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Cross section measurement of ^{144}Sm(p, γ) reaction for astrophysical *p*-process study using Activation technique

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Abstract. The cross section measurement of ^{144}Sm (p, γ) ^{145}Eu has been carried out around proton energies 2.6−6.8 MeV using the activation technique. Measured cross sections are compared with the previous measurement and theoretical predictions using TALYS 1.96. The molecular deposition method was used to prepare the enriched ^{144}Sm targets of thickness 100−350 μg/cm^2 on Al backing.

1 Introduction

Most of the heavier elements (above iron) are produced mostly via the slow (*s*)- or rapid (*r*) neutron capture process. But there are around 35 stable nuclei, between ^{76}Se and ^{196}Hg, which are not produced via this *s* or *r*-process and are called *p*-nuclei [1]. These nuclei have relatively low solar abundance in comparison with the neighbouring *s* or *r*-process seed nuclei. The typical abundance of these *p*-nuclei in the $34 \leq Z \leq 50$ region is 1% and less than 0.3% in the higher (Z>50) region. Heavier *p*-nuclei are produced mainly through a series of photodisintegration processes, viz. (γ, n), (γ, p), and (γ, α). The temperature required for such processes is between 1.5−3.5 GK, and generally occurs in the O/Ne layer of type II supernovae. Although abundances of *p*-nuclei decrease with the increase in atomic number, there are a few, like ^{92}Mo and ^{144}Sm, which have relatively higher abundances of 14.52% and 3.08% respectively. More precise and detailed information about the reaction cross section is extremely important in order to study the reaction rate for these nuclei. Molecular deposition technique was used to prepare the 67% enriched ^{144}Sm targets of thickness 100−350 μg/cm^2 on a 25 μm Al foil. Measured ^{144}Sm(p, γ) cross sections were compared with the theoretically predicted values using TALYS 1.96 [2].

2 Experiment

The experiment was performed at the K130 Cyclotron facility at VECC, Kolkata, using the activation technique [3]. The minimum available proton energy from the Cyclotron was 7

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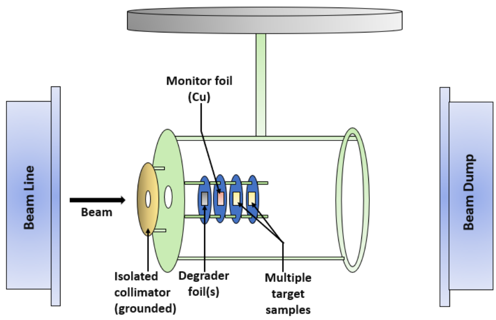
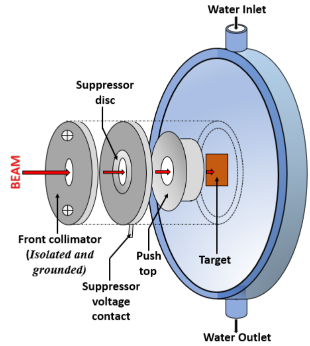


(a) Setup used for multiple target irradiation between 4.2 and 6.8 MeV.



(b) Setup used to irradiate single (one at a time) ^{144}Sm targets below 4.2 MeV.

Figure 1: Setups used for multiple (a) and single (b) ^{144}Sm target irradiations.

Table 1: List of γ-rays used for cross section measurement of ^{144}Sm(p, γ)^{145}Eu reaction [4].

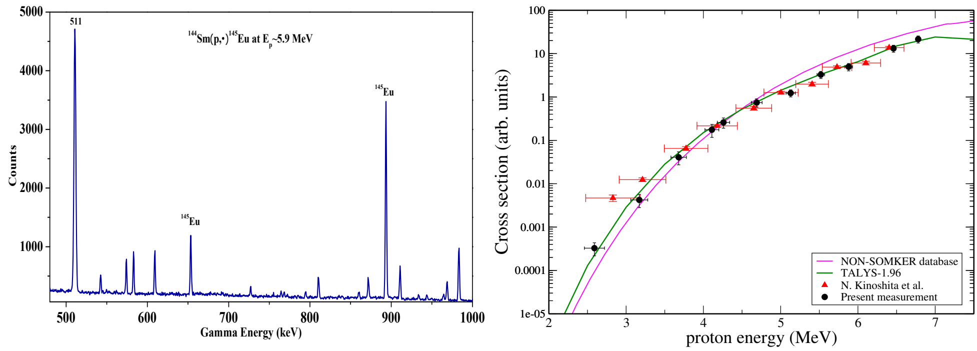
Reaction	Product nuclei	Half-life ($T_{1/2}$)	Detected γ-rays (%)
^{144}Sm(p, γ)	^{145}Eu	5.93(4) d	653.5 (15%)
			896.7 (66%)

MeV, and the stacked foil degradation method was used to irradiate targets at lower energies [5]. Irradiation was carried out for a few hours to a couple of days with a beam current of approximately 1 μA.

Two different types of irradiation setups were used, as shown in figures 1a and 1b. Figure 1a was used to irradiate multiple ^{144}Sm targets simultaneously between energies 4.2 and 6.8 MeV in two sets (five energies). Copper foil (99% pure) of thickness 7 μm was used in between targets to calculate the irradiation beam current using the activity of ^{65}Zn ($T_{1/2}$ =243.93(9) days) produced via the ^{65}Cu(p, n)^{65}Zn reaction. Whereas the setup shown in figure 1b was utilised to irradiate a single (one) ^{144}Sm target at a time for energies below 4.2 MeV (four energies). A stack of Al foils was placed as a degrader in front of ^{144}Sm targets to reduce the proton energy. The current information for the second setup was collected from the faraday cup placed at the end. A −500 V electron suppressor was used to suppress the secondary electrons coming out of the faraday cup. Proton energy after degradation and energy straggling were calculated using LISE ++ code [6]. γ-rays coming from ^{144}Sm(p, γ)^{145}Eu reaction used for cross section determination are listed in Table 1. Irradiations were done for 17−45 hours.

3 Results

After the irradiation, targets were cooled for an hour to a couple of days before measuring the γ-activity. The activity was measured using a CANBERRA HPGe detector having 40% relative efficiency and shielded by 7.5 cm thick lead bricks. The data acquisition was carried out using CANBERRA DSA1000 (a digital signal processing module) and a spectroscopy software suite named GENIE 2000. A typical γ-spectrum is shown in figure 2a. Cross sections



(a) (b)

Figure 2: (a) A typical γ-spectrum for ^{144}Sm(p, γ) reaction at ~5.9 MeV proton energy; (b) The measured cross sections compared with previously measured by Kinoshita *et. al* [7] and Hauser-Feshbach calculations obtained from TALYS 1.96 and NON-SMOKER database [8].

of the reaction were calculated using equation 1,

$$\sigma = \frac{C_\gamma \, \lambda}{\phi_b \, N_t \, I_\gamma \, \varepsilon_d \, (1 - e^{-\lambda t_{irr}})(e^{-\lambda t_{cool}} - e^{-\lambda (t_{cool} + t_{meas})})} \tag{1}$$

where C_γ and λ are the peak area count for E_γ and decay constant; ϕ_b, N_t are beam intensity and number of atoms in the target. I_γ, ε_d are γ-intensity and detector efficiency for E_γ; t_{irr}, the irradiation time; t_{cool}, the cooling time between the end of irradiation and the start of counting; t_{meas}, the counting time. Measured cross section values are compared with the theoretical predictions obtained from TALYS 1.96 (Figure 2b). The error in the measured cross sections reported in this article is calculated by considering all possible uncertainties, like counting statistics, target thickness, etc. Energy uncertainty (due to straggling) is significantly small due to the use of a 7 MeV proton instead of a 14 MeV beam like Kinoshita *et al.*

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