

<https://doi.org/10.15407/ujpe71.11.847>

V.O. ZHELTONOZHSKY,¹ A.M. SAVRASOV,¹ P.S. DERECHKEY,² O.M. ROKITSKYI¹

¹ Institute for Nuclear Research, Nat. Acad. of Sci. of Ukraine

(47, Nauky Ave., Kyiv 03028, Ukraine; e-mail: asavrasov@kinr.kiev.ua)

² Institute of Electron Physics, Nat. Acad. of Sci. of Ukraine

(21, Universytets'ka Str., Uzhhorod 88017, Ukraine)

EXCITATION OF ISOMERIC STATES OF CADMIUM AND TELLURIUM NUCLEI IN (γ, n) REACTION

The flux-weighted average yields of the $^{120}\text{Te}(\gamma, n)^{119}\text{Te}^m$, $^{122}\text{Te}(\gamma, n)^{121}\text{Te}^m$, $^{124}\text{Te}(\gamma, n)^{123}\text{Te}^m$, $^{126}\text{Te}(\gamma, n)^{125}\text{Te}^m$, $^{128}\text{Te}(\gamma, n)^{127}\text{Te}^m$, $^{130}\text{Te}(\gamma, n)^{129}\text{Te}^m$, $^{112}\text{Cd}(\gamma, n)^{111}\text{Cd}^m$, and $^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}^m$ reactions at the endpoint energy of bremsstrahlung γ -quanta $E_{\text{br}} = 17.5$ MeV have been measured for the first time. A completely statistical character of the reactions on cadmium nuclei and a significant contribution of non-statistical mechanisms in the case of tellurium nuclei have been found. In the former case, the measured flux-weighted average yields were in satisfactory agreement with the results of modeling within the framework of the TALYS-1.96 and TALYS-2.2 codes, whereas deviations were observed in the latter case.

Keywords: flux-weighted average yields, cross sections, activation method, gamma-spectrometry, TALYS-1.96, TALYS-2.2, photonuclear reactions, cadmium, tellurium.

1. Introduction

Photonuclear reactions with neutron emission in the giant dipole resonance (GDR) energy region [1] have been extensively studied for various nuclei over the past decades. At the same time, considerably fewer experimental data are available for (γ, n) reactions with the population of isomeric states; the same is also valid for cadmium and tellurium isotopes. Most studies have been focused on the measurements of isomeric yield ratios. However, data on the yields and the population cross sections of those isomers can provide

information both on the mechanisms of (γ, n) reactions and on the structure of excited levels in the vicinity of isomeric-state energies. Based on the above considerations, the aim of this work was to study the production yields of $^{119}\text{Te}^m$, $^{121}\text{Te}^m$, $^{123}\text{Te}^m$, $^{125}\text{Te}^m$, $^{127}\text{Te}^m$, $^{129}\text{Te}^m$, $^{111}\text{Cd}^m$, and $^{115}\text{Cd}^m$ nuclei in (γ, n) reactions induced by irradiating metallic cadmium and tellurium targets by bremsstrahlung γ -quanta with energies in the GDR interval.

2. Experimental Part and Measurement Results

The flux-weighted average yields were studied using the activation method and bremsstrahlung γ -beams with the endpoint energy $E_{\text{br}} = 17.5$ MeV. Specimens of natural metallic tantalum 30 μm in thickness and gold specimens 10 μm in thickness were used to monitor the bremsstrahlung γ -quantum fluxes. During irradiation, metallic tellurium and cadmium

Citation: Zheltonozhsky V.O., Savrasov A.M., Derechkey P.S., Rokitskyi O.M. Excitation of isomeric states of cadmium and tellurium nuclei in (γ, n) reaction. *Ukr. J. Phys.* **71**, No. 11, 847 (2026). <https://doi.org/10.15407/ujpe71.11.847>.

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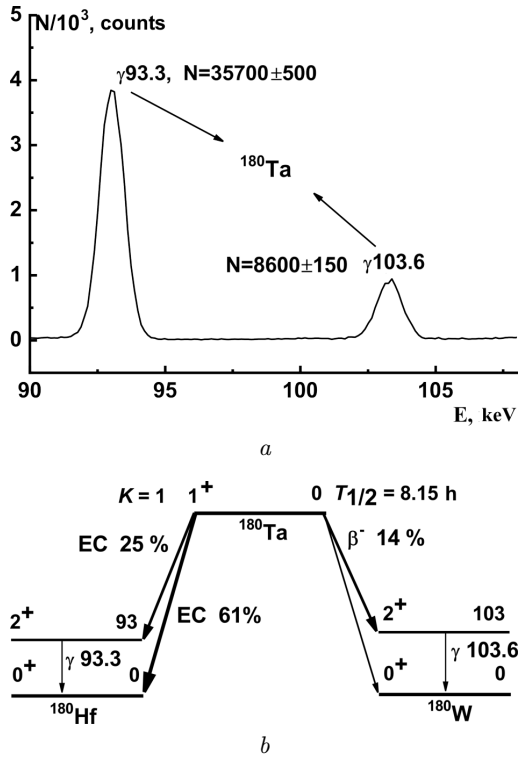


Fig. 1. Fragments of the γ -spectrum of the activated tantalum target (a) and the schematic diagram of ^{180}Ta decay [5] (b)

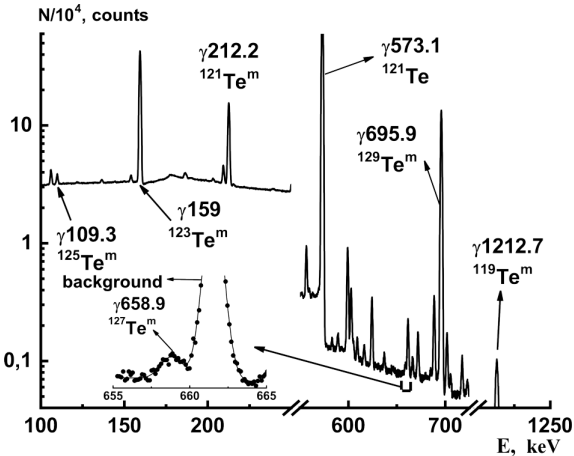


Table 1. Reactions and spectroscopic information on decay products [8]

Reaction	Half-life of the produced radionuclide	Energy of the γ -quantum used for identification, keV	Quantum yield of γ -quantum, %	Self-absorption coefficient, arb. units
$^{120}\text{Te}(\gamma, n)^{119}\text{Te}^m$	4.7 days	1212.73(7)	66.1	1.32(3)
$^{122}\text{Te}(\gamma, n)^{121}\text{Te}^m$	164.2 days	212.189(27)	81.5	1.83(5)
$^{124}\text{Te}(\gamma, n)^{123}\text{Te}^m$	119.2 days	159.00(3)	84.3	2.62(9)
$^{126}\text{Te}(\gamma, n)^{125}\text{Te}^m$	57.4 days	109.276(15)	0.280(3)	5.29(21)
$^{128}\text{Te}(\gamma, n)^{127}\text{Te}^m$	106.1 days	658.9(1)	0.0125(19)	1.33(3)
$^{130}\text{Te}(\gamma, n)^{129}\text{Te}^m$	33.6 days	695.88(6)	3.0(6)	1.33(3)
$^{112}\text{Cd}(\gamma, n)^{111}\text{Cd}^m$	48.54 minutes	245.395(20)	94(7)	1.12(2)
$^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}^m$ *	44.56 days	933.838(4)	2.00(4)	1.07(2)

* Information on the quantum yield was taken from Ref. [9] because the uncertainty of this parameter is substantially lower in this reference.

$= 6.02 \times 10^{23}$ nucleus/g $\times$ mol is the Avogadro number; m is the target mass (in gram units); A is the mass number of the atoms ^{120}Te , ^{122}Te , ^{124}Te , ^{126}Te , ^{128}Te , ^{130}Te , ^{112}Cd , and ^{116}Cd , respectively (in a.m.u.); R is the conversion coefficient; N is the number of counts under the photopeaks accompanying the decay of $^{119}\text{Te}^m$, $^{121}\text{Te}^m$, $^{123}\text{Te}^m$, $^{125}\text{Te}^m$, $^{127}\text{Te}^m$, $^{129}\text{Te}^m$, $^{111}\text{Cd}^m$, and $^{115}\text{Cd}^m$ isotopes; α denotes the γ -quantum yields accompanying the decay of $^{119}\text{Te}^m$, $^{121}\text{Te}^m$, $^{123}\text{Te}^m$, $^{125}\text{Te}^m$, $^{127}\text{Te}^m$, $^{129}\text{Te}^m$, $^{111}\text{Cd}^m$, and $^{115}\text{Cd}^m$ isotopes; ξ is the detection efficiency for the decay γ -quanta; t_{irr} , t_{cool} , and t_{meas} are the irradiation, cooling, and measurement times, respectively (in s units); k is the self-absorption coefficient for the decay γ -quanta; λ denotes the decay constant of $^{119}\text{Te}^m$, $^{121}\text{Te}^m$, $^{123}\text{Te}^m$, $^{125}\text{Te}^m$, $^{127}\text{Te}^m$, $^{129}\text{Te}^m$, $^{111}\text{Cd}^m$, and $^{115}\text{Cd}^m$ isotopes (in s^{-1} units); and F is the bremsstrahlung γ -quantum flux [in $\gamma \times \text{mol}/(\text{s} \cdot \text{cm}^2)$ units].

The γ -spectra were processed using the Winspec-trum software [6]. This software makes it possible to register spectra at specified time intervals. Thus the corresponding nuclides were identified by both their energies and their half-life periods. The efficiency of the decay γ -quantum detection was determined using the standard point calibration sources $^{152,154}\text{Eu}$ and ^{133}Ba . The calibration was additionally tested with the help of the GEANT4 software package [7], in which calculations were performed using the Monte Carlo method. The simulation results agreed with the experimental values within the limits of experimental uncertainty. The values of the parameters λ , p , α , and A were taken from Refs. [8, 9], and the

parameter N was determined from the experimental γ -spectra. The magnitudes of the coefficient k were calculated from the difference between the simulated detection efficiencies of the relevant γ -quanta for point sources and the examined specimens. The simulations were carried out within the framework of the GEANT4 and MCNP-4c [10] codes for additional verification. The simulated detection efficiencies obtained for point sources were consistent with each other and with the experimental values. The energies of γ -quanta used to determine the yields, their yields, and the self-absorption coefficients are quoted in Table 1. The coefficient R was calculated following the procedure described in Ref. [11].

The values obtained for the flux-weighted average yields $\langle Y \rangle_{\text{exp}}$ are presented in Table 2.

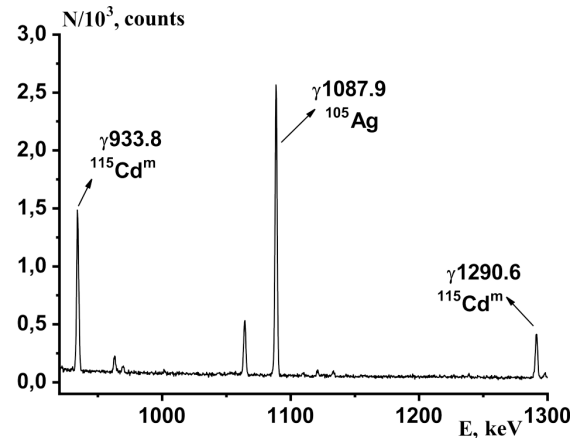


Fig. 3. Fragment of the γ -spectrum of the activated metallic cadmium target 0.6 g in mass. The cooling time was 6 days, and the measurement time was 1 h

Table 2. Flux-weighted average yields of (γ, n) reactions on tellurium and cadmium nuclei

Reaction	Q , MeV	$\langle Y \rangle$, mb					
		$\langle Y \rangle_{\text{exp}}$	TALYS-1.96, $\langle Y \rangle_{\text{stat}}^{\text{theor}}$		TALYS-2.2, $\langle Y \rangle_{\text{stat}}^{\text{theor}}$		$\langle Y \rangle_{\text{other}}^{\text{exp}}$
			ld1	ld6	ld1	ld6	
$^{120}\text{Te}(\gamma, n)^{119}\text{Te}^m$	10.5	8.6(8)	6.7(3)	8.5(4)	11.6(6)	13.8(7)	11.5(14) [12, 13], 12.3(14) [14]
$^{122}\text{Te}(\gamma, n)^{121}\text{Te}^m$	10.1	18(2)	7.6(4)	8.6(4)	17.3(8)	19.1(10)	17.3(21) [15]
$^{124}\text{Te}(\gamma, n)^{123}\text{Te}^m$	9.7	23.1(21)	17.3(9)	16.4(8)	17.4(8)	16.4(8)	17.9(23) [16]
$^{126}\text{Te}(\gamma, n)^{125}\text{Te}^m$	9.3	22.6(23)	14.3(7)	13.5(7)	16.8(8)	14.0(7)	
$^{128}\text{Te}(\gamma, n)^{127}\text{Te}^{m*}$	8.9	15(2)	11.1(6)	12.4(6)	15.2(8)	14.6(7)	19.2(23) [16], 26.7(35) [17, 13]
$^{130}\text{Te}(\gamma, n)^{129}\text{Te}^{m*}$	8.5	20.3(18)	13.8(7)	17.9(9)	10.8(5)	14.2(7)	16.6(20) [16], 21(3) [17, 13]
$^{112}\text{Cd}(\gamma, n)^{111}\text{Cd}^m$	9.8	5.6(6)	4.9(3)	4.5(2)	5.80(3)	5.70(3)	
$^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}^m$	8.9	8.9(7)	9.3(5)	8.7(4)	10.7(5)	9.9(5)	

* For these reactions, no systematic uncertainties of quantum yields were taken into account.

The contribution of neutrons produced in both the bremsstrahlung target and the target assemblies to the population of the $^{121}\text{Te}^m$, $^{123}\text{Te}^m$, $^{125}\text{Te}^m$, $^{127}\text{Te}^m$, $^{129}\text{Te}^m$, $^{111}\text{Cd}^m$, and $^{115}\text{Cd}^m$ isotopes through (n, γ) reaction should also be evaluated. The neutron fluxes were evaluated using the $^{181}\text{Ta}(n, \gamma)^{182}\text{Ta}$ reaction, which was reliably identified in the spectra. An analysis of the ^{182}Ta decay showed that the total contribution of (n, γ) reactions to the population of the above-mentioned nuclei did not exceed 0.1%.

To evaluate the contribution of (γ, p) reactions to the population of the researched isomeric states, it should be taken into account that the cross sections of the (γ, p) reactions in the region of medium nuclear masses are approximately two orders of magnitude lower than those of the (γ, n) reactions. In addition, the ground and isomeric states of the nuclei produced in (γ, p) reactions decay predominantly into the ground states of the examined nuclei. In this work, however, the decay of their isomeric states was studied. Therefore, the contribution of the products of (γ, p) reactions to the population of the researched isomeric states, in cases where the decay of the parent nucleus proceeded to an isomeric state, did not exceed 0.5 %.

For the contribution of $(\gamma, 2n)$ reactions to be taken into account, one should bear in mind that their cross sections are about one order of magnitude lower than those of the investigated (γ, n) reactions. In addition, in our case, the energy thresholds of the $(\gamma, 2n)$ reactions fall within an interval of 15.9–16.8 MeV. For

our bremsstrahlung endpoint energy of 17.5 MeV, the bremsstrahlung photon fluxes are approximately 100 times lower than those in the case of (γ, n) reactions. Together with the lower cross-section, the contribution of $(\gamma, 2n)$ reactions to the population of the studied isomeric states does not exceed 0.3%.

3. Discussion

The analyzed reactions were simulated using the TALYS-1.96 and TALYS-2.2 codes [18]. The theoretical yields $\langle Y \rangle_{\text{stat}}^{\text{theor}}$ were calculated by convolution using a step of 1 MeV according to the formula

$$\langle Y \rangle_{\text{stat}}^{\text{theor}} = \frac{\sum_{i=1}^N \sigma_i \varphi_i}{R \sum_{i=1}^N \varphi_i}, \quad (2)$$

where σ_i are the simulated cross sections of the examined reactions for monochromatic γ -quanta, φ_i are the relative flux values in the bremsstrahlung γ -spectrum calculated in the Geant4 simulation toolkit [7], and R is the conversion coefficient.

The results are presented in Table 2 together with the energy thresholds Q of the researched reactions. As one can see from Table 2, the flux-weighted average yields of both (γ, n) reactions on cadmium isotopes agree satisfactorily with the theoretical results within the experimental accuracy. This fact testifies to a statistical character of the given (γ, n) reactions, since this mechanism dominates in the TALYS-1.96 and TALYS-2.2 codes.

At the same time, the flux-weighted average yields of most (γ, n) reactions on tellurium nuclei regu-

larly exceed the theoretical values, particularly in the case of the TALYS-1.96 code. This systematic excess indicates a shift of the density of the levels associated with higher spins toward lower excitation energies. When the TALYS-2.2 code was used, the agreement with the experimental data was better in general. Nevertheless, the experimental values for the reactions $^{124}\text{Te}(\gamma, n)^{123}\text{Te}^m$, $^{126}\text{Te}(\gamma, n)^{125}\text{Te}^m$, and $^{130}\text{Te}(\gamma, n)^{129}\text{Te}^m$ remain higher than the theoretical ones.

There are six models in the TALYS-1.96 code to describe the level density, whereas the TALYS-2.2 code contains seven models. These models were varied for all examined reactions. In Table 2, the theoretical yields calculated using both a model with a constant temperature and a Fermi-gas (CT + FG) (ld1) [19], which was used by default, and a microscopic model based on temperature-dependent Hartree–Fock–Bogoliubov calculations with the Gogny forces (ld6) [20] are quoted. The resulting theoretical flux-weighted average yields calculated using other models fell within the interval between ld1 and ld6. These data demonstrate that for the lightest tellurium isotope, the microscopic approach in the TALYS-1.96 code provides better agreement with the experiment; however, the discrepancy does not disappear completely. In our view, a substantial correction has to be introduced when the density of high-spin levels shifts toward lower energies.

It should be noted that, although there are some direct measurements of the cross sections of the studied reactions, a considerable amount of work was done to measure the isomeric yield ratios. In some cases, total cross sections were measured for the population of tellurium isotopes in (γ, n) reactions at monochromatic γ -quantum energies. Therefore, by calculating the flux-weighted average yields $\langle Y \rangle_{\text{stat}}^{\text{theor}}$ of the (γ, n) reactions for $E_{\text{gr}} = 17.5$ MeV using Eq. (2) and employing experimental isomeric yield ratios at this endpoint energy taken from the works of other authors, the flux-weighted average yields for the population of isomeric states can be obtained. If the results of direct measurements of the cross sections for the population of the isomeric states are available, the yield can be obtained directly from Eq. (2). The corresponding results obtained for $\langle Y \rangle_{\text{exp}}^{\text{other}}$ together with the references where the experimental data used in the calculations were taken from are presented in Table 2. One can see that these yields, within the experimental un-

certainties, are in agreement with our results in most cases; they are higher than the calculated values, especially when the TALYS-1.96 code was used.

For the flux-weighted average yields $\langle Y \rangle_{\text{stat}}^{\text{theor}}$ calculated according to the results obtained from the TALYS-1.96 and TALYS-2.2 codes, the uncertainty arises from the simulation of the bremsstrahlung spectrum using the Geant4 code. For the given bremsstrahlung endpoint energies, it did not exceed 5%. When experimental data from the works of other authors were used, the total uncertainty was somewhat higher because, in addition to the simulation uncertainties, the uncertainties in the experimental cross sections and isomeric yield ratios were included. For each cross-section, the uncertainty was taken with its individual weighting coefficient; i.e., the weight-averaged uncertainty was calculated, and it amounted to 8–11%. Therefore, the total uncertainty in the determination of the flux-weighted average yields $\langle Y \rangle_{\text{stat}}^{\text{theor}}$ found from the works of other authors and used in our calculations was within the limits of 12–15%.

The uncertainty in the bremsstrahlung γ -quantum flux dominated in most cases when calculating the flux-weighted average yields $\langle Y \rangle_{\text{exp}}$; it did not exceed 7%. In our case, there were no uncertainties in some cases when determining the quantum yields because the most intense γ -lines were used as a rule; in the other cases, the uncertainties ranged from 1 to 20%. The statistical uncertainties in determining the peak areas were within 1–6%. The uncertainties in the detection efficiencies ranged from 2% to 3%. Since relative measurements were performed, the uncertainties in the self-absorption coefficients were within the limits of 2–4%. Based on measurements performed at various spectrometers, the systematic uncertainties were estimated at a level of 2%. As a result, the total uncertainties in the most flux-weighted average yields ranged from 8% to 13% (excluding systematic uncertainties for the yields of γ -quanta with energies of 658.9 and 695.9 keV, which accompany the decay of the $^{127}\text{Te}^m$ and $^{129}\text{Te}^m$ isotopes, respectively).

4. Conclusions

The flux-weighted average yields of the reactions $^{120}\text{Te}(\gamma, n)^{119}\text{Te}^m$, $^{122}\text{Te}(\gamma, n)^{121}\text{Te}^m$, $^{124}\text{Te}(\gamma, n)^{123}\text{Te}^m$, $^{126}\text{Te}(\gamma, n)^{125}\text{Te}^m$, $^{128}\text{Te}(\gamma, n)^{127}\text{Te}^m$, $^{130}\text{Te}(\gamma, n)^{129}\text{Te}^m$, $^{112}\text{Cd}(\gamma, n)^{111}\text{Cd}^m$, and $^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}^m$ have been measured for the first time at a bremsstrahlung γ -

quantum endpoint energy of 17.5 MeV. The following values were obtained: 8.6(8), 18(2), 23.1(21), 22.6(23), 15(2), 20.3(18), 5.6(6), and 8.9(7) mb, respectively. A completely statistical character of the reactions on cadmium nuclei and a substantial contribution of non-statistical mechanisms in the case of tellurium nuclei have been found because, in the former case, the measured flux-weighted average yields agree satisfactorily with the results of simulations using the TALYS-1.96 and TALYS-2.2 codes, whereas in the latter case, they mainly exceed them. The flux-weighted average yields of the reactions $^{122}\text{Te}(\gamma, n)^{121}\text{Te}^m$ and $^{130}\text{Te}(\gamma, n)^{129}\text{Te}^m$ calculated from other experimental studies agree with our experimental data within the experimental uncertainties.

The work was sponsored by IAEA Grant No. 28137.

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Received 22.01.26

Translated from Ukrainian by O.I. Voitenko

*B.O. Желтонозський, А.М. Саврасов,
П.С. Деречкей, О.М. Рокицький*

ДОСЛІДЖЕННЯ ЗБУДЖЕННЯ ІЗОМЕРНИХ СТАНІВ НА ЯДРАХ Cd ТА Te В (γ, n) -РЕАКЦІЇ

Вперше виміряно середньозважені виходи реакцій $^{120}\text{Te}(\gamma, n)^{119}\text{Te}^m$, $^{122}\text{Te}(\gamma, n)^{121}\text{Te}^m$, $^{124}\text{Te}(\gamma, n)^{123}\text{Te}^m$, $^{126}\text{Te}(\gamma, n)^{125}\text{Te}^m$, $^{128}\text{Te}(\gamma, n)^{127}\text{Te}^m$, $^{130}\text{Te}(\gamma, n)^{129}\text{Te}^m$, $^{112}\text{Cd}(\gamma, n)^{111}\text{Cd}^m$ та $^{116}\text{Cd}(\gamma, n)^{115}\text{Cd}^m$ з граничним значенням енергії гальмівних γ -квантів 17,5 MeV. Встановлено повністю статистичний характер реакцій на ядрах кадмію та значний внесок нестатистичних механізмів у випадку ядер телуру, оскільки в першому випадку виміряні середньозважені виходи задовільно узгоджуються з результатами моделювання за допомогою програмних кодів TALYS-1.96 та TALYS-2.2, а в другому спостерігаються відмінності.

Ключові слова: середньозважені виходи, перерізи, активаційний метод, гамма-спектрометрія, TALYS-1.96 та TALYS-2.2, фотонейтронні реакції, кадмій, телур.