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α-induced reaction cross section measurements on ^{197}Au

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Abstract.
The γ-process is responsible for creating the majority of the isotopes of heavier elements on the proton rich side of the valley of stability. The γ-process simulations fail to reproduce the measured solar system abundance of these isotopes. The problem can lie in the not well known astrophysical scenarios where the process takes place, or in the not sufficiently known nuclear physics input. To improve the latter part, α-induced reaction cross section measurements on ^{197}Au were carried out at Atomki. With this dataset new experimental information will become available, which can be later used as validation of the theoretical cross section calculations used in the γ-process simulations.

1 Introduction

The majority of the nuclei beyond iron are produced by neutron capture reactions in the s- and r-processes [1]. There are a few dozens of isotopes on the proton rich side of the valley of stability which cannot be produced by these processes. Those are the so-called p-nuclei [2] mainly produced via the γ-process [3], which is a series of photo-emission of neutrons and charged particles converting the pre-existing s- and r-process seed nuclei. In the γ-process network the charged particle photo-emissions occur mostly on unstable nuclei, thus the network calculations cannot use direct experimental reaction rate values. These rates are usually derived from Hauser-Feshbach statistical model [4] calculations. The input parameters of these calculations have to be validated. To maximize the experimental constraint on the stellar rate of the photodisintegration reactions, those should be derived from the inverse radiative capture reaction cross sections [5]. The experimental data of α-capture reactions in the relevant energy region are however still scarce [6].

In this work we present a new experimental campaign targeting α-induced reaction cross section measurements on ^{197}Au close to the astrophysically relevant energy region.

2 Reactions to be investigated

Beside the radiative capture on ^{197}Au, the (α,n) and (α,2n) reactions take also place in the investigated energy range of $E_\alpha = 14 - 20$ MeV. All the three reaction channels lead to radioactive nuclei with half-lives ranging from a few hours to a few days (see table 1.), thus can be investigated by the activation technique.

The ^{197}Au(α,2n)^{199}Tl and ^{197}Au(α,n)^{200}Tl reaction cross sections were determined by counting the γ-rays released during the decay of the reaction products (see table 1.). These cross sections were measured by many groups mostly at higher energies e.g. [10]. The ^{197}Au(α,γ)^{201}Tl reaction was

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Table 1. α-induced reactions on ^{197}Au and decay parameters of the reaction products [7–9].

Reaction	(α,2n)		(α,n)		(α,γ)	
Threshold	17.14 MeV		9.94 MeV		1.56 MeV	
Product	^{199}Tl		^{200}Tl		^{201}Tl	
Half-life	7.42 ± 0.08 h		26.1 ± 0.1 h		73.01 ± 0.04 h	
	E / keV	I / %	E / keV	I / %	E / keV	I / %
X-ray	70.82	45.5 ± 2.5	70.82	40.4 ± 1.7	70.82	44.6 ± 0.6
γ-rays	158.4	5.0 ± 0.5	367.9	87.0	167.4	10.00 ± 0.06
	208.2	12.3 ± 1.3	579.3	13.7 ± 1.2		
	247.3	9.3 ± 1.0	828.3	10.8 ± 1.0		
	455.5	12.4 ± 1.4	1205.6	30 ± 3		

measured so far down to E_α = 17.9 MeV [10] by counting the only one intense γ-ray of the reaction product (see table 1.), well above the astrophysically relevant energy region of 7 − 11 MeV [11].

3 Experimental details

The α-induced reactions were investigated in the energy range of E_α = 14 − 20 MeV, with two types of targets. For the energies above the (α,2n) reaction threshold 0.1 − 0.3 μm thick gold layers evaporated on thin aluminium foils were used. The foil with 0.6 cm radius was placed at 4 cm distance from the evaporation boat, thus the evaporated layer assumed to be uniform within 1% which was considered in the thickness uncertainty. The thickness of the gold layers were measured by weighting the aluminium foil before and after the evaporation. For the lower energies self supporting gold foils of 0.6 − 0.8 μm thickness were used to have increased number of target atoms. The thickness of these foils was determined by measuring the energy loss of α-particles from a triple isotope α-source. From the measured energy loss, the thickness was determined using the SRIM [12] tables. Additionally, the thickness and uniformity of all targets will be determined via PIXE and RBS methods.

The irradiations were done at the cyclotron of Atomki. After the beam defining aperture and a secondary electron suppressor the whole irradiation chamber was electrically isolated from beamline to allow the beam current measurement by charge integration. Typical irradiation length was 24 − 28 hours with an α^{++} current of 1.0 − 2.5 μA.

After the irradiations the target was transported to a LEPS (low energy photon spectrometer) detector. This kind of HPGe detector is equipped with a thin germanium crystal having better resolution for low energy γ-rays and X-rays besides lower efficiency for disturbing high energy background. The detector is placed in a 4π shielding consisting of copper, cadmium and lead layers to suppress the environmental background [13]. For the countings 3 cm sample to detector end-cap distance was used. The detector efficiency calibration was done with calibrated multi-line gamma sources at 10 cm distance, where the true coincidence summing is negligible. Then the close distance efficiency was determined by counting a sample irradiated with 19.5 MeV α-beam in both geometry. A scaling factor was derived between the two geometries which includes the correction for true-coincidence summing-effect, and used later in the analysis.

The γ-ray from the decay of ^{201}Tl was only visible above 17.5 MeV in our case, because of the very intense 367.9 keV γ-line of the (α,n) reaction product. Below this energy the ^{197}Au(α,γ)^{201}Tl cross section was determined by X-ray counting. Although all the reaction products releases the same X-rays, the contribution from ^{199}Tl and ^{200}Tl can be well estimated from their known activity measured by their γ-rays, and than that can be subtracted. To get a measurable signal after the subtraction more than 4 half-life of ^{201}Tl should elapse, but thanks to the higher X-ray branching (see table 1.) the signal is still visible (see figure 1).

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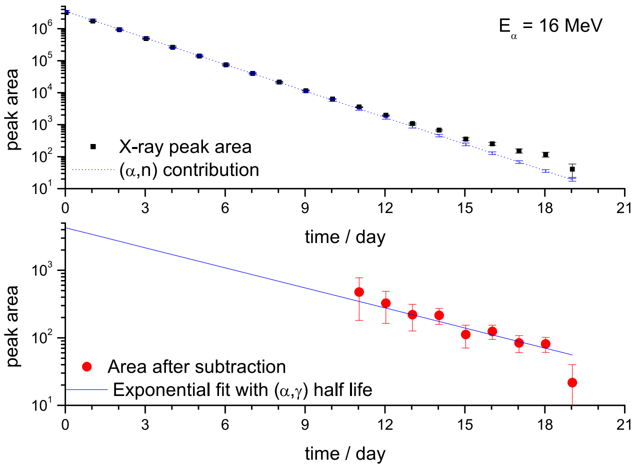

Figure 1. Example X-ray decay curves. In the upper panel the black dots indicate the measured X-ray peak area in one day. The blue dashed line with error bars is the calculated contribution from the ^{200}Tl with known activity.
The lower panel shows the X-ray peak area after subtraction. Detectable signal can be seen after 10 days, and the signal is still visible until the 19th day. These nine points were fitted by an exponential with the known half life of ^{201}Tl, thus the activated target atoms at the end of the irradiation was determined.

4 Outlook

As can be seen in figure 1. the measurement is feasible at beam energy of 16MeV, which is already closer to the astrophysically relevant energy region than any previous investigations. Already a few hundred nb cross section has been successfully measured, one order of magnitude lower than the previous $4 \pm 1\,\mu$b [10]. Knowing the laboratory background of the LEPS detector and the measured count rates, an additional factor of $10 - 30$ lower (α,γ) cross section is foreseen to be measurable. Regarding the $(\alpha$,n) cross section, it is anticipated to be measured at lower energies with higher precision as the most recent investigation by Basunia *et al* [10]. The future comparison of the results with statistical model calculation will give an information about the goodness of the used alpha-nucleus optical model potential.

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