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Experimental approaches for charged-particle induced reactions for the p process

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The accuracy of predicted isotopic abundance distributions of heavy elements stemming from reaction-network calculations depends on uncertainties regarding the astrophysical scenarios as well as the nuclear physics input. For the p process, *i.e.*, for the synthesis of the nuclei which are not originating from neutron-capture processes, thousands of reactions on mainly unstable nuclei in an explosive astrophysical scenario have to be considered. Therefore, reducing the uncertainties of nuclear-physics input means either to measure key-reaction rates as precise as possible or performing systematic studies to improve theoretical predictions of reaction-rates. Using the Cologne Clover Counting Setup, cross sections for charged-particle capture reactions at astrophysically relevant energies can be investigated via the activation method. Moreover, the combination of the 10 MV FN Tandem accelerator and the high-efficient γ-ray spectrometer HORUS in Cologne allows the study cross sections of radiative-capture reactions in-beam via the spectroscopy of prompt γ-rays with high-purity germanium detectors (HPGe). Besides the presentation of the different experimental setups we will show recent experimental results on the key-reactions as ^{92}Mo(p,γ), ^{130}Ba(p,γ), and ^{112}Sn(α,γ) as well as on other reactions which are sensitive to different nuclear-physics input for the theoretical predictions of reaction-rates.

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1. Introduction

The origin of the elements heavier than iron is still one of the main question in nuclear astrophysics. Although neutron-capture processes are responsible for the production of most of the heaviest isotopes [1, 2], there are 30 to 35 neutron-deficient nuclei whose abundance cannot be explained by such processes [3]. These nuclei between selenium and mercury are referred to as p nuclei. The largest contribution to the synthesis of these elements is believed to be stemming from a reaction network of photodisintegration reaction - the γ process [3]. This process describes a huge network of (γ,n) reactions starting on stable seed nuclei which can be deflected by (γ,p) and (γ,α) reactions towards other isotopic chains. However, this reaction network consists of more than 20,000 reactions on about 2,000 different nuclei [3]. At astrophysical energies the cross section of these reactions are very low which is challenging for experimental approaches to measure cross sections. Moreover, most of these reactions involve unstable nuclei with half-lives unfeasible for nuclear physics experiments in normal kinematics. Although exotic beams could enable the measurement of some cross sections important for γ-process nucleosynthesis, theoretical predictions of cross sections via Statistical Model calculations would still be irreplaceable. However, the uncertainties of cross sections predicted by Statistical Model calculations can be traced back to the uncertainties of the underlying nuclear physics input-parameters like nuclear-level densities, γ-strength functions and optical-model potentials (OMPs). Therefore, experiments aiming at the improvement of the adopted models are an important contribution to a better understanding of γ-process nucleosynthesis. In Cologne, several experiments were recently performed addressing the improvement of proton- or α-OMPs and γ-strength functions. First, the different experimental setups and methods will be introduced in Sec. 2 and Sec. 3. In Sec. 4 more details and recent results for the studied reactions are given.

2. Activation Technique: The Cologne Clover Counting Setup

The activation technique is based on the idea of temporal and often spatial separation of irradiation of the target material and detection of the γ-rays emitted after the decay of the radioactive reaction products. In the case of the reactions discussed in Sec. 4, the irradiations were performed partly using the 10 MV FN Tandem accelerator at the Institute for Nuclear Physics of the University of Cologne, Germany, and partly using the cyclotron of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. In all cases, the γ-ray spectroscopy of the subsequent decay was performed using the Cologne Clover Counting Setup, see Fig. 1 a). By observing the decay of the reaction product, the number of produced nuclei and thus the cross section of the reaction can be obtained. The Cologne Clover Counting Setup, which already was successfully used in previous experiments [4, 5], was specifically designed for purposes of nuclear astrophysics cross-section measurements. This setup, as exhibited in Fig. 1 a), consists of two clover-type high-purity germanium (HPGe) detectors in a close face-to-face geometry which cover in its closest target-to-detector distance a solid angle of almost 4π resulting in an full-energy peak efficiency of up to 8% at 1.3 MeV. The whole setup is passively shielded against natural background radiation and X-rays by 10 cm lead and 3 mm copper. The signal processing is fully digitized and allows the usage of either an online or offline addback-algorithm. Moreover, the event-by-event listmode format of

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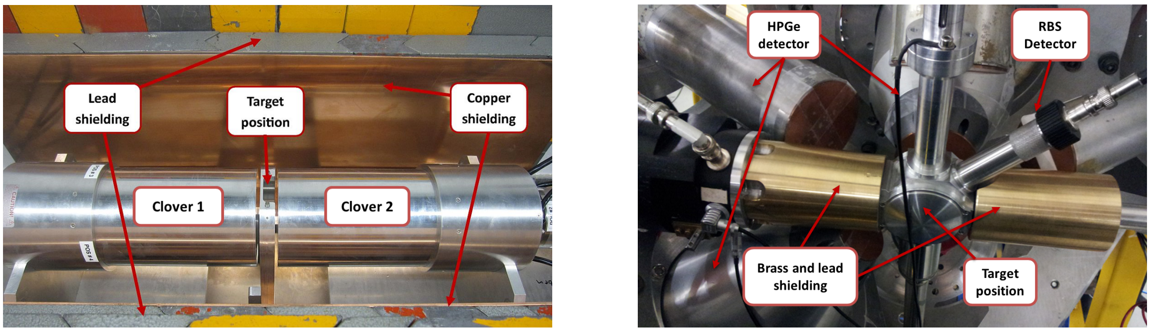

(a) (b)

Figure 1: a) Photograph of the Cologne Clover Counting Setup. Two clover-type HPGe detectors in a close face-to-face geometry provide a large full-energy peak efficiency and enable the usage of $\gamma\gamma$-coincidences to determine total cross sections. b) The target chamber for nuclear astrophysics experiments installed inside the HORUS γ-ray spectrometer. See text for details.

the collected data allows for the determination of total cross sections applying the $\gamma\gamma$-coincidence method as described in Ref. [4].

3. In-beam method with HPGe detectors: The HORUS γ-ray spectrometer

Another approach for measuring total cross sections of charged-particle induced reactions is the detection of prompt γ-rays emitted during the deexcitation of the compound nucleus. The total cross section is obtained by measuring the angular distributions of all γ-ray transitions to the ground-state. Moreover, via the detection of γ-rays populating an excited state in the reaction product, partial cross sections can be measured. These partial cross sections lead to information about the γ-strength function and can, therefore, be used to constrain adopted models.

The combination of the 10 MV Tandem accelerator and the high-efficient HORUS γ-ray spectrometer [6] enables the application of the in-beam method with HPGe detectors in an excellent way. The HORUS γ-ray spectrometer consists of up to 14 HPGe detectors covering five different angles with respect to the beam axis. Six of these detectors can be equipped with BGO-shields for an active Compton-background suppression. The target chamber, see Fig. 1 b), specifically designed for purposes of nuclear astrophysics, contains a built-in silicon detector monitoring the target thickness and stability during the whole experiment. A cooling-trap at temperatures of liquid nitrogen surrounding the target ladder hampers the condensation of residual carbon and oxygen on the target surface. See Ref. [6] for more information about this setup as well as for information about the efficiency determination at high γ-ray energies.

4. Selection of recently studied reactions

4.1 Activation Measurements: ^{130}Ba(p,γ) and ^{187}Re(α,n)

The mass region around the *p* nuclei ^{130}Ba is, by means of proton-induced reactions at astrophysical energies, barely explored. Therefore, the ^{130}Ba(p,γ) reaction was studied at eight different

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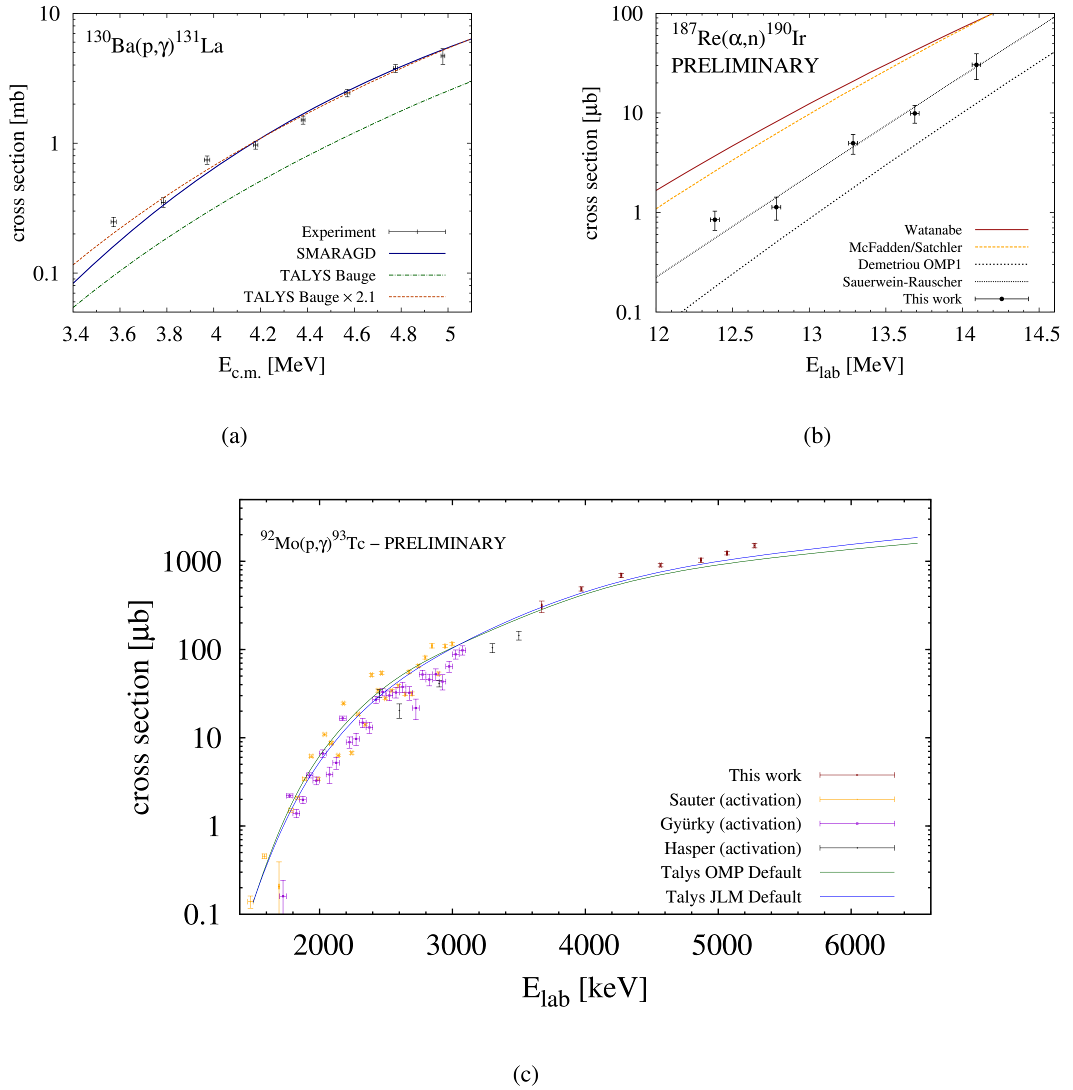

Figure 2: Experimentally determined total cross sections for the reactions a) ^{130}Ba(p,γ) [12], b) ^{187}Re(α,n) via the activation technique and c) ^{92}Mo(p,γ) via the in-beam technique using HPGe detectors.

proton-energies between 3.6 MeV and 5.0 MeV, thus, partly within the Gamow window which covers the range from $E_{c.m.} = 2.32$ MeV to $E_{c.m.} = 4.52$ MeV for a temperature of 2.5 GK [7]. The irradiation of the enriched barium carbonate targets (11.8(2)% in ^{130}Ba) was performed at the 10 MV FN Tandem accelerator at the University of Cologne. The half-life of the produced isotope ^{131}La is stated with 59(2) min [8]. It was possible to dismount and transport the activated target within about 30 min to the Cologne Clover Counting Setup (see Sec. 2) for the spectroscopy of the activated targets. Some results of this activation measurement are shown in Fig. 2 a). Statistical Model calculations using TALYS [9] and SMARAGD [10] confirmed the semi-microscopic proton-OMP approach of Bauge using a constant renormalization factor [11]. More details on this experiment can be found in Ref. [12].

The activation experiment on the ^{187}Re(α,n)^{190}Ir reaction was aimed to constrain different

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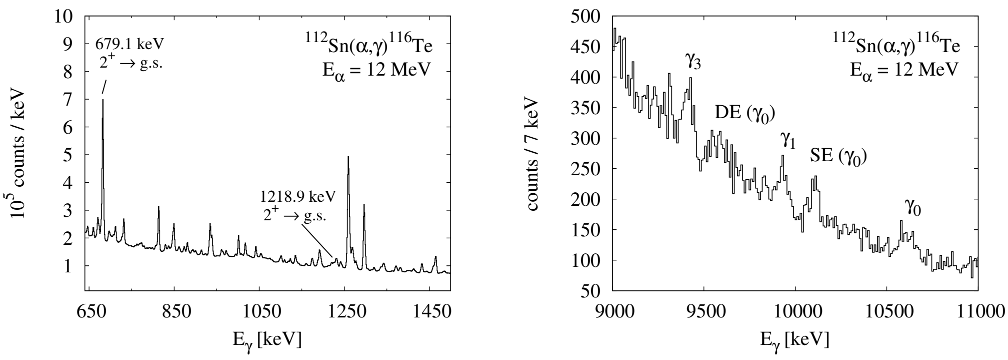

(a) (b)

Figure 3: Measured spectrum of the ^{112}Sn(α,γ) reaction for an α-energy of 12 MeV. a) The γ-ray transitions from the first 2^+ states of ^{112}Sn and ^{116}Te to their ground-states are clearly identifiable in the low-energy part of the spectrum. b) The high-energy part of the spectrum shows the prompt γ-ray transitions after the reaction to the ground state and the two first excited states in ^{116}Te.

adopted models of the α-OMP in the mass region A≈190. After the irradiation of natural rhenium targets at the PTB, cross-section values at five different α-particle energies between 12.4 MeV and 14.1 MeV could be measured using the Cologne Clover Counting Setup. The results are given in Fig. 2 b). Statistical Model calculations with TALYS [9] revealed huge variations for the predicted cross-section value using the α-OMPs of Watanabe [13], McFadden and Satchler [14] and Demetriou *et al*. [15] implemented by default and none of these OMP's were able to reproduce the experimental values. However, using the Sauerwein-Rauscher [4] approach for an α-OMP led to an excellent reproduction of the measured cross-section values and confirms the global character of this α-OMP for $141 \leq A \leq 187$.

4.2 In-beam Measurements: ^{92}Mo(p,γ) and ^{112}Sn(α,γ)

The nucleus ^{92}Mo is the isotopically most abundant *p* nucleus and therefore is its nucleosynthesis of special interest. For the first time, the ^{92}Mo(p,γ) reaction was measured in-beam with HPGe detectors using the HORUS γ-ray spectrometer. The existing data [16, 17, 18] was extended towards the energy region between 3.7 MeV and 5.3 MeV (see Fig. 2 c)) and revealed discrepancies between the measured values of the total cross section and the prediction by Statistical Model Calculation. The information obtained by the measurement of partial cross section are very promising to improve the adopted model for the γ-strength function of ^{93}Tc.

The (γ,α) reaction on the unstable nucleus ^{116}Te is a key reaction in the nucleosynthesis of the *p* nucleus ^{112}Sn. The inverse reaction was measured twice before applying the activation method with conflicting results [19, 20]. Recently, we measured the ^{112}Sn(α,γ) reaction via the in-beam technique at HORUS at four α-particle energies between 10.5 MeV and 12 MeV. In Fig. 3 parts of the measured spectrum at an α-particle energy of 12 MeV are shown to visualize the principle feasibility of (α,γ) experiments at HORUS. In addition to a validation of the measurement of Ref. [19] and α-OMPs in Sn/Cd-region, the in-beam measurement at HORUS enables insight into the γ-strength function of ^{116}Te.

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