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Determining reaction cross sections via characteristic X-ray detection: α-induced reactions on ^{169}Tm for the astrophysical γ-process

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ABSTRACT

The cross sections of the $^{169}\text{Tm}(\alpha,\gamma)^{173}\text{Lu}$ and $^{169}\text{Tm}(\alpha,n)^{172}\text{Lu}$ reactions have been measured first time using a new method, by detecting the characteristic X-ray radiation following the electron capture-decay of ^{172,173}Lu. Despite the relatively long half-life of the reaction products ($T_{1/2} = 500$ and 6.7 days, respectively) it was possible to measure the cross section of the $^{169}\text{Tm}(\alpha,\gamma)^{173}\text{Lu}$ reaction close to the Gamow window ($T_9 = 3.5$ GK), between $E_{\text{c.m.}} = 13.16$ and 17.08 MeV. The $^{169}\text{Tm}(\alpha,n)^{172}\text{Lu}$ reaction cross section was measured from $E_{\text{c.m.}} = 11.21$ MeV up to $E_{\text{c.m.}} = 17.08$ MeV. The experimental results have been compared to theoretical predictions.

1. Introduction

In stellar nucleosynthesis involving charged particles two probability distributions are playing crucial role: the Coulomb penetration probability and the Maxwell–Boltzmann energy distribution. The first strongly increases with increasing particle energy, but at a given temperature the probability of a particle having high energy falls off rapidly, following the Maxwell–Boltzmann distribution. The Coulomb penetration probability folded with the Maxwell–Boltzmann distribution forms the so-called Gamow peak, and the nuclear reactions are occurring in this narrow energy window [1,2]. In order to provide reliable nuclear data for the astrophysical calculations, the experiments have to be performed in the Gamow window or at energies as close as possible. At higher burning temperatures this energy window can be shifted up to higher energies, however, it remains mostly well below the Coulomb barrier, making it hard or even impossible to perform experiments at astrophysically relevant energies [1]. Here – since experimental data is missing in the most relevant mass range for the so-called astrophysical γ-process, too – we propose a new experimental approach to measure the cross sections of important nuclear reactions.

In order to understand the synthesis of the so-called p nuclei – the rare proton rich isotopes between ^{74}Se and ^{196}Hg [3] – experimental data at sub-Coulomb energies are particularly important. Despite the tremendous experimental and theoretical efforts of recent years, the synthesis of the p nuclei is still one of the least known processes of nucleosynthesis. It is generally accepted, however, that the main stellar mechanism synthesizing these nuclei – the so-called γ-process – is initiated by (γ,n) photodisintegration reactions on preexisting more neutron-rich seed nuclei. As the neutron separation energy increases along the (γ,n) path towards more neutron deficient isotopes, (γ,p) or (γ,α) reactions become faster and process the material towards lower masses [4–6]. Recently, consistent studies of the nucleosynthesis of the p nuclei become available, employing theoretical reaction rates in large reaction networks [5,6], proving that in the case of the production of the heavy p nuclei ($140 \leqslant A \leqslant 200$) the reaction flow is strongly sensitive to the (γ,α) photodisintegration rates. If those reaction rates are high, more material will contribute to the synthesis of lower mass p isotopes. On the other hand, if the reaction rates are lower, processing toward lower atomic numbers is weaker, resulting in a relative enrichment in the higher mass p isotopes such

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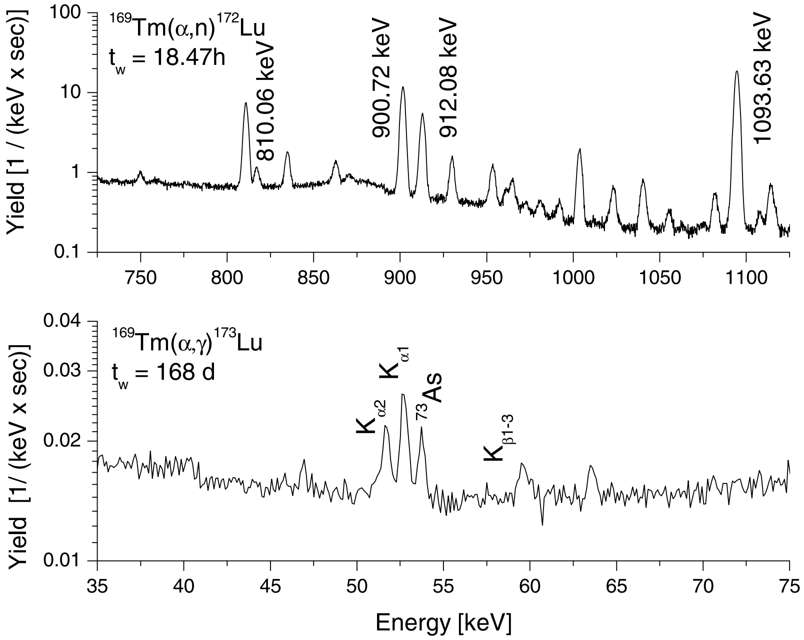

Fig. 1. Off-line γ- (upper panel) and characteristic X-ray (lower panel) spectra normalized to the length of the countings, taken after irradiating a ^{169}Tm target with 15.5 MeV α beam. The γ-lines used to measure the cross section of the $^{169}\mathrm{Tm}(\alpha,n)$ reaction and the characteristic X-ray radiation used to determine the $^{169}\mathrm{Tm}(\alpha,\gamma)$ reaction cross section are marked.

Table 1
Existing experimental (α,γ) database relevant for the astrophysical γ-process measured via activation method and γ-counting in the $A \geqslant 100$ region. The target nuclei, the half-lives of the reaction products, the Gamow windows [2] and the lowest energies measured (E_{min}) are given.

Target nucleus	Half-life [d]	Gamow window [MeV] ($T_9 = 3.5$ GK)	E_{min} [MeV]	Ref.
^{106}Cd	0.17	6.6–10.1	7.57	[13]
^{112}Sn	0.10	6.8–10.7	9.97	[14,15]
^{113}In	0.12	6.5–9.4	8.66	[16]
^{117}Sn	154	6.1–9.6	11.9	[17]
^{197}Au	3.05	8.5–11.7	17.5	[19]
^{169}Tm	500.5	8.2–11.3	13.2	this work

as ^{174}Hf, ^{180}W, and ^{190}Pt [6]. Consequently, to reproduce the path of the γ-process, experimental data is highly needed in this mass range.

2. Experimental approaches used in γ-process studies

In principle, photodisintegration cross sections can be determined directly by photon induced reaction studies [7]. However, in such an experiment the target nucleus is always in its ground state, whereas in stellar environments thermally populated excited states also contribute to the reaction rate leading to large corrections of the ground state rate which can only be modeled theoretically [8]. It has been shown that the influence of thermal population is much less pronounced in capture reactions and therefore it is advantageous to measure in the direction of capture and convert the measured rate to the rate of the inverse reaction by applying the principle of detailed balance [9,10]. Recently, several (α,γ) cross sections around $A \approx 100$ have been measured using the activation method [11–17] (see Table 1). Above the $A \approx 100$ mass region, however, there are practically no experimental (α,γ) data below the Coulomb barrier except the $^{144}\mathrm{Sm}(\alpha,\gamma)^{148}\mathrm{Gd}$ reaction [18]. The results of this latter experiment (using a method being limited by the fact that the yield of emitted α-particles had to be measured) showed that there are large discrepancies between the experimental results and theoretical predictions [18].

Though the activation method proves to be successful to measure α-induced cross sections it has numerous limitations which can be sorted into two groups (physical and technical limitations):

(1) In order to have reasonable count rates, reactions producing nuclei with long half-life (more than few days) were typically excluded. Furthermore, the product nuclei must decay via the emission of at least one high intensity (typically 70–97%) γ transition.

(2) A detector with a good signal-to-noise ratio is necessary for going to low energies. A high efficiency detector must be used to compensate the low cross sections, long half-lives or unfavorable γ-branching ratios. The laboratory background can be reduced using lead shielding but the beam-induced background on the impurities of the target and/or the backing will still be present. Furthermore, if the reaction product decays via γ cascades, the true coincidence summing effect has to be taken into account.

In this work the cross sections of the $^{169}\mathrm{Tm}(\alpha,\gamma)^{173}\mathrm{Lu}$ and $^{169}\mathrm{Tm}(\alpha,n)^{172}\mathrm{Lu}$ reactions have been measured, by detecting the characteristic $K_{\alpha 1-2}$ X-ray lines following the electron capture-decay of produced lutetium isotopes. It has to be realized that unstable nuclei above the mass $A \approx 150$ on the proton-rich side close to the valley of stability typically decay by electron capture. Such an electron capture is usually followed by X-ray emission. The characteristics X-ray counting approach has numerous advantages: the relative intensities are high since the electron capture is followed dominantly by the emission of either a $K_{\alpha 1}$ or a $K_{\alpha 2}$ X-ray (the probability of Auger electron or K_β X-ray emission are typically an order of magnitude smaller). Furthermore, after the decay of one product nucleus only one K_α characteristic X-ray is emitted and consequently the target can be put close to the surface of the detector the summing effect is not present.

To measure these X-ray lines a so-called LEPS (Low Energy Photon Spectrometer) detector – consisting of a thin germanium crystal with large surface and a thin entrance window – was used. This detector has high efficiency for the K_α lines and insensitive to the high energy γ-s of the background. Consequently – compared to a standard shielded HPGe detector – the observable minimum counting rates were orders of magnitude smaller (see Fig. 1). This way, despite the relatively long half-life of the re-