PHOTOEXCITATION OF THE ^{111m}Cd ISOTOPE AT $E\gamma < 3.0$ MeV

O.S. SHEVCHENKO, YU.N. RANYUK, A.N. DOVBNJA, V.N. BORISENKO, I.G. GONCHAROV, V.N. GOSTISHCHEV, E.L. KUPLENNIKOV, A.A. NEMASHKALO, V.I. NOGA, I.I. SHAPOVAL

UDC 621.384.6

National Scientific Center "Kharkiv Institute for Physics and Technology"
(1, Academichna Str., Kharkiv 61108, Ukraine; e-mail: kupl@kipt.kharkov.ua)

The resonant absorption of γ-quanta by ^{111}Cd nuclei with the excitation of its isomeric state has been measured with a step of 200 keV within the interval of end-point energies of the bremsstrahlung spectrum, $E_{\gamma\,\max} = 1.0 \div 3.0$ MeV. The investigation of the metastable state population has been performed making use of the activation technique. The integral cross-sections have been derived for the first time for the intermediate levels with energies of 2006 and 2495 keV which take part in the photoexcitation of the ^{111}Cd isomer.

1. Introduction

Despite the fact that researches in nuclear isomer physics have been carried on for about 70 years, they are now still in progress with an increasing activity. A significant place in these researches belongs to the works dealing with studying the new collective transitions $M1$ [1] and $E1$ with enhanced probability in heavy deformed nuclei [2] and with the problem of creating a γ-laser [3] and nuclear quantum generators [4]. The issues concerning the isotope synthesis in the Universe are also of importance in those studies [5].

The experimental studies of regularities in the photo-induced formation of isomers bring about the solution not only to the fundamental problems but to a number of applications as well. More than a half of the isotopes that are applied in medicine and activation analysis is isomers. Among nuclear constructional materials, there is a lot of elements, the nuclei of which have isomeric levels. Long-lived isomers contribute to the activity of nuclear waste products.

Not in the last place, the permanent interest to the isomer researches is caused by the steady improvement of methods: the increase of the photon source intensities, enhancement of the efficiency and the energy resolution ability of detectors, and so on) [6, 7].

Photonuclear reactions possess certain advantages when studying the excitation of isomeric states. The absence of both the binding energy and the Coulomb barrier for γ-quanta allows one to investigate nuclei effectively in a wide range of energies, including those below the binding energy of nucleons in nuclei. The momentum contributed to a nucleus is equal to 1 $\hbar$ (the contributions of other momenta do not exceed 1%) and does not depend on the γ-quantum energy. It substantially confines the range of spin amplitudes of the activation levels, through which the population of the isomer occurs.

The experimental procedure has its own peculiarities in the indicated energy range, namely, the small cross-sections of the interaction between photons and nuclei (by several orders of magnitude lower than those for the giant resonance) and the resonant character of photon absorption. On the one hand, these features make researches, which are carried on at low photon energies, attractive, because the obtained results contain a large body of information and can be interpreted reliably. On the other hand, they complicate the fulfillment of the same studies.

The data on the ^{111}Cd$(\gamma,\gamma')^{111m}$Cd reaction which are available in the literature were obtained mainly with the help of permanent ^{60}Co sources which emitted photons with energies of 1170 and 1332 keV and a

half-life period of the isotope of 5.25 years. When studying the excitation of isomers, the application of such a source of photons does not avoid difficulties. The probability of the isomer excitation, provided that photons with a fixed energy are used, equals practically zero, owing to different energies of the photons from the source and the levels concerned. Therefore, in the course of experiments, one has to broaden the energy spectrum of applied photons by means of absorbers – the procedure, which inserts uncertainties not only to the measured integral cross-sections but to the energy levels. It is adopted that two activation levels close by energy to 1200 and 1330 keV are excited in the experiments with permanent photon sources.

A great many authors emphasize that there exists a wide spread of values obtained for the integral cross-sections of the photoexcitation of activation levels in experiments where the permanent sources of photons, ^{60}Co, were used. For example, the authors of works [8, 9] note that three of the most recent (with respect to the year 1991) measurements of the integral cross-section for a ^{111}Cd nucleus, which were executed in 1979, 1982, and 1987, gave the results of 0.35, 0.058, and 0.14 barn × eV, respectively. At the same time, the measurement errors indicated in these works amounted to 7–14%. This discrepancy served as a basis for putting forward the assumption about non-resonant nuclear photoabsorption, which was not confirmed experimentally afterwards [8, 9].

Here are the values (in units of barn × eV) of the integral cross-sections of excitation reported for the activation levels in the ^{111}Cd$(\gamma,\gamma')^{111m}$Cd reaction "near 1200 keV" [9] and the 1330-keV level [10–16]: 0.098 ± 0.025 [9], 0.06 ± 0.02 [10], 0.102 ± 0.026 [11], 0.08 ± 0.005 [12], 0.14 ± 0.01 [13], 0.058 ± 0.008 [14], 0.083 ± 0.005 [15], and 0.062 ± 0.005 [16].

A substantial spread of the available experimental data for the ^{111}Cd$(\gamma,\gamma')^{111m}$Cd reaction stimulated the discussion [8, 9, 14], where it was marked that the very existence of the activation level with an energy of 1332 keV in a ^{111}Cd nucleus is doubtful. Uncertain is also the energy position of "a level near 1200 keV".

We have carried out the researches of the ^{111}Cd$(\gamma,\gamma')^{111m}$Cd reaction in the range $1.0 - 3.0$ MeV of the end-point energy of the photon bremsstrahlung spectrum in order to revise the available experimental data.

2. Method of Experiment

The experiment was carried out at an ELIAS electrostatic accelerator of electrons at the National Scientific Center "Kharkiv Institute for Physics and Technology", with the voltage applied to a conductor being up to 3.0 MV. Such properties of the electron beam produced at this accelerator as high intensity (up to 500 μA), monochromaticity, and stability, as well as the opportunity to vary the electron energy smoothly, allowed the experiments to be carried on effectively.

Our experiment was carried out following the photoactivation technique within the photon energy range of $1.0 - 3.0$ MeV with a step of 0.2 MeV. An electron beam 2 mm in diameter and with a current up to 200 μA was slowed down in a tantalum radiator 0.5 mm in thickness cooled with flowing water. The layout of a test bench for the irradiation of specimens was presented in work [17]. The total current of electrons, which reached the radiator, was determined with the help of a device of the Faraday-cup type. The voltage across the conductor of the generator was measured by a rotor voltmeter which had been calibrated using the reaction of beryllium photodisintegration. The uncertainty of the calibration was 50 keV [18].

The isomeric state ^{111m}Cd with an energy of 396 keV has the spin $J^\pi = 11/2^-$ and the half-life period $T_{1/2} =$ 48.54 min, whereas the ground state is stable and has the spin $J^\pi = 1/2^+$. The natural abundance of the ^{111}Cd isotope is 12.81%. The decay of the isomer was determined by registering γ-quanta with an energy of 245.4 keV and the relative probability of the decay of 94.2% [19]. The probability of the emission of a 150.8-keV cascade photon is 31.0% [20] (see Fig. 1).

Pieces of a cadmium foil 15 mm in diameter and 0.2 mm in thickness served as targets. The measurement of the activity induced in the target was carried out with the help of a Ge(Li) γ-spectrometer with a useful capacity of about 40 cm^3 and the energy resolution of 2.5 keV for the γ-line at 1332 keV of the ^{60}Co nucleus. The pulses from the spectrometer were analyzed by a 4096-channel peak analyzer.

3. Results of Measurements

In Fig. 1, one of the spectra of a cadmium target activated in the course of experiment is presented. The experimental parameters were as follows: the beam exposition 60 min, the energy of electrons 3 MeV, and the electron current 50 μA. The term of the activity measurement was 50 min, and the time interval between

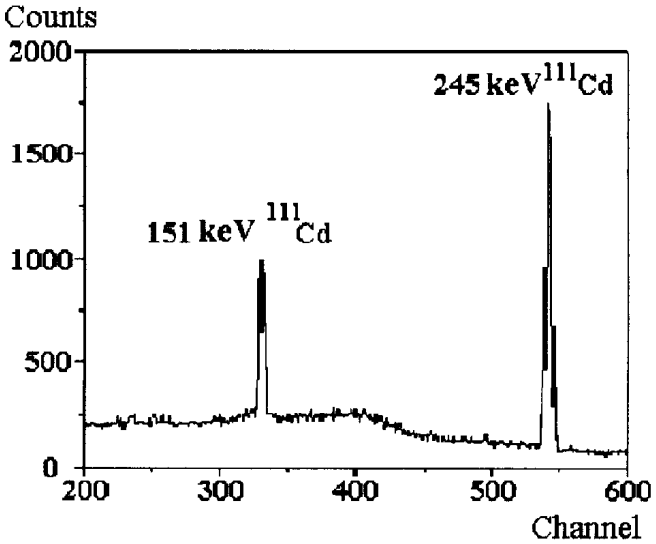

Fig. 1. Emission spectrum of an irradiated cadmium target

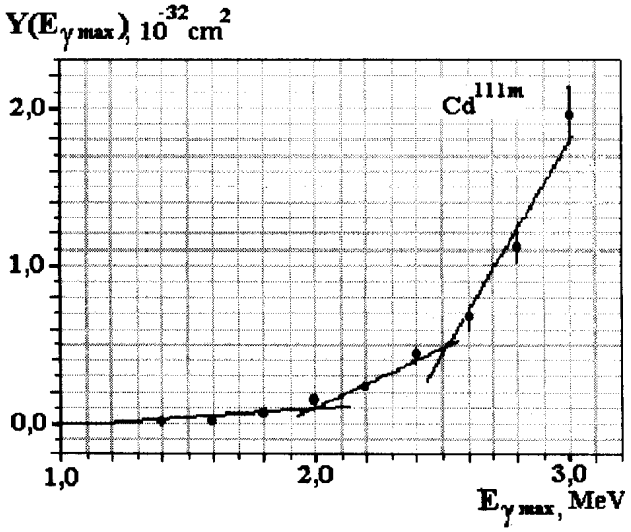

Fig. 2. Yield of the ^{111}Cd$(\gamma,\gamma')^{111m}$Cd reaction versus the end-point energy. The points correspond to experimental data. The broken line is described in the text

the termination of irradiation and the beginning of the measurement 40 min.

The yield of the ^{111}Cd$(\gamma,\gamma')^{111m}$Cd reaction as a function of the end-point energy of the photon bremsstrahlung spectrum was determined by the relation

$$Y(E_{\gamma\,\max}) = \frac{N_{\rm iso}(E_{\gamma\,\max})}{N_e N_T}, \qquad (1)$$

where $Y(E_{\gamma\,\max})$ is the isomer yield per one electron which reached the radiator and per one nucleus of the target; $N_{\rm iso}$ the number of isomer nuclei which were formed in the target; N_e the number of electrons which reached the radiator; and $N_{\rm T}$ the number of nuclei per 1 cm^2 of the target. The dependence $Y(E_{\gamma\,\max})$ is shown in Fig. 2. The errors are equal to the sum of statistical and systematic errors.

4. Analysis of the Results

The populating of the isomer occurs through the process of photon absorption by the so-called activation levels of the isomer and their following decay, directly or through a cascade, into an isomeric state. The reaction yield $Y(E_{\gamma\,\max})$ can also be written down in the form

$$Y(E_{\gamma\,\max}) = \int\limits_{E_{\rm th}}^{E_{\gamma\,\max}} \sigma(E_\gamma) N_\gamma(E_\gamma, E_{\gamma\,\max}) dE_\gamma, \qquad (2)$$

where $\sigma(E_\gamma)$ is the dependence of the cross-section of the photonuclear reaction concerned on the energy of γ-quanta E_γ, and $N_\gamma(E_\gamma, E_{\gamma\,\max})$ is the spectral intensity of the photon beam for the end-point energy $E_{\gamma\,\max}$. The cross-section σ can be presented as a sum of several separate activation resonances.

Since the activation resonances are narrow, the quantity $N_\gamma(E_\gamma, E_{\gamma\,\max})$ can be regarded constant within the range of a single resonance, so that Eq. (2) can be replaced by the system of equations

$$Y_i = \sum_j (\sigma\Gamma)^j_{\rm iso} N^j_i \qquad (3)$$

where Y_i is the reaction yield at the i-th point of the investigated range of $E_{\gamma\,\max}$; j the number of the nuclear activation level; $(\sigma\Gamma)^j_{\rm iso}$ the integral cross-section of isomer activation through the j-th level which is to be determined by analyzing the yield curve; and N^j_i the number of photons in a 1-keV energy interval of the bremsstrahlung spectrum with the energy of the j-th activation level and with the i-th end-point energy of the bremsstrahlung spectrum.

The processing of the results of measurements consists in finding the energy and the integral cross-sections of activation levels. In principle, this task can be tackled by solving the system of equations (3). This problem is quite similar to that of the definition of the reaction cross-section from the yield curve when dealing with a bremsstrahlung beam of photons [21]. The latter is a standard problem for the physics of photonuclear reactions. But, in our case, it is practically impossible

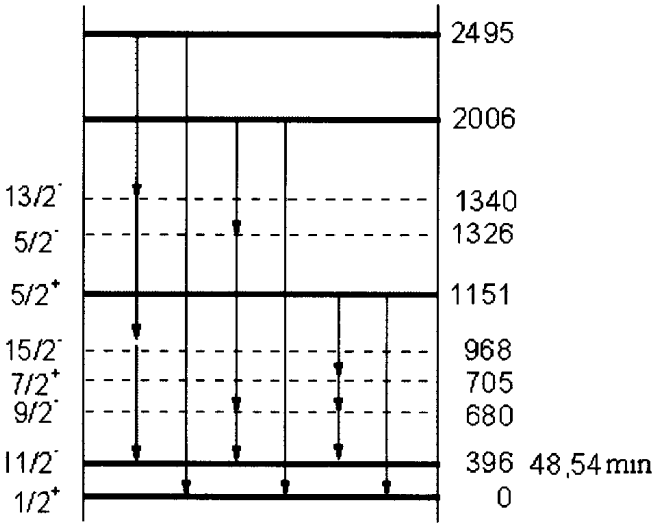

Fig. 3. Simplified schematic representation of the levels of a ^{111}Cd nucleus

to solve Eqs. (3) correctly, owing to the experimental errors made while determining the reaction yield (the incorrectness of the problem) and the values of the end-point energy of the bremsstrahlung spectrum and to the discrete character of the energy dependence of the photoabsorption cross-section.

In Fig. 2, we see the reaction yield function as a broken line increasing with energy with cusps at the energies corresponding to those of excitation of the next activation levels. Within the intervals between the activation level energies, the energy dependence of Y_i is close to straight lines. The activation experiment does not allow one to determine the coordinates of the cusps in the yield versus the energy, i.e. the energy positions of activation levels, in other words. They can be found from spectroscopic data. According to the literature data [20], the even-odd nucleus ^{111}Cd which is composed of 48 protons and 63 neutrons has about 100 levels within the interval of excitation energy $416.7 - 2977.9$ keV. Not all of these levels are activation ones, because the last levels include only those states which are excited in (γ, γ') reactions and are characterized by a non-zero probability of the direct or cascade decay into the isomeric and, simultaneously, direct decay into the ground state [22].

Having analyzed the data of tables [20], we came to the conclusion that only the levels at 1151, 2006, and 2495 keV can be the activation ones, which is in a good agreement with our experimental data (Fig. 2).

Fig. 3 shows a simplified schematic representation of the decay of levels of the nucleus ^{111m}Cd. The spin and parity of the states are indicated on the left, while their energies (in units of keV) are given on the right. The activation levels are marked by bold lines. One can see that all of them undergo a direct decay into the ground state and a cascade one into the isomeric state.

The integral cross-sections were determined as the parameters in Eqs. (3) used for the fitting of experimental yield data, as was done in works [17, 22]. In so doing, the bremsstrahlung spectrum of electrons in a tantalum radiator was modeled with the help of a GEANT3.21 code. Each experimental point corresponds to the averaging over 10^7 measurements, the interval of grouping was 1 keV, and the cut-off energy of the cascade with respect to photons and electrons amounted to 0.5 MeV.

The integral cross-sections $(\sigma\Gamma)^j_{\rm iso}$ calculated in this work for the activation levels with energies of 1151, 2005, and 2495 keV are equal to 0.06 ± 0.02, 0.35 ± 0.06, and 1.2 ± 0.4 barn $\times$ eV, respectively. The errors of the definition of the integral cross-sections are equal to the sum of statistical and systematic ones.

5. Conclusions

By measuring the yield of the ^{111}Cd$(\gamma, \gamma')^{111m}$Cd reaction in the interval of the end-point energies of photons up to 3.0 MeV, we have been obtained the evidences for the existence of two cusps at energies of about 2 and 2.5 MeV, as well as the data on the excitation of the isomer at the photon energies below 1.4 MeV. We have analyzed the most recent spectroscopic data for the isotope ^{111}Cd and have found 3 candidates for activation levels, i.e. the levels through which the isomer is excited.

Unfortunately, the published tables of isotopes do not contain the data necessary for the calculation of the integral cross-sections of activation levels (their lifetimes, spins, and parities).

Most of the data available in the literature on the excitation of the ^{111}Cd isomer were obtained with the help of ^{60}Co sources. The corresponding results cannot adequately reflect the processes that accompany the photoexcitation of the ^{111}Cd isomer. As was already noted, there is no activation level with an energy of 1330 keV in the ^{111}Cd isotope. Concerning the level "close to 1200 keV", the matter may concern the level with an energy of 1151 keV. The value of the integral cross-section for this level calculated by us coincides with the value of (0.058 ± 0.008) barn $\times$ eV obtained in work [14]. There is no information in the literature concerning the levels at 2005 and 2495 keV.

1. *Richter A.* // Nucl. Phys. A. — 1991. — **522**. — P. 139—166.
2. *Collins C.B., Eberhard C.D., Glesener J.W. et al.* // Phys. Rev. C. — 1988. — **37**. — P. 2267—2269.
3. *Collins C.B., Lee F.W., Shemwell D.M. et al.* // J. Appl. Phys. — 1982. — **53**. — P. 4645—4649.
4. *Collins C.B., Davanlo F., Iosif M.C. et al.* // Phys. Rev. Lett. — 1999. — **82**, N 4. — P. 695—698.
5. *Collins C.B., Carrol J.J., Sinor T.W. et al.* // Phys. Rev. C. — 1990. — **42**. — P. 1813—1816.
6. *Gangrskii Yu.P., Tonchev A.P., Balabanov N.P.* // Fiz. Elem. Chast. At. Yadra. — 1996. — **27**, N 4. — P. 1043—1076.
7. *Gangrskii Yu.P., Mazur V.M.* // Ibid. — 2002. — **33**, N 1. — P. 159—200.
8. *Carroll J.J., Byrd M.J., Richmond D.G. et al.* // Phys. Rev. C. — 1991. — **43**, N 6. — P. 1238 — 1247.
9. *Anderson J.A, Byrd M.J., Collins C.B.* // Ibid. — 1988. — **38**, N 6. — P. 2838—2842.
10. *Chertok B.T., Booth E.C.* // Nucl. Phys. — 1965. — **66**. — P. 230—232.
11. *Lakosi L., Csuros M., Veres A.* // Nucl. Instrum. and Meth. — 1974. — **13**. — P. 114—17.
12. *Boivin M., Cauchois Y., Heno Y.* // Nucl. Phys. A. — 1969. — **137**. — P. 520 — 530.
13. *Bikit I., Slivka J., Anicin I.V. et al.* // Phys. Rev. C. — 1987. — **35**, N 5. — P. 1943—1945.
14. *Krcmar M., Ljubicic A., Pisk K. et al.* // Ibid. — 1982. — **25**, N4. — P. 2097—2099.
15. *Krcmar M., Kaucic S., Tastonic T. et al.* // Ibid. — 1990. — **41**. — P. 771 — 773.
16. *Krcmar M., Ljubicic A., Logan B. et al.* // Ibid. — 1993. — **47**. — P. 906—608.
17. *Ranyuk Yu.N., Shevchenko O.S., Gostishchev V.N. et al.* // VANT. Ser. Fiz. Rad. Povrezhd. i Rad. Mater. — 2004. — N85. — P. 108—111.
18. *Astakhov A.M., Barankov D.Yu., Borisenko V.N. et al.* // Ibid. — P. 91 — 94.
19. *Gusev N.G., Dmitriev P.P.* Quantum Emission of Radioactive Nucleons. — Moscow: Atomizdat, 1971 (in Russian).
20. Table of Isotopes / Ed. by R.B. Firestone, V.S. Shirley. 8-th Edition. — New York: Wiley, 1996.
21. *Kuzmenko V.S., Ranyuk Yu.N.* Calculation of Photonuclear Reaction Cross-sections. — Kharkiv, 1971. — (Preprint KhFTI AN UkrSSR 71—26) (in Russian).
22. *Von Neumann-Cosel P., Huxel N., Richter A. et al.* // Nucl. Instrum. and Meth. A. — 1994. — **338**. — P. 425—431.

Received 10.03.05.
Translated from Ukrainian by O.I. Voitenko

ФОТОЗБУДЖЕННЯ ІЗОТОПУ ^{111m}Cd ПРИ $E_\gamma < 3{,}0$ МеВ

О.С. Шевченко, Ю.М. Ранюк, А.М. Довбня, В.М. Борисенко, І.Г. Гончаров, В.Н. Гостіщев, Е.Л. Купленніков, А.А. Немашкало, В.І. Нога, І.І. Шаповал

Р е з ю м е

Резонансне поглинання γ-квантів на ядрі ^{111}Cd із збудженням ізомерного стану досліджено в інтервалі граничних енергій гальмівного спектра $1{,}0 \le E_{\gamma\,\max} \le 3{,}0$ МеВ з кроком 200 кеВ. Заселення метастабільного стану досліджено з використанням активаційної методики. Для двох проміжних станів з енергією 2006 та 2495 кеВ, які беруть участь у фотозбудженні ізомеру ^{111}Cd, вперше отримано інтегральні перерізи.