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(α,n) reaction cross section measurement on ^{92,94}Mo isotopes

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Summary. — The cross section of the ^{92,94}Mo(α,n)^{95,97}Ru reactions were measured recently at MTA Atomki using the activation method and thick targets to study the origin of the proton-rich nuclei heavier than iron. The experimental details of the cross section measurement are presented in this paper.

1. – Introduction

The bulk of stable isotopes heavier than iron are synthetized by neutron capture reactions in the s- [1] and r-processes [2]. However, on the proton-rich side of the valley of stability about 30-35 — mainly even-even — nuclei exists, which cannot be formed by neutron capture reactions. According to our knowledge these — so-called p — nuclei has been synthetized by photodisintegration reactions [3, 4] in the γ-process during the explosion of a type Ia or a core collapse supernovae. In the high temperature environment — T≈few GK — a sufficient amount of high energy γ-photons are available to induce (γ,n) reactions on seed nuclei previously produced by the s- and/or r-process. As the neutron separation energy increases along the (γ,n) path towards more neutron deficient isotopes (γ,p) or (γ,α) reactions may become faster [5, 6].

The modelling of the γ-process requires the use of reaction network calculations. A typical network involves thousands of reactions on more than two thousand mainly radioactive nuclei [5]. The predictive power of a γ-process model relies on astrophysical inputs — temperature, timescale, initial abundances etc. — and nuclear physics inputs. The necessary cross sections are usually taken from the Hausher-Feshbach (H-F) statistical model, which relies on nuclear inputs such as γ-strength functions, level densities and global optical model potentials (OMPs). Recently, consistent studies of γ-process nucleosynthesis became available, proving that the reaction flow is strongly sensitive to the (γ,α) rates [5]. The reliability of the used α-nucleus OMPs can be studied by measuring α-induced reaction cross sections [7-11]. To study the global OMPs, the cross section measurements of the ^{92,94}Mo(α,n)^{95,97}Ru reactions were carried out at Atomki using thick targets and the activation technique.

TABLE I. – *Properties of the investigated reactions.* [13, 14].

Isotope	^{92}Mo	^{94}Mo
Abundance	14.53 ± 0.30 %	9.15 ± 0.09 %
(α, n) product	^{95}Ru	^{97}Ru
Half-life	1.643 ± 0.013 h	2.83 ± 0.23 d
(α, n) threshold	9.39 MeV	8.28 MeV
Investigated energy range	10-13 MeV	8.7-13 MeV
Studied γ-transitions: $E_\gamma(I_\gamma)$	336.4 keV ($69.9 \pm 0.5\%$)	215.7 keV ($85.6 \pm 1.3\%$)
	626.8 keV ($17.8 \pm 0.5\%$)	324.5 keV ($10.79 \pm 0.17\%$)
	1096.8 keV ($20.9 \pm 1.0\%$)	

2. – Thick target yield measurement

The experiment was carried out at MTA Atomki, Debrecen, Hungary. Half mm thick natural isotopic composition molybdenum targets were irradiated using the K=20 cyclotron accelerator. This target thickness was proved to be enough — according to the stopping power calculations carried out by the SRIM code [12] — to stop completely the α-beam even at the highest energy which was $E_\alpha = 13$ MeV. Therefore, the measured thick target yield ($Y_{TT}(E)$) is the integral of the cross section ($\sigma(E)$) over the energy range between the initial beam energy (E_i) an the reaction threshold energy (E_{th}) taking into account the effective stopping power ($\epsilon_{eff}(E)$):

$$Y_{TT}(E) = \int_{E_{th}}^{E_i} \frac{\sigma(E)}{\epsilon_{eff}(E)} dE \tag{1}$$

The effective stopping power is derived by dividing the stopping power by the relative isotopic abundance of the target nuclei. The cross sections between E_1 and E_2 ($\sigma(E)$) are calculated by subtracting the neighboring yields. The stopping power ($\overline{\epsilon_{eff}}(E_2; E_1)$) between E_1 and E_2 is the average of the two effective stopping powers:

$$\sigma(E) = \frac{[Y_{TT}(E_2) - Y_{TT}(E_1)]\overline{\epsilon_{eff}}(E_2; E_1)}{E_2 - E_1} \tag{2}$$

3. – Activation technique

The experiment was carried out using the activation technique which is a two steps method where the irradiation and the counting phase is separated in time (and often in space). The method has some major advantages over the in-beam approach. Namely, the angular distribution of the emitted γ-rays is isotropic, the spectra are often simple and the background is usually lower than the one characterizing the in-beam approach. The drawback of the method is the limited applicability, the product must be radioactive with a reasonable half-life, typically between a few minutes and several days. Furthermore, its β-decay must be followed by the emission of at least one strong γ-transition.

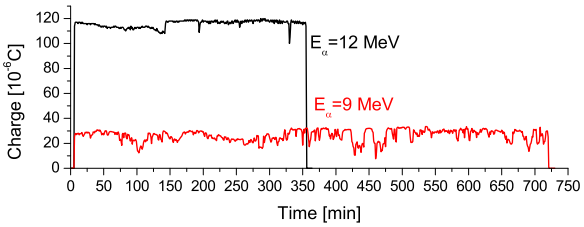

Fig. 1. – Two typical charge integrator histograms collected during α-irradiations. The total number of incident beam particles in the E_α = 12 MeV and E_α = 9 MeV irradiations were $1.28 \pm 0.04 \times 10^{17}$ and $5.78 \pm 0.17 \times 10^{16}$ α-particles, respectively.

3˙1. *Irradiation*. – The α-beam was produced by the K=20 cyclotron accelerator of Atomki. The cross section was measured between 8.7 and 13 MeV, this energy region was covered by 0.5 MeV steps. The duration of the irradiations varied between 3 and 21 hours. Typical beam currents were between 0.3-2 μA depending on the beam energy. To suppress the secondary electrons a -300 V suppression voltage was used at the entrance of the chamber. In each irradiation, the number of projectiles were derived using current measurement carried out in multichannel scaling mode. The current values were stored in every minute to monitor the beam stability. Typical current integrator histograms can be seen in Fig 1.

3˙2. γ-*counting*. – The use of natural isotopic composition molybdenum target offered the opportunity to measure several reactions simultaneously. The main properties of the investigated reactions are summarized in Table I. The number of produced ^{95}Ru and ^{97}Ru atoms were derived from the yield of the emitted γ-rays following the β-decay. The γ-counting was carried out using a 50% relative efficiency, coaxial HPGe detector equipped with 5 cm thick lead shielding. Two counting geometries were used during the measurement: the targets irradiated at and above E_α = 10.5 MeV were placed 21 cm distance from the detector endcap (far geometry). At energies below E_α = 10.5 MeV the activity of the samples were not sufficient for performing the γ-counting in far geometry, therefore, these countings were carried out using 5 cm source-detector endcap distance (close geometry). The absolute detector efficiency was measured before and after the experiment using calibrated ^{60}Co, ^{133}Ba, ^{137}Cs and ^{152}Eu sources. The efficiency measurement was carried out solely in far geometry where the probability of the so-called true coincidence summing effect is negligible. In order to derive the efficiencies in close geometry, strong ruthenium sources were produced using E_α= 13, 12, 10.5 and 10 MeV energy beams and the activity of these samples were measured in both geometries. The efficiency correction factor — that contains the effect of true coincidence summing in close geometry — was derived from the rate of yields in close and far geometry.

The γ-spectra were stored regularly to follow the decay of the ^{95}Ru and ^{97}Ru isotopes. In the first 8 hours, to follow the decay of ^{95}Ru, the spectra were saved in every 10 minutes and after that in every hour. Typical γ-spectra can be seen in Fig 2. The upper part shows a T_C = 10 min spectrum measured T_W = 1 hour after the irradiation, while the lower part is a T_C = 1 hour spectrum collected T_W = 100 hours after the end of the irradiation. The data analysis is in progress. The new cross section values will be compared to the literature data and predictions calculated using different open access OMPs.

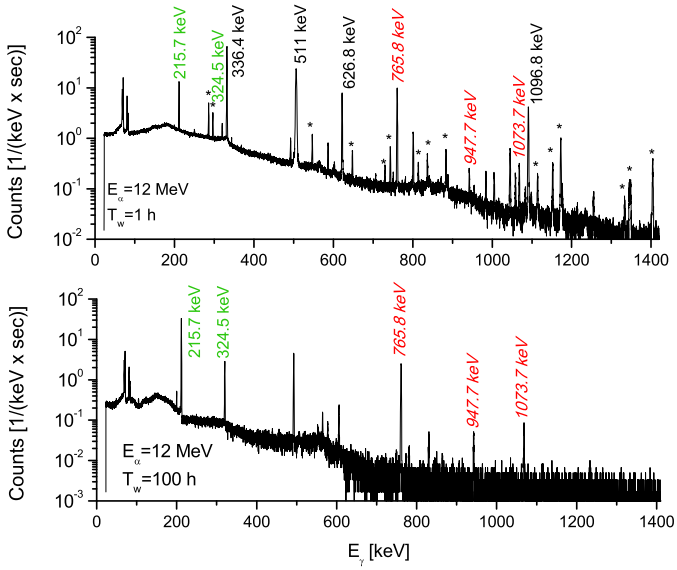

Fig. 2. – Typical γ-spectra taken 1 hour (T_W = 1 h) and 100 hours (T_W = 100 h) after irradiating a Mo target with E_α = 12.0 MeV beam. Transitions belonging to the decay of ^{95}Ru, ^{95}Tc (daughter of ^{95}Ru) and ^{97}Ru are indicated by black, red slanted and green letters, respectively (the stars represents the weaker transitions belonging to the decay of ^{95}Ru).

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