture reaction $^{118}\mathrm{Sn}(p,\gamma)^{119}\mathrm{Sb}$ reaction using the activation method by detecting the emitted X-rays. The gamma emission associated to the electron capture decay in ^{119}Sb will be used to validate the method. The results are compared to theoretical predictions using the TALYS code, and show the potential of using this technique to further constrain the nuclear input in astrophysical network calculations.

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2. Introduction

The synthesis of elements heavier than Fe requires neutron-rich environments, where slow and rapid neutron capture processes (known, respectively, as the *s*- and *r*-process) can occur. These two processes can explain the existence and abundance of most of the nuclei heavier than iron. However, about 30 to 35 proton-rich naturally occurring isotopes between Se and Hg cannot be produced via neutron capture processes, as β^- decay is blocked by more neutron-rich isobars. Since the famous B^2FH paper [1] it has been theorized that these nuclei are produced in explosive events, like Type-II [2] or Type-Ia [3] SuperNova Explosions. However, one of the remaining issues is that the current *p*-process nucleosynthesis codes are not able to produce in sufficient amount the light Mo, Ru, In, and Sn *p*-nuclei[2]. Complementary processes such as the rapid proton capture *rp*-process [4] or the *νp*-process [5] have been proposed to explain the underproduction of these elements.

Predicting stellar abundances depends upon complex reaction network calculations within a given astrophysical environment that may involve 2×10^4 reactions on 2000 stable and unstable nuclei [6]. In view of the huge number of reactions, *p*-process studies will always have to rely on reaction cross-sections obtained from theoretical models. It is of utmost importance to base these calculations on a grid of experimental cross-sections spread over the entire reaction network. Such data are crucial since the calculated cross-sections exhibit uncertainties up to several hundred percent even for stable isotopes [7].

Among the light *p*-nuclei, several reaction cross-sections have already been measured for several tin isotopes. For example, for the ^{112}Sn the (α,γ), the (α,n), the (α,p) and the (p,γ) cross-sections have all been measured [8–10]. In the present work, the focus will be on the determination of the unmeasured $^{118}\mathrm{Sn}(p,\gamma)^{119}\mathrm{Sb}$ (Q = 5.112 MeV) reaction cross-section using the Activation Method.

The main objective is to benchmark this method using the X-ray emission associated to the electron capture decay of ^{119}Sb. This reaction is an optimal candidate to test the method proposed by G. G. Kiss et al. [11], since it is possible to apply the Activation Method simultaneously to the γ-emission and X-ray emissions of the ^{119}Sb decay, in the same experiment.

3. Experimental Procedure

In this work, we used natural Sn to develop and optimize the experimental methodologies and data analysis that will be used with targets of pure ^{118}Sn in the future.

The use of a natural target, offers the possibility to study several reaction channels simultaneously. For instance the radioactive product of the $^{116}(p,\gamma)^{117}$Sb reaction has a half-life very different from ^{119}Sb, making it possible to separate the contribution of each radioactive isotope to the total decay. This means that we are able not only to calculate the cross-section for $^{118}\mathrm{Sn}(p,\gamma)^{119}\mathrm{Sb}$ but also for $^{116}\mathrm{Sn}(p,\gamma)^{117}\mathrm{Sb}$. The latter has already been measured, as we mentioned before, which means we can use it to validate our method.

A major drawback of relying on X-ray emissions in the Activation Method is that they are characteristic of the atomic element and not of the isotope. If the target consists of several stable isotopes of the same chemical element, different products with the same characteristic X-ray

emissions will be created during the irradiation. If these isotopes decay by electron capture with similar half-life, it will be almost impossible to differentiate between them, as the total number of decays will be described by an overlap of the different individual decays. Another disadvantage is that several reactions can lead to the production of the same isotope. For example, the (p,n) reaction on ^{119}Sn also produces ^{119}Sb, which can lead to an overestimation of the cross-section of the (p,γ) reaction. Even though it's not possible to eliminate completely this contamination, it is possible to estimate their effect and correct it in the analysis.

In this work, natural tin targets with different backings were produced using the vacuum evaporation process. Target thicknesses were characterized using α-particles energy loss method and Rutherford Backscattering Spectrometry (RBS) with low-energy protons and alpha particles.

The targets were then irradiated with protons in the 3-4 MeV energy range using the Tandem accelerator at the Nuclear and Technological Campus (CTN/IST) in Sacavém, Portugal. These energies lie in the astrophysical energy region of interest known as the Gamow window [12].

Following irradiation, the decay spectra were measured using two silicon drift detectors (SDDs) widely used in X-ray analysis. The energy calibration of the SSD was measured experimentally using X-ray sources, and the total response function of the detectors was simulated using the Geant4 toolkit [13].

4. Cross-section calculation

After analysing the γ- and X-ray emission spectra as a function of the decay time, and by normalizing the measurement using in-beam RBS spectra registered during the irradiation period [14], it is possible to derive the reaction cross-section. Table 1 shows the results obtained. For both analyses with the γ-emission and Kα line peaks the differences are negligible. This first approach provides us confidence to advance in the usage of X-ray yields as a complement or a substitute to γ-decay analysis.

Table 1: Cross section values obtained for the reactions ^{116}Sn$(p,\gamma)^{117}$Sb and ^{118}Sn$(p,\gamma)^{119}$Sb considered in this work. Results are provided for the analysis of the Kα and γ decay lines.

		σ [mbarn]		
	Reaction	^{116}Sn$(p,\gamma)^{117}$Sb	^{118}Sn$(p,\gamma)^{119}$Sb	
	Yield	Kα	Kα	γ
Ep [MeV]	2.80	0.023 ± 0.005	0.040 ± 0.005	0.040 ± 0.006
	3.29	0.015 ± 0.005	0.20 ± 0.02	0.20 ± 0.02
	3.66	0.51 ± 0.03	0.99 ± 0.06	0.99 ± 0.05

Figure 1 shows the comparison between the ^{118}Sn$(p,\gamma)^{119}$Sb and ^{116}Sn$(p,\gamma)^{117}$Sb reaction cross-section calculated with the TALYS code [15] (version 1.95 using the default parameters) and the measured data, which are of the same order of magnitude of our results. For the latter reaction, the experimental values obtained by N. Özkan et al. [16] and M. Famiano et al. [17] are also shown. Our results do not agree quite well with them, however we have to take into account that our measurements were done using natural tin, and these differences will probably disappear when we use enriched targets.

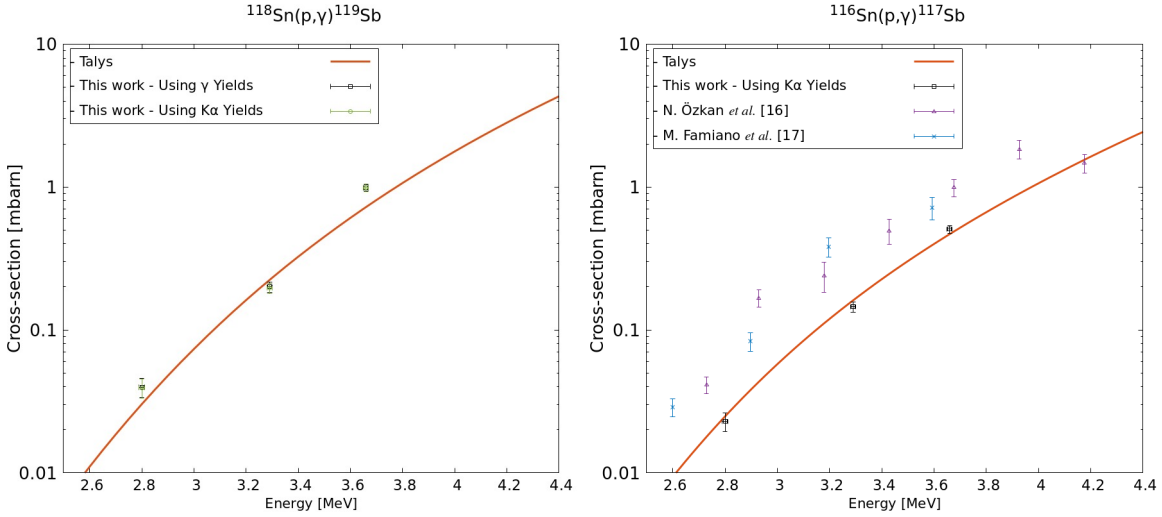

Figure 1: Comparison of ^{118}Sn$(p,\gamma)^{119}$Sb (left) and ^{116}Sn$(p,\gamma)^{117}$Sb (right) reaction cross-section obtained in this work by the Activation Method with calculated cross-section using the TALYS code. Cross-section for the ^{116}Sn$(p,\gamma)^{117}$Sb are also compared with data from [16] and [17].

5. Conclusions

In this work we aimed at validating the use of X-ray yields to determine the ^{118}Sn$(p,\gamma)^{119}$Sb reaction cross-section. This was done by comparing the cross-sections obtained from the analysis of the γ-emission and the X-ray K-lines associated to the decay of ^{119}Sb. This validation is very important as, in some reactions, the radioactive products only decay via electron capture, without subsequent gamma emission or with very low intensity. In these cases, the measurement of X-ray yields is the only possible way to determine the cross-section through the Activation Method.

The cross-section values obtained are in the same order of magnitude as the ones given by TALYS code calculations. Furthermore, the ^{116}Sn$(p,\gamma)^{117}$Sb reaction cross-sections obtained trough the relative method follow the trend observed in the measurements done by N. Özkan et al. [16] and M. Famiano et al. [17].

The use of natural tin produced interesting results. For instance, the accumulated spectra exhibits not only the K-lines analysed in this work, but also the Lα and Lβ lines of tin. The lines are very well defined, since they are positioned at an energy where the detector has a higher efficiency and sufficient resolution, making it an interesting study to do in the future. The analysis of these lines is beyond the scope of this manuscript.

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