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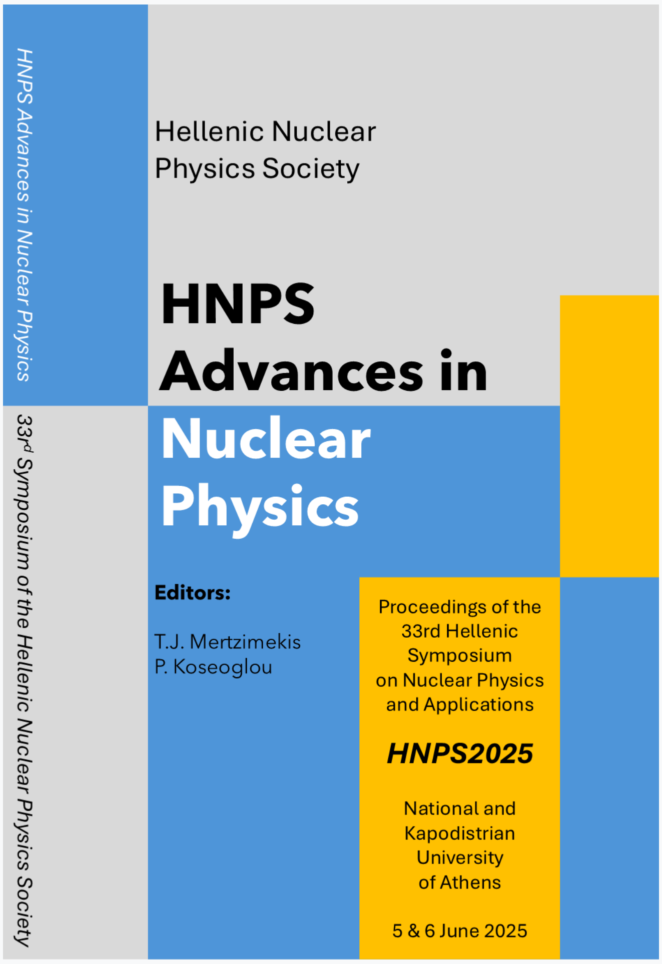

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ARTICLE

Estimation of cross section for proton-induced reactions in stable Yb isotopes at astrophysical energies.

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Abstract

In this work, we address a piece of an open problem in nuclear astrophysics: the synthesis of elements heavier than iron. While the formation of light elements up to iron is well understood, the origin and abundance of heavier nuclei, particularly those with atomic mass number $A > 56$, remain under investigation. Among the proposed mechanisms, proton-capture reactions play a central role for p-nuclei, especially in extreme astrophysical environments. In this study, we focus on the theoretical modeling of proton-capture reactions on stable isotopes of Ytterbium (Yb). Although Yb is not a p-nucleus itself, its isotopes (^{168}Yb to ^{176}Yb) are relevant to understanding nucleosynthesis pathways near the limits of stability. Due to the scarcity of experimental cross-section data in the energy range of 1–8 MeV, we have employed the Hauser-Feshbach model to simulate (p,γ) reactions and extract cross section values and the astrophysical S-factor, running TALYS v2.0 with various parameter options. Our main motivation is two-fold: first, to prepare the grounds for experimental work in this series of isotopes at such low energies, and second, improve our understanding of heavy element formation via the proton-capture process in an energy region, where the high Coulomb barrier works as an impeding factor.

Keywords: Yb isotopes; cross section; TALYS

1. Introduction

This study focuses on the investigation of reactions between protons and isotopes heavier than ironat astrophysically interesting energies [1]. Special focus is given on radiative proton-capture (p,γ) reactions, some of which are related to the astrophysical p-process [2]. In particular, we undertake detailed calculations to study the behavior of protons beams captured by stable ytterbium (Yb) isotopes. With the sole exception of the lightest stable Yb isotope with mass 168, the heavier Yb isotopes are not classified as “typical” p-nuclei [3]. However, as their mass increases, Yb isotopes ap-

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proach regions of the nuclear chart where the production of heavy nuclei in explosive astrophysical environments is enhanced, such as in Type Ia and Type II supernovae [4]. In addition, the profound scarcity of experimental data for proton-induced reactions with stable Yb [5] is a highly-motivating argument for both experimental and theoretical work.

The Hauser-Feshbach (HF) statistical model [1] is often involved in simulating reactions of a proton beam collision, at various energies, onto a target. In the present case, the main focus is on studying proton reaction with all stable Yb isotopes to calculate cross section rates at astrophysically relevant energies (1 to 8 MeV). Such energies are available at Tandem accelerator facilities, such IFIN-HH in Romania. For much lower proton energies (below 1 MeV), the astrophysical S factor is used [6], since cross sections values drop several order of magnitude.

Theoretical predictions of both the cross sections and the S-factor may provide valuable input for the design of future laboratory measurements and contribute to a better understanding of the role of (p,γ) reactions in the reaction networks at masses heavier than iron [7]. The results are expected to offer insights into the isotopic abundances of Yb in the universe and enhance the theoretical modeling in this mass region, which remains an open challenge. To the best of our knowledge, this is the first theoretical attempt to model proton-induced reactions with stable Yb isotopes [8].

2. Methodology

2.1 Simulation of the p-Yb reaction

As mentioned above, the calculations are based on the Hauser–Feshbach statistical model [1] by employing the TALYS v2.0 nuclear reaction code [9]. To explore the dependence of calculations on different parameters of the HF model, six (6) Nuclear Level Density (NLD) models [10], ten (10) γ-strength functions (γSF) [11], and two (2) Optical Model Potentials (OMP) [12] were considered, resulting in 120 unique combinations. It should be stressed that no particular weights have been considered for the parameters involved in the calculations producing the results discussed later. The reaction cross sections were computed for energies ranging from 1 to 8 MeV with a step of 20 keV, forming a dense 351-point energy grid.

Automation of all parameter runs was achieved through a Linux bash script, which executed all 120 model combinations sequentially. The main outputs provide the total reaction cross sections, $\sigma(E)$ in mb, from which the astrophysical S-factor, $S(E)$, is calculated in MeV·b (see §2.3).

2.2 Data Processing and Visualization

The TALYS output files were processed in a Python environment to extract the cross sections and generate plots for both the (p,γ) and competing (p,n) channels along with the scarce experimental data extracted from the EXFOR database [5, 13, 14]. A secondary script extracted the minimum and maximum cross-section values for each energy point, producing the shaded (unweighted) uncertainty bands shown in Figs. 1-2 to provide guidance for experimental design. Also, fits on the two dashed lines, demonstrating the two Optical models ($gprod - n$ for the production of γ particles using the Global Optical Model and $gprod - y$ for the production of γ particles using the Local Optical Model) was performed to offer a qualitative visual comparison of the deduced values. The Gamow window for 2–3 GK (vertical dashed lines) was included in each plot to identify the most astrophysically relevant energy regions.

2.3 Calculation of the Astrophysical S-Factor

The astrophysical S-factor, defined as [6]

$$S(E)\ [\mathrm{MeV\,b}] = E\ [\mathrm{MeV}]\ \sigma(E)\ [\mathrm{b}]\ e^{2\pi\eta} \tag{1}$$

was calculated from the reaction cross section results. $S(E)$ is often used to remove the strong energy dependence introduced by Coulomb barrier penetration and enable reliable extrapolation towards low energies (1–3 MeV), where both experimental and theoretical data are very scarce. The S-factor provides a smoother and more physically meaningful representation of the reaction probability as a function of energy [15]. The parameter η in Eq. (1) is the dimensionless *Sommerfeld parameter*, which accounts for the Coulomb repulsion between the interacting nuclei and is given by:

$$\eta = a\,Z_1 Z_2 \sqrt{\frac{\mu c^2}{2E}} \tag{2}$$

where a is the fine structure constant ($\approx 1/137$), Z_1 and Z_2 are the atomic numbers of the projectile and target nuclei, μ is their reduced mass (in MeV/c^2), c is the speed of light, and E is the center-of-mass energy of the reaction in MeV [16].

This procedure allows for the extraction of the astrophysical S-factor from the calculated cross sections $\sigma(E)$ and facilitates the comparison of different nuclear models at low energies. Furthermore, it enables extrapolation into the astrophysically relevant energy region, improving the predictive accuracy of the calculations and providing guidance for future experimental measurements of the ^{A}Yb(p,γ)$^{A+1}$Lu reactions.

3. Results and Discussion

The computational analysis of the radiative proton-capture (p,γ) and neutron-emission (p,n) reactions on the stable isotopes of ytterbium (Yb) was carried out over the energy range of 1–8 MeV using TALYS v2.0. The study focused on identifying the behavior of the reaction cross sections $\sigma(E)$ and the influence of different optical model potentials (Local and Global OMPs) within the Gamow energy window relevant to the p-process nucleosynthesis (T=2-3 GK). See Table 1 for details.

Table 1. Comparing cross section values generated by TALYS v2.0 vs. computed values calculated using the S-factor linear equation for the case of reactions with all stable Yb isotopes (energy variation is due to TALYS failure to produce xs values in low energy rates for some isotopes in order to calculate the S(E) factor).

Isotope	E (MeV)	$S(E)$ (MeV·b)	$\sigma(E)$ (b)-linear equation	$\sigma(E)$ (b)-TALYS v2.0
Yb-176	1.5	3.42448×10^{17}	7.07500×10^{-8}	0.00
	6.5	1.52980×10^{17}	3.96353×10^{4}	3.97723×10^{4}
Yb-174	1.5	3.64845×10^{16}	7.54640×10^{-9}	0.00
	6.5	2.54750×10^{16}	6.60391×10^{3}	6.60392×10^{3}
Yb-173	3.0	2.13086×10^{17}	2.99745×10^{-1}	2.43349×10^{-1}
	6.5	1.22002×10^{17}	2.94904×10^{4}	2.94904×10^{4}
Yb-172	2.7	3.55196×10^{17}	6.37693×10^{-2}	6.37693×10^{-2}
	6.5	1.22419×10^{17}	2.95926×10^{4}	2.95926×10^{4}
Yb-171	1.5	1.74909×10^{17}	3.62804×10^{-8}	0.00
	6.5	9.07777×10^{16}	2.35644×10^{4}	2.35644×10^{4}
Yb-170	1.5	2.11056×10^{17}	3.77511×10^{-8}	0.00
	6.5	1.01066×10^{17}	2.44333×10^{4}	2.44333×10^{4}
Yb-168	1.5	0.00	0.00	0.00
	6.5	8.96127×10^{16}	2.16663×10^{4}	2.16663×10^{4}

For the (p,γ) reactions, all isotopes displayed a general trend of smoothly increasing cross sections with energy, followed by a gradual or sharp decline near the threshold [5], where the competing (p,n) channel opens (see Figs. 1 and 2). The Local OMP predictions were consistently found within the range of maximum–minimum values obtained from all parameter combinations, demonstrating overall consistency of the model. However, significant discrepancies and uncertainties were observed at lower energies (below 3 MeV), where the theoretical models struggle to reproduce reliable results due to Coulomb barrier penetration effects and limited experimental constraints. The Hauser-Feshbach model seems to break down around 1-3 MeV for proton reactions with Yb isotopes. The Coulomb barrier suppresses the entrance channels that reside inside the Gamow window, while a sudden drop appears due to very low values of the calculated cross sections.

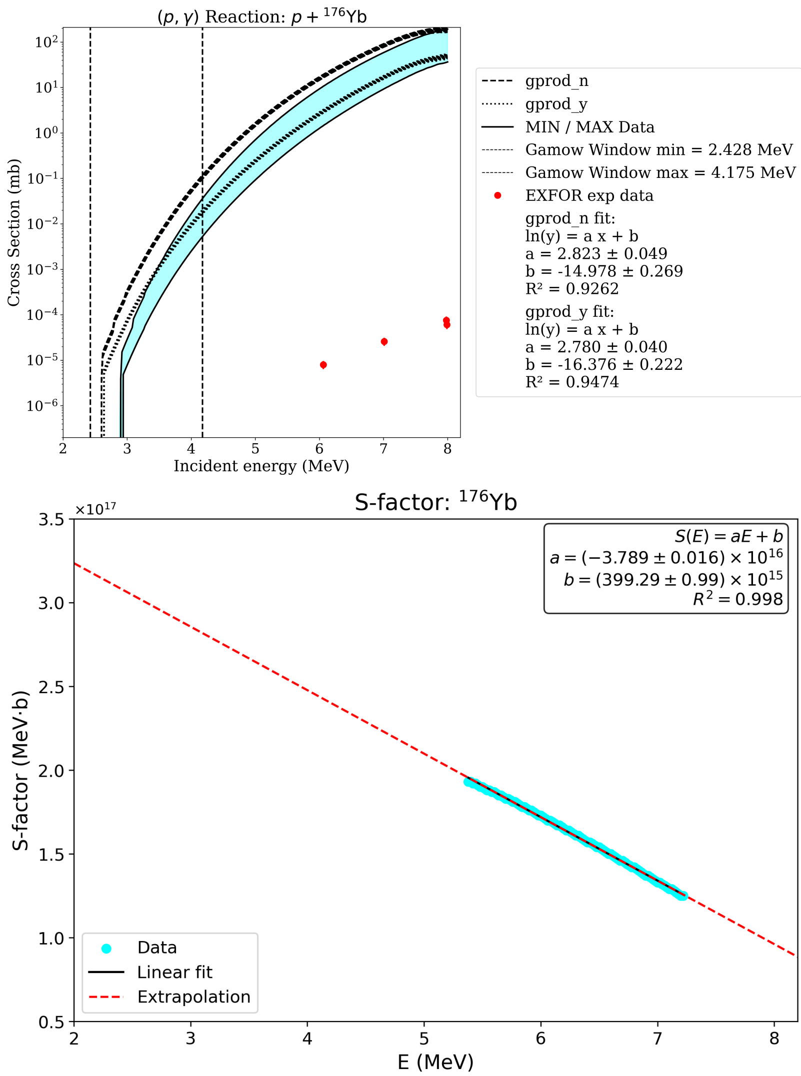

Figure 1. Reaction cross section and astrophysical $S(E)$ factor for the ^{176}Yb(p,γ) reaction.

In the case of (p,n) reactions, the cross sections increased steadily once the neutron-production channel became energetically accessible. The opening energy varied between isotopes, typically between 4.5 and 5.5 MeV. The maximum cross sections reached values on the order of 100 mb. Overall, the transition between (p,γ) and (p,n) channels followed the expected physical behavior, confirming the

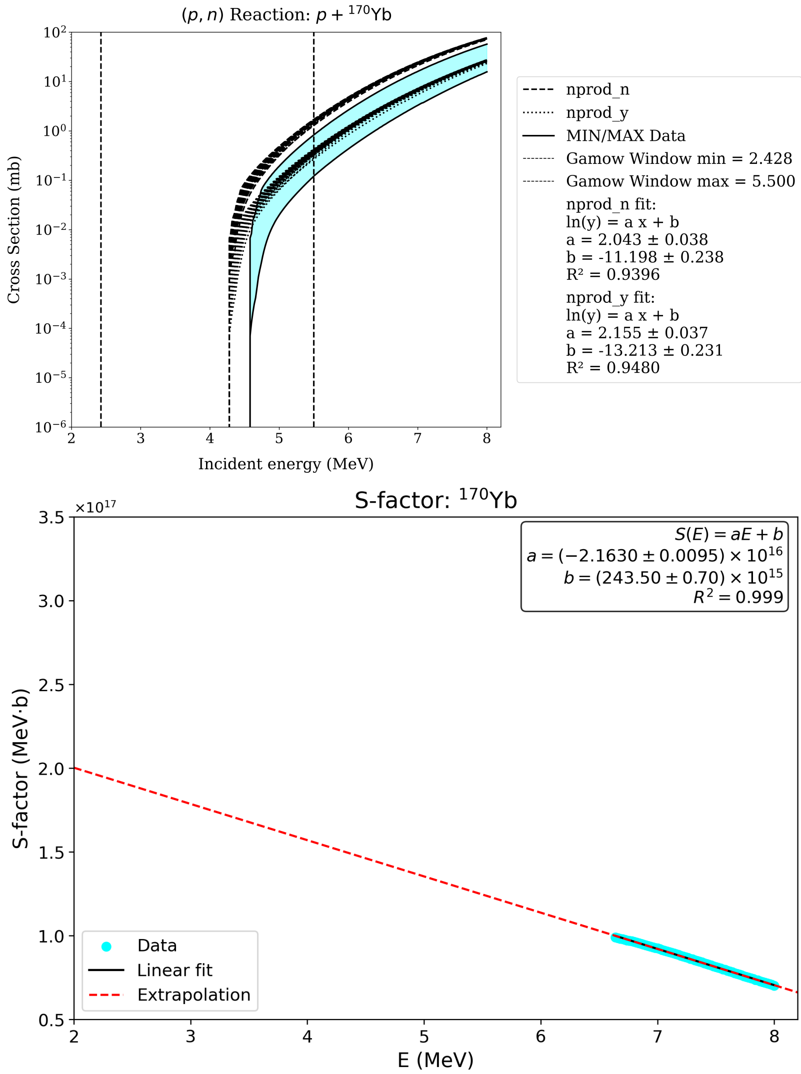

Figure 2. Reaction cross section and astrophysical $S(E)$ factor for the ^{170}Yb(p,n) reaction.

validity of the simulation approach and highlighting regions where future experimental measurements are most needed.

In addition, the S factor calculations using a linear model for extrapolation (qaudratic behavior becomes significant at $\approx$ 100 keV [15]) provide an opportunity to predict cross-section values near or inside the Gamow Window and at low energies where the TALYS v2.0 predictions become null.

4. Conclusion

This work contributes to the theoretical estimation of radiative proton-capture (p,γ) reaction cross sections by stable ytterbium isotopes in the mass range 168-176 at energies overlapping the astrophysically relevant Gamow window. In lieu of experimental measurements, the theoretical estimation with the HF model provides a first –and reliable to our humble opinion– set of values in support of future theoretical and experimental work.

The computed cross sections $\sigma(E)$ become significant above 5 MeV (10–100 μb), identifying this region as experimentally accessible. Competing (p,n) channels appear at similar energies, suggesting the need for detector shielding in future setups to avoid neutron damaging of the crystals. Overall, 120 parameter combinations of optical potentials, γ-strength functions, and nuclear level densities were employed, paving the way for more detailed studies of the parameter space via sensitivity analysis. The results are also consistent with the (limited) available experimental data, particularly for the ^{176}Yb(p,γ) reaction, measured by Pålsson *et al.* in the early 1980s [14].

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