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Chemistry of Transactinides**

**FINAL REPORT ON THE
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Photodisintegration of the Isotope ^{116}Cd

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Abstract

This study presents an experimental investigation of the photonuclear reactions of the isotope ^{116}Cd . The emission of neutrons and protons resulting from γ -irradiation was analyzed to determine the yields of the (γ, n) and (γ, p) reaction channels across a range of photon energies. Their energy dependence and relative behavior were examined in detail.

Special attention was given to the measurement of the isomeric yield ratio between the metastable and ground states of the residual nuclei ^{115m}Cd and ^{115g}Cd . These ratios provide insight into the angular momentum transfer and spin population effects during the reaction process.

The isomeric yield ratios obtained in this study show good agreement with the results reported by other researchers, confirming the consistency of the experimental methodology and supporting the reliability of the data.

Introduction

Investigation of the photodisintegration of nuclei that lie in the vicinity of the $Z = 50$ closed proton shell is of interest since this would furnish information about the role of single-particle excitations in low-lying states. The hierarchy of the yields of various reaction channels depends on the mechanism of excitation and decay of nuclear states in the energy range between about 20 and 50 MeV. The nucleus of the isotope ^{116}Cd is one of such nuclei. In the isotope ^{116}Cd ($Z = 48$), two protons are missing for filling the $1g_{9/2}$ shell.

According to the independent-particle model, 18 neutrons of the isotope ^{116}Cd are in the $N = 50-82$ shell. In a number of studies, it was shown that the set of five states, $1g_{7/2}$, $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$, forming this shell is broken down into two groups, that of $1g_{7/2}$ and $2d_{5/2}$ states and that of $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$ states [1],[2],[3]. From an analysis of spectroscopic data obtained for stripping and pickup reactions, it follows that a nearly parallel filling of five quasiparticle states occurs in cadmium isotopes. Even in light cadmium isotopes ($A < 120$), neutrons begin filling the $1h_{11/2}$ state. Fig.1 shows the shell model of nuclei for cadmium isotopes. In photonuclear reactions on the ^{116}Cd isotope, special features of the filling of quasiparticle states are expected to manifest themselves in the decay of a giant resonance to the $J^P = 11/2^-$ isomeric state. One experiment [4] in which the cross sections $\sigma(\gamma, n)$, $\sigma(\gamma, 2n)$ and $\sigma(\gamma, sn)$ for the respective reactions on a natural mixture of cadmium isotopes were measured in a beam of monochromatic photons in the energy region extending up to 25 MeV have been performed to date.

The results obtained by measuring the yields of photodisintegration of the isotope ^{116}Cd irradiated with bremsstrahlung photons whose spectrum had an endpoint energy of 23 MeV and 55 MeV are presented in [5],[6], [7], respectively.

The objective of the present study was to measure the yields of various photonuclear reactions on the ^{116}Cd isotope and to compare the experimental data obtained in this way with the results of theoretical calculations.

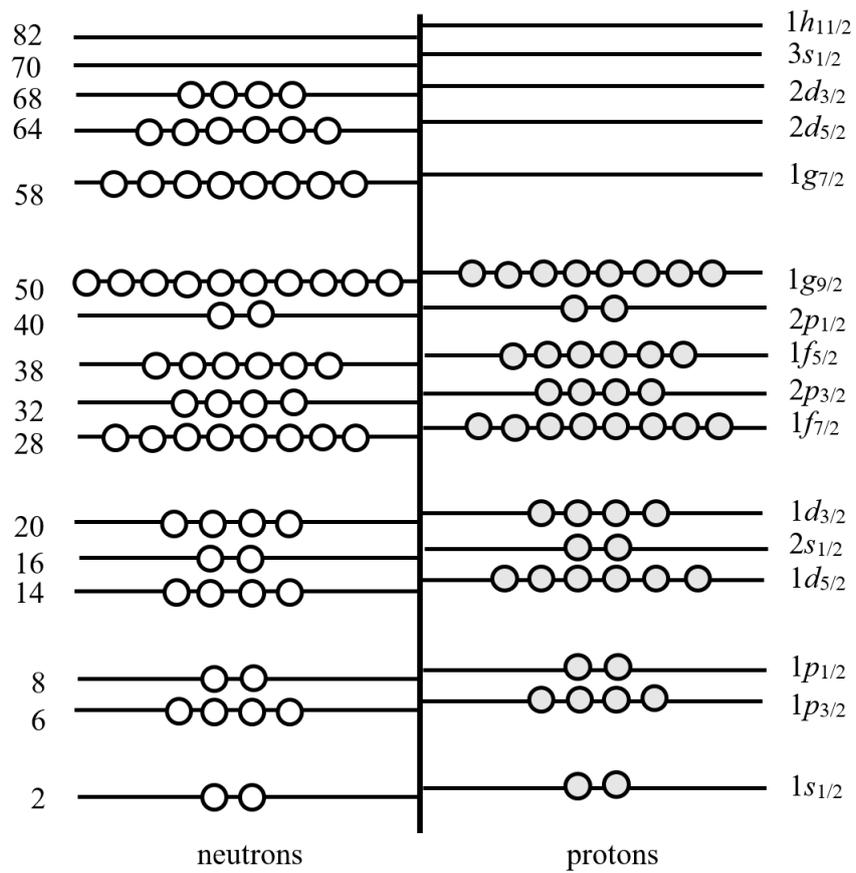


Figure 1: Shell model of nuclei for Cd isotopes

Materials and Methods

2.1 Experimental setup and procedures

This work was performed with the output electron beam of the MT-25 microtron [8]. The electron energies were in range of 10–23 MeV with an energy step of 1 MeV. To produce γ -radiation, a radiator target made of tungsten, which is a common converter material, was used. The tungsten target was sufficiently thick (3 mm) to maximize the number of photons in the energy range of the giant dipole resonance (GDR) that dominates the photonuclear cross section from the nucleon separation threshold to 20–30 MeV. To remove the remaining electrons from the bremsstrahlung beam, a 30 mm thick aluminum absorber was placed behind the tungsten converter. The target of natural cadmium had dimensions 10×10×0.5 mm (at 10–19 MeV) and 5×5×0.5 mm (at 20–23 MeV) as well as was at a distance of 1 cm from the converter. In the trials, a bremsstrahlung flux created in the tungsten converter was used to irradiate metallic natural cadmium samples.

Using a Faraday cup and a calibrated ionisation chamber in the beam, the variations in beam current were measured and entered into a web-accessible database for use in the study using LabView software and an analog-to-digital converter card [9]. Along with the Faraday cup and ionisation chamber, the beam current was measured by digitising the electrical charge that was gathered on the target. A Faraday cup was used to measure the accelerator's electron current while it was being irradiated. By comparing the $^{65}\text{Cu}(\gamma,n)^{64}\text{Cu}$ reaction's experimentally observed yield, the accelerator current was adjusted. The yield was calculated using the estimated cross section, and the bremsstrahlung spectrum was computed with Geant4 [10]. A 0.15-mm-thick copper monitor was placed behind the irradiated Cd target. Copper was chosen because the cross section of the reaction $^{65}\text{Cu}(\gamma,n)^{64}\text{Cu}$ was measured with an acceptable precision [11]. The main parameters of the experiments are listed in Table 1. Following irradiation, the targets were moved to a different measurement room where the induced activity in the irradiated target was measured once the radiation levels in the experimental hall were safe. We employed a 16K ADC/MCA (Multiport II Multichannel Analyser,

CANBERRA) in conjunction with standard measurement electronics and a high purity germanium (HPGe) γ -detector with a resolution of 16 keV at 1332 keV. Standard γ -ray sources were used to calibrate the HPGe detector's energy and efficiency. A detailed description of the γ -activation measuring process employed in this work may be found in [12],[13].

Table 1. Main parameters of the experiments

Energy of electron (MeV)	Mass of cadmium target (mg)	Integral charge (mC)	Integral number of electrons incident on the tungsten converter ($\times 10^{16}$ particle)	Irradiation time (min)	Total measuring time of spectra (h)
10	475.6	50 ± 5	31 ± 3	97	44
11	447.8	50 ± 5	31 ± 3	150	44
12	454.5	50 ± 5	31 ± 3	125	44
13	451.0	50 ± 5	31 ± 3	155	47
14	451.2	30 ± 3	19 ± 2	175	39
15	413.8	20 ± 2	13 ± 1	65	41
16	427.2	10 ± 1	6.2 ± 0.6	65	40
17	427.4	4.0 ± 0.4	2.5 ± 0.3	37	39
18	401.5	3.0 ± 0.3	1.9 ± 0.2	24	36
19	389.3	3.0 ± 0.3	1.9 ± 0.2	32	39
20	113.6	3.0 ± 0.3	1.9 ± 0.2	51	39
21	116.3	3.0 ± 0.3	1.9 ± 0.2	35	37
22	115.8	3.0 ± 0.3	1.9 ± 0.2	27	40
23	112.0	3.0 ± 0.3	1.9 ± 0.2	21	40

The time from the end of irradiation to the start of measurement (cooling time) was in range from 10 to 15 min. For each sample, the spectra were measured at several times during an overall period of 0.5, 1, 12, and 24 h. Typical γ -ray spectra of the reaction products produced from the ^{nat}Cd are shown in Fig. 2. The sample was irradiated with bremsstrahlung radiation with end-point energy of 23 MeV.

The DEIMOS32 code [14], which fits the count area of the full-energy peaks with the Gaussian function, was used to process the γ -ray spectra. The half-life of the produced leftover nuclei as well as the γ -ray energy and intensity were used to identify the processed peaks. The distinctive γ -ray energies and half-lives of the generated radionuclides were used to identify them. Table 2 lists the primary γ -ray energies and intensities that are used to calculate the reaction product yield.

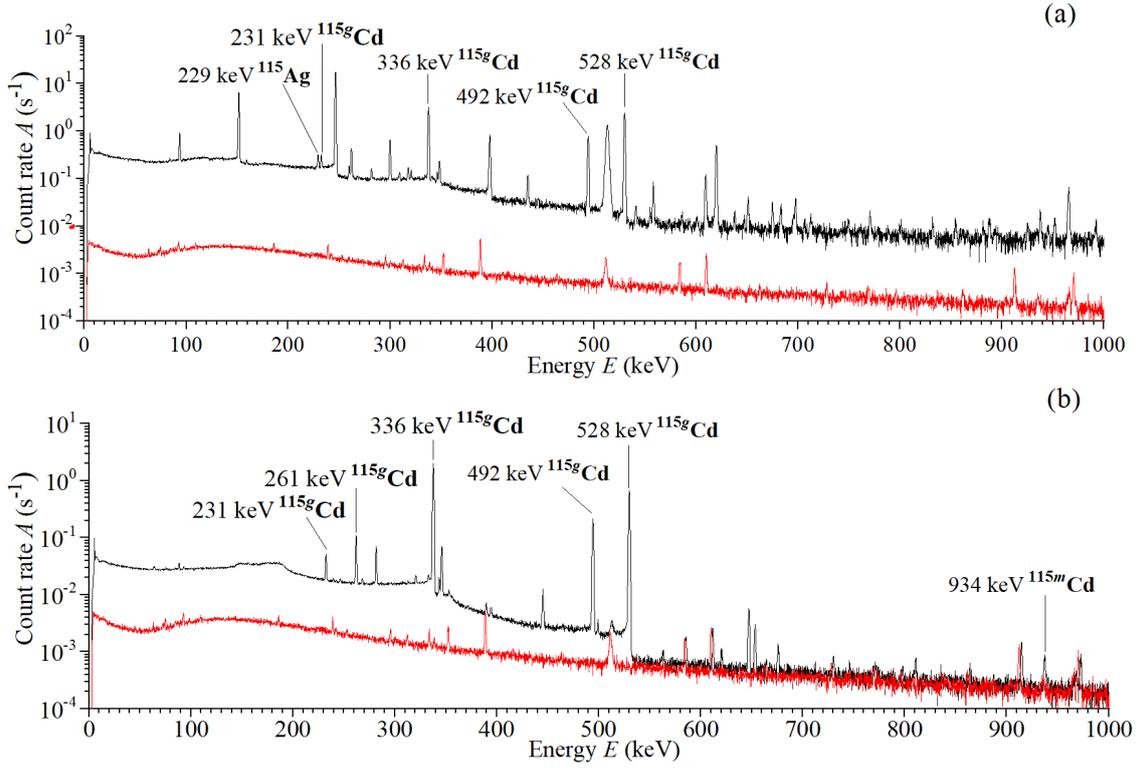


Figure 2: Spectra of residual activity of the irradiated sample of ^{nat}Cd (top-to-bottom) 3 h (a) and 4 days (b) after irradiation. The spectra measurement duration was 1 h (a) and 1 day (b), respectively. The bremsstrahlung end-point energy used for the irradiation was 23 MeV

Table 2. Product nuclei from the photonuclear reactions on ^{116}Cd

Nucleus	Half-life $T_{1/2}$	Decay mode	γ -ray energy E_γ (keV) (I_γ (%))	Reaction	E_{th} (MeV)
^{115g}Cd	53.46 h	β^-	336.24 (46.02), 527.9 (27.45)	$^{116}\text{Cd}(\gamma, n)^{115g}\text{Cd}$	8.7
^{115m}Cd	44.56 d	β^-	933.8 (2)	$^{116}\text{Cd}(\gamma, n)^{115m}\text{Cd}$	8.7
^{115g}Ag	20 min	β^-	229.1 (18)	$^{116}\text{Cd}(\gamma, p)^{115g}\text{Ag}$	11
^{115m}Ag	18 s	β^-	41.1(0.0147)	$^{116}\text{Cd}(\gamma, p)^{115m}\text{Ag}$	11.041

2.2 Yields of the reaction

The experimental yields of the reactions Y_{exp} were normalized to one electron of the accelerated beam incident on the bremsstrahlung target and calculated using the following formula:

$$Y_{exp} = \frac{S \cdot C_{abs}}{\epsilon \cdot I_{\gamma}} \cdot \frac{t_{real}}{t_{live}} \cdot \frac{1}{N} \cdot \frac{1}{N_e} \cdot \frac{e^{\lambda \cdot t_{cool}}}{1 - e^{-\lambda \cdot t_{real}}} \cdot \frac{\lambda \cdot t_{irr}}{1 - e^{-\lambda \cdot t_{irr}}} \quad (1)$$

where S is the full-energy-peak area; ϵ is the full-energy-peak detector efficiency; I_{γ} is the γ - emission probability; C_{abs} is the correction for self-absorption of γ -rays in the sample; t_{real} and t_{live} are the real time and live time of the measurement, respectively; N is the number of atoms in the activation sample; N_e is the integral number of incident electrons; λ is the decay constant; t_{cool} is the cooling time; and t_{irr} is the irradiation time.

The yields Y_{theor} of photonuclear reactions representing the convolution of the photonuclear reactions cross section $\sigma(E)$ and the distribution density of the number of bremsstrahlung photons over energy per one electron of the accelerator $W(E, E_{\gamma max})$ were determined as a result of the experiment. For the yield measurement of a natural mixture of isotopes, the result is the yield of isotope production in all possible reactions on the natural mixture:

$$Y_{theor} = \sum_i \alpha_i \int_{E_{th}}^{E_{\gamma max}} \sigma_i(E) W(E, E_{\gamma max}) dE \quad (2)$$

where $E_{\gamma max}$ is the kinetic energy of electrons hitting the tungsten radiator, E is the energy of bremsstrahlung photons produced on the radiator, E_{th} is the threshold of the studied photonuclear reaction, α is the percentage of the studied isotope in the natural mixture of cadmium isotopes, and the index i corresponds to the number of the reaction contributing to the production of the studied isotope.

The main disadvantage of bremsstrahlung beam experiments is that the yield of photonuclear reaction depends both on the studied cross section of the reaction $\sigma(E)$ and the shape of the bremsstrahlung spectrum $W(E, E_{\gamma max})$, which is often known with insufficient accuracy. The use of the relative yields makes it possible to obtain the dependence of the probability of photonuclear reactions on the maximum energy of bremsstrahlung under different experimental conditions. In our case, the dominant reactions is $^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}$. Theoretical values of the relative yields can be calculated using the following formula:

$$Y_{rel,i} = \frac{\sum_i \eta_i \int_{E_{th}}^{E_{\gamma max}} \sigma_i(E) W(E, E_{\gamma max}) dE}{\eta_{\text{Cd-116}} \int_{E_{th}}^{E_{\gamma max}} \sigma_{(\gamma, n)}(E) W(E, E_{\gamma max}) dE} \quad (3)$$

Results and Discussion

3.1 Relative yields of the reactions (γ, n) and (γ, p) on the ^{116}Cd

$^{116}\text{Cd}(\gamma, n)^{115m,g}\text{Cd}$ reaction. The ^{115}Cd radionuclide exists in both isomeric and unstable ground states. Decay schemes of the nuclei ^{115g}Cd and ^{115m}Cd are shown in Fig. 3. The ^{115m}Cd ($T_{1/2} = 44.6$ d) decays to ^{115}In and its activity was measured using γ -rays of 933.8 keV (2%) and 1290.58 keV (0.89%). For the ground state ^{115g}Cd ($T_{1/2} = 53.46$ h), the interference-free γ -rays of 336.24 keV (45.9%), 492.3 keV (8.03%) and 527.9 keV (27.45%) were suitable for the activity measurement. Here, given that the $^{115m,g}\text{Cd}$ are produced in both photonuclear reactions and decay of the parent nucleus ^{115}Ag ($T_{1/2} = 20$ min), the measurement using these γ -rays represents the cumulative activity for $^{115}\text{Cd} + ^{115}\text{Ag}$. Here, need to pay attention to how comparable the yields of the nuclei ^{115}Ag and ^{115}Cd are. If the ratio $Y_{\text{Ag}-115}/Y_{\text{Cd}-115}$ is less than 1%, then the contribution of the decay of ^{115}Ag to the formation of ^{115}Cd can be neglected.

$^{116}\text{Cd}(\gamma, p)^{115}\text{Ag}$ reaction. The ^{115}Ag radionuclide exists in both isomeric and unstable ground states. Decay schemes of the nuclei ^{115g}Ag and ^{115m}Ag are shown in Fig. 4. Because the half-life of the isomeric state of ^{115m}Ag ($T_{1/2} = 18$ s) is short, its activity could not be measured. The activity of the ^{115g}Ag ($T_{1/2} = 20$ min) radionuclide was measured using γ -rays of 212.8 keV (4.4%), 229.08 keV (18%), 472.7 keV (4%) and 649.1 keV (3%). Here, given that ^{115m}Ag decays to ^{115g}Ag with an IT coefficient of 21%, the measurement using these γ -rays represents the cumulative activity for $^{115(0.21m+g)}\text{Ag}$.

The measured results for the yields and relative yields of the $^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}$ and $^{116}\text{Cd}(\gamma, p)^{115}\text{Ag}$ reactions are shown in Fig. 5 (Table 3) and Fig. 6 (Table 4), respectively. There is only one literature data for the $^{116}\text{Cd}(\gamma, n)^{115m,g}\text{Cd}$ reaction [6] in 23 MeV. In Fig. 6, it was seen that for the ^{116}Cd reaction yield (γ, n) , a tenfold smaller fraction of ^{115m}Cd is produced compared to ^{115g}Cd , while in the (γ, p) reaction, a very small fraction belongs to ^{115}Ag .

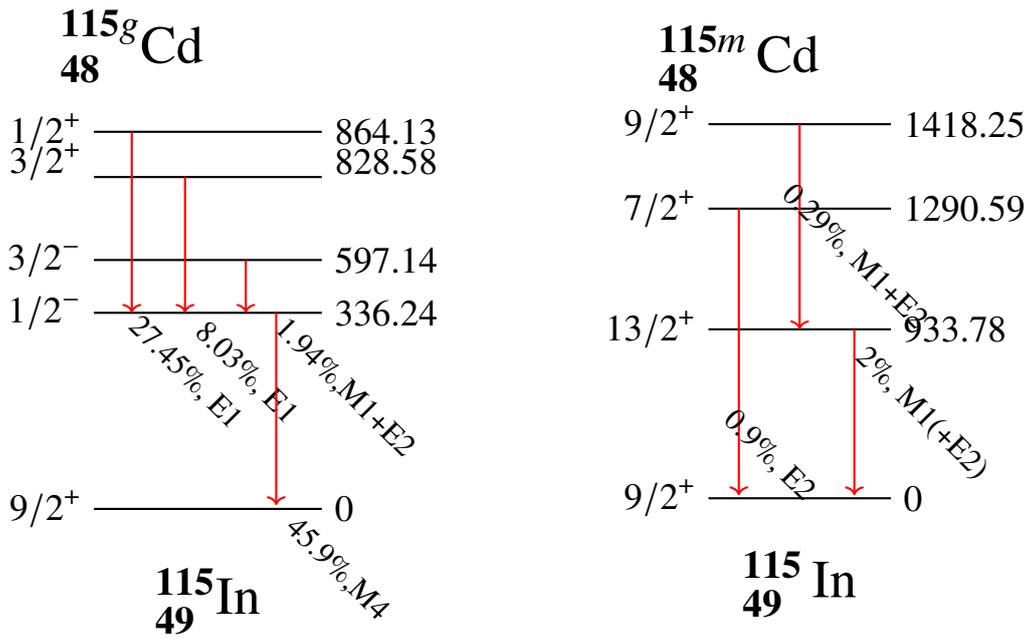


Figure 3: Decay schemes of the nuclei ^{115g}Cd and ^{115m}Cd

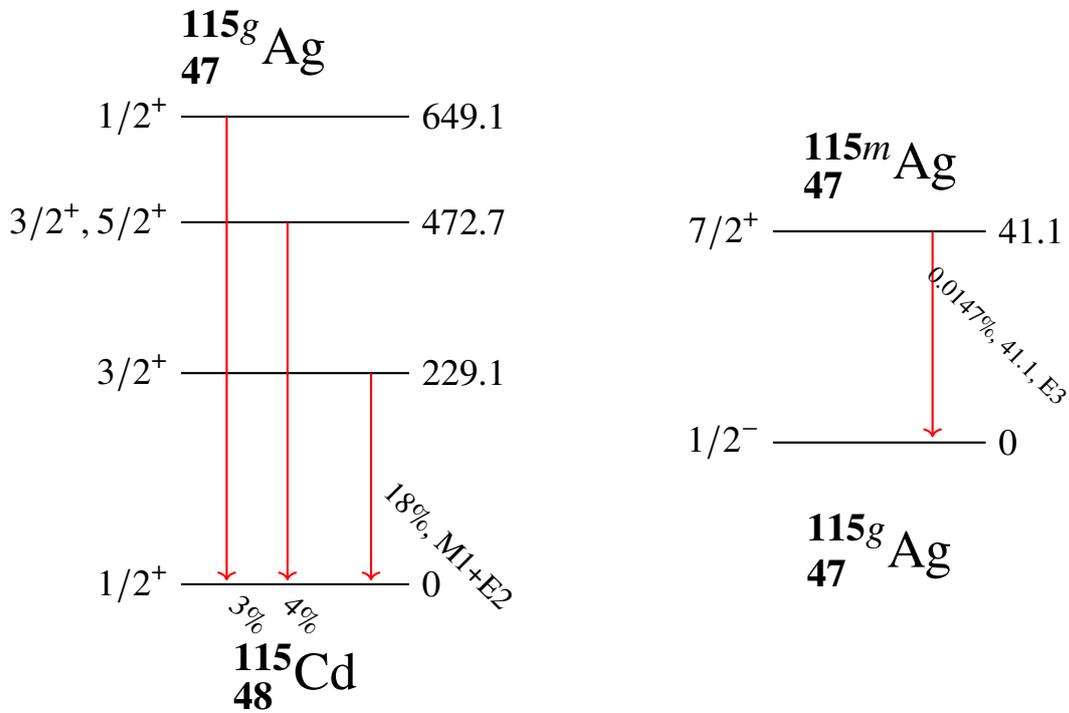


Figure 4: Decay schemes of the nuclei ^{115g}Ag and ^{115m}Ag

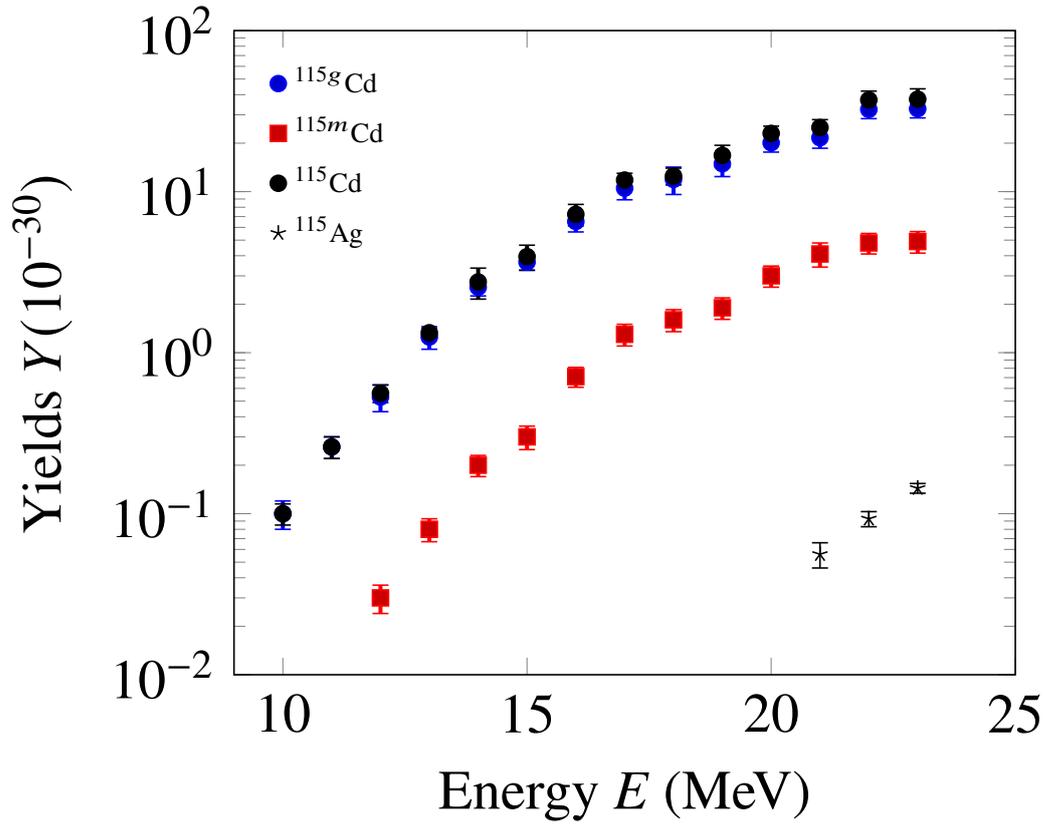


Figure 5: Yields of the photonuclear reactions on the nucleus ^{116}Cd

Table 3. Yields of the photonuclear reactions on ^{116}Cd

Energy, MeV	Yields (10^{-30})			
	^{115g}Cd	^{115m}Cd	^{115}Cd	^{115}Ag
10	0.1 ± 0.01		0.1 ± 0.01	
11	0.26 ± 0.02		0.26 ± 0.03	
12	0.53 ± 0.05	0.03 ± 0.01	0.56 ± 0.06	
13	1.2 ± 0.1	0.08 ± 0.01	1.3 ± 0.2	
14	2.5 ± 0.2	0.20 ± 0.02	2.7 ± 0.3	
15	3.6 ± 0.4	0.30 ± 0.03	3.9 ± 0.4	
16	6.5 ± 0.6	0.7 ± 0.1	7.2 ± 0.7	
17	11 ± 1	1.3 ± 0.2	12 ± 1	
18	12 ± 1	1.6 ± 0.2	13 ± 1	
19	15 ± 2	1.9 ± 0.2	17 ± 2	
20	20 ± 2	3.1 ± 0.4	23 ± 3	
21	22 ± 3	4.1 ± 0.5	25 ± 3	0.056 ± 0.006
22	32 ± 3	4.8 ± 0.5	37 ± 4	0.093 ± 0.01
23	33 ± 4	4.9 ± 0.5	38 ± 4	0.144 ± 0.02

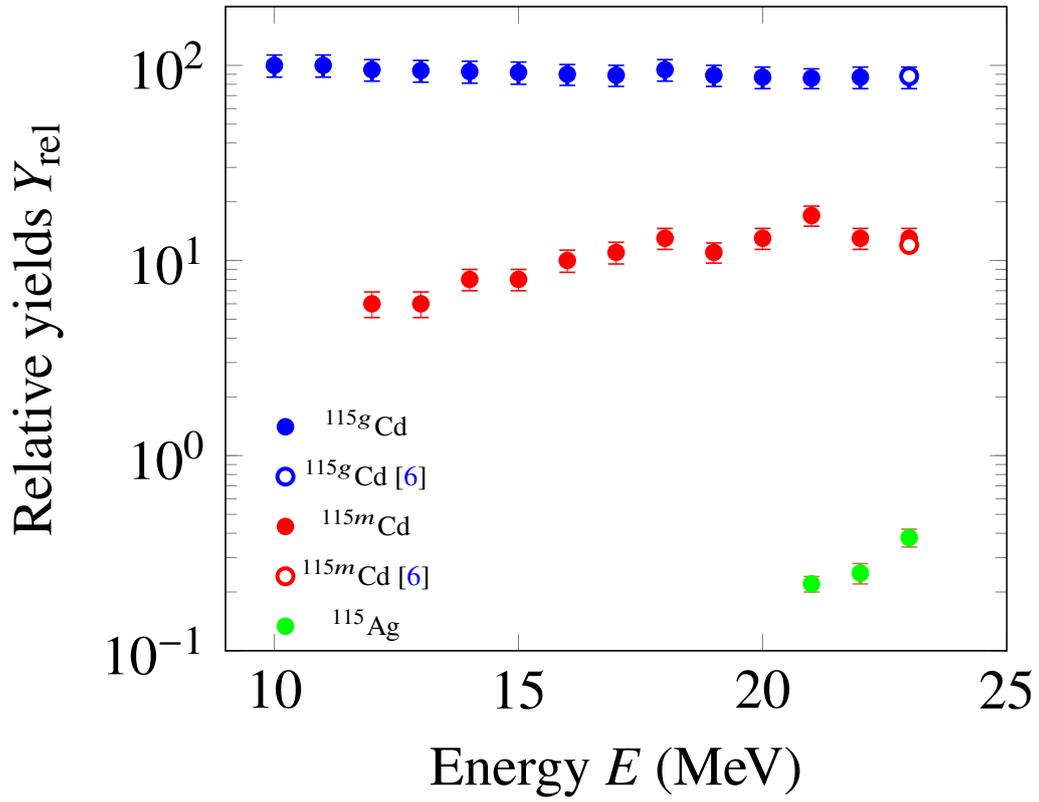


Figure 6: Relative yields of the photonuclear reactions on the nucleus ^{116}Cd

Table 4. Relative yields of the reactions

Energy, MeV	Relative yields (%)		
	^{115}Cd	^{115m}Cd	^{115g}Ag
10	100 ± 13		
11	100 ± 14		
12	95 ± 12	6 ± 1	
13	94 ± 12	6 ± 1	
14	93 ± 12	8 ± 1	
15	92 ± 12	8 ± 1	
16	90 ± 11	10 ± 1	
17	89 ± 11	11 ± 1	
18	95 ± 12	13 ± 2	
19	89 ± 11	11 ± 1	
20	87 ± 11	13 ± 2	
21	86 ± 10	17 ± 2	0.22 ± 0.02
22	87 ± 11	13 ± 2	0.25 ± 0.03
23	87 ± 11	13 ± 2	0.38 ± 0.04

3.2 Isomeric ratio of the pairs $^{115m,g}\text{Cd}$

Based on the measured experimental yields of the metastable and ground states from Table 4, we obtained the isomeric yield ratio ($\text{IR}=\sigma_h/\sigma_l$) of ^{115g}Cd (nuclear spin= $1/2^+$) and ^{115m}Cd (nuclear spin= $11/2^-$) in the $^{nat}\text{Cd}(\gamma,n)$ reactions, which are given in Table 5 for various bremsstrahlung end-point energies. The photon induced isomeric ratio values from this study and the literature data in the GDR region [15, 16, 17, 18, 19, 20, 21, 22] are shown in Fig. 7. As seen in Fig. 7, the experimental isomeric ratio values in the $^{116}\text{Cd}(\gamma,n)$ reaction are in agreement with the theoretical values. Furthermore, the figure shows that the isomeric ratio values of $^{115m,g}\text{Cd}$ increase with increasing excitation energy.

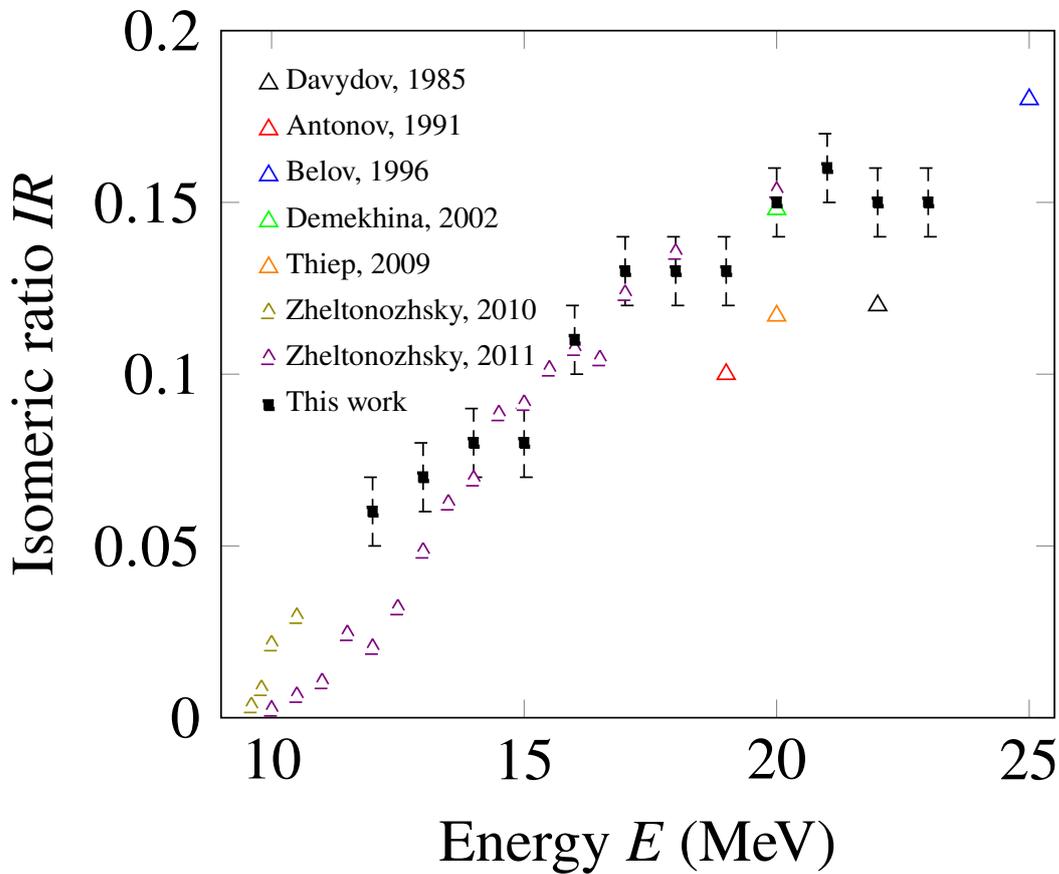


Figure 7: Isomeric ratio of the pairs $^{115m,g}\text{Cd}$

Table 5. Isomeric ratio of the pairs $^{115m,g}\text{Cd}$

Energy, MeV	Isomeric ratio	
	This work	Literature data
9.6		0.003 ± 0.001 [15]
9.8		0.0080 ± 0.0015 [15]
10		0.021 ± 0.002 [15]
		0.002 ± 0.001 [16]
10.5		0.029 ± 0.002 [15]
		0.006 ± 0.002 [16]
11		0.010 ± 0.003 [16]
11.5		0.024 ± 0.006 [16]
12	0.06 ± 0.01	0.020 ± 0.004 [16]
12.5		0.0315 ± 0.030 [16]
13	0.07 ± 0.01	0.048 ± 0.003 [16]
13.5		0.062 ± 0.004 [16]
14	0.08 ± 0.01	0.069 ± 0.005 [16]
14.5		0.088 ± 0.006 [16]
15	0.08 ± 0.01	0.091 ± 0.007 [16]
15.5		0.101 ± 0.007 [16]
16	0.11 ± 0.02	0.107 ± 0.008 [16]
16.5		0.104 ± 0.010 [16]
17	0.13 ± 0.02	0.123 ± 0.008 [16]
17.5		0.130 ± 0.008 [16]
18	0.13 ± 0.02	0.135 ± 0.008 [16]
19	0.13 ± 0.02	0.10 ± 0.01 [17]
20	0.15 ± 0.02	0.148 ± 0.02 [18]
		0.117 ± 0.012 [22]
		0.153 ± 0.017 [16]
21	0.19 ± 0.03	
22	0.15 ± 0.02	0.12 ± 0.02 [19]
23	0.15 ± 0.02	
23.5		0.158 ± 0.016 [22]
25		0.18 ± 0.02 [20, 21]

Conclusions

This study has presented an experimental investigation of the photonuclear reactions of the ^{116}Cd isotope. The yields of the (γ, n) and (γ, p) reaction channels were measured and analyzed with respect to photon energy. The resulting data demonstrated clear energy-dependent behavior, which reflects the underlying nuclear structure and the mechanisms of photon-induced reactions.

A central aspect of the study was the determination of isomeric yield ratios between the metastable and ground states of the residual ^{115}Cd nuclei. These ratios serve as sensitive indicators of angular momentum transfer and nuclear spin population following the photoabsorption process. The precise measurement of these ratios provides valuable insight into the nuclear de-excitation mechanisms.

Furthermore, the isomeric yield ratios obtained in this work are in good agreement with data reported in the literature. This consistency confirms the reproducibility and accuracy of the present results, validating them as a reliable contribution to the field of photonuclear reaction research.

Overall, the study provides important nuclear data for ^{116}Cd and contributes to a deeper understanding of photon-induced reactions in medium-mass nuclei. These results are expected to support further advancements in nuclear physics applications, including radiation shielding design, reactor physics, and the production of medically relevant isotopes.

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