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^{106,108}Cd(p,γ)^{107,109}In cross-sections for the astrophysical p-process

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Abstract. The proton capture cross-sections of the two most proton-rich, stable isotopes of cadmium have been measured for the first time in the energy range relevant to the astrophysical p-process. The ^{106}Cd(p,γ)^{107}In and ^{108}Cd(p,γ)^{109}In cross-sections have been determined using the activation technique. Highly enriched as well as natural Cd targets have been irradiated with proton beams from both the Van de Graaff and Cyclotron accelerators of the ATOMKI. The cross-sections have been derived by measuring the γ-radiation following the β-decay of the ^{107}In and ^{109}In reaction products. The measurements were carried out in the energy range between 2.4 and 4.8 MeV which is the relevant energy region (Gamow window) for the astrophysical p-process. Preliminary results are presented here and are compared with the predictions of the Hauser-Feshbach statistical model calculations using the NON-SMOKER code.

PACS. 25.40.Lw Radiative capture – 26.30.+k Nucleosynthesis in novae, supernovae, and other explosive environments – 26.50.+x Nuclear physics aspects of novae, supernovae, and other explosive environments – 27.60.+j $90 \leq A \leq 149$

1 Introduction

Despite the tremendous experimental and theoretical efforts of recent years, the synthesis of the so called p-nuclei (the heavy, proton-rich isotopes which cannot be synthesized by neutron capture reactions in the s- or r-process) is still one of the least known processes of nucleosynthesis. It is generally accepted that the synthesis of the p-nuclei, the astrophysical p-process, involves mainly γ-induced reactions on abundant seed nuclei produced at earlier stages of nucleosynthesis by the s- (or to a less extent the r-) process [1]. During the p-process flow, material from the bottom of the valley of stability is driven to the proton-rich side by subsequent (γ, n) reactions. As the neutron separation energy increases along this path, charged-particle–emitting (γ, α) and (γ, p) reactions start to play a role contributing significantly to the final abundance distribution of p-nuclei.

The high-energy γ-photons necessary for the γ-induced reactions are available only in explosive nucleosynthetic scenarios. The generally accepted models locate the p-process in the deep O-Ne-rich layers of massive stars either in their pre-supernova or supernova phases where temperatures of a few times 10^9 K are reached.

The comprehensive modeling of the p-process requires, on the one hand, detailed information about the stellar environment (temperature, original seed abundances, burning time scale, etc.). On the other hand, nuclear physics plays also an important role. In the p-process modeling, the reaction rates of the thousands of nuclear reactions involved in nuclear reaction networks must be known. The reaction rates of the dominant γ-induced reactions are generally calculated with Hauser-Feshbach–type statistical models. The rates of γ-induced reactions can be calculated from the inverse capture reactions using the detailed balance theorem if the cross-sections of the capture reactions are known experimentally. While there are compilations for the (n,γ) cross-sections, very few charged-particle–induced reactions above the iron region have been investigated experimentally leaving the statistical model calculations largely untested.

Realizing the need for testing experimentally the statistical model calculations, several (p, γ) and a few (α, γ) reaction cross-sections have been measured in recent years, and the results have been compared with model predictions (see, *e.g.*, [2] and references therein). In general, the models are able to reproduce the experimental results within about a factor of two, however, some larger deviations are also found. The existing experimental database is still not enough to check the reliability of

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model calculations globally, therefore further experimental data are highly needed.

Recently, the (α,γ) cross-section of ^{106}Cd has been measured in the energy range relevant to the p-process [3]. The results are compared with statistical model predictions using different input parameters, *e.g.* different optical potentials. The $\alpha+$nucleus optical potential is one of the key input parameters for the model calculations. This potential can directly be determined from (α,α) elastic-scattering experiments. Such an experiment is also in progress on ^{106}Cd, preliminary results are already available [4]. To give a complete description of ^{106}Cd, the measurement of its proton capture cross-section is also necessary.

In the present work the proton capture cross-sections of ^{106}Cd and ^{108}Cd (the other p-isotope of cadmium) have been measured. The ^{106,108}Cd$(\mathrm{p},\gamma)^{107,109}$In cross-sections have been measured using the activation technique and the results are compared with the predictions of the statistical model calculations using the NON-SMOKER code [5].

The relevant energy region (the Gamow window) for the investigated reactions is between 2.4 and 4.7 MeV (for a temperature of 3×10^9 K, typical for the p-process). The aim of the present work is to measure the capture cross-sections within the Gamow window. Consequently, the results can be compared with model predictions right at the astrophysically relevant energies.

2 Investigated reactions

Cadmium has 8 stable isotopes with mass numbers 106, 108, 110, 111, 112, 113, 114 and 116. The two lightest isotopes ^{106}Cd and ^{108}Cd are p-isotopes with low natural abundances of 1.25% and 0.89%, respectively. The proton capture of these two isotopes leads to unstable In isotopes (^{107}In and ^{109}In) decaying by β^+-decay or electron capture to ^{107}Cd and ^{109}Cd, respectively. For both isotopes the β-decay is followed by γ-radiation which makes it possible to determine the proton capture cross-section using the activation method. In this method Cd targets are irradiated by a proton beam and the capture cross-section is derived from the off-line measurement of the decay of reaction products.

Table 1 shows the decay parameters of the two In isotopes. Note, that only the strongest γ-radiations following the β-decay of the reaction products are listed.

Owing to the different decay patterns of the two reaction products, it is possible to measure both cross-sections in a single activation experiment if the target contains both ^{106}Cd and ^{108}Cd isotopes. Cd targets of natural isotopic abundance could in principle be appropriate for the cross-section determination. Proton-induced reactions on the heavier Cd isotopes, however, can be disturbing if they also lead to off-line γ-radiation. In the astrophysically relevant low-energy region the cross-sections of the two investigated capture reactions are very low, thus the elimination of any disturbing γ-radiation from the spectra is highly needed. Such disturbing γ-radiation can come, *e.g.*, from ^{110}Cd$(\mathrm{p},\gamma)^{111}$In or ^{113}Cd$(\mathrm{p},\mathrm{n})^{113}$In. Therefore, in order to avoid the disturbing activity produced on heavier Cd isotopes, enriched targets were used in the lower-energy region where the cross-section, and consequently the yield of the studied reactions, is very low.

Table 1. Decay parameters of ^{107}In and ^{109}In isotopes. Only the strongest γ-radiations following the β-decay of the reaction products which were used for the analysis are shown. The data for ^{107}In are taken from [6] and for ^{109}In from [7] with the exception of the ^{109}In half-life which is taken from a more recent work [8].

Product nucleus	Half life	Gamma energy (keV)	Relative intensity per decay (%)
^{107}In	32.4 ± 0.3 min	204.96	47.2 ± 0.3
^{109}In	4.168 ± 0.018 h	203.5	73.5 ± 0.5

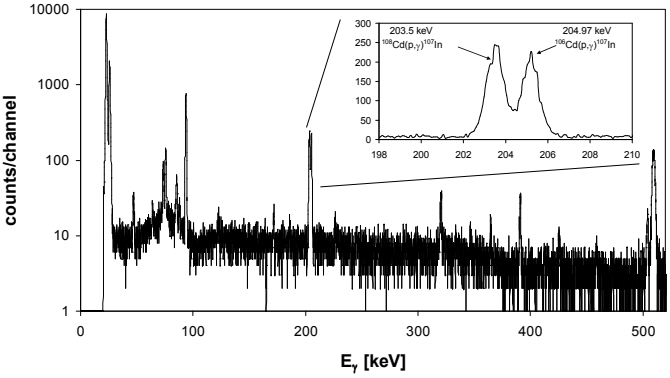

Fig. 1. Typical activation γ-spectrum taken after the irradiation of a natural Cd target with a 3.8 MeV proton beam. This spectrum was taken for 3 hours starting 8 minutes after the end of the irradiation. The inset shows the two resolved γ-peaks from the two reactions studied. The higher energy peaks visible in the spectrum are coming from beam-induced activities on heavier Cd isotopes.

3 Experimental procedure

3.1 Target preparation

The targets were prepared by evaporating natural or highly enriched Cd onto thin ($d=3\,\mu$m) Al foil. The enriched Cd consisted of 96.47% ^{106}Cd and 2.05% ^{108}Cd. Note, that this target material is enriched primarily in ^{106}Cd; however, it also contains more ^{108}Cd than natural Cd (0.89%), and the ratio of heavier Cd isotopes is reduced from 97.86% to 1.48%. The Cd powder was evaporated from a Mo crucible heated by electron bombardment. The Al foil was placed 5 cm above the crucible in a holder defining a circular spot with a diameter of 12 mm on the foil for Cd deposition. This procedure made it possible to determine the target thickness by weighting. The weight of the Al foil was measured before and after evaporation with a precision better than 5 μg and from the

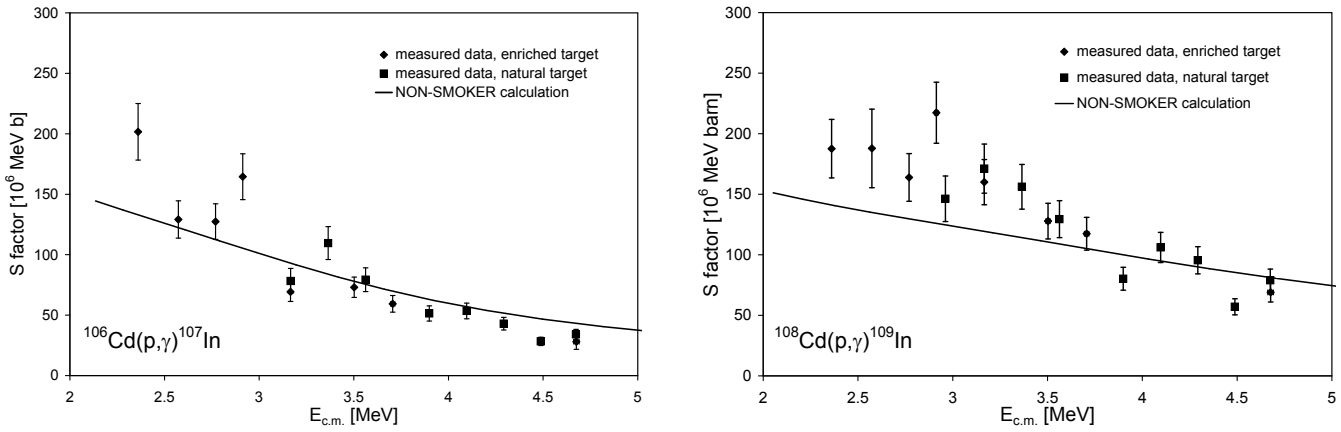

Fig. 2. Astrophysical S-factor of the ^{106}Cd(p, γ)^{107}In (left) and ^{108}Cd(p, γ)^{109}In (right) reactions as a function of the c.m. energy measured in the present work. Measurements carried out using natural and enriched Cd targets are represented by different symbols. The solid line is the statistical model prediction from the NON-SMOKER code [5].

difference the ^{106}Cd number density could be determined. Several natural and enriched targets were prepared with thicknesses varying between 100 and 600 μg/cm^2.

3.2 Irradiations

The energy range from $E_p = 2.4$ to 4.8 MeV was covered in 200 keV steps. The activations have been performed at the Van de Graaff accelerator of ATOMKI (low-energy part $E_p = 2.4$ to 3.6 MeV) and at the MGC cyclotron of ATOMKI (high-energy part $E_p = 3.6$ to 4.8 MeV). Each irradiation lasted about 10 hours and the beam current was restricted to 500 nA in order to avoid target deterioration. The current was kept as stable as possible but to follow the changes the current integrator counts were recorded in multichannel scaling mode in time steps of 10 s. This recorded current integrator spectrum was then used for the analysis solving the differential equation of the population and decay of the reaction products numerically.

A surface barrier detector was built into the chamber at $\Theta = 150°$ relative to the beam direction to detect the backscattered protons and to monitor the target stability. The RBS spectra were taken continuously and the number of counts in the Cd peak was checked regularly during the irradiation. Having the beam current restricted to 500 nA, no target deterioration was found within the 1% precision of the RBS measurement. This is also supported by the weight measurement of the target foils after irradiation.

The beam stop was placed 10 cm behind the target from where no backscattered particles could reach the surface barrier detector. The beam stop was directly water cooled.

In order to find any possible systematic difference between the results obtained at the two accelerators, the $E_p = 3.6$ MeV point has been measured with both accelerators, and perfect agreement was found (see sect. 4). Similarly, the energy points of $E_p = 3.2$ and 4.8 MeV have been measured twice using natural as well as enriched Cd targets. The results with enriched and natural targets are again in good agreement.

3.3 Detection of the induced γ-radiation

The γ-radiation following the β-decay of the produced In isotopes was measured with a HPGe detector of 40% relative efficiency. The target was mounted in a holder at a distance of 3.5 cm from the end of the detector cap. The whole system was shielded by 10 cm thick lead against laboratory background.

The γ-spectra were taken for at least 10 hours and stored regularly in order to follow the decay of the different reaction products.

The absolute efficiency of the detector was measured with calibrated ^{133}Ba, ^{60}Co and ^{152}Eu sources. Monte Carlo simulations have also been carried out to determine the detector efficiency. From the error of the efficiency determination with radioactive sources and from the deviation between the measured and simulated efficiencies, a final error of 9% has been assigned to the detector efficiency.

Figure 1 shows an off-line γ-spectrum taken after irradiation with 3.8 MeV protons in the first 3 h counting interval. The γ lines used for the analysis are indicated by arrows.

The strongest γ-radiations from the decay of the two In isotopes are very close to each other in energy (203.5 and 204.97 keV). However, the energy resolution of the HPGe detector at this low energy is about 0.8 keV (FWHM), hence the two peaks could be resolved (see the inset of fig. 1). Moreover, the different half-lives of the two reaction products make the separation even easier. In the case of enriched targets *e.g.*, the γ-radiation from ^{107}In (the reaction product of the highly enriched ^{106}Cd) is dominant at the beginning of the counting, but owing to its much shorter half-life, it decays out fast making the detection of the weaker ^{109}In decay easier.

Taking into account the detector efficiency and the relative intensity of the emitted gamma rays, coincidence summing effects were for both reactions well below 1% and were neglected.

4 Results and conclusion

The cross-sections of both investigated reactions have been determined in the astrophysically relevant energy range. The final analysis of the experimental data is still in progress, preliminary results are presented here. The measured cross-sections cover more than 3 orders of magnitude from about 3 to 5000 μb. Figure 2 shows the experimental results in terms of the astrophysical S-factor. The data points measured using natural or enriched targets are plotted with different symbols. The good agreement for the points measured both with natural and enriched targets at energies $E_{\mathrm{p}} = 3.2$ and 4.8 MeV is clearly visible. Owing to the different energy calibration of the two accelerators (which was done after the measurement) the 3.6 MeV points which were measured with both accelerators do not coincide perfectly in energy. However, it is clearly visible that there is no systematic difference between the two points. The predictions of the Hauser-Feshbach statistical model code NON-SMOKER are also plotted for comparison. For both isotopes the model is able to reproduce fairly well the experimental result; however at low energies the model seems to underpredict the experimental results in the case of ^{106}Cd(p, γ)^{107}In and to a smaller extent also in the case of ^{108}Cd(p, γ)^{109}In. This might be the consequence of the slope of the theoretical curve which seems to be higher than what the experimental points show. It is also instructive to examine the dependence of the model predictions on the choice of input parameters such as nuclear level densities and optical model potentials. This work is still in progress and is beyond the scope of the present paper.

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