Investigation of reactions relevant for the $\gamma$ process using in-beam $\gamma$-ray spectroscopy

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Abstract. The reaction $^{89}$Y(p,$\gamma$)$^{90}$Zr was studied at five proton energies close to the Gamow window. This reaction is of astrophysical importance, since it is located in a mass region, where the $p$-nuclei abundances are not well reproduced by network calculations. For this purpose, the in-beam technique utilizing the high-efficiency high-purity germanium (HPGe) detector array HORUS at the Tandem ion accelerator at the University of Cologne was used. The excellent agreement of the measured total cross sections with previous data shows, that the setup in Cologne is well suited for such measurements. An additional interesting outcome of this measurement are partial cross sections of the de-excitation of the $^{90}$Zr compound nucleus up to the 15$^{th}$ excited state, an observable only accessible in this kind of high-resolution in-beam experiments. The experimental setup and preliminary results of the total and partial cross sections obtained for the $^{89}$Y(p,$\gamma$) reaction are presented. Additionally, we show results of a first test measurement of the $\alpha$-capture reaction on the $p$-nucleus $^{92}$Mo using the in-beam technique with HPGe detectors.

1. Introduction
Mostly all of the stable nuclei heavier than iron are synthesized by neutron-capture reactions during the $s$ and $r$ process [1, 2]. However, 30 to 35 neutron-deficient nuclei are bypassed by these processes, referred to as $p$ nuclei [3]. The astrophysical scenario of the $p$-nuclei production is still under discussion. It is believed, that these nuclei are mainly produced by sequences of photodisintegration reactions in O/Ne shells of core-collapse supernovae [4]. However, type Ia supernovae were also found to be a possible scenario for the synthesis of $p$ nuclei [5]. This production mechanism by photodisintegration reactions is referred to as $\gamma$ process. In order to account for the huge reaction network of the $\gamma$ process, reaction rates are usually calculated within the scope of the Hauser-Feshbach (HF) model [6]. Although the model itself is well established, nuclear-physics uncertainties of the models that enter these calculations are significant. In particular, the reproduction of the $p$-nuclei abundances in the mass region around $90 \lesssim A \lesssim 130$ remains problematic [7]. In order to investigate, whether these deficiencies stem from the nuclear physics or astrophysical side, it is important to experimentally constrain the nuclear physics input parameters entering the HF calculations. These include optical-model potentials, $\gamma$-strength functions, and nuclear level densities. Different experimental approaches have been used to study reactions relevant for the $\gamma$ process, such as the activation technique, see,
e. g., Refs. [8, 9, 10], the 4π summing method [11, 12], and the in-beam method with high-purity germanium (HPGe) detectors [13, 14], which is also used in the present study. This method has the tremendous advantage compared to the activation method, that it enables measurements of astrophysically relevant reactions with a stable reaction product, since the prompt γ-decays of the excited reaction products are detected. Recently, a dedicated setup for in-beam experiments for nuclear astrophysics was developed at the Institute for Nuclear Physics at the University of Cologne. In this article, we report on this experimental setup which has been designed for the measurement of reactions relevant for the γ process at energies far below the Coulomb barrier.

The motivation to measure the \(^{89}\)Y(p,γ)^{90}\)Zr reaction is twofold. First, this reaction serves as an excellent test case for the recently developed experimental setup in Cologne, since the total cross sections were already measured in two recent experiments, see Ref. [11] and Ref. [14]. Secondly, this reaction is located within a mass region, where the p-nuclei abundances are not well reproduced. Hence, systematic measurements of proton- and α-induced reactions in this mass region are important to reduce these deficiencies from the nuclear physics point of view. This is also the astrophysical motivation of the measurement of the α-capture reaction on the p nucleus \(^{92}\)Mo, besides the fact, that no α-induced measurement of astrophysical interest using the in-beam method with HPGe detectors has been successfully performed so far on target nuclei heavier than \(^{70}\)Ge [15]. Furthermore, an earlier attempt to measure this reaction in Cologne did not succeed due to the enormous beam-induced background [16].

2. Experimental setup and results

The proton and α-particle beam for the respective experiments was delivered by the 10 MV FN TANDEM ion accelerator at the Institute for Nuclear Physics in Cologne. The beam current was determined by the measurement of the charge deposited in a Faraday Cup behind the target, the target itself, and the target chamber. The chamber additionally houses a silicon detector at an angle of 135° to monitor the target stability during the experiment by elastic scattering. The prompt γ decays of the respective reaction products were measured for both reactions using the high-efficiency γ-ray detector array HORUS. This array was equipped with 13 HPGe detectors, five of them had additional BGO shields for an active background suppression. The detectors are mounted at five different angles relative to the beam axis which allows the measurement of angular distributions of the emitted γ rays, which is mandatory to determine absolute cross sections. Additionally, the high granularity of the setup enables the measurement of γγ coincidences, which is a powerful tool to suppress beam-induced background.

The absolute full-energy peak efficiency was determined using calibrated \(^{152}\)Eu and \(^{226}\)Ra sources. In order to determine detector efficiencies for γ-ray energies of up to ≈10 MeV, the 3674.4-keV resonance of the \(^{27}\)Al(p,γ)^{28}\)Si reaction was used [17]. Using this resonance, relative full-energy peak efficiencies at energies of \(E_\gamma = 4.5\) MeV, 6.2 MeV, 8.2 MeV, and 10.5 MeV were obtained. These relative efficiencies were subsequently scaled to fit the slope of the absolute full-energy peak efficiencies that was obtained using the aforementioned calibration sources.

The \(^{89}\)Y(p,γ)^{90}\)Zr reaction was measured at five different proton energies between \(E_p = 3.7\) MeV and 4.7 MeV. Thus the investigated energy range is very close to the Gamow window, which is located between 1.7 MeV and 3.6 MeV for a temperature of 3 GK [18]. For this experiment, a natural Y target containing 99.9% of \(^{89}\)Y was used, that was prepared by vacuum evaporation on a 130 \(\mu\)g cm\(^{-2}\) thick Ta backing. The target had a thickness of (583 ± 24) \(\mu\)g cm\(^{-2}\). The target thickness was measured using the Rutherford Backscattering Spectrometry (RBS) facility at the RUBION Dynamitron-tandem accelerator at the Ruhr-Universität Bochum, Germany. A second measurement after the experiment ensured that no target material was dissipated during the irradiation.

During the experiment, the target was bombarded for several hours with beam currents varying from 1 nA to 60 nA depending on the proton energy. The large span of the beam
Figure 1. Parts of a γ-ray spectrum of the $^{89}$Y(p,γ) reaction. The depicted γ-ray spectrum was recorded by six HPGe detectors at an angle of 90° relative to the beam axis. The incident proton energy was $E_p = 4.2$ MeV. In the upper panel a) the low-energy part is shown. Despite strong beam-induced background reactions on, e.g., 27Al, the ground-state transitions at 2186 keV, 2319 keV, and 2748 keV in the reaction product $^{90}$Zr are clearly visible. In the lower panel b) the high-energy part of the γ-ray spectrum is shown. One can distinctly identify the de-excitation of the compound nucleus to various excited states (γ up to γ$_{15}$), as well as to the ground state (denoted as γ$_0$). Note, that the middle part of the spectrum was omitted, where the remaining ground-state transitions are located. All ground-state transitions are used to determine the total reaction cross section, whereas the de-excitations to the excited states are used to determine the partial cross sections. In total, nine partial cross sections up to γ$_{15}$ could be determined.

A typical γ-ray spectrum for the (p,γ) reaction that was recorded using a proton energy of $E_p = 4.2$ MeV is shown in Fig. 1 a). This spectrum was obtained by summing the spectra of all HPGe detectors at an angle of 90° relative to the beam axis. Besides a lot of beam-induced background transitions, the ground-state transitions in the compound nucleus $^{90}$Zr are clearly visible. The total reaction cross section can be determined by summing up the reaction yields of all ground-state transitions. Additionally, from the determination of the reaction yield of the transitions from the compound state to different excited states, it is possible to derive the respective partial cross sections. The de-excitations of the compound nucleus are clearly visible in the high-energy part of the γ-ray spectrum, which is shown in Fig. 1 b). These partial cross sections are an important observable in in-beam experiments, since they may allow additional experimental constraints on γ-ray strength functions upon condition that the γ width is not sensitive to the nuclear level density. One has to emphasize, that the determination of partial cross sections is usually only possible with in-beam experiments using HPGe detectors as in the present case. In the cases of the activation or in-beam 4π-summing method, this is only possible for isomeric states with a sufficiently long half-life.
Figure 2. Experimental total cross sections of the $^{89}$Y($p,\gamma$) reaction as a function of center-of-mass energies. For comparison, the former results obtained by the $4\pi$-summing method from Tsagari et al. [11] and the in-beam measurement with HPGe detectors by Harissopulos et al. [14] are shown. The results obtained in this work are in excellent agreement with the previous measurements.

Figure 3. Experimental partial cross sections of the $^{89}$Y($p,\gamma$) reaction as a function of center-of-mass energies. In total, nine partial cross sections of the de-excitation of the compound nucleus up to $\gamma_{15}$ could be observed. The determination of partial cross sections can yield experimental constraints on $\gamma$-strength functions.

Figure 2 shows the total cross-section results for the $^{89}$Y($p,\gamma$) reaction. These results are compared to previous measurements using the $4\pi$ summing method [11] and the in-beam technique with HPGe detectors [14]. The present results are in excellent agreement with the previous experiments. Hence, with respect to this results we can conclude that the recently developed setup at the Institute for Nuclear Physics in Cologne has become fully operational and the deficiencies of the earlier measurements from Ref. [16] are removed. Note, that the uncertainties of the present data are significantly higher than the ones from Ref. [14]. This is mainly due to the fact, that only a relative full-energy peak efficiency calibration for high-energy $\gamma$-rays was possible in the present case. This results in a higher systematic uncertainty of the efficiency calibration. Figure 3 shows the measured partial cross sections of the $^{89}$Y($p,\gamma$) reaction. In total, nine partial cross sections of de-excitations up to the 15th excited state were determined. The remaining partial cross sections could not be analyzed because of the low transition probabilities from the compound-state to the excited states, caused by the large angular momentum difference.

For the $\alpha$-induced measurement on $^{92}$Mo, a self-supporting 700 $\mu$g/cm$^2$ thick Mo foil with an isotopic enrichment of 94.1% in $^{92}$Mo was used as a target. It was irradiated with $\alpha$-particles with an energy of $E_\alpha = 9.3$ MeV and an average beam current of $\approx 20$ nA. It was found in Ref. [16], that the beam-induced background is too high to measure the cross section of the $^{92}$Mo($\alpha,\gamma$) reaction. Hence, a test measurement of this reaction using the same $\alpha$-particle energy was
Figure 4. Measured γ-ray spectrum of the \(^{92}\text{Mo}(\alpha,\gamma)^{96}\text{Ru}\) reaction. The incident \(\alpha\)-particle energy was \(E_\alpha = 9.3\) MeV. In the upper panel a) only the transition from the first excited \(2^+\) state to the \(0^+\) ground-state in the reaction product \(^{96}\text{Ru}\) at \(E_\gamma = 833\) keV can be observed due to the enormous beam-induced background. The strongest background transitions are also marked in the spectrum. The lower panel b) shows a γ-ray spectrum obtained by claiming a γ coincidence with the γ-ray transition of 833 keV. The beam-induced background can be strongly suppressed and several feeding transitions of the 833-keV state are revealed.

performed to facilitate a comparison between these two experiments. Figure 4 a) depicts a γ-ray spectrum recorded for the \(^{92}\text{Mo}(\alpha,\gamma)^{96}\text{Ru}\) reaction. Contrary to proton-induced reactions, the beam-induced background is by orders of magnitude higher. This is mainly caused by \((\alpha,n)\) and \((\alpha,\alpha')\) reactions on \(^{181}\text{Ta},^{19}\text{F},\) and \(^{56}\text{Fe}\). Due to the enormous background, only one ground-state transition (\(2^+_1 \rightarrow 0^+_\text{gs}\)) in the compound nucleus \(^{96}\text{Ru}\) with an energy of \(E_\gamma = 833\) keV could be observed. This makes a determination of the reaction cross section impossible. Nevertheless, a powerful tool to suppress the beam-induced background is the requirement of \(\gamma\gamma\) coincidences. In Fig. 4 b), a γ-ray spectrum that was obtained by claiming a γ coincidence with the ground-state transition with \(E_\gamma = 833\) keV is shown. By this procedure, a lot of γ-ray transitions feeding the 833-keV state are revealed. However, although the beam-induced background is reduced compared to Ref. [16], a determination of the \(^{92}\text{Mo}(\alpha,\gamma)\) reaction cross-section is still challenging. Hence, further improvements of the experimental setup are necessary, including a lead and copper shielding of the apertures and collimators.

3. Conclusion and Outlook
The high-efficiency γ-ray detector array HORUS was used to determine total and partial cross sections of the \(^{89}\text{Y}(p,\gamma)^{90}\text{Zr}\) reaction at five different proton energies between \(E_p = 3.7\) MeV and 4.7 MeV close to the Gamow window for \(T = 3\) GK. The excellent agreement of the total cross sections with previous measurements of Refs. [11] and [14] shows, that the setup at the Institute for Nuclear Physics in Cologne is fully operational. Moreover, nine partial cross sections
up to the $15^{th}$ excited state were measured, which may allow experimental constraints on the \(\gamma\)-strength function. Since the method of in-beam \(\gamma\)-ray spectroscopy allows to study reactions with stable reaction products, the experimental data needed for \(\gamma\)-process network calculations can be widely extended. Hence, the HORUS array embodies an excellent tool to study charged-particle induced reactions at energies of astrophysical interest.

Additionally, a test experiment on the \(^{92}\text{Mo}(\alpha,\gamma)^{96}\text{Ru}\) reaction with an \(\alpha\)-particle energy of \(E_\alpha = 9.3\) MeV was performed. The dominating beam-induced background makes a determination of the reaction cross section impossible. For this reason, improvements of the target chamber are planned, which include a lead and copper shielding of the tantalum apertures and collimators.

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