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Re-Investigation of Cross Sections for (α, γ) Reactions on P-Nuclei ^{90}Zr, ^{121}Sb, ^{151}Eu, and ^{162}Er

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Abstract

Investigation of the cross sections for (α, γ) reactions for p-nuclei ^{90}Zr, ^{121}Sb, ^{151}Eu, and ^{162}Er was conducted by varying different α- Optical Model Potentials (OMPs) for a set of Level Density Model (LDM) and Radiative Strength Function (RSF). The calculations were performed within the framework of TALYS-1.96 code, with the primary inputs being the OMP, the LDM, and the RSF. We have fine-tuned the input models of TALYS-1.96 to regenerate the experimental data of cross sections. The present investigation was analyzed based on the root mean square error (rms). Good agreement was achieved for all nuclei under study using various model combinations. Based on the radiative capture cross sections, we have computed the rates which can be used as inputs to various astrophysical models.

Keywords: Cross Section, Talys-1.96, P-Nuclei, α- Optical Model Potentials and Radiative Strength Functions.

1. Introduction

Nuclei more massive than iron are formed in the stars through the slow neutron capture process (s- process) and the rapid neutron capture process (r- process). These processes differ by their time scales and the density of neutrons [1]. To accurately reproduce the observed abundances of the ^{90}Zr, ^{121}Sb, ^{151}Eu and ^{162}Er, neutron-deficient isotopes is a significant problem in the field of nuclear astrophysics. These p-nuclei are shielded by the valley of stability from production via the s- and r- neutron capture processes, which create the majority of isotopes heavier than iron. The p-nuclei must be produced through an alternative mechanism known as the p- process [2, 3]. They are not hypothesized to form directly from the s- and r- processes [4]. Presently, it is uncertain whether the p- process is composed of one astrophys ical scenario or multiple. Alternate processes, such as photodisintegrations in supernova environments, are thought to contribute to their formations [5]. Due to the limitations of current stellar evolution models the theoretical predictions of these nuclei remain under-accounted [6-8].

Gyürky et al. measured the cross sections for the ^{151}Eu (α, γ) reaction using the activation technique at energies between E_{cm} = (12 - 17) MeV [9]. Furthermore, they performed statistical model calculations and found that the predictions are overestimated by a factor of 2. Kiss et al. employed the activation technique to measure the cross sections for the reaction ^{162}Er (α, γ) at the astrophysically relevant energies of E_{cm} = (11.21 - 16.09) MeV [10]. Their investigated cross sections were in good agreement with the statistical predictions. Kelmar et al. measured the cross sections for the reaction ^{90}Zr (α, γ) using HECTOR and the γ-summing technique for the energies E_{cm} = (7.5 - 11.5) MeV [11]. Their measurements were complemented with the predictions of statistical models, and the parameter-adjusted results agreed with the measurements [12]. Korkulu et al. measured the cross sections for the ^{121}Sb (α, γ) reaction for astrophysically relevant energies E_{cm} = (9.74 - 15.48) MeV using the activation technique [11]. Their measurements were then compared with the statistical predictions that were found to be overestimated. Recently, Nguyen Nhu Le employed an α- optical model potential (OMP) that uses the double folding method (DFM) to achieve high accuracy for α particle absorption width [13, 14]. The effects of RSFs were studied on the cross sections of the p-nuclei ^{90}Zr, ^{121}Sb, ^{151}Eu, and ^{162}Er for the (α, γ) reactions. The study concluded that the empirical SMLO (SMLOg) and the global semi-microscopic (D1M-QRPAg) models regenerated the experimental data having rms < 0.2, whereas the HF-BCS model, the HFB-QRPA model, and the SMLO model had the rms values of 0.541, 0.460, and 0.325, respectively [15-20].

In the present investigation, we have analyzed whether changing the α- OMP for a fixed set of Level Density Model (LDM) and Radiative Strength Function (RSF) had any improvement on the agreement with the experimental data. The present analyses were performed within the framework of the statistical code TALYS-1.96 [21]. The TALYS-1.96 code is based on the Hauser-Feshbach theory, which generates cross sections by calculating the transmission coefficients in

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the entrance and all exit channels. The transmission coefficients for the emission of photons are calculated by the RSF while the rest are done by OMPs. The model combinations were fine-tuned to achieve the best fit with experiment. In the next sections, we have presented the discussions, and the conclusion is summarized.

2. Results and Discussions

The TALYS-1.96 code includes a vast range of nuclear models, and all reaction mechanisms encountered in the analysis and the prediction of light particle induced nuclear reactions [21]. The predictions from the code are employed in regions where the measurements are not available. The parameters of the code can also be fine-tuned for all reaction channels and energy ranges as we did in the present analysis. The α-OMPs that were employed in this work include Normal α potential, the α potential of McFadden and Satchler, the α potentials of Demetriou and Goriely, the α potentials of Avrigeanu et al. and the α potential of Nolte et al. [22-27]. The LDM and RSF were constrained to be the Constant Temperature Model (CTM), and the Kopecky-Uhl Lorentzian respectively [28, 29]. The agreement with the experimental data was evaluated through the calculation of rms, which has the form;

$$\mathrm{rms} = \sqrt{\frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{\mathrm{N}}(\sigma_{\mathrm{i}} - \sigma_{\mathrm{exp}})^2}.$$

The σ_{exp} were taken from Refs. [9, 10, 12, 15].

Fig. (1) depicts the cross sections for all p-nuclei under investigation for the different α- OMPs. The rms values were calculated for the suitable combinations. For the ^{90}Zr nucleus, the Normal α potential, the α potential of McFadden and Satchler, and the α potential of Demetriou and Goriely seemed to give the closest agreement. Their rms errors were 0.0468, 0.0495, and 0.0388 respectively. Based on the rms error, it was concluded that the α potential of Demetriou and Goriely provided the best fit with the experimental data. For the ^{121}Sb nucleus, only the α Potential of Avrigeanu et al. provided the best fit. Its calculated rms error with experiment was 0.0081, which agrees with the analysis performed by [16]. Similarly, for the ^{151}Eu nucleus, only the α Potential of Avrigeanu et al. provided the optimum fit. Its calculated rms error was 0.0391. Lastly, for the ^{162}Er nucleus, the Normal α potential, the α potential of McFadden and Satchler, and the α potential of Avrigeanu et al. seemed to give the closest agreement.

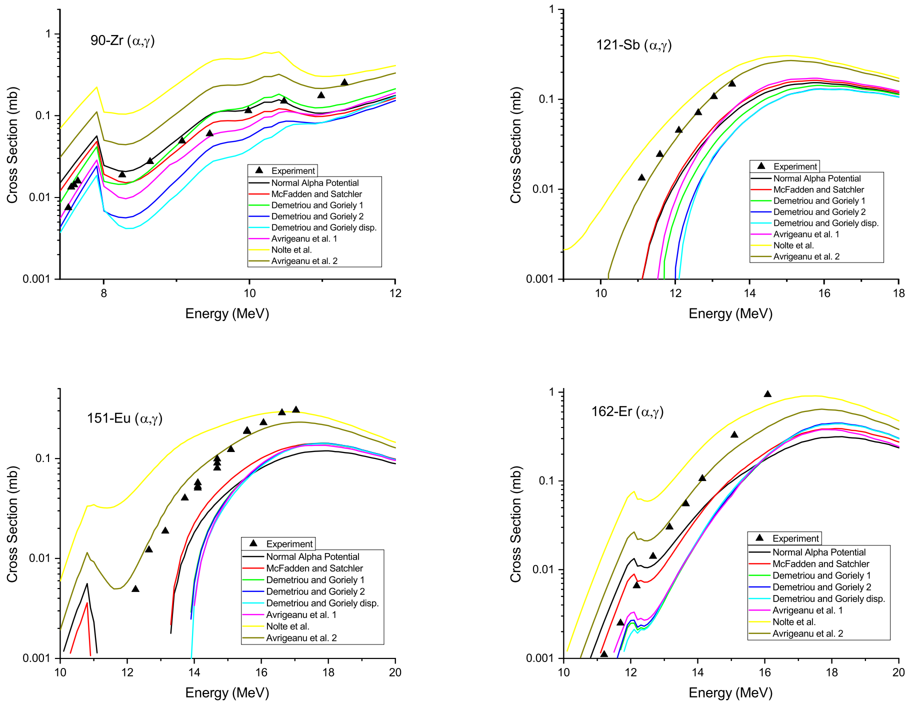

Figure 1: (a) ^{90}Zr (α, γ) (b) ^{121}Sb (α, γ) (c) ^{151}Eu (α, γ) (d) ^{162}Er (α, γ) Cross Sections Using the Different α- Optical Model Potentials.

Their rms errors were 0.2639, 0.2516, and 0.1796 respectively. Though the agreement in this case was not that good, the α potential of Avrigeanu et al. provided the best fit with the experimental data based on the least calculated rms.

Furthermore, we have computed the nuclear reaction rates using the model combinations with the least rms errors. The nuclear reaction rates are critical for the descriptions of stellar models. They are heavily dependent on the resonance position in the cross-section. The nuclear reaction rate for the α + X → Y + γ process was defined using;

$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi\mu(k_BT_9)^3}\right)^{1/2} \times \int_0^\infty \sigma(E)E\exp(-E/k_BT_9)dE, \qquad (1)$$

Where N_A represents Avogadro number, μ is the reduced mass of interacting system, T_9 is the core temperature of star taken in the unites of 10^9 K, k_B is the Boltzmann constant, σ(E) is reaction cross-section, v is the relative velocity and E is the collision energy calculated in the CM frame [30]. The computed rates are depicted in Table. (1) for the ^{90}Zr (α, γ), ^{121}Sb (α, γ), ^{151}Eu (α, γ) and ^{162}Er (α, γ) reactions. It was found that the at low temperatures, the rates for ^{162}Er (α, γ) were very small. This is because the Coulomb interaction between the ^{162}Er and α nuclei is very strong at those energies. The ^{90}Zr (α, γ) reaction rates are higher by a factor 3 at low temperatures, while at higher temperatures they are in good agreement with the rates mentioned in Ref. [11].

Table 1: The (α, γ) Radiative Capture Rates in Units of $cm^3mol^{-1}s^{-1}$.

T_9	^{90}Zr (α, γ)	^{121}Sb (α, γ)	^{151}Eu (α, γ)	^{162}Er (α, γ)
1.0	9.49185×10^{-22}	8.98182×10^{-25}	1.22492×10^{-29}	7.71741×10^{-32}
1.5	2.20741×10^{-15}	1.01835×10^{-17}	1.86465×10^{-21}	5.21422×10^{-23}
2.0	1.37988×10^{-11}	1.26652×10^{-13}	8.36736×10^{-17}	4.19066×10^{-18}
2.5	6.54734×10^{-9}	8.32267×10^{-11}	1.33387×10^{-13}	9.68449×10^{-15}
3.0	6.28672×10^{-7}	9.36787×10^{-9}	3.22245×10^{-11}	3.16523×10^{-12}
3.5	1.97841×10^{-5}	3.10674×10^{-7}	2.14616×10^{-9}	2.86746×10^{-10}
4.0	2.82513×10^{-4}	4.27475×10^{-6}	5.44315×10^{-8}	9.96778×10^{-9}
5.0	1.20896×10^{-2}	1.33620×10^{-4}	4.40841×10^{-6}	1.32198×10^{-6}
6.0	1.36041×10^{-1}	9.07311×10^{-4}	5.30786×10^{-5}	1.97065×10^{-5}
7.0	6.38845×10^{-1}	3.00254×10^{-3}	1.97751×10^{-4}	8.31794×10^{-5}
8.0	$1.61118 \times 10^{+0}$	7.71356×10^{-3}	4.07145×10^{-4}	1.91660×10^{-4}
9.0	$2.67290 \times 10^{+0}$	1.66841×10^{-2}	6.48769×10^{-4}	3.25774×10^{-4}
10	$3.49954 \times 10^{+0}$	2.98142×10^{-2}	9.09081×10^{-4}	4.63139×10^{-4}

3. Conclusion

The cross sections for the (α, γ) reactions on the p-nuclei including ^{90}Zr, ^{121}Sb, ^{151}Eu, and ^{162}Er were analyzed within the framework of TALYS-1.96 [21]. The calculations were performed by using the different α- Optical Model Potentials. The present investigation concluded that the α potential of Demetriou and Goriely produced the best fit for ^{90}Zr (α, γ) while the α potential of Avrigeanu et al. produced the optimum fits for ^{121}Sb (α, γ), ^{151}Eu (α, γ), and ^{162}Er (α, γ). Based on the total cross sections for the selected nuclear reactions, we have computed the radiative capture rates which show an agreement with the existing data.

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