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Investigation of Alpha-Induced Reactions on ^{107}Ag at Astrophysical Energies

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Abstract. Cross sections of the ^{107}Ag(α,γ)^{111}In and ^{107}Ag(α,n)^{110}In reactions have been measured with the activation method at effective center-of-mass energies between 7.79 MeV and 12.00 MeV close to the astrophysical energy range. The irradiation and counting of the ^{107}Ag targets was carried out at ATOMKI using the cyclotron accelerator and the low background counting facility, respectively. Cross section results are presented and compared with the predictions of Hauser-Feshbach statistical model calculations using the NON-SMOKER and TALYS-1.4 codes. In general, above 10 MeV, the model calculation are able to reproduce reasonably well the experimental data, but below 10 MeV, depending on some input parameters strong deviations are also found.

1. Introduction

The so-called astrophysical p process, which is responsible for production of about 35 rare nuclei along the proton-rich side of the stability line, is one of the least known among those processes which describe the synthesis of elements heavier than iron [1, 2, 3] The p process nucleosynthesis is modeled by using an extended nuclear reaction network, for which reaction rate information of thousands of neutron, proton and α-induced reactions as well as their inverse reactions is needed. Astrophysical reaction rates are mostly derived from theoretical cross sections owing to the lack of experimental data. On the other hand, experiments performed so far have shown that there are considerable differences between predictions and experimental cross sections [4, 5, 6]. In order to extend the experimental database for the astrophysical p process and to test the reliability of statistical model predictions in this mass range, cross sections of ^{107}Ag(α,γ)^{111}In and ^{107}Ag(α,n)^{110}In reactions have been measured with the activation method at effective center-of-mass energies between 7.79 MeV and 12.00 MeV, close to the astrophysical energy range (the Gamow window at 3.0 GK is between 5.83 MeV and 8.39 MeV).

2. Experimental Method

Since reaction products are radioactive and their half-lives are convenient, the activation method was used to determine the reaction cross sections. Detailed information about activation method can be found at reference [4].

Table 1. Decay parameters of reaction products taken from [7, 8]. Only the γ-transitions used for the analysis are listed.

Reaction	Half-life	E_γ (keV)	I_γ (%)
^{107}Ag$(\alpha,\gamma)^{111}$In	2.8047 ± 0.0004 d	171.28	90.7 ± 0.9
^{107}Ag$(\alpha$,n$)^{110g}$In	4.92 ± 0.08 h	641.68	26.0 ± 0.8
		937.16	68.4 ± 1.9
^{107}Ag$(\alpha$,n$)^{110m}$In	69.1 ± 0.5 min	2129.40	2.15 ± 0.03
		2211.33	1.74 ± 0.03

Natural Ag and isotopically enriched (99.50 %) ^{107}Ag targets were produced by evaporating onto high purity thin aluminum foils. Thickness of the targets were determined with weight measurement and varying between 410 μg/cm^2 and 1042 μg/cm^2. The targets were irradiated between 8.16 MeV and 12.50 MeV laboratory energies at the ATOMKI cyclotron accelerator. Because the cyclotron could not produce all beam energies directly, energies of $E_{Lab.}$ = 8.16, 8.51, 10.00, 10.50 MeV were obtained with an energy degrader foil. The thickness of the energy degrader foils was determined by the energy loss of the α particles emitted from ^{241}Am. The typical beam current was between 150 nA and 800 nA. During the irradiation, targets were monitored with a ion implanted Si detector placed into the target chamber at 165° relative to the beam direction and no target deterioration was observed.

After each irradiation, the targets were taken from the reaction chamber and placed into a low-background counting area to measure ^{111}In and ^{110}In activities, which are produced through the ^{107}Ag$(\alpha,\gamma)^{111}$In and ^{107}Ag$(\alpha$,n$)^{110}$In reactions, respectively. Depending on the count rate of reaction products the target was placed at 10 cm or 1 cm from the end cap of a HPGe detector having 100 % relative efficiency. A typical γ spectrum taken after 8.7 h irradiation with a 10 MeV α beam is shown in Fig. 1. The absolute efficiency calibration of the detection system was done at

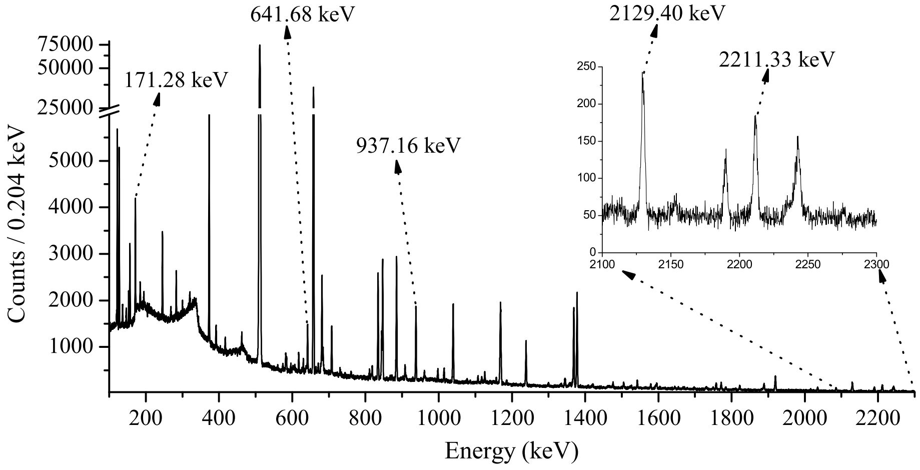

Figure 1. Activation γ spectrum taken after 8.7 h irradiation of a target with a 10 MeV α beam. The γ-lines used for the analysis are indicated in the spectrum. The other peaks are from either laboratory background or other γ-transitions (1 Channel=0.204 keV).

27 cm detector-target distance, where the coincidence-summing effect is negligible. Calibrated multiline ^{57}Co, ^{60}Co, ^{133}Ba, ^{152}Eu, ^{241}Am and single line ^{7}Be, ^{22}Na, ^{54}Mn, ^{60}Co, ^{65}Zn, and ^{137}Cs sources were used for the calibration. The efficiencies at the measurement distances 1 cm and 10 cm were determined by scaling the efficiencies obtained at 27 cm. Experimentally found coincidence correction factors were applied to the efficiency for each γ-line which was used for the analysis (see Table 1) [9].

The (α,n) reactions of ^{107}Ag populated the ground state ($T_{1/2}$ = 4.92 h) and isomeric state ($T_{1/2}$ = 69.1 min) of ^{110}In. The total cross section of the ^{107}Ag(α,n)^{110}In reaction was determined by taking the sum of the partial cross sections of ^{107}Ag(α,n)^{110g}In and ^{107}Ag(α,n)^{110m}In measured independently. Cross section of the ground and isomeric states were found by weighed average of the different gamma lines at Table 1.

3. Results and Discussion

The ^{107}Ag(α,γ)^{111}In and ^{107}Ag(α,n)^{110}In reaction cross sections have been measured at laboratory energies between 8.16 MeV and 12.50 MeV, which include a part of the astrophysically relevant energy range. Laboratory energies have been converted into effective center-of-mass energies ($E^{\text{eff}}_{\text{c.m.}}$) that correspond to beam energies in the target at which one-half of the yield for the full target thickness is obtained [10]. A comparison of the results with the theoretical calculation using NON-SMOKER [11, 12, 13] and TALYS-1.4 [14, 15] codes is shown in Fig. 2. Previous results from Baglin [16] and Stelson [17] also included in the figure. Two calculations with the NON-SMOKER code are shown, using level densities obtained with microscopic corrections from two different theoretical mass tables (FRDM [18] and ETFSI [19], see [20] for details) but the same optical α+nucleus potential of McFadden-Satchler [21]. In

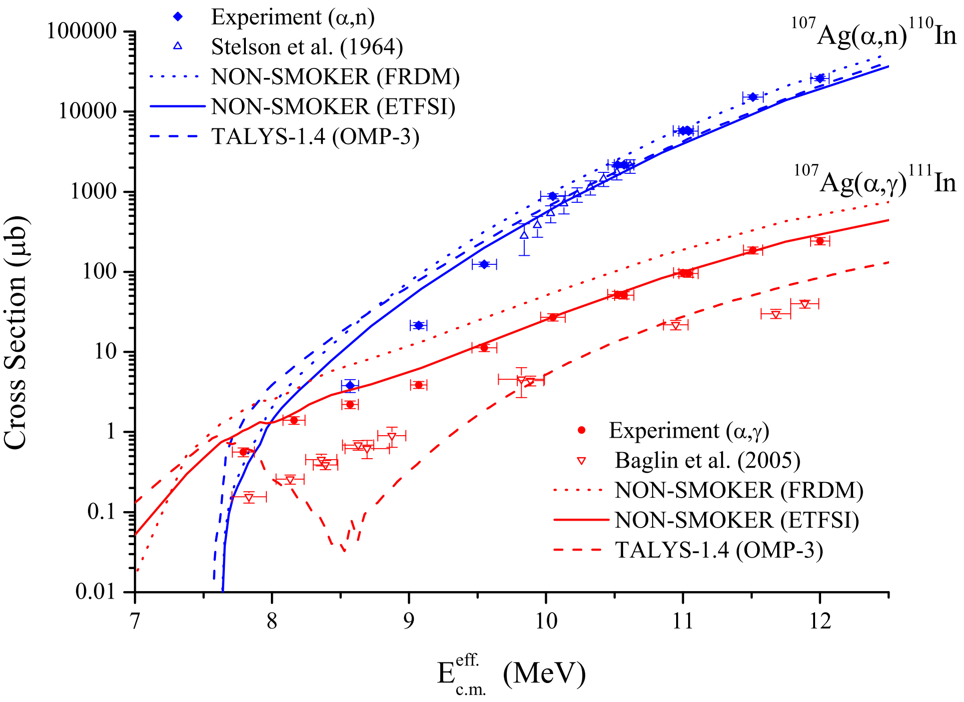

Figure 2. (Color online) Measured cross sections of the ^{107}Ag(α,γ)^{111}In and ^{107}Ag(α,n)^{110}In reactions compared to theory using the NON-SMOKER[11, 12, 13] and TALYS[14, 15] code. Previous results from Baglin [16] and Stelson [17] are also shown.

the TALYS-1.4 calculations, because the phenomenological model for the α break-up reaction is not stable in the low-energy region of the experiment [22], the adjustable parameter for the break-up process (Cbreak) in the (α,n) and (α,p) channels was set to zero and the double folding potential of Demetriou, Grama and Goriely (Table 1 in Ref. [23]) was used.

We conclude that for the ^{107}Ag$(\alpha,\gamma)^{111}$In reaction, experimental data are acceptably well described by the NON-SMOKER code when the ETFSI input is used for the calculation, on the other hand the calculation with the FRDM input overestimates the cross sections but the energy dependence is correctly described. These differences in the two calculations stem from the differences in the γ widths obtained with the different level densities. Above 10 MeV, the cross sections predicted with TALYS-1.4 are lower than the experimental results by factors of between 2.8 and 4.5. Below 10 MeV, the energy dependence of the cross section is strongly different and thus around 8.50 MeV the discrepancy between experimental and theoretical results increase up to factors of 60.

For the ^{107}Ag(α,n)^{110}In reaction, all theoretical calculations acceptably reproduce the measured cross sections above 10 MeV but in the same way all calculations overestimate the values below 10 MeV. The deviations from the experimental results are gradually increasing with decreasing energy.

Further details about the experiment and the full analysis will be presented in a forthcoming publication.

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