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TARGET CHARACTERIZATION FOR ASTROPHYSICAL γ PROCESS RELATED EXPERIMENTS BY PIXE

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Abstract

The stable proton rich heavy nuclei above Fe are the so-called p nuclei. For an improved modeling of the synthesis of p isotopes, experimental low energy charged-particle induced reaction cross sections are needed. To provide solid ground for the nucleosynthesis calculations, series of proton- and alpha capture cross sections on p isotopes were measured in recent years at Atomki using the activation technique. The necessary targets were produced using vacuum evaporation. The absolute target thicknesses, their uniformity and the possible contaminants were determined with very high precision by PIXE technique.

I. Introduction

Despite of the synthesis of the light nuclei where charged particles are playing a particularly important role [1], two neutron capture processes, the s- and r- process [2, 3] are required to produce the bulk of naturally occurring nuclides above Fe. However, these two neutron capture processes are unable to create the p nuclei: the 35 neutron-deficient, stable, rare isotopes between ^{74}Se and ^{196}Hg [4]. The suggested production mechanism for these nuclei is the so-called γ process. This process is the photodisintegration of stable nuclei either in the outer shells of massive stars during a core-collapse supernova explosion [5] or during the explosion of a White Dwarf

[6]. The γ-process commences at 2-3 GK by sequences of (γ,n) reactions. These reactions are replaced by (γ,p) and (γ, α) reactions when reaching sufficiently neutron deficient nuclides in an isotopic chain. The whole process lasts only about 1-2 seconds, before the environment becomes too cool for the photodisintegrations. However, based solely on this model, even the most recent calculations are underpredicting the p nuclei abundances in the Mo-Ru mass region or between e.g. $150 \leq A \leq 165$ [7, 8]. It remains unclear whether this deficiency is due to nuclear cross sections, stellar physics, or alternative / additional process has to be invoked [7].

In order to resolve this ambiguity, improvements in describing the astrophysical conditions of the process (seed isotope abundances, peak temperatures, time scale, etc) are needed. On the other hand, large uncertainties are introduced into the calculations by the nuclear physics input, most importantly by the reaction rates (determined from cross sections). The γ process models require the use of huge reaction networks including tens of thousands of nuclear reactions. The rates of these reactions at a given stellar temperature are necessary inputs to the network calculations. The reaction rates are generally taken from calculations using the Hauser-Feshbach (H-F) statistical model [9, 10, 11]. The accuracy of the H-F predictions mainly depends on the adopted nuclear models for the proton- neutron- α widths, γ-ray strength functions, and nuclear level densities. Experimental information about these quantities can be obtained from the study of the inverse capture reactions. This approach is not only technically less challenging, but also provides more relevant astrophysical information than the direct study of the γ induced reactions [12, 13]. Therefore, recent years the alpha capture cross sections on ^{127}I, ^{162}Er, ^{168}Yb and ^{169}Tm have been measured at Atomki [14, 15, 16, 17, 18, 19].

Since the chemical composition of the target is important for the nuclear cross section calculation, it is necessary to know the contribution of the impurities and contaminations. With the help of ion beam analytical techniques the concentrations of impurities in the background can be determined.

II. Target characterization using the particle induced X-ray emission technique

Before detailing the role of PIXE technique in the characterization of targets used for experimental nuclear astrophysics, the activation technique have to be briefly discussed. The activation technique is a two-step procedure. At first the targets (made by reductive vacuum evaporation from Mo, Ta boats or from C crucible onto thin high purity aluminum foils) are irradiated by an ion-beam provided by the cyclotron accelerator of Atomki. The second step is the determination of the induced activity. For this purpose the yield of the γ radiation – emitted following the β decay of the produced unstable isotopes – is measured using various HPGe detectors available at Atomki.

The accurate knowledge of the absolute target thickness is crucial important in these experiments. In Atomki various techniques, such as gravimetric analysis, Rutherford backscattering spectroscopy (RBS) [20] and particle induced X-ray emission spectroscopy (PIXE) [21] are available. For precise target characterization, at least two of these techniques are used to reduce the possible systematic uncertainty [14, 15, 16, 17, 18, 19].

Furthermore, it is necessary to obtain precise information on not only the absolute number of target atoms, but also on the reaction cross sections. The PIXE technique is exceptional, since with the use of this technique information on the chemical composition of the target can be gained. To determine the experimental excitation function, the E_{lab} energy of the α particles have to be corrected by the ΔE energy loss inside the target material. This energy loss is usually calculated using the SRIM [22] code. Appropriate input on the chemical composition of the target is necessary to obtain correct results (e.g. in the case of the KI compound targets used to measure the $^{127}I(\alpha,\gamma)^{131}Cs$ reaction cross sections [14] the calculated energy loss can differ up to 18% assuming different K to I ratios).

PIXE technique was also applied for the role of the determination of the target impurities. Charged-particle induced reactions on the impurities of the target or backing material could pollute the γ spectra making difficult or impossible the determination of the induced activity of our interest. Different evaporation boats / crucibles can be used for target preparation, the target material can thermally heated or by using an electron beam. Furthermore, it was need to prepare targets from oxides of rare-earth metals. Since the melting point of these compounds are usually too high for our

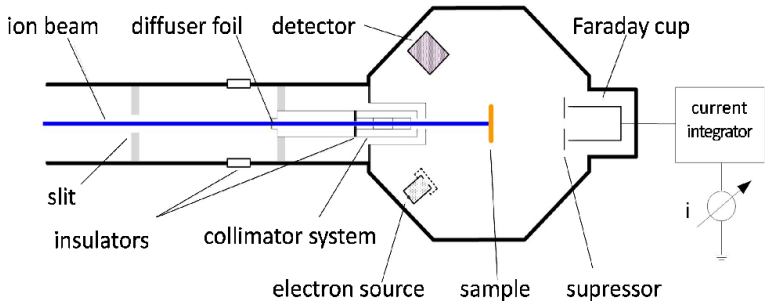

Figure 1: The schematic view of the macro-PIXE chamber used to determine the absolute target thickness of the I, Er and Tm targets.

equipment to produce the targets (e.g. metallic Er targets from Er_2O_3 oxid [19]) reductive vacuum technique had to be used. To reduce amount of the target material La, Ti or Zr are widely used as additives [23]. In summary, the targets can be prepared using slightly different evaporation techniques. The PIXE measurements offers the opportunity to select the method (best combination of the boat/crucible material, the evaporation technique (thermal or electron beam heating) and the reducing agent), which is optimal to make targets as clean as possible.

II.1 Macro-PIXE experimental set-up

The macro-PIXE chamber is installed on the left 45° beamline of the 5 MV VdG accelerator in the Ion Beam Application (IBA) Laboratory of the Atomki [24]. Concentration of $Z \geq 13$ elements can be determined with this experimental setup. The schematic view of the PIXE chamber can be seen in Figure 1. The system is equipped with an X-ray detector, a target holder, an electron source and a suppressor. We can use different types of target holders depending on the analyzed samples. For measuring the elements above Al, a Si(Li) detector with 20 μm thick beryllium window is used. The detector is placed at 135° to the beam direction. A 24 μm thick Mylar foil is used as an absorber before the detector. An electron source can be found in the PIXE chamber, which floods the insulating samples with low energy electrons and keeps it close to the ground potential. The

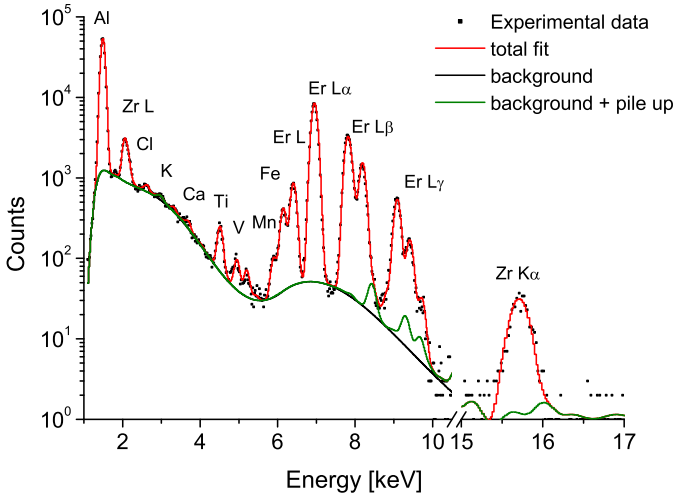

Figure 2: PIXE spectrum measured on an Er target. Peaks belonging to impurities in the target and the backing are indicated, too [19].

samples used later for the cross section measurements were bombarded with H^+ beam of 2 MeV energy and of proton currents within 1-10 nA depending on the evaporated target material. The accumulated charge on samples was about 1-2 μC. The solid angle of the X-ray detector was determined using Fe standard and was crosschecked regularly during the measurement. For the PIXE measurements the accurate knowledge on the total number of impinging protons are needed. The determination of the number of bombarding particles is based on current measurements. The whole macro-PIXE chamber is electrically isolated from surroundings, it acts as a Faraday cup. To prevent secondary electrons escaping the cup, a negatively biased ring electrode (suppressor) is placed at the chamber.

III. Results

Figure 2 shows a typical PIXE spectrum measured by bombarding the Er targets with 2 MeV protons. The peaks used for the analysis are marked.

Table 1: Comparison of PIXE, RBS and gravimetric analysis on Ba targets. The absolute number of target atoms are given in 10^{15} atoms/cm^2.

sample	**PIXE**	**weighing**	**RBS**
D3	69	70	65
D4	49	50	45
D6	37	38	35

Peaks belonging to impurities in the target and/or the backing are indicated, too. The evaluation of the X-ray spectra was done with the PIXEKLM program code [25]. The absolute number of target atoms were measured with high precision ($\leq$ 5% uncertainty) in all cases. This results were in very good agreement with the target thicknesses based on weighing and / or RBS measurements. Table 1 shows absolute number of Ba target atoms, which were measured with all three techniques.

Based on the PIXE studies the most suitable evaporation method was chosen to produce the KI, Tm and Er targets. Furthermore, the contaminants of the targets (and their backings) were also determined and the following impurities were found below 100 ppm: Si, Cl, K, Ca, Ti, V, Mn, Fe, Zn. Using micro-PIXE set-up can be determined the homogeneity of targets. From results is possible to conclude the goodness of evaporation.

In summary, the PIXE technique was found to be useful to characterize the targets in γ process related experiments. Further studies are planned to be carried out in the future.

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