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In-beam experiments for the astrophysical *p* process*

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We studied the proton-capture reaction on the neutron-magic nucleus ^{92}Mo at energies relevant for the astrophysical p process. The reaction was investigated by the in-beam technique using the γ-ray detector array HORUS (High efficient Observatory for γ-Ray Unique Spectroscopy) at the TANDEM ion accelerator of the University of Cologne. The preliminary experimental results are compared to data stemming from two different activation measurements. Furthermore, the experimental data sets are compared to statistical model predictions.
Additionally, we present our new 6 MV Tandetron for Accelerator Mass Spectrometry (AMS), which is currently installed at the University of Cologne. It can be used to detect very small concentrations of long-lived radionuclides which have e.g. been produced by cosmic events or in the laboratory.
The combination of experimental approaches available at the University of Cologne gives access to a large number of astrophysically relevant reactions and allows detailed investigations of some key reactions within the p process network.

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1. Astrophysical motivation

Most nuclei heavier than iron are synthesized by the *s* and *r* processes via neutron-capture reactions [1]. However, 30-35 proton-rich nuclei are bypassed by these processes [2]. These nuclei, referred to as *p* nuclei, are believed to be synthesized by the *p* process in a supernovae explosion [3, 4]. In this astrophysical scenario, the *p* nuclei can be produced by a sequence of photodisintegration reactions, i.e. (γ,n), (γ,p), and (γ,α). In total, the *p* process involves an extensive reaction network consisting of about two thousand nuclei and twenty thousand reactions. Due to the nearly complete absence of experimental data, network calculations for the *p* process are based almost completely on theoretically predicted reaction rates stemming from Hauser-Feshbach statistical model calculations. Experimental data for the *p* process relevant reactions are strongly required to test the reliability and the 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. Comprehensive experimental data for astrophysically relevant reactions are mandatory to derive reliable global nuclear models for reaction codes, but so far the experimental data base is not sufficient for this purpose.
Increasing experimental efforts have been made in the last decade to study *p* process relevant reactions. It has been shown that proton and α-particle capture reactions are particularly well suited to constrain theoretical calculations [5, 6]. Most of the experiments to study 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 β decays of the radioactive reaction products [7]. 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 γ decays of the excited reaction products rather than by their subsequent β decays. So far, in-beam experiments have either made use of highly-efficient large-volume 4π NaI detectors [8] which are available e.g. at the National Centre for Scientific Research Demokritos, Athens, and at RUBION, University of Bochum, or have used the setup of up to four high-resolution HPGe detectors which were installed at the former DYNAMITRON accelerator, University of Stuttgart [9].
In this article, we report on another high resolution experimental setup for in-beam measurements available at the TANDEM ion accelerator of the University of Cologne, which is dedicated to study *p* process relevant reactions at energies far below the Coulomb threshold. This setup will be presented in the following in the context of the experiment ^{92}Mo(p,γ)^{93}Tc.
In addition to the in-beam measurement, this reaction allows the determination of the cross section by measuring the β decay of ^{93}Tc as well. Therefore, this reaction is particularly favorable.

2. The reaction ^{92}Mo(p,γ)^{93}Tc

We have measured the ^{92}Mo(p,γ)^{93}Tc reaction at seven different proton energies varying between $E_p = 2450$ keV and $E_p = 3500$ keV. The metallic isotopically-enriched molybdenum, self supporting targets of 400 $\frac{\mu g}{cm^2}$ thickness each, were bombarded for several hours with protons at beam currents of about 200 nA. The beam current was determined from the charge deposited in a Faraday cup behind the target. In addition, a silicon detector was placed at a backward angle of

135° to monitor the stability of the target thickness during the experiment by measuring the Rutherford scattered protons from the target.

The proton capture reactions were measured by detecting the prompt γ decays of the reaction products with 13 HPGe detectors of the Cologne γ-ray detector array HORUS. Each detector features a relative efficiency between 40% and 80% compared to a 7.62×7.62 cm^2 NaI detector. The detectors were mounted as close as possible around the target chamber so that in total an absolute photopeak efficiency of almost 5% for photons at $E_\gamma = 1332.5$ keV could be reached.

Figure 1 depicts the summed photon spectrum observed for the (p,γ) reaction at a proton energy of $E_p = 3300$ keV. Whereas the lower-energetic part of the spectrum reveals most of the γ transitions from the lower lying excited states of the reaction product ^{93}Tc, the higher-energetic part shows the transitions from the compound state to the lower-lying states. Besides the opportunity to derive the total capture cross section from the reaction yields of all the γ transitions feeding the ground state, the observation of many individual γ transitions provides a detailed picture of the γ-decay pattern of the reaction. This information can be used, e.g., to determine partial cross sections of single transitions which serve as a comprehensive test for theory. Furthermore, the HORUS spectrometer gives access to the angular distributions of the decays and coincidence methods can be used to suppress the background efficiently.

In general, the total capture cross-section can be derived by adding up the reaction yields of all prompt γ transitions going to the ground state of the reaction product. ^{93}Tc has an isomeric state with a rather long half-life of $t^m_{1/2} = 43.5$ min which does not show a prompt γ decay to the ground state. Therefore, the cross section for the capture reactions populating the ground state and the isomeric state had to be analyzed separately.

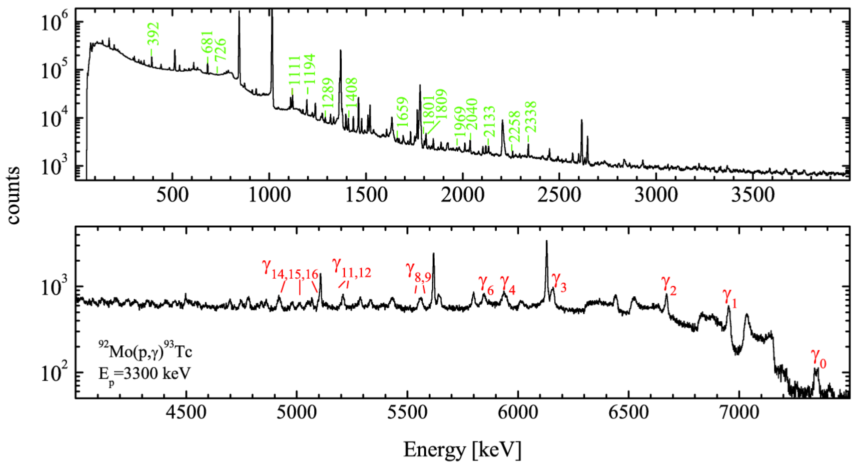

Figure 1: Typical γ spectrum for a proton energy of $E_p = 3300$ keV. The de-excitations of the compound nucleus are marked with γ_X, where γ_X corresponds to the transition to the xth excited state of the reaction product, i. e. γ_0 corresponds to the transition to the ground state, and so forth. By means of these transitions a determination of partial cross sections is possible. Furthermore, the transitions to the ground states are labeled with the corresponding energy in keV in green. The sum over the reactions yields of all transitions to the ground state result in the total cross-section.

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Figure 2 shows preliminary results for the (p,γ) 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 β decay activity of the radioactive reaction product ^{93}Tc, which has a half-life of $t_{1/2}^{\mathrm{g.s.}} = 2.7$ h. As illustrated in figure 2, the two different methods are in excellent agreement. In addition, we compared our results to a previous activation experiment published in reference [10]. Although the agreement between the two data sets looks quite reasonable, some discrepancies can be seen. An additional Rutherford backscattering experiment at RUBION Bochum will be performed to measure the thicknesses of the targets again to exclude a systematic error in the determination of the target thicknesses.

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 [11] and $\mathrm{NON-SMOKER}^{\mathrm{WEB}}$ [12] code, respectively. All theoretical predictions overestimate the cross sections.

In conclusion, two different experimental techniques have succesfully been used for the first time at the TANDEM accelerator in Cologne to study proton-induced reactions. Furthermore, this allows a detailed study of astrophysically relevant reactions like ^{80}Se(p,γ) or ^{92}Mo(α,γ) [13, 14].

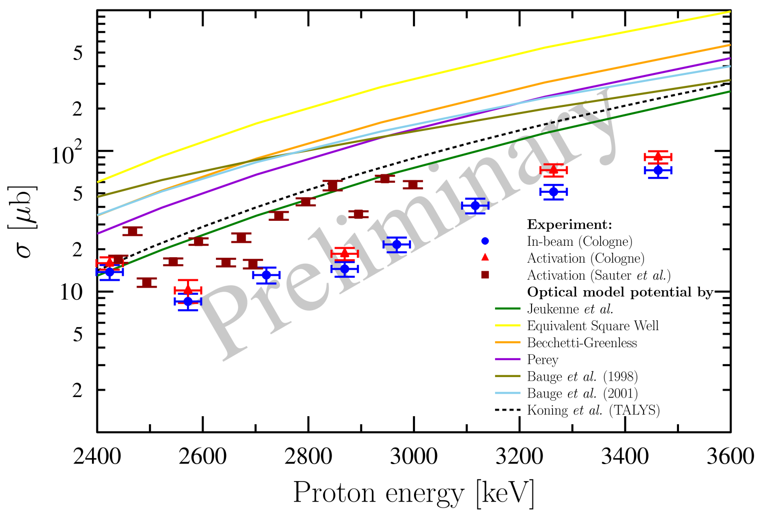

Figure 2: Ground state cross section for the reaction ^{92}Mo$(\mathrm{p},\gamma)^{93}$Tc. Besides the experimental results from the in-beam measurements, additional results from the activation experiment are shown. Furthermore, the total cross sections obtained in an activation experiment from reference [10] are shown. For comparison with theoretical results, cross section calculations obtained with different proton-nucleus optical potential are also plotted.

3. Accelerator Mass Spectrometry - CologneAMS

Accelerator Mass Spectrometry (AMS) can be used to detect long-lived radionuclides down to concentrations of 10^{-15} to 10^{-16} relative to the stable isotopes. Thus, the method offers an alternative way to detect the radioactive reaction products from reactions with very small cross sections if other methods, like the methods presented above, cannot be applied. The German Research Foundation (DFG) recently initiated the setup of a 6 MV high performance AMS user facility at the University of Cologne [15]. The machine is mainly used for the geosciences and for pre- and protohistory. However, ample beamtime is reserved for development and applications in nuclear physics and nuclear astrophysics. This opens new unique opportunities in these fields. The start of standard operation of CologneAMS is scheduled for summer 2011.

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