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Alpha induced reaction cross section measurements on ^{162}Er for the astrophysical γ process

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ABSTRACT

The cross sections of the ^{162}Er$(\alpha,\gamma)^{166}$Yb and ^{162}Er$(\alpha,\text{n})^{165}$Yb reactions have been measured for the first time. The radiative alpha capture reaction cross section was measured from $E_{c.m.} = 16.09$ MeV down to $E_{c.m.} = 11.21$ MeV, close to the astrophysically relevant region (which lies between 7.8 and 11.48 MeV at 3 GK stellar temperature). The ^{162}Er$(\alpha,\text{n})^{165}$Yb reaction was studied above the reaction threshold between $E_{c.m.} = 12.19$ and 16.09 MeV. The fact that the ^{162}Er$(\alpha,\gamma)^{166}$Yb cross sections were measured below the (α,n) threshold at first time in this mass region opens the opportunity to study directly the α-widths required for the determination of astrophysical reaction rates. The data clearly show that compound nucleus formation in this reaction proceeds differently than previously predicted.

1. Introduction

Low-energy (α,γ) and (α,n) measurements are of great interest for an improved determination of certain astrophysical reaction rates in γ-process nucleosynthesis. Photodisintegration of nuclei above Fe in explosive stellar processes (such as core-collapse supernovae or type Ia supernovae) is called γ-process [1]. While the bulk of naturally occurring heavy nuclei is produced in neutron-capture processes [2,3], about 35 proton-rich nuclides between Se and Hg are bypassed by these. Hypothetically, the γ-process could be responsible for 32 among these so-called p-nuclei, with other nucleosynthesis processes contributing to the remaining ones [4]. The main problem of the γ-process is the production of the isotopes ^{92,94}Mo and ^{96,98}Ru which cannot be synthesized in core-collapse events in an amount observed in the Solar System. There may be further problems at mass numbers $150 \leq A \leq 165$, although they are less pronounced. While the γ-process initially proceeds with (γ,n) reactions, at neutron numbers $N \geq 82$ (γ,α) reactions can compete at proton-rich isotopes and lead to a deflection or branching in the synthesis path.

Theoretical studies of the nuclear uncertainties in the γ-process make use of large reaction networks with mainly theoretical reaction rates (taken from the Hauser–Feshbach (H–F) model [5]). They have shown that the reaction flow for the production of heavy p-nuclei ($140 \leq A \leq 200$) is strongly sensitive to the (γ,α) photodisintegration rates [6,7]. Experimental information about the most important γ-induced reactions can be obtained from the study of the inverse capture reactions and using the detailed balance theorem. This approach is not only technically less challenging, but also provides more relevant astrophysical information than the direct study of the γ-induced reactions [8–10]. Recent experiments, however, indicate that the H–F predictions may overestimate the α-capture cross sections at low energies by factor of 3 to 20 and the difference between the predictions and the experimental results are increasing with decreasing energies [11–13] (it is worth to emphasize that the astrophysically relevant energy region, the so-called Gamow window, lies few MeV below the experimentally reachable energy region [23]). This would strongly impact the astrophysical reaction rates and through this affects the results of the γ-process reaction network studies. In summary, experimental data at low energies are urgently needed to confirm the path of the γ-process at mass numbers $150 \leq A \leq 165$.

The H–F cross section calculations are sensitive to different nuclear properties such as α-, neutron-, γ- and proton-widths [14]. At energies covered by the previous α-induced reaction studies

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Table 1
Available experimental database above the $A \approx 100$ mass region which can be used to constrain the alpha widths at low energies (taken from the KADoNiS database [22]), the astrophysically relevant energy region – calculated at $T_9 = 3$ GK – [23] is indicated, too.

Target nucleus	Gamow window [MeV]	(α,γ) energy range [MeV]	(α,n) energy range [MeV]	(α,n) threshold [MeV]	Reference
^{127}I	6.21–8.64	9.50–15.15	9.62–15.15	7.97	[24]
^{130}Ba	6.82–10.17	11.61–16.00	12.05–16.00	10.81	[25]
^{139}La	6.91–9.17	11.96–31.59	9.82–38.49	9.34	[26]
^{151}Eu	7.44–10.40	12.25–17.04	11.31–17.04	10.41	[27]
^{169}Tm	7.77–10.65	11.21–17.08	11.21–17.08	10.43	[13]
^{168}Yb	7.98–11.63	12.53–14.73	12.53–14.73	12.07	[28]
^{162}Er	7.80–11.48	11.21–16.09	12.18–16.09	11.98	present work

Table 2
Decay parameters of the $^{162}Er(\alpha,\gamma)^{166}Yb$ and $^{162}Er(\alpha,n)^{165}Yb$ (which decays by electron-capture to ^{165}Tm) reaction products taken from the literature [30,31] and calculated (marked with *) using the I(Tm K X-ray)/I(82.3 keV) ratio, available from [32,33].

Residual nucleus	Half-life [h]	Energy [keV]	Relative intensity [%]
^{166}Yb	56.7 ± 0.1	82.3	16.0 ± 0.7*
^{166}Tm	7.70 ± 0.03	80.6	11.5 ± 0.9
^{165}Tm	30.06 ± 0.03	242.9	35.5 ± 0.7
		297.4	12.71 ± 0.25

available above the $A \approx 100$ mass region (listed in Table 1), the cross section predictions are not only sensitive to the α-widths, but additionally to the γ- and neutron-widths. Therefore, the extrapolation of the experimental data toward the astrophysically relevant energy region could be questionable since the impact of the different sensitivities on the cross section predictions has to be disentangled. However, at even lower energies, the picture changes, the uncertainty in the astrophysical (γ,α) reaction rates is completely dominated by the uncertainty in the prediction of the subCoulomb α width, which is calculated using global alpha + nucleus optical potentials [15–19]. On one hand the parameters of the α-nucleus optical potential can be derived in elastic alpha scattering experiments at energies roughly 5–8 MeV above the Gamow window [20] and as a second step the parameters have to be extrapolated down to the astrophysically relevant energy region. On the other hand the subCoulomb α width can be probed in low-energy (α,γ) and (α,n) cross section measurements [12, 21]. Despite several attempts, the bulk of the present experimental data cannot be described consistently by any global α + nucleus optical potential, yet.

The present measurement of the $^{162}Er(\alpha,\gamma)^{166}Yb$ and $^{162}Er(\alpha,n)^{165}Yb$ reactions provides another important milestone in the test of the predicted α strengths at low energies. Not only consistently measured (α,γ) and (α,n) cross sections on the p-nucleus ^{162}Er become available but for the first time in this mass region (α,γ) cross sections also below the (α,n) threshold – where in the (α,γ) H–F predictions among all widths only the α-widths contribute – become available. This fact was found to be essential for an unambiguous study of the α width and its energy dependence.

2. Experimental approach

The cross section measurement was carried out at the Institute for Nuclear Research of the Hungarian Academy of Sciences (MTA Atomki) using the activation technique. The electron capture decay of the Yb reaction products is followed by γ-ray emission which was detected using a Low Energy Photon Spectrometer (LEPS). The decay parameters of the investigated reactions are summarized in Table 2. In the next paragraphs a detailed description on the experiment can be found.

The targets were made by reductive vacuum evaporation of Er_2O_3 powder enriched to 25.8% in ^{162}Er onto 2 μm thick, high purity Al foils. The Er_2O_3 powder was mixed with Zr powder and placed into a C crucible heated by electron beam. The absolute target thicknesses, the target impurities and the Zr contamination – similar to [13] – were determined using the PIXE technique [29] and by X-ray fluorescence spectroscopy. The target thicknesses were found to be between 114 and 188 μg/cm^2 and the level of the Zr contamination was always below 4 atom%. A typical PIXE spectrum can be seen in Fig. 1.

The Er targets were then irradiated with α beams from the MGC cyclotron of MTA Atomki. The energy of the α beam was between $E_{lab} = 11.5$ MeV and 16.5 MeV, this energy range was scanned with energy steps of 0.5 MeV–1.0 MeV using beam currents of typically 2 μA. After the beam-defining aperture, the chamber was insulated and a secondary electron suppression voltage of -300 V was applied at the entrance of the chamber. The number of incident α particles in each irradiation was between 3.9×10^{17} and 6.1×10^{17}. After the irradiations, $T_{waiting} = 0.25$ h waiting time was used in order to let short-lived activities, which would impact the quality of the measurement, decay. The duration of the γ-countings were about 150–160 h in the case of each irradiation. To determine the $^{162}Er(\alpha,\gamma)^{166}Yb$ reaction cross section the yield of the 82.3 keV transition was measured. Furthermore, the ^{166}Tm nucleus, the daughter of the produced unstable ^{166}Yb, decays by electron capture to ^{166}Er with emission of 80.6 keV γ-ray, which was also used to determine the radiative α capture cross section. Since the half-life of ^{165}Yb, produced by the $^{162}Er(\alpha,n)$ reaction, is relatively short, to determine the (α,n) cross section on ^{162}Er, the decay of its daughter (^{165}Tm nucleus) was investigated. A typical off-line γ spectrum can be seen in Fig. 2.

The uncertainty of the relative intensity of the 82.3 keV gamma transition is missing in [30]. In [32,33] the I(Tm K X-ray)/I(82.3 keV) ratio is given (8.68 ± 0.21 and 8.17 ± 0.23, respectively), the weighted average of these data (8.44 ± 0.27) together with the known X-ray intensities taken from [30] were used to calculate the value given in Table 2. The agreement between the cross sections based on the counting of the 82.3 keV and the 80.6 keV γ rays where always within 3.4%.

The low yields encountered in the present work necessitated the use of short source-to-detector distances for the γ-countings. The distance between the activated target and the Be window of the LEPS was 1 cm, the detector efficiencies had to be known in this geometry with high precision. For this purpose the following procedure was used: first the absolute detector efficiency was measured in far geometry: at 15 cm distance from the surface of the detector, using calibrated ^{57}Co, ^{133}Ba, ^{152}Eu, and ^{241}Am sources. Since the calibration sources (especially ^{133}Ba, ^{152}Eu) emit multiple γ-radiations from cascade transitions, in close geometry