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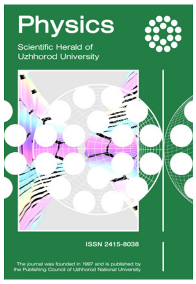


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# Study of the Cross-Section for the $^{122}$Te($\gamma$, $n$)$^{121}$Te Reaction by the Activation Method

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## Abstract

**Relevance.** The study of photonuclear reactions plays a defining role in the formation of modern ideas about high-localized collective excitations in nuclei of the giant resonance type. The giant dipole E1-resonance (GR) is the main feature in γ-quantum absorption cross-sections of nuclei. The presence of isotopes with multiple isotopes makes it possible to trace the evolution of GR characteristics from changes in the number of neutrons in the nuclei. One such element is tellurium.

**Purpose.** The purpose of this research is an experimental and theoretical study of the cross-section of $^{22}$Te(γ, $n$)$^{121}$Te reaction in the region of giant E1-resonance energies.

**Methods.** The study of the cross-section of (γ, n) reaction on $^{122}$Te isotope was performed on the bremsstrahlung γ-beam of the M-30 microtron of the Institute of Electronic Physics of the National Academy of Sciences of Ukraine. The yield curves were measured in the range of maximum gamma-quantum energies $E_{max}$=10-18 MeV. The reaction cross-section was calculated by the inverse matrix method. When registering the reaction products, an activation technique was used, while the gamma activity of the products was recorded by the spectrometric method. The theoretical calculations of the cross-section for the $^{122}$Te(γ, $n$)$^{121}$Te reaction were performed using the TALYS-1.9 software package.

**Results.** The measured experimental yield ratios of the $^{122}$Te(γ, $n$)$^{121}$Te and $^{130}$Te(γ, $n$)$^{129}$Te $d = Y_n^{121} / Y_n^{129} = f(E_{max})$ reactions allowed the experimental cross-section for the $^{122}$Te(γ, $n$)$^{121}$Te reaction to be calculated. The cross-section has a single hump shape with a maximum at an energy of ~ 15.3 MeV. It was approximated by the Lorentz curve with the parameters $\delta_0$=(274.1±2.1) MB, $E_0$ (15.27±0.10) MeV, $\Gamma_0$=(4.76±0.08) MeV. The cross-section obtained was compared with similar cross-sections for $^{126}$Te and $^{130}$Te isotopes, as well as with theoretical calculations according to the TALYS-1.9 program.

**Conclusions.** The obtained cross-section for the $^{122}$Te(γ, $n$)$^{121}$Te reaction is consistent with the evolution of the parameters of (γ, n) reaction cross-section on tellurium isotopes $^{130}$Te(γ, $n$)$^{129}$Te with a change in the number of neutrons. The theoretical approaches used are satisfactorily consistent with the experimental data. This agreement indicates the main contribution of the statistical mechanism to the cross-section of the considered (γ, n) reaction and a relatively small contribution of semi-direct processes.

**Keywords:** microtron, bremsstrahlung gamma radiation, photonuclear reaction cross-section, $^{122}$Te, gamma spectrometry

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## Introduction

The main feature in the gamma-ray absorption cross-sections of atomic nuclei in the 10-20 MeV range is the giant E1 resonance (GR). The study of its characteristics has played an important role in the formation of modern understandings of nuclear collective perturbations. Therefore, an empirical study of the GR parameters was carried out as a direct measurement of the $\sigma_{tot}$ cross-section both by the absorption method [1; 2] and by summing the cross-sections of the partial decay channels of the E1 resonance, i.e. by summing the (γ, n), (γ, 2n), (γ, 3N), etc. reaction cross-sections [3]. Recently, the focus of research on giant dipole resonance has largely shifted from the study of its gross characteristics and taxonomics to the study of partial channels of GR decay with fixation of specific isolated, isomeric states of daughter nuclei [4].

The growing interest in the study of photonuclear reactions in the region of 10-20 MeV, which is observed today, can be associated with several reasons, in particular, both with the need to obtain missing information about the cross-sections of photonuclear reactions, for example, for astrophysical calculations, for which there is a need [5], and with the creation of fundamentally new intensive sources of quasi-monochromatic gamma radiation [6; 7].

To date, cross-section for the $^{122}$Te(γ, n)$^{121}$ reaction has not been explored. A detailed study of the evolution of giant resonance characteristics from changes in nuclear mass for $^{124-130}$Te heavy isotopes was carried out in the work [8]. The work was performed on a beam of quasi-monochromatic photons from positron annihilation on the fly. The measurement was performed in the range of gamma-ray quantum energies of 8-26 MeV. By registering neutrons, was determined the complete cross-section of photoneutron reaction s At the same time, the possibility of 1n, 2n, and 3n neutrons escape was determined experimentally.

Natural tellurium samples are known to contain very few light isotopes $^{120}$Te, $^{122}$Te: $^{120}$Te (0.09%), $^{122}$Te (2.4%). That is why, until recently, photoneutron cross-sections on them have not been studied. Such studies began to be conducted only with the advent of highly enriched targets of light tellurium isotopes [8]. However, getting such targets is very difficult and expensive.

*The purpose of this paper* is to study the cross-section for the $^{122}$Te(γ, n)$^{121}$Te reaction in the energy range 10-18 MeV, as well as to compare the results with theoretical calculations.

### Materials and Methods

This study presents the results of studying targets in the form of disks of high-purity vitreous tellurium oxide TeO, with a diameter of 25 mm and a thickness of 2 mm. Natural tellurium was used. Despite the insignificant content of $^{122}$Te in the studied samples, the present activity of $^{121}$Te was accurately recorded and identified. Measurement of the $^{122}$Te(γ,n)$^{121}$Te reaction yields was performed using the activation technique. Gamma radiation from the decay of reaction products (γ, n) was recorded.

Irradiation of the studied samples was carried out in the Department of Photonuclear Processes Institute of Electron Physics of the National Academy of Sciences of Ukraine on a braking gamma beam of the M-30 microtron, the parameters of which are given in [9]. The average current was 5 $\mu$a, monitoring was performed every 1.2 seconds and was recorded. The energy of accelerated electrons was changed by changing the number of orbits of the electron beam (within a wide range) and changing the magnitude of the conducting magnetic field strength (within one number of orbits). The value of the conducting magnetic field strength was controlled by the method of nuclear magnetic resonance. The irradiation was performed in the maximum energy range of the bremsstrahlung gamma-ray beam 10-18 MeV in increments of ΔE=0.5 MeV.

The irradiation time $t_{irr}$ it was 20 minutes at high energies and 2 hours near the threshold (γ, n) reactions, irradiation time, and measurements were selected from the optimal conditions for recording gamma lines from the decay of daughter nuclei. The error of recording equipment was less than 5%. Measurements of the reduced gamma activity of the studied targets were performed on a 175 cm$^3$ HPGe detector (2 keV resolution for a 1332 keV $^{60}$Co line). A typical instrumental gamma spectrum is shown in Figure 1.

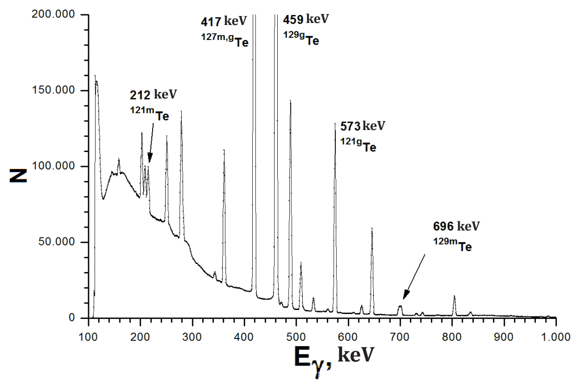


**Figure 1**. Instrumental gamma spectrum of an irradiated $TeO_2$ target

## Results and Discussion

Along with the measurement of gamma lines from the decay of $^{121}$Te obtained in $^{122}$Te(γ, n)$^{121m,g}$Te reaction gamma lines were measured from $^{129}$Te decay obtained in $^{130}$Te(γ, n)$^{129m,g}$Te reaction, that were used to calibrate $^{122}$Te(γ, n)$^{121}$Te reaction yield. The cross-sections for the $^{130}$Te(γ, n)$^{129}$Te reaction were taken from [8]. Basic spectroscopic parameters from the decay of both the main and isomeric states of isotopes $^{121}$Te and $^{129}$Te is shown in Table 1 [10-13].

**Table 1**. Main spectroscopic parameters

| No. | Isotope | $B_n$ | $J^\pi$ | $E_{iso}$ (KeV) | E (KeV) | $T_{1/2}$ | α (%) |
|---|---|---|---|---|---|---|---|
| 1 | $^{121m}$Te | | $11/2^-$ | 294 | 212 | 154 days | 81.4 |
| 2 | $^{121g}$Te | 9.834 | $1/2^+$ | | 573 | 19.16 hours | 80.3% |
| 3 | $^{129m}$Te | | $11/2^-$ | 105 | 696 | 33.6 days | 2.6 |
| 4 | $^{129g}$Te | 8.419 | $3/2^+$ | | 456 | 69.6 min | 7.7 |

The table shows the following values: $B_n$ – thresholds of (γ, n) reactions, $J^\pi$ – spin parity, $E_{iso}$ – energy of the isomeric level, $E_\gamma$ – energy of the analytical gamma line, $T_{1/2}$ – half-life, α – intensity. Experimentally obtained ratios of the ground state excitation yield of isotope $^{121}$Te ($Y_{g1}$) to the ground state excitation yield of isotope $^{129}$Te ($Y_{g2}$):

$$\eta_1 = Y_{g1}/Y_{g2} = c_{12} \cdot b_{12}(\lambda_1 \cdot \varphi_2 \cdot f_2/\lambda_2 \cdot \varphi_1 \cdot f_1) \cdot (N_1/N_2) \quad (1)$$

where $c_{12}$ – coefficient that takes into account miscalculations and pulse overlays, $b_{12}$ – the ratio of the content of the corresponding isotopes in the target ($b_{12}=b_2/b_1$), λ – decay coefficient, $\phi_{12}=\xi k\alpha$, where ξ – photoefficiency of analytical gamma-ray line registration during the decay of ground states, $k$ – coefficient of self-absorption of these lines in the material of the target under study, $\alpha$ – the intensity of analytical gamma lines, $f$ – time function: *$f(t)=[1-\exp(t_{itr})]\cdot\exp(t_{cool})[1-\exp(t_{meas})]\cdot(t_{itr},t_{cool},t_{meas}$ –times of irradiation,cooling and measurement)*, $N$ – the number of pulses under photo peak of analytical gamma lines.

Both $^{121}$Te and $^{129}$Te tellurium isotopes have isomeric states and thus in the reaction (γ, n) both their ground states and isomeric states are populated. At the same time, the total yield (γ, n) of the $Y_n$ reactions, related to the excitation yields of the ground $Y_g$ and the isomeric state $Y_m$ is as follows:

$$Y_n = Y_g + Y_m = Y_g(1 + Y_m/Y_g) = Y_g(1 + d) \quad (2)$$

Experimentally obtained isomeric ratio of d yields for $^{121}$Te and $^{129}$Te isotopes is described in [14]. Studying the ratio of population yields in (γ, n) reactions of the ground states of tellurium isotopes can be determined by $Y_n^{121}/Y_n^{129}$ – ratio of the total reaction yield (γ, n) on $^{122}$Te isotope until the complete $^{130}$Te(γ, n)$^{129}$Te reaction yield, (Fig. 2). The root-mean-square error is less than 1% and does not exceed the point size.

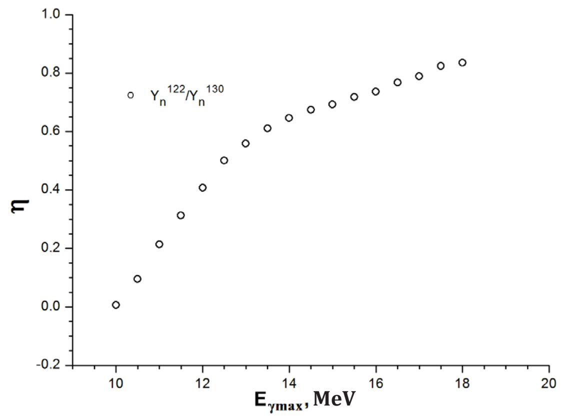


**Figure 2**. Dependence of the $Y_n^{122}/Y_n^{130}$ yield ratio on the maximum energies of the braking beam spectrum

Using the cross-section for $^{130}$Te(γ, n)$^{129}$Te reaction in [8] and the resulting experimental dependence $\eta=Y_n^{121}/Y_n^{129}$ from the energy of the inhibitory gamma spectrum, the cross-section for the $^{122}$Te (γ, n)$^{121}$Te reaction can be calculated. The calculation was performed by the inverse matrix method [15] in increments of 1 MeV. The resulting reaction cross-section (γ, n) is shown in Figure 3.

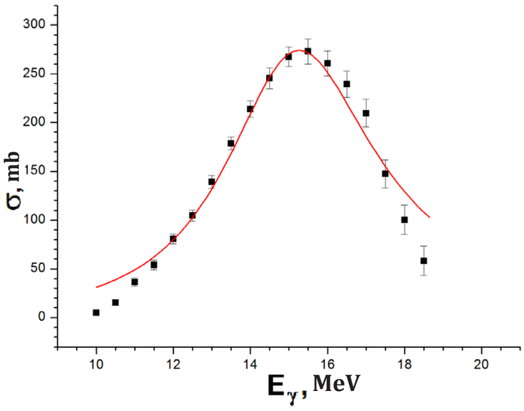


**Figure 3**. $^{122}Te(\gamma, n)^{121}Te$ reaction cross-section

As can be seen from Figure 3, the resulting cross-section has a single-humped shape with a maxim at an energy of ~15.3 MeV, the result of approximation of the cross-section by the Lorentz curve is shown as a solid curve:

$$\sigma(E) = \sigma_0 E^2 \Gamma_0^2 [(E^2 - E_0^2) + E^2 \Gamma_0^2] \quad (3)$$

Here $\sigma_0$, $E_0$, $G_0$ are parameters. The approximation was carried out using the least squares method. The following parameter values are obtained: $\sigma_0$=(274.1±2.1) mb, $E_0$=(15.27±0.10) MeV, $G_0$=(4.76±0.08) MeV.

Figure 4 shows a comparison of the cross-sections for the $^{122}Te(\gamma, n)^{121}Te$ reaction with cross-sections for (γ, n) reactions on $^{126}Te$ and $^{130}Te$ heavier tellurium isotopes [8]. The evolution of cross-sections from light to heavy isotopes is observed. General trends can be noted: shift of the $^{122}Te$ cross-section threshold in the direction of higher energies and some growth of the $^{126}Te$ and $^{130}Te$ cross-sections is most likely due to an increase in the mass of these isotopes.

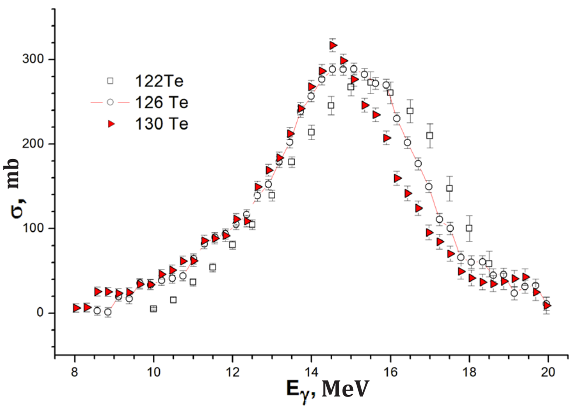


**Figure 4**. Comparison of (γ, n) reaction cross-sections on $^{122}Te$, $^{126}Te$, $^{130}Te$ isotopes

In order to compare the obtained experimental cross-sections with theoretical estimates, calculations of the cross-sections for the $^{122}Te(\gamma, n)^{121}Te$ reaction are performed using the TALYS-1.9 software package [16]. For theoretical evaluation, the following scheme is used: a target core with the following characteristics ($Z_i$, $N_i$) and spin parity ($J_i$, $\pi_i$) absorbs a dipole gamma quantum with $E_\gamma$ energy and forms a compound nucleus with excitation energy $E_c$ ($E_c = E_\gamma$) and the spectrum of possible spin and parity values ($J_c$, $\pi_c$). The total absorptions section $\sigma_{tot}$ is calculated using the parameterized characteristics of the giant E1 resonance. The decay of the excited nucleus occurs in accordance with the Hauser-Feshbach statistical mechanism [17]. Additionally, the impurity of semi-direct processes is considered, which was a fraction of a percent at the energy $E_\gamma$=12 MeV and 8% at energy $E_\gamma$=18 Mev. Neutron emission at specific levels (zones) of the daughter nucleus was calculated using $T_l$ permeability coefficients, which were based on the optical model. At the same time, specific discrete levels from the RIPL-3 base were taken to the excitation energy of the daughter nuclei E=3 MeV [18]. At higher excitation energies, the spectrum was considered continuous, described by the density of levels ρ(E, J, $\pi$) and was divided into a certain number of energy bands. In this case – 50. The effective permeability coefficient $T^{ef}_l$ was determined for each band.

The density of ρ levels was described in two approaches: the constant temperature model and the energy-shifted Fermi-gas model [16; 19]. Results of calculating the cross-section for the $^{122}Te(\gamma, n)^{121}Te$ reaction and their comparison with the experiment are shown in Figure 5. Light circles indicate the result of calculations using the constant temperature model, triangles – the energy-shifted Fermi-gas model, dark dots – the experimental results.

The figure shows that both theoretical approaches used give very similar results and are in satisfactory agreement with the experimental data. This agreement indicates the main contribution of the statistical mechanism to the cross-section of the considered (γ, n) reactions and, accordingly, a relatively small contribution of semi-direct processes.

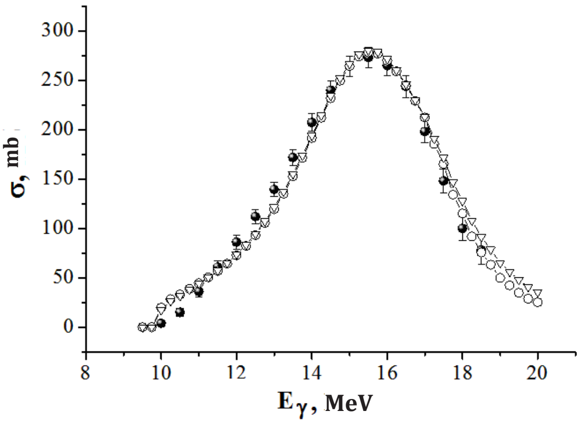


**Figure 5**. Comparison of (γ, n) reaction cross-sections on $^{122}Te$, $^{126}Te$, $^{130}Te$ isotopes

## Conclusions

The presented experimental studies of the $^{122}Te(\gamma, n)^{121}Te$ reaction were carried out on the bremsstrahlung gamma-ray beam of the M-30 microtron of the Institute of Electronic Physics of the National Academy of Sciences of Ukraine in the maximum energy range of the bremsstrahlung spectrum $E_{\gamma max}$=10-18 MeV. The activation method was used in the measurements.

As a result of the measurements performed, the ratio of the $^{122}Te(\gamma, n)^{121}Te$ total reaction yield to $^{130}Te(\gamma, n)^{129}Te$ total reaction yield was determined, which allowed, using the cross-section for the $^{130}Te(\gamma,n)^{129}Te$ reaction [8], calculate both the absolute yield and the cross-section for the $^{122}Te(\gamma,n)^{121}Te$ reaction. Theoretical calculations of the (γ, n) reaction cross-section for $^{122}Te$ isotope have been performed. Calculations were performed using the TALYS-1.9 software package. In the process of comparing theoretical and experimental results, their satisfactory agreement was obtained.

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## Вивчення перерізу реакції $^{122}$Te(γ, n)$^{121}$Te активаційним методом

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**Анотація**

**Актуальність**. Дослідження фотоядерних реакцій відіграє визначальну роль у формуванні сучасних уявлень про високорозташовані колективні збудження в ядрах типу гігантських резонансів. Гігантський дипольний E1-резонанс (ГР) – головна особливість у перерізах поглинання γ-квантів ядрами. Наявність ізотопів із багаточисленими ізотопами дає змогу простежити еволюцію характеристик ГР від зміни числа нейтронів в ядрах. Одним з таких елементів являється телур

**Мета**. Метою роботи є експериментальне та теоретичне дослідження перерізу реакції $^{122}$Te(γ, $n$)$^{121}$Te в області енергій гігантського E1-резонансу.

**Методи**. Дослідження перерізу реакції (γ, $n$) на ізотопі $^{122}$Te проводилося на гальмівному γ-пучку мікротрону М-30 Інституту електронної фізики НАН України. Криві виходу вимірювалися в інтервалі максимальних енергій гамма-квантів $E_{\gamma max}$=10–18 МеВ. Переріз реакції розраховувався методом оберненої матриці. У процесі реєстрації продуктів реакції використовувалася активаційна методика, водночас реєструвалася гамма-активність продуктів спектрометричним методом. Теоретичні розрахунки перерізу реакції $^{122}$Te(γ, $n$)$^{121}$Te проводилися за допомогою програмного пакету TALYS-1.9.

**Результати**. Виміряні експериментальні відношення виходів реакцій $^{122}$Te(γ, $n$)$^{121}$Te і $^{130}$Te(γ, $n$)$^{129}$Te $d = Y_n^{121} / Y_n^{129} = f(E_{max})$ дали змогу розраховувати експериментальний переріз реакції $^{122}$Te(γ, $n$)$^{121}$Te. Переріз має одногорбу форму з максимумом при енергії ~15,3 МеВ. Він апроксимувався кривою Лоренца з параметрами $\delta_0$ = (274,1±2,1) мб, $E_0$ (15,27±0,10)МеВ, $\Gamma_0$=(4,76±0,08) МеВ. Проведено порівняння одержаного перерізу з аналогічними перерізами для ізотопів $^{126}$Te і $^{130}$Te, а також теоретичними розрахунками за програмою TALYS-1.9.

**Висновки**. Одержаний переріз реакції $^{122}$Te(γ, $n$)$^{121}$Te узгоджується з еволюцією параметрів перерізів (γ, $n$) реакції на ізотопах телуру $^{130}$Te(γ, $n$)$^{129}$Te зі зміною числа нейтронів. Використані теоретичні підходи задовільно узгоджуються з експериментальними даними. Таке узгодження свідчить про основний вклад статистичного механізму в переріз розглянутої (γ, $n$) реакції і порівняно малий вклад напівпрямих процесів

**Ключові слова**: мікротрон, гальмівне гамма-випромінювання, переріз фотоядерної реакції, $^{122}$Te, гамма-спектрометрія