Measurement of ^{144}Sm(p, γ) cross section and S-factor calculation for astrophysical p-process study

Tanmoy Bar[1],* Dipali Basak[2], Lalit Kumar Sahoo[3,4],† Sukhendu Saha[3,4], Jagannath Datta[5], Sandipan Dasgupta[5], and Chinmay Basu[3,4]

[1]*Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi - 110067, INDIA*
[2]*Department of Physics, University of Calcutta, 92, Acharya Prafulla Chandra Rd, Rajabazar, Machuabazar, Kolkata-00009, INDIA*
[3]*Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700 064, INDIA*
[4]*Homi Bhabha National Institute, BARC Training School Complex, Anushaktinagar, Mumbai-400094, INDIA and*
[5]*Analytical Chemistry Division, Bhabha Atomic Research Centre; Variable Energy Cyclotron Centre, 1/AF Bidhannagar, Saltlake City, Kolkata - 700 064, INDIA*

Introduction

One of the fundamental goals of experimental nuclear astrophysics is to calculate the rates of nuclear reactions in stars under diverse astronomical scenarios. The reaction rates are calculated by measuring the cross sections at energy as close as feasible to the astrophysically significant ones (around the Gamow window). In many circumstances, the final nucleus of an astrophysical reaction is radioactive, therefore the cross-section can be estimated from offline measurement of the produced isotopes (activation method). Beyond Fe, there is a class of 35 neutron deficit nuclides, between ^{74}Se and ^{196}Hg, known as p-nuclei [1]. They are bypassed by the *s* and *r* neutron capture processes and are typically 10−1000 times less abundant than s and/or r isotopes in the solar system. The average abundance is 1% for lighter nuclei with $34 \leq Z \leq 50$, and 0.01−0.3% for medium and heavy nuclei with atomic numbers >50. The *p*-nuclei are mostly created through the $\gamma-$process, where either (γ, n), (γ, p), or (γ, α) reactions produced it. The $\gamma-$ process requires a high temperature to produce a high density of photons. The abundance of *p*-nuclei declines with increasing atomic number, however for neutron magic *p*-nuclei ^{92}Mo and ^{144}Sm, it is 14.52% and 3.08%, respectively. This study presents the ^{144}Sm(p,γ) reaction cross-section in the astrophysically significant energy range (T_9 =2 and 3). Previously, N. Kinoshita *et al.* [2] conducted this experiment in the 2.8−7.5 MeV energy regime utilising a 14 MeV proton beam and degrader foils. Their measurements had a substantial degree of uncertainty in proton energy. This study reduced energy uncertainty on cross-section measurements while also obtaining a new measurement around 2.6 MeV energy. The (p, γ) reaction cross-sections were analysed using the Hauser-Feshbach statistical model and satisfactory results were obtained.

*Electronic address: amitanmoybar@gmail.com
†Present affiliation: Computational Analysis Division, Bhabha Atomic Research Centre, Visakhapatnam - 531011, INDIA

1. Experiment

The experiment was carried out at VECC, Kolkata, utilising the stacked foil activation technique. This was followed by an offline $\gamma-$ray spectroscopy measurement using HPGe detectors. Several stacks were individually bombarded with a 7 MeV proton beam. Cross-sections were measured for proton energy ranging from 2.6 to 6.8 MeV. The energy of the proton beam was reduced using degrader foils. ^{144}Sm targets were irradiated for hours or days with a beam current of ∼1 μA. Copper foils put in some stacks were used to measure beam intensity.

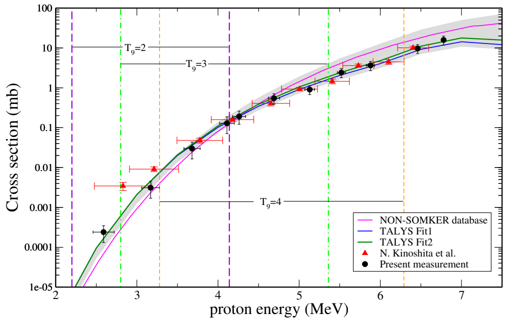

FIG. 1: The experimental cross-sections and Hauser-Feshbach calculations obtained from TALYS 1.96 and NON-SMOKER database are presented. Grey shaded area denotes the theoretically calculated cross-section from TALYS by varying different parameters. Gamow window corresponding to different stellar temperatures are also marked.

A. Target preparation

Irradiation targets were created from 67% isotopically enriched $^{144}Sm_2O_3$ powder using molecular deposition technique [3]. Targets of thickness between 100−350 μg/cm^2 was prepared for the experimental purposes.

B. Cross section and S-factor calculations

Cross-section of ^{144}Sm(p,γ)^{145}Eu (Q-value=3.315 MeV) reaction was measured for eleven different proton energies [4]. Monitor foil (natural Cu) was bombarded at four different energies to find beam intensity. Cross sections of the reaction were calculated using equation 1,

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

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. The reaction cross-section of ^{144}Sm(p, γ) has been measured in the center of mass energies between 2.6 and 6.8 MeV (FIG. 1). Astrophysical S-factor has been calculated for the above reaction in the measured energy range. S-factor is defined as,

TABLE I: Calculated S-factors from measured cross-sections.

Energy (E_{cm}) in MeV	S-factor ($\times 10^{10}$) in MeV-b
6.73 ± 0.02	0.198 ± 0.050
6.42 ± 0.03	0.206 ± 0.051
5.84 ± 0.05	0.227 ± 0.060
5.48 ± 0.05	0.295 ± 0.074
5.09 ± 0.06	0.318 ± 0.080
4.66 ± 0.07	0.567 ± 0.167
4.23 ± 0.08	0.728 ± 0.262
4.08 ± 0.09	0.816 ± 0.368
3.65 ± 0.10	0.952 ± 0.429
3.15 ± 0.11	1.020 ± 0.464
2.57 ± 0.13	2.542 ± 1.152

$$S(E_{cm}) = E_{cm}\ \sigma(E_{cm})\ e^{2\pi\eta} \quad (2)$$

Where $\sigma(E_{cm})$ is the measured cross-section at centre of mass energy, E_{cm}. The second term ($e^{2\pi\eta}$) removes the strong energy dependence of σ. It accounts for the s−wave Coulomb barrier transmission at low energies with η being the Sommerfeld parameter.

Acknowledgments

We acknowledge the kind support provided by the staffs of K130 Cyclotron at VECC, Kolkata and Mr. A. A. Mallick of Analytical Chemistry Division, BARC; VECC for his assistance during irradiation experiment.

References

[1] Arnould M and Goriely S Physics Reports **384** 1–84 (2003).

[2] N. Kinoshita *et al.*, Physical Review C **93** 025801 (2016).

[3] T. Bar *et al.,* Proceedings of the DAE-BRNS symposium on nuclear physics. V. **66** (2022).

[4] T. Bar *et al.* J. Phys. G: Nucl. Part. Phys. **51** 075104 16pp (2024).