In-beam experiments on $(p, \gamma)$ and $(\alpha, \gamma)$ reactions for the astrophysical $p$ process

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Abstract. We have recently performed an experiment for the $(p, \gamma)$ and $(\alpha, \gamma)$ reactions on the nucleus $^{92}$Mo at energies of relevance for the astrophysical $p$ process. The reactions were investigated by the in-beam technique using the $\gamma$-ray detector array HORUS at the ion TANDEM accelerator of the University of Cologne. The experimental results are compared to data stemming from activation measurements and to statistical-model calculations.

1. Introduction

The $p$ process describes the nucleosynthesis of 35 proton-rich nuclei which are bypassed by the neutron-capture reactions of the $s$ and $r$ processes, the so-called $p$ nuclei. This process is mainly driven by photodisintegration reactions in explosive astrophysical environments such as Type-II supernovae and involves a huge reaction network of about 2000 nuclei and 20000 reactions [1, 2]. To account for such a large number of reactions, the corresponding reaction rates are usually derived from statistical-model calculations performed within the framework of the Hauser-Feshbach theory. Experimental data for $p$-process relevant reactions are strongly required to test the reliability and robustness of these calculations. Whereas the Hauser-Feshbach theory itself is well established, significant uncertainties are introduced by uncertainties of the nuclear models which enter the calculations. Therefore, one of the major aim of experimental studies is to improve the descriptions for nuclear properties like photon-strength functions, nuclear level densities and optical-model potentials on the basis of reliable experimental data.

Increasing experimental efforts have been made in the last decade to study $p$-process relevant reactions. An overview of the various experimental approaches is given, e. g., in Ref. [3]. It has been shown that proton and $\alpha$-particle capture reactions are particularly well suited to determine stellar photodisintegration reaction rates via the Detailed Balance theorem [4, 5]. Most of the experiments on these type of reactions have so far applied the activation technique in which the reaction yield is measured offline under low-background conditions by tracing the $\beta$ decays of the radioactive reaction products, e. g., see Ref. [6]. However, since activation experiments are restricted to reactions that produce radionuclides with appropriate half-lives, complementary in-beam experiments have been performed in which the reaction is identified by the prompt $\gamma$ decays of the excited reaction products rather than by their subsequent $\beta$ decays. So far, in-beam experiments have either made use of highly-efficient large-volume $4\pi$ NaI detectors [7] which are available at the National Centre for Scientific Research Demokritos, Athens, and at
In this article, we report on another experimental setup for in-beam measurements available at the ion TANDEM accelerator of the University of Cologne, which is dedicated to study process relevant reactions at energies far below the Coulomb threshold. This setup will be presented in the following in the context of a recent experiment.

2. Experiment

We have measured the \((p, \gamma)\) and \((\alpha, \gamma)\) reaction on \(^{92}\)Mo at several energies within the so-called Gamow window, i.e., the energy window of astrophysical relevance for charged-particle capture reactions under stellar conditions. In this experiment, metallic isotopically-enriched molybdenum targets of about \(400 \mu\text{g/cm}^2\) thickness each were bombarded for several hours with protons and \(\alpha\) particles at beam currents of about \(200\) nA and \(30\) nA, respectively. The beam current was determined from the charge deposited in a Faraday cup behind the target. In addition, a silicon detector was placed under a backward angle of \(135^\circ\) to monitor the target thickness during the experiment by measuring the Rutherford scattering off the target.

The \((p, \gamma)\) and \((\alpha, \gamma)\) reactions were measured by detecting the prompt \(\gamma\) decays of the reaction products with 13 HPGe detectors at the Cologne \(\gamma\)-ray detector array HORUS. Each detector features a relative efficiency between 40% and 80% compared to a \(7.62 \times 7.62 \text{ cm}^2\) NaI detector. The detectors were mounted as close as possible around the target chamber, so that an excellent absolute photopeak efficiency of almost 5% for photons of energy \(E_\gamma = 1332.5\) keV could be provided.

Figure 1 depicts the lower-energetic part of the summed photon spectrum observed for the \((p, \gamma)\) reaction at a proton energy of \(E_p = 3500\) keV. The spectrum clearly reveals most of the low-energetic \(\gamma\) transitions from the reaction product \(^{93}\)Tc. In general, the total capture cross section

![Figure 1. Measured photon spectrum of the proton capture reaction \(^{92}\)Mo\((p, \gamma)\)^{93}\)Tc at an incident proton energy of \(E_p = 3500\) keV. The spectrum was obtained from the sum of 13 HPGe detectors at the \(\gamma\)-ray detector array HORUS. Observed transitions from the reaction product \(^{93}\)Tc are marked by black lines.](image1)

![Figure 2. Experimental data for the ground-state cross section of the proton capture reaction \(^{92}\)Mo\((p, \gamma)\)^{93}\)Tc measured in different experiments are compared to statistical-model calculations. The calculations were carried out by applying different optical-model potentials (see colored lines).](image2)
can be derived by adding up the reaction yields of all prompt $\gamma$ transitions going to the ground state of the reaction product. However, since $^{93}$Tc has an isomeric state with a rather long half-life of $t_{1/2}^{m} = 43.5$ min, this state does not show a prompt $\gamma$ decay to the ground state, and the cross section for capture reactions populating the ground state and isomeric state, respectively, had to be analyzed separately. Figure 2 shows preliminary results for the $(p, \gamma)$ ground-state cross section as derived from the in-beam technique. As a cross-check for the in-beam method, we also determined the cross-section from the $\beta$-decay activity of the radioactive reaction product $^{93}$Tc, which has an appropriate half-life of $t_{1/2}^{g.\beta} = 2.7$ h. As depicted in the figure, the two different methods are in excellent agreement to each other. In addition, we compared our results to a previous activation experiment performed by Sauter and Käppeler [9]. Although the agreement between the two data sets looks quite reasonable, some discrepancies can be seen which require further investigation in the ongoing data analysis. Finally, we compared the experimental data to theoretical predictions from statistical-model calculations using different proton-nucleus optical-model potentials as an input. The calculations were performed with the TALYS [10] and NON-SMOKER code [11], respectively. The best agreement with the experimental data was found for the models by Jeukenne et al. and Koning et al., respectively. Nevertheless, the cross section is still slightly overestimated for both descriptions.

Figure 3 shows a spectrum measured for the $(\alpha, \gamma)$ reaction on $^{92}$Mo for incident $\alpha$ particles of energy $E_{\alpha} = 9300$ keV. In comparison to the $(p, \gamma)$ experiment, $\alpha$-particle capture experiments are faced with a much larger background from competing reactions, in particular from $\alpha$-particle capture reactions on light elements like carbon and oxygen. Due to the dominating background, only the strongest transitions in the reaction product $^{96}$Ru could be observed, and a reliable

Figure 3. Measured photon spectrum of the $\alpha$-particle capture reaction $^{92}$Mo$(\alpha, \gamma)^{96}$Ru at an incident $\alpha$-particle energy of $E_{\alpha} = 9300$ keV. Upper panel: Due to the large background from $\alpha$-particle capture reactions only a few low-energetic transitions in the reaction product $^{96}$Ru can be observed (marked by black lines). Lower panel: Background can be strongly suppressed by requiring a $\gamma$ coincidence with the $\gamma$ transition of energy $E_{\gamma} = 833$ keV. The coincidence spectrum reveals many more $\gamma$ transitions of the reaction product $^{96}$Ru.
determination of the ($\alpha, \gamma$) cross section from the raw $\gamma$ spectra was strongly hampered. A powerful tool, however, to eliminate background lines from the spectra is to make use of $\gamma$-coincidence techniques. A first analysis of the data applying this technique looks very promising and shows that an almost background-free spectrum can be obtained which reveals many more low-lying $\gamma$ transitions of the reaction product (see Fig. 3). We are confident that this technique will allow an accurate determination of the $\alpha$-particle capture cross section on $^{92}$Mo in the ongoing analysis.

3. Conclusion and Outlook

For the first time, the $\gamma$-ray detector array HORUS was used to measure absolute cross sections for proton and $\alpha$-particle capture reactions at astrophysically relevant energies. Although the data analysis for the ($p, \gamma$) and ($\alpha, \gamma$) experiment is still ongoing, first results are already in reasonable agreement to previous experimental data proving that the experimental setup and the in-beam method are working well. Compared to activation experiments, in-beam techniques have the major advantage that they can be used to study reactions on almost any stable nucleus. Thus, the number of experimentally accessible reactions can be widely extended. The advantage of using HPGe detectors instead of large-volume NaI detectors is that the measured high-resolution photon spectra provide detailed information about the decay pattern of the reaction product. This, e.g., allows to determine the partial cross sections of many single transitions, although this could not be discussed explicitly in this article. Information on partial cross sections are very valuable to further constrain the nuclear models adopted for statistical-model calculations. Thus, the $\gamma$-ray detector array HORUS provides an excellent tool to improve the experimental data base for $p$-process relevant reactions in the future.

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