Empirical estimation of astrophysical photodisintegration rates of ^{106}Cd

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Abstract. It has been noted in previous experiments that the ratio between the photoneutron and photoproton disintegration channels of ^{106}Cd might be considerably different from predictions of statistical models. The thresholds of these reactions differ by several MeV and the total astrophysical rate of photodisintegration of ^{106}Cd, which is mostly produced in photonuclear reactions during the *p*-process nucleosynthesis, might be noticeably different from the calculated value. In this work the bremsstrahlung beam of a 55.6 MeV microtron and the photon activation technique is used to measure yields of photonuclear reaction products on isotopically-enriched cadmium targets. The obtained results are compared with predictions of statistical models. The experimental yields are used to estimate photodisintegration reaction rates on ^{106}Cd, which are then used in nuclear network calculations to examine the effects of uncertainties on the produced abundances of *p*-nuclei.

1 Introduction

This work continues a series of measurements of photonuclear reactions on isotopes of cadmium [1, 2]. It has been noted in [1] that the experimental yields of (γ, n) and (γ, p) reactions on ^{106}Cd in E_e = 55.6 MeV bremsstrahlung beam were significantly different from predictions of statistical model calculations. The obtained relative yields of the (γ, n) and (γ, p) reactions on this isotope were, respectively, 0.57 ± 0.02 and 0.47 ± 0.06, as opposed to the theoretical values of, respectively, 0.97–1.06 and 0.12–0.143 given by models (CM [3] and TALYS [4] with default parameters). At the same time a good agreement was observed for reactions on other isotopes from ^{108}Cd to ^{116}Cd (e.g., 1.15 ± 0.08 experimental vs. 1.04–1.2 theoretical yield for the ^{108}Cd(γ, n) reaction). The experimental target was made of cadmium oxide and contained less than 10^{-2} of ^{106}Cd (see table 1). An improved measurement was performed using a natural cadmium target [2]. The obtained absolute yields of the same reactions (in $1/\mu$C) were: 1.41 ± 0.05 (exp.) and 2.8 ± 0.1 (theor.) for the ^{106}Cd(γ, n)^{105}Cd reaction, 1.5 ± 0.1 (exp.) and 0.33 ± 0.02 (theor.) for the ^{106}Cd(γ, p)^{105}Ag reaction, and 2.7 ± 0.2 (exp.) and 2.8 ± 0.1 (theor.) for the ^{108}Cd(γ, n)^{107}Cd reaction. In addition, experimental estimates were made to exclude possible contribution of secondary neutrons produced during irradiation. Thus, the initial result, that the photoproton reaction yield on ^{106}Cd is approximately equal to or exceeds the photoneutron reaction yield, was repeated, which is unexpected for medium and heavy nuclei. In experiments with natural cadmium targets a large background from radioactive products of reactions on ^{111}Cd was observed. In this work the results of

an experiment on an isotopically enriched ^{106}Cd target are presented.

Table 1. Isotopic composition of the experimental targets used in previous works [1, 2] and in this work

Target	CdO	Nat. Cd	Enriched Cd
Irradiation	Ref. [1]	Ref. [2]	This work
Isotopes, at.%			
106	0.63	1.25	74.2 ± 0.4
108	0.44	0.89	0.52
110	6.25	12.49	4.16
111	6.4	12.80	3.70
112	12.07	24.13	6.6
113	6.11	12.22	3.10
114	14.37	28.73	6.6
116	3.75	7.49	1.12
Mass, g	0.3	0.64	0.25

2 Experimental technique and results

The measurement was performed using the photon activation technique, described in detail in [5]. The target was irradiated by bremsstrahlung beam produced in a 2.1-mm-thick tungsten radiator by an electron beam of the RTM-55 racetrack microtron with the energy of 55.6 MeV. Two identical targets with dimensions $10 \times 10 \times 0.3$ mm were made of isotopically enriched Cd (isotopic concentrations shown in table 1. With these targets four irradiations were performed with the average beam current of 0.2–0.3 μA from 10 min to 1 hr for activation of reaction products with short and long half-lives. The electron beam intensity was monitored using a Faraday cup and by collecting the charge left in the experimental target setup. In addition a copper foil monitor target of the same shape as the

cadmium target was positioned closely to it and was later used to normalize the bremsstrahlung intensity. After each irradiation the target was placed in the low-background measurement chamber of a HPGe detector, where gamma-ray spectra of induced activity were measured in continuous mode (the time step for measurements was 3.5 s) for 2 days after irradiations. To measure decays with long half-lives additional measurements were performed 3 months after the irradiations for about 4 weeks.

The obtained series of gamma-ray spectra were analyzed using the spectrum analysis software described in [6]. Unstable products of photonuclear reactions were identified in the spectra by energies and intensities of their peaks and for each peak a decay curve was fitted to obtain the yield. Finally, a weighted average of yields of the same reaction product from different gamma-ray peaks was calculated (using 7–8 peaks for each reaction product). The yield of the ^{65}Cu(γ,n)^{64}Cu reaction was used as a reference value and its theoretical value calculated from the cross section [7] was used for normalization to obtain absolute yields of other nuclei in 1/μC units, that is, the number of reaction products per 1 μC of electron beam.

The obtained yields of the photonuclear reaction products ^{105}Cd and ^{105}Ag are shown in table 2. Due the low isotopic concentration of ^{108}Cd and heavier cadmium isotopes in the target these yields can be almost entirely attributed to, respectively, the (γ,n) and (γ,p) reactions on ^{106}Cd (e.g., the expected yield of the (γ, 3n) reaction on the next lightest isotope ^{108}Cd is about four orders of magnitude less than the ^{106}Cd(γ, n)^{105}Cd yield, and within the experimental error limits).

Table 2. Experimental and theoretically calculated yields Y of photonucleon reaction products on ^{106}Cd in $10^7 \times 1/\mu$C units

Reaction yield, Y	^{105}Cd	^{105}Ag
Experiment	3.0 ± 0.1	4.4 ± 0.4
TALYS (default)	6.39 ± 0.09	0.73 ± 0.01
TALYS (as in [8])	6.48 ± 0.09	0.57 ± 0.01
CM	7.0 ± 0.1	1.04 ± 0.01
TALYS+isospin	6.61 ± 0.09	1.27 ± 0.02

The experimental results were compared with theoretical calculation of the reaction yields using statistical models. The calculations were performed using the TALYS nuclear reaction package [4] and the combined model of photonuclear reactions [3] (denoted as "CM" in the table and figures) to calculate the reaction cross sections, which were subsequently folded with bremsstrahlung spectrum. The obtained theoretical yields are shown in the same table. Several TALYS calculations using different sets of level density and strength function parameters were performed producing more or less similar results. The table lists the TALYS yields for the default parameter set and also using the strength function and level density parameters from experimental measurement [8]. It is seen that the same difference between the experimental and predicted yields as in previous measurements using natural targets takes place. The experimental (γ,n) reaction yield is less by a factor of about two, and the (γ,p) reaction yield is about 4–5 times greater than the theoretical values, sug-

gesting that the calculated cross sections are correspondingly off.

The sum of the (γ,n) and (γ,p) yields shows a much better agreement with the experimental results (and with the dipole sum rule), from which it follows that the photoabsorption cross section (γ,abs) is correctly simulated by both models, and the disagreement is introduced during calculation of the partial reaction channels. A major source of underestimation of the photoproton yield in medium and heavy nuclei is the isospin splitting effect of the isovector giant dipole resonance (IVGDR). The isospin components of the IVGDR are explicitly described in the CM model, and a modification was made to TALYS to add the isospin dependence in a similar manner as described in [9], using CM to calculate the (γ,abs) components. The corresponding calculation is labeled "TALYS+isospin".

The comparison of the calculated theoretical cross sections of the photoproton and photoneutron reactions is shown in Figs. 1–2.
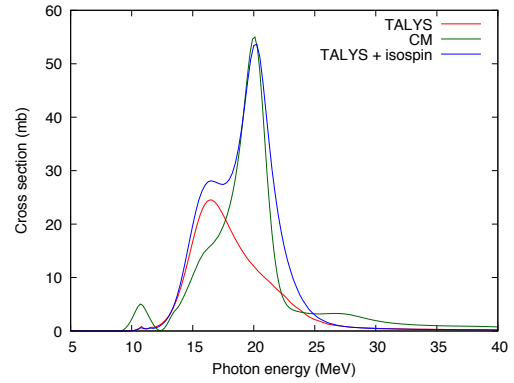

Figure 1. Cross section of the ^{106}Cd(γ,p) reaction calculated using statistical models.
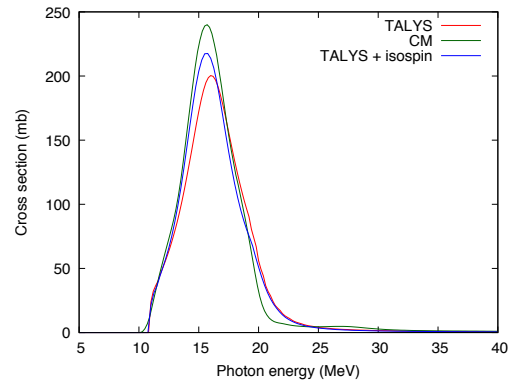

Figure 2. Cross section of the ^{106}Cd(γ,n) reaction calculated using statistical models.

The $T_<$ and $T_>$ branches of the isospin splitting of the IVGDR are clearly seen in the isospin-enabled calculations, and the "TALYS+isospin" theoretical photoproton yield is closer to the experimental value, but the experimental result is still not reproduced, meaning that other

sources of enhanced photoproton yield have to be considered, such as the giant quadrupole resonance (GQR), the direct proton knockout, and the competition with the (γ,γ') channel at energies between the p and n separation thresholds (respectively, 7.4 and 10.9 MeV). The GQR is included in the CM calculation and is visible as the small bump at about 27 MeV in the (γ,p) cross section. The direct proton knockout is expected at about 34 MeV. The cross section increase due to both of these options is relatively small and concentrates at higher energies and can not therefore explain the observed photoproton yield enhancement, since the bremsstrahlung spectrum also decreases at higher energies. On the other hand, the gamma-deexcitation of the IVGDR or the (γ,γ') reaction channel leads to inhibited proton cross section in the near-threshold region and, thus, affects significantly the photoproton yield. There are indications of increased diffuseness of the proton optical potential in the neutron-deficit ^{106}Cd, and, consequently, a higher probability of penetration through the Coulomb barrier, which is not taken into account by the global optical model in our calculations [1].

3 Nuclear network calculations

Photonuclear reactions play a central role in nucleosynthesis of the p-nuclei ^{106,108}Cd. Most of the naturally abundant p-nuclei are produced in astrophysical photodisintegration reactions during the core-collapse supernova stage at temperatures of several GK [10]. Due to the lack of experimental cross sections most of the photodisintegration reaction rates in astrophysical rate libraries are based on theoretical photonuclear cross sections calculated using statistical models.

To study the effect of the observed disagreement on the resulting abundances of p-nuclei nuclear network calculations were performed. The burning routine from the MESA star evolution package [11] was used to calculate final abundances of nuclei in the Ne/O p-process layer of a $25M_\odot$ Type II supernova star under the burning conditions and initial abundances described in [12]. In this calculation during the p-process phase which takes about 1 s the temperature increases from 1.4 GK to 3 GK, and the density from $1.5 \cdot 10^5$ g/cm^3 to $5.7 \cdot 10^5$ g/cm^3. The cross sections of the (γ,p) and (γ,n) reactions on ^{106}Cd calculated using "TALYS+isospin" were used to calculate theoretical photodisintegration rates for this nucleus (alternatively, the rates calculated using TALYS with parameters from [8] could be used, but we found that their difference from the "TALYS+isospin" rates did not exceed 20% in the 1–4 GK region). Other rates were taken unmodified from the JINA REACLIB database [13]. The nuclear reaction network was based on the "mesa833" network, consisting of 833 isotopes up to ^{128}Sn and about ten thousand nuclear reactions.

To quantify the effect of uncertainties of the photodisintegration rates the final abundances of nuclei in the network at the end of the p-process phase were calculated as a function of scaling factors applied to the (γ,p) and (γ,n) rates of ^{106}Cd. The obtained dependencies are shown in Figs. 3 and 4.
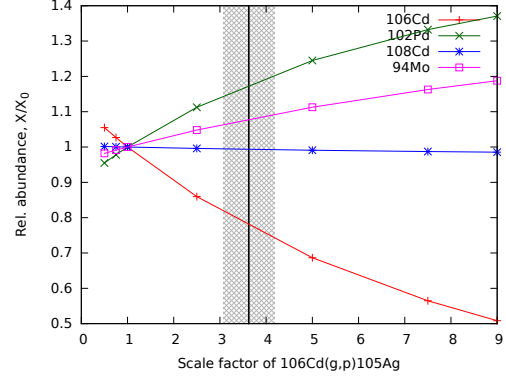

Figure 3. Calculated abundances of ^{106,108}Cd, ^{102}Pd, ^{94}Mo relative to the initial value X/X_0 as a function of a scaling factor applied to the (γ,p) theoretical photodisintegration rate of ^{106}Cd. The scaling factor $Y_{\mathrm{exp}}/Y_{\mathrm{theor}}$ suggested from the experiment is shown with error area.
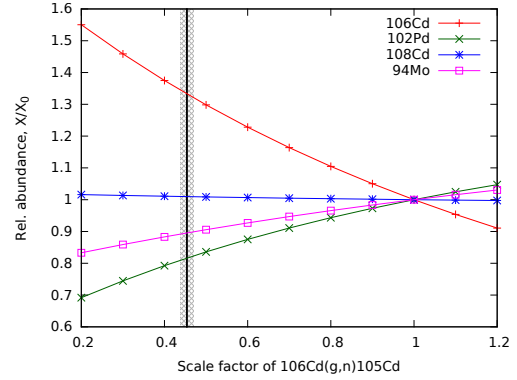

Figure 4. Calculated abundances as a function of a scaling factor of the ^{106}Cd (γ,n) photodisintegration rate. Same notation as in Fig. 3.

It is seen that variation of the scaling factors within the experimentally suggested limits results in about 30% changes of the final ^{106}Cd abundances. The variation also results in changes of abundances of light p-nuclei and has almost no effect on heavier p-nuclei.

It should be mentioned that the procedure of normalization of the photodisintegration rates based on the results of the present experiment has obvious limitations, since the bremsstrahlung spectrum of 55.6 MeV electrons is rather wide in comparison with the Planck spectrum of photons at 2.5–3.5 GK. The astrophysical protonuclear reactions mostly take place in a narrow energy range near the reaction threshold. However, in the view of the above discussion of the origin of the observed increased photoproton yields, it can be expected that the enhancement of the (γ, p) cross section is not concentrated in the high-energy part of the energy range. In this case the performed normalization using the ratio of the observed and theoretical reaction yields is therefore justified, and may be even a conservative estimate if the cross section enhancement is most prominent in the near-threshold region 7–12 MeV where the competition of the (γ,p) and (γ,γ')

channels takes place. No other experimental photonuclear measurements on ^{106}Cd were described in literature, and, clearly, dedicated experiments with monochromatic photons on Cd are needed for accurate measurement of the cross sections and reaction rates.

Taking into account this argumentation the estimated (γ, p) and (γ, n) reaction rates λ_{est} were calculated by normalization of the corresponding theoretical reaction rates with the ratio of the experimental and theoretical reaction yields using the relationship

$$\lambda_{est} = \lambda_{theor} \frac{Y_{exp}}{Y_{theor}} \qquad (1)$$

where "theor" denotes the "TALYS+isospin" calculation. The obtained estimated photodisintegration rates are shown in Figs. 5–6. In comparison wih the correspoding rates from the JINA REACLIB library the proposed (γ,p) rate is by almost an order of magnitude larger, and the (γ,n) rate is within a factor of two smaller than the library rate.
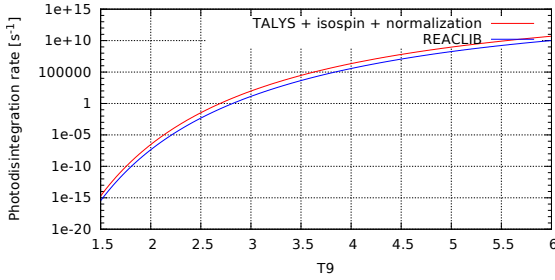
Figure 5. Estimated rate of the (γ,p) reaction on ^{106}Cd (red), corresponding reaction rate from the JINA REACLIB library (blue).
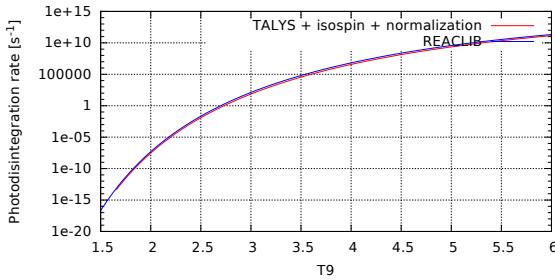
Figure 6. Estimated rate of the (γ,n) reaction on ^{106}Cd (red), corresponding reaction rate from the JINA REACLIB library (blue).

In addition the obtained estimated rates were parameterized in the REACLIB format. The parameterization coefficients for the ^{106}Cd$(\gamma,p)^{105}$Ag reaction rate are:
a_0 = -2.278902e+03, a_1 = -5.612792e+02, a_2 = 7.767336e+03, a_3 = -5.150742e+03, a_4 = 1.580728e+02, a_5 = -5.632337e+00,

a_6 = 3.708693e+03;
for the ^{106}Cd$(\gamma,n)^{105}$Cd reaction rate:
a_0 = -3.167238e+03, a_1 = -7.286351e+02, a_2 = 8.503323e+03, a_3 = -4.819095e+03, a_4 = 1.304085e+02, a_5 = -4.259804e+00, a_6 = 3.735719e+03.

4 Conclusions

Experimental measurement of photonuclear reaction yields on an enriched ^{106}Cd target was performed, and the obtained results were compared with the predictions of statistical models. A large difference between the experimental and calculated photoproton and photoneutron yields from ^{106}Cd was observed. The difference is probably due to individual structure properties of ^{106}Cd which are not taken into account by the global optical model (see also [8]). The theoretically calculated photonuclear cross sections were used to obtain photodisintegration rates of ^{106}Cd and examine the effect of their variation on the produced abundances of p-nuclei, which was of the order of tens of percent when the experimentally suggested scaling factors were applied separately. The estimated (γ,p) and (γ,n) rates on ^{106}Cd were calculated by applying the experimental scaling factors on theoretical rates calculated using the modified TALYS model. The photodisintegration rates on ^{108}Cd did not require normalization.

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