γ-process reaction studies via in-beam γ-ray spectroscopy at HORUS

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\textbf{\gamma\text{-process reaction studies via in-beam \gamma\text{-ray spectroscopy at HORUS}}}

\textbf{Philipp Scholz, Jan Mayer, Lars Netterdon, and Andreas Zilges}

Institute for Nuclear Physics, University of Cologne, Zülpicher Straße 77, 50937 Cologne, Germany

E-mail: pscholz@ikp.uni-koeln.de

\textbf{Abstract.} The predictions for reaction rates from the Hauser-Feshbach statistical model as they are needed for \gamma\text{-process reaction-network calculations crucially depend on the accuracy of the nuclear physics input-parameters like nuclear-level densities, \gamma\text{-ray strength functions, and particle+nucleus optical-model potentials. At the Institute for Nuclear Physics of the University of Cologne, several charged-particle induced reactions were investigated via the in-beam method with HPGe detectors at the high-efficiency \gamma\text{-ray spectrometer HORUS. One outstanding feature of this experimental method is the access to partial cross-sections, thus, cross-sections for the population of excited states in the reaction product via a radiative capture of an charged particle. Here, recent results for the reactions $^{89}$Y($p,\gamma$)$^{90}$Zr and $^{112}$Sn($\alpha,\gamma$)$^{116}$Te will be presented.}

\section{1. Introduction}

Despite the enormous effort and progress in the field during the last years, the nucleosynthesis processes for the $p$ nuclei are still not fully understood [1]. However, although several other processes in various astrophysical scenarios were proposed, the $\gamma$-process [2] is still believed to be responsible for the largest contributions to the abundance of the $p$ nuclei for masses $A > 100$. Speaking about network calculations for the $\gamma$-process means considering thousands of reactions on many mainly unstable nuclei [3] and, therefore, relying on theoretically calculated reaction rates within the Hauser-Feshbach statistical model [4]. The accuracy of these calculated reactions rates, however, strongly depends on the adopted theoretical models for nuclear physics input-parameters as nuclear-level densities (NLD), $\gamma$-ray strength functions and particle + nucleus optical-model potentials (OMP). In order to constrain or invalidate different models for these input-parameters, precise cross-section measurements of nuclear reactions inside or close to the astrophysical relevant energy region are needed. In the last years, many different charged particle induced reactions at sub-Coulomb energies were investigated in Cologne and a selection should be shown here. After the experimental setup for nuclear astrophysics experiments in Cologne will be presented in Sec. 2, a selection of recent results on studied charged-particle induced reactions will be discussed in Sec. 3.

\section{2. In-beam \gamma\text{-ray spectroscopy at HORUS}}

All in-beam experiments presented in the following were carried out at the Institute for Nuclear Physics of the University of Cologne. The charged-particle beam was delivered by the 10 MV FN-Tandem accelerator to the experimental setup at HORUS. This high-efficiency $\gamma$-ray...
A particle detector for Rutherford Backscattering Spectrometry measurements assures the monitoring of the target stability throughout the whole time of irradiation. Around the target position, a cooling trap at temperatures of liquid nitrogen prevents condensation of residual molecules on the target surface.

3. In-beam reaction studies for the $\gamma$-process nucleosynthesis

3.1. The $^{89}$Y(p,$\gamma$)$^{90}$Zr reaction

The $^{89}$Y(p,$\gamma$)$^{90}$Zr reaction is located in a region of the chart of nuclei where the $p$ isotopes are normally underproduced within $\gamma$-process reaction-network calculations [6]. Since the total cross section of this reaction was measured twice before [7,8], this reaction was an excellent candidate for a commissioning experiment of the nuclear astrophysics setup at HORUS in Cologne [5]. Moreover, since $^{90}$Zr was investigated using nuclear-resonance fluorescence before [9], it was possible to extract valuable input for the adopted $\gamma$-ray strength function in the compound nucleus of this reaction. For five different proton energies between 3.65 MeV and 4.7 MeV total cross-section values could be obtained. In addition, via the detection of the prompt $\gamma$-rays seven partial cross-section values could be measured which are particularly sensitive to the input of the $\gamma$-ray strength function entering the statistical model calculations between $\gamma$-ray energies of 7.71 MeV and 12.98 MeV. Figure 2 shows some of the obtained values in comparison with theoretical predictions calculated using the TALYS code in version 1.6 [11]. The dashed line in Fig. 2 corresponds to calculations using the $\gamma$-ray strength from Ref. [9]. As it can be seen in Fig. 2, the values from the statistical model calculation cannot reproduce the experimental ones properly. However, a rather good reproduction for the total and all partial cross sections could be obtained by adjusting the $\gamma$-strength in $^{90}$Zr simultaneously for all the different channels. The results of the statistical model calculations using this adjusted $\gamma$-strength is shown as a blue band in Fig. 2, labeled as “Fit” The band represents the uncertainty in the statistical
Figure 2. Some of the measured partial cross-sections compared to statistical model calculations using the \((\gamma,\gamma')\) data from Ref. [9] as input for the \(\gamma\)-ray strength function in \(^{90}\text{Zr}\) [10]. The yellow shaded area corresponds to the results using the adjusted \(\gamma\)-ray strength functions.

model calculations one obtains by varying all the other input-parameters. It turned out that an adequate description of the experimental values needs additional \(\gamma\)-strength between \(E_{\gamma} = 10\) MeV and \(E_{\gamma} = 12\) MeV as well as between \(E_{\gamma} = 12\) MeV and \(E_{\gamma} = 13.5\) which was not seen in Ref. [9]. For more information, see Ref. [10].

3.2. The \(^{112}\text{Sn}(\alpha,\gamma)^{116}\text{Te}\) reaction

The radiative \(\alpha\)-capture reaction on the \(p\) nucleus \(^{112}\text{Sn}\) was also investigated by means of the in-beam technique with HPGe detectors [12]. At four center-of-mass energies between 10.1 MeV and 11.5 MeV, i.e. below the neutron threshold, total and partial cross sections could be measured. In this energy region, the total cross section of the reaction as calculated in the scope of the statistical model is almost exclusively sensitive to the \(\gamma\)-ray strength functions and the \(\alpha\)-OMP [13]. Since partial cross sections for this reaction could be extracted, comparing them to statistical model calculations based on different models for the \(\gamma\)-ray strength function made it possible to reduce this uncertainty. A very good agreement was found by using the microscopic HFB + QRPA model [14]. However, constraining the input for the \(\gamma\)-ray strength function entering the statistical model calculations enabled tracing back the remaining deviations between the measured total cross sections and the calculated ones to the input for the \(\alpha\)-OMP. Different TALYS calculations based on various models for the \(\alpha\)-OMP were not able to reproduce the experimental values (see Fig. 3). In detail, each of the calculated value sets tend to underestimate the cross-section values at the highest energies which already indicates that the calculations are penalizing the absorption in comparison to the scattering of the \(\alpha\)-particles due to an incorrect value for the depth of the real part of the \(\alpha\)-OMP. After adjusting this value as well as the proton-width, a very good agreement was found with the disperive \(\alpha\)-OMP of Demetriou et al. [15] ("TALYS Fit" in Fig. 3). For more information, see Ref. [12].

4. Outlook

The experimental program measuring radiative \(\alpha\)-capture reactions via the in-beam method with HPGe detectors was continued by the end of 2014. At \(\alpha\)-particle energies between 12.0 MeV and 13.5 MeV, the total cross section of the \(^{108}\text{Cd}(\alpha,\gamma)^{112}\text{Sn}\) was measured at HORUS. After the irradiation, the targets were placed inside the Cologne Clover Counting Setup [18-20] in order to additionally measure the \(^{108}\text{Cd}(\alpha,n)^{111}\text{Sn}\) reaction cross section. The latter experiment was continued at the beginning of 2015 where cross-section values for \(^{108}\text{Cd}(\alpha,n)^{111}\text{Sn}\)
Figure 3. Measured total reaction cross-section values for the $^{112}\text{Sn}(\alpha,\gamma)^{116}\text{Te}$ reaction and the values from references [16] and [17] compared to different TALYS calculations [12]. "TALYS OMP3" and "TALYS Fit" denote the calculations using the $\alpha$-OMP of Ref. [15] before and after adjusting the depth of the real-part of the OMP as well as the proton- and $\gamma$-width. See text for details.

The reaction could be measured by means of the activation method down to 10.2 MeV. The analysis of these experiments is still ongoing but the data is expected to be published in 2015.

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