Towards in-beam ($\alpha, \gamma$) cross section measurements for the astrophysical $\gamma$-process

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Abstract. The activation technique has proven to be a very successful tool in measuring charged particle induced reaction cross sections relevant for the astrophysical $\gamma$-process. This method is, however, only applicable when the product nucleus of the reaction is radioactive and its decay can well be measured. In other cases the technically much more challenging in-beam measurements are inevitable. Here we present the first steps of a new research program aiming at the in-beam measurements of ($\alpha, \gamma$) cross sections. As a first test case, the study of the $^{116}\text{Sn}$(,$\alpha$,$\gamma$)$^{120}\text{Te}$ reaction has been started.

1. Introduction
The astrophysical $\gamma$-process is probably the most important sub-process of the more general p-process, which is the production mechanism of the so-called p-isotopes, those heavy, proton rich isotopes which are not produced by the s- and r-processes [1]. The p-process is one of the least understood processes of nucleosynthesis, the models are not able to reproduce well the p-isotope abundances observed in nature. The experimental study of nuclear reactions involved in a $\gamma$-process network is therefore very important for eliminating a possible source of error in the model calculations.

Detailed calculations show that $\gamma$-process models are very sensitive to the cross sections of $\alpha$-induced reactions. On the other hand, very limited experimental information is available for these reactions in the relevant mass and energy range. Therefore, ($\alpha, \gamma$) cross section measurements are needed to provide data for the models. In recent years, an increased effort has been made to carry out such measurement [2, and references therein]. These measurements were almost exclusively carried out with the activation technique. In this method the cross section is determined by measuring the radioactive decay of an isotope produced by $\alpha$-irradiation. This means that the method is limited to those cases where the reaction product is unstable and its decay can be measured.

In a $\gamma$-process network, reactions leading to stable isotopes are of course also involved and the results of the calculations can be sensitive to these reactions, too [3]. Therefore, the measurement of these reactions is also important even though they can only be studied with in-beam technique. The in-beam technique is technically much more challenging than the activation, and results obtained with this method for the $\gamma$-process are practically limited to proton-induced reactions (see e.g. [4]). Realizing the importance of ($\alpha, \gamma$) reactions, the method is to be extended to these reactions, and such a program is being carried out at different laboratories using various
approaches like the application of a $4\pi$ summing crystal or a HPGe detector array [5, 6]. Here we present some details of our research initiatives towards this goal.

2. The $^{116}$Sn$(\alpha, \gamma)^{120}$Te reaction
For the first reaction to be studied with in-beam cross section measurement we have chosen $^{116}$Sn$(\alpha, \gamma)^{120}$Te based on the following reasons. In ref. [3] this reaction is suggested for measurements with high priority and since $^{120}$Te is stable, it cannot be measured with activation. The target of this reaction is an even-even nucleus, thus a simpler $\gamma$-decay scheme of the $^{120}$Te compound nucleus is expected. The isotope is available in high (close to 100 %) enrichment, so the disturbing effect of other Sn isotopes can be avoided. Target preparation tests showed that high purity self supporting Sn targets can be prepared with vacuum evaporation reducing this way the beam-induced background on target or backing impurities.

3. Gamma-detector calibration
The $\gamma$-radiation from the target has been measured with a 100 % relative efficiency HPGe detector and a composite Clover detector. The $Q$ value of the $^{116}$Sn$(\alpha, \gamma)^{120}$Te reaction is 0.3 MeV and the alpha energy range to be studied is around about 10 MeV. Therefore, the prompt $\gamma$-radiation from the reactions includes high energy $\gamma$-lines up to around 10 MeV. For an absolute cross section measurements the absolute detector efficiency at these energies must be known. At low energies the 100 % detector has been calibrated using standard radioactive sources while at high energies some well known resonances of different proton capture reactions emitting cascade $\gamma$-transitions have been used. Figure 1 shows the measured efficiency curve and lists the used sources. The resonant reactions were the following: $^{27}$Al$(p, \gamma)^{28}$Si, $^{23}$Na$(p, \gamma)^{24}$Mg, $^{39}$K$(p, \gamma)^{40}$Ca. With these measurements the detector efficiency has been measured up to 11.6 MeV and a fourth degree polynomial has been fitted to the high energy data.

4. The first in-beam measurements, conclusion and outlook
For the first test measurements the cyclotron accelerator of ATOMKI provided a 10.7 MeV $\alpha$-beam with a typical intensity of 200 nA. The beam bombarded an enriched self-supporting $^{116}$Sn target. The thickness of the target has been measured with $\alpha$ energy loss and Rutherford
Backscattering. The target has been put into a target chamber developed for in-beam \(\gamma\)-spectroscopy measurements. The inner surface of the chamber is covered with Ta in order to reduce the background caused by scattered beam. The \(\gamma\)-detectors have been placed next to the chamber at 55° with respect to the beam direction. The schematic view of the target chamber and a photo of the setup can be seen in Fig. 3.

Figure 2 shows a \(\gamma\)-spectrum which we acquired with the 100% detector. At 560 keV the transition between the first excited state and ground state in \(^{120}\text{Te}\) is well visible and indicated by an arrow. The Coulomb-excitation peak of \(^{116}\text{Sn}\) (the decay of the 1294 keV first excited state) is also shown in the figure. This peak can be used to monitor the target stability. Both at low and high energies the spectrum is, however, dominated by beam-induced background. In the inset of the figure the region where the \(\gamma\)-transition (the direct decay of the compound state to the ground state) is indicated and due to the background no peak can be identified. The identification of the sources of the beam induced background and its reduction is in progress.

Acknowledgments
This work was supported by the European Research Council StG. 203175 and OTKA grants K68801 and NN83261(EuroGENESIS).

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