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V.M. MAZUR, Z.M. BIGAN, P.S. DERECHKEY, O.M. POP

Institute of Electron Physics, Nat. Acad. of Sci. of Ukraine
(21, Universytets'ka Str., Uzhhorod 88017, Ukraine; e-mail: pop.ksenja@gmail.com)

ON THE MECHANISM OF PHOTONEUTRON REACTIONS AT LIGHT TELLURIUM ISOTOPES IN THE 10–18 MeV INTERVAL

The yield of the ^{122}Te$(\gamma,n)^{121}$Te reaction is measured, and its cross-section is calculated in a gamma-ray energy interval of 10–18 MeV. The obtained cross-section is compared with the cross-section of the reaction ^{120}Te$(\gamma,n)^{119}$Te. The experimental results are compared with those of theoretical calculations performed with the use of the software package TALYS-1.9. The statistical mechanism dominant in (γ,n) reactions at the studied nuclei is found.

Keywords: giant dipole resonance, atomic nucleus, nuclear reactions, cross-section, bremsstrahlung gamma spectrum, isomeric ratio.

1. Introduction

The giant dipole resonance (GDR) is the main specific feature in the cross-sections $\sigma_{\rm tot}$ of gamma quantum absorption by atomic nuclei in the energy interval of 10–20 MeV, being one of the fundamental modes of their excitation. The study of the GDR has played a substantial role in the formation of modern concepts about collective perturbations in nuclei.

The GDR parameters were studied both by directly measuring the cross-section $\sigma_{\rm tot}$ with the use of the absorption method [1, 2] and by summing up the cross-sections of the partial channels of the GDR decay: the reactions (γ,n), $(\gamma,2n)$, $(\gamma,3n)$, and so forth [3]. In recent years, the focus of research was rather strongly shifted from the study of the gross characteristics of the GDR and its systematization to the study of partial channels of the GDR decay with the fixation of specific distinguished states of daughter nuclei [4].

A new burst of interest in the study of photonuclear reactions in the GDR region, which has been observed recently, is a result of several factors. The latter include both the creation of basically new intense sources of quasimonochromatic gamma radiation [5,6] and the necessity in obtaining the information about the cross-sections of photonuclear reactions, in particular, for astrophysical calculations [7].

As is known from astrophysics, nuclei heavier than iron were mainly synthesized in neutron capture reactions (r- and s-processes). But there are several dozens of neutron-deficient stable isotopes that are shielded by stable isobars from the capture of fast neutrons. Those nuclei, which are commonly referred to as p-nuclei, are produced in a chain of photonuclear reactions: (γ,n), (γ,p), (γ,α) [8, 10]. For the calculation of a lot of p-processes, the corresponding database including dozens of reaction cross-sections is required. In spite of the efforts made in the last years, the experimental information about the parameters of photonuclear reactions, including the running of p-processes, is very scarce.

In particular, the p-nuclei also include the light isotope ^{120}Te [10]. The light isotopes of tellurium ^{120}Te and ^{122}Te are similar by their nature. So, when analyzing the mechanisms of (γ,n) reactions for them, it is reasonable to consider those isotopes together. The cross-section of (γ,n) reactions at the ^{122}Te nucleus

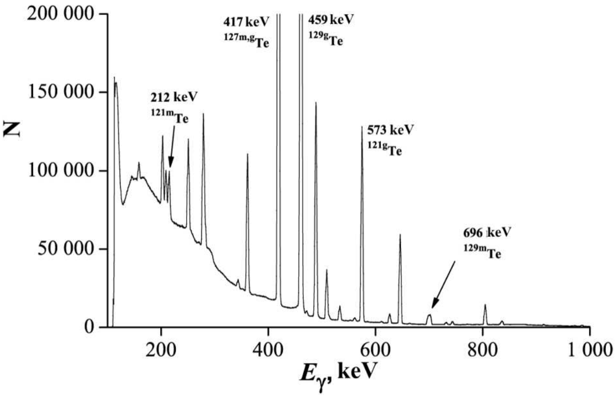

Fig. 1. A section of the apparatus spectrum from the irradiated target

has not been determined till now. However, for ^{120}Te, this cross-section was measured by us recently [11].

A systematic study of the evolution of the giant resonance form was carried out for the heavy isotopes $^{124-130}$Te and ^{140,142}Ce in work [12]. Since the number of neutrons in those isotopes varies from 72 to 84, the cited authors aimed to study the evolution of the GDR parameters near the closed shell with $N = 82$ (^{140}Ce). The measurements were done in an interval of 8–26 MeV. The total cross-section of photoneutron reactions, $\sigma_{\rm tot} = \sigma(\gamma,n) + \sigma(\gamma,2n) + \sigma(\gamma,pn) + ...$, was determined.

The aim of this work was to study the cross-sections and the mechanism of the reactions $^{120}\mathrm{Te}(\gamma,n)^{119}\mathrm{Te}$ and $^{122}\mathrm{Te}(\gamma,n)^{121}\mathrm{Te}$ in an energy interval of 10–18 MeV.

2. Experimental Technique

In our research, the activation method was applied. The examined targets were fabricated from vitreous tellurium oxide TeO with a purity of 99.99% in the form of disks 25 mm in diameter and 2 mm in thickness. The experimental specimens were irradiated in the bremsstrahlung gamma beam on an M-30 microtron at the Department of Photonuclear Processes of the Institute of Electronic Physics of the National Academy of Sciences of Ukraine. The main characteristics of the microtron were described in work [13].

Table 1. **Spectroscopic parameters**

No.	Isotope	B_n	J^π	$E_{\rm iso}$, keV	E_γ, keV	$T_{1/2}$	α, %
1	^{119m}Te	–	$11/2^-$	261	1212	4.7 days	66.2
2	^{119g}Te	10.292	$1/2^+$	–	644	16.05 h	84.0
3	^{121m}Te	–	$11/2^-$	294	212	154 days	81.4
4	^{121g}Te	9.834	$1/2^+$	–	573	19.16 h	80.3
5	^{129m}Te	–	$11/2^-$	105	696	33.6 days	2.6
6	^{129g}Te	8.419	$3/2^+$	–	456	69.6 min	7.7

The energy of accelerated electrons was varied in a wide interval by making use of two methods: either by changing the orbit number of the electron beam or, for the fixed orbit number, by changing the magnitude of the guide magnetic field. The field strength was controlled with the help of the magnetic resonance method. The energy spread in the electron beam in the accelerator did not exceed $\pm(5\div20)\times\Omega$ keV [13]. Here, $\Omega = H/H_0$, where H is the magnitude of the guide magnetic field in the microtron, and H_0 the cyclotron field. In the case of microtron, $\Omega \cong 1$, as a rule [13]. The average current was equal to 5 μA. The current was registered automatically with a time step of 1.2 s.

The experimental specimens were γ-irradiated in an interval of 10–18 MeV with the step $\Delta E = 0.5$ MeV. The irradiation time $t_{\rm irr}$ was 20 min at high energies and 2 h near the threshold of (γ,n) reactions. The cooling and measurement times were selected to provide optimal conditions for the registration of gamma lines from the decay of daughter nuclei. The relevant errors of the registration equipment were less than 5%.

The gamma spectra of irradiated targets were measured with the help of a high-resolution gamma spectrometer on the basis of a 175-cm^3 HPGe detector and an 8192-channel CANBERRA analyzer connected to a computer for the data accumulation. The detector resolution was 1.9 keV for the 1332-keV line of cobalt-60. A section of the apparatus spectrum obtained from the irradiated target is shown in Fig. 1.

3. Experimental Results and Their Analysis

Together with the measurement of gamma lines from the decay of the ^{119}Te and ^{121}Te nuclei, we measured gamma lines from the decay of the ^{129}Te nucleus obtained in the reaction $^{130}\mathrm{Te}(\gamma,n)^{129m,g}\mathrm{Te}$. The measurement results were used to normalize and calibrate the yields of the reactions $^{120}\mathrm{Te}(\gamma,n)^{119}\mathrm{Te}$ and $^{122}\mathrm{Te}(\gamma,n)^{121}\mathrm{Te}$. The cross-section values for the reaction $^{130}\mathrm{Te}(\gamma,n)^{129}\mathrm{Te}$ were taken from work [12].

The spectroscopic characteristics for the decay of the ground and isomeric states of the isotopes ^{119}Te, ^{121}Te, and ^{129}Te are quoted in Table 1 [14–17]. The table contains the following parameters: B_n is the threshold of (γ, n) reactions, J^π the spin parity, E_{iso} the energy of isomeric level, E_γ the energy of analytical gamma line, $T_{1/2}$ the half-life, and α the intensity of corresponding gamma line.

In the experiment, we obtained the ratios of the excitation yields of the ground states of the isotopes ^{119}Te and ^{121}Te (Y_1 and Y_2, respectively) to the excitation yield of the ground state of the isotope ^{129}Te (Y_3),

$$\eta_1 = Y_1/Y_3 = c_1\, b_{13}(\lambda_1\, \varphi_3\, f_3/\lambda_3\, \varphi_1\, f_1)\,(N_1/N_3);$$

$$\eta_2 = Y_2/Y_3 = c_1\, b_{23}(\lambda_2\, \varphi_3\, f_3/\lambda_3\, \varphi_2\, f_2)\,(N_2/N_3).$$

Here, $c_{1,2}$ are coefficients that are related to the errors and pulse overlapping, $b_{13} = b_3/b_1$ and $b_{23} = b_3/b_2$ are the content ratios for the corresponding isotopes in the target, $\lambda_{1,2}$ are the decay constants, $\varphi_{1,2} = \xi k \alpha$, ξ is the registration photoefficiency of analytical gamma lines at the decay of ground states, k is the self-absorption coefficient of those lines in the studied target material, α the intensity of analytical gamma lines,

$$f = [1 - \exp(t_{\rm irr})]\exp(t_{\rm cool})[1 - \exp(t_{\rm meas})]$$

is the function depending on the irradiation, $t_{\rm irr}$, cooling, $t_{\rm cool}$, and measurement, $t_{\rm meas}$, times, and N is the number of pulses under the photopeaks of analytical gamma lines.

The ground and isomeric states of all tellurium isotopes were populated in the (γ, n) reactions. In this case, the total yield of the (γ, n) reaction, Y_n, is related to the excitation yields of the ground, Y_g, and isomeric, Y_m, states as follows:

$$Y_n = Y_g + Y_m = Y_g \left(1 + \frac{Y_m}{Y_g}\right) = Y_g(1 + d).$$

The yield ratio of isomers, d, was determined by us earlier [18]. Hence, by measuring the yield ratio in the (γ, n) reactions with the ground states of tellurium isotopes, we can determine the ratios of the total yields in the (γ, n) reactions at the isotopes ^{120}Te and ^{122}Te to the total yield of the reaction ^{130}Te$(\gamma, n)^{129}$Te , i.e. Y_n^{120}/Y_n^{130} and Y_n^{122}/Y_n^{130}. The obtained results are exhibited in Fig. 2. The filled and hollow circles correspond to the yield ratios

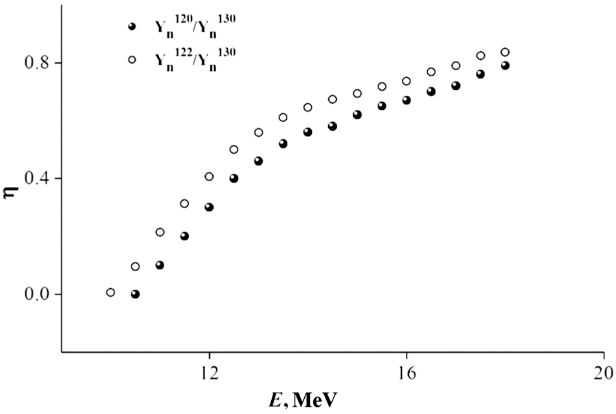

Fig. 2. Ratios of the yields of Y_n^{120}/Y_n^{130}, and Y_n^{122}/Y_n^{130}

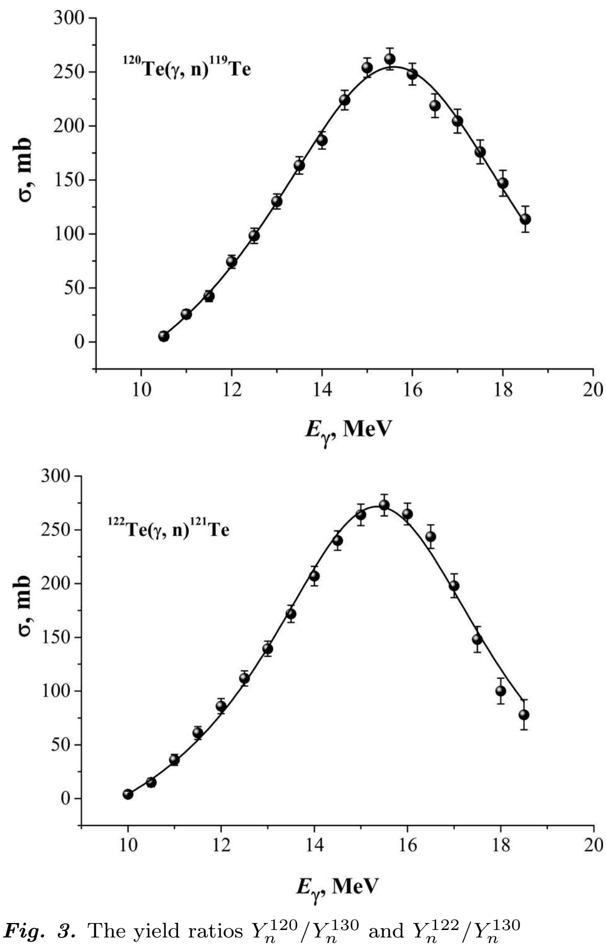

Fig. 3. The yield ratios Y_n^{120}/Y_n^{130} and Y_n^{122}/Y_n^{130}

Y_n^{120}/Y_n^{130} and Y_n^{122}/Y_n^{130}, respectively. The root-mean-square error is less than 1% and does not exceed the symbol size.

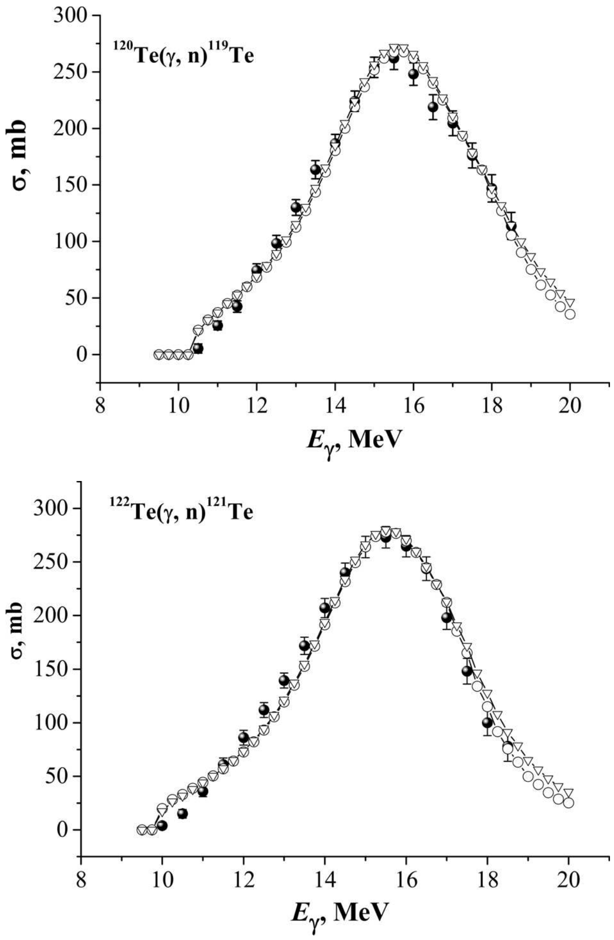

Fig. 4. Cross-sections of the reactions ^{120}Te$(\gamma,n)^{119}$Te and ^{122}Te$(\gamma,n)^{121}$Te

Table 2. **Lorentzian parameters**

Isotope	σ_0, mb	E_0, MeV	Γ_0, MeV
^{120}Te	262.6 ± 2.1	15.47 ± 0.10	5.33 ± 0.11
^{122}Te	274.1 ± 2.1	15.27 ± 0.10	4.76 ± 0.08

The experimental dependence of the yield ratio on the maximum energy in the bremsstrahlung gamma spectrum allows the calculation of the cross-sections for the reactions ^{120}Te$(\gamma,n)^{119}$Te and ^{122}Te$(\gamma,n)^{121}$Te to be done with the help of the cross-section data for the reaction ^{130}Te$(\gamma,n)^{129}$Te, which were measured earlier [12]. The cross-sections were calculated making use of the inverse matrix method [19] with a step of 1 MeV.

The results obtained for the (γ,n) reactions are shown in Fig. 3. The cross-section dependences have a single-hump shape with a maximum at an energy of about 15.4 MeV. The solid curves illustrate their approximations by the Lorentzian function

$$\sigma(E) = \sigma_0 \frac{E^2\Gamma_0^2}{(E^2 - E_0^2)^2 + E^2\Gamma_0^2},$$

where σ_0, E_0, and Γ_0 are fitting parameters. The approximation was carried out using the least-squares method. The resulting values of fitting parameters are quoted in Table 2.

In order to compare the experimental results with theoretical estimates, we calculated the cross-sections of the reactions ^{120}Te$(\gamma,n)^{119}$Te and ^{122}Te$(\gamma,n)^{121}$Te with the help of the software package TALYS-1.9 [20]. The following scenario was used for the calculation procedure. A target nucleus characterized by the parameters (Z_i, N_i) and the spin-parity (J_i, π_i) absorbs a gamma quantum with the energy E_γ so that a compound nucleus is formed with the excitation energy $E_c (E_c = E_\gamma)$ and a spectrum of possible spin and parity values (J_c, π_c). At this stage, the total photoabsorption cross-section $\sigma_{\rm tot}$ was calculated using the parametrized characteristics of the giant $E1$ resonance. Then, the excited nucleus decays in accordance with the Hauser–Feschbach statistical mechanism [21], which involves the admixture of semidirect processes. The latter was found to amount to a fraction of a percent for both isotopes at the energy $E_\gamma = 12$ MeV and to 6–8% at the energy $E_\gamma = 18$ MeV. The neutron emission onto specific levels (zones) of the daughter nucleus was calculated using the permeability coefficients T_1 determined in the framework of the optical model. In so doing, the specific discrete levels from the RIPL-3 database [22] were taken, if the excitation energy of daughter nuclei does not exceed $E = 3$ MeV. At higher excitation energies, the spectrum was considered continuous. It was described by the level density $\rho(E, J, \pi)$ and divided into a certain number of energy zones: 50 in our case. The effective permeability coefficient $T_l^{\rm eff}$ was determined for each zone.

To describe the level density ρ, two models were used in the calculations: the constant-temperature and energy-back-shifted Fermi-gas models [20–24]. The results of cross-section calculations for the reactions ^{120}Te$(\gamma,n)^{119}$Te and ^{122}Te$(\gamma,n)^{121}$Te are compared with the experimental ones in Fig. 4. The hollow circles describe the result of calculations in the framework of the constant-temperature model, the triangles correspond to the results of the back-shifted Fermi-gas model, and the filled circles demonstrate experimental results. From the figure, one can see that the calculations in the constant-temperature and energy-shifted Fermi-gas models produce very similar results.

Thus, a comparison between the theoretical and experimental data testifies to their satisfactory agreement. In turn, this fact testifies to the main contribution given by the statistical mechanism to the cross-section of the considered (γ, n) reactions and, accordingly, a relatively small contribution of semidirect processes.

4. Conclusions

The experimental studies of the reactions ^{120}Te$(\gamma, n)^{119}$Te and ^{122}Te$(\gamma, n)^{121}$Te in the interval of 10–18 MeV for the maximum energies of gamma quanta are carried out making use of the bremsstrahlung gamma beam of the M-30 microtron at the Department of Photonuclear Processes of the Institute of Electronic Physics of the NAS of Ukraine. The activation technique was applied.

As a result of the measurements, the ratios of the total yields of the (γ, n) reactions at the isotopes ^{120}Te and ^{122}Te to the total yield of the reaction ^{130}Te$(\gamma, n)^{129}$Te, i.e. Y_n^{120}/Y_n^{130} and Y_n^{122}/Y_n^{130}, are determined, which allowed us, using the cross-section of the reaction ^{130}Te$(\gamma, n)^{129}$Te measured earlier [12], to calculate both the absolute yields and the cross-sections of the reactions ^{120}Te$(\gamma, n)^{119}$Te and ^{122}Te$(\gamma, n)^{121}$Te.

Using the TALYS-1.9 software package, the cross-sections of the (γ, n) reactions were calculated for the ^{120}Te and ^{122}Te isotopes in an energy interval of 10–18 MeV. A satisfactory agreement was obtained between the theoretical and experimental results, which allowed us to conclude that the statistical mechanism dominates in the ^{120}Te$(\gamma, n)^{119}$Te and ^{122}Te$(\gamma, n)^{121}$Te reactions.

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В.М. Мазур, З.М. Біган, П.С. Деречкей, О.М. Поп

ДО ПИТАННЯ ПРО МЕХАНІЗМ ФОТОНЕЙТРОННИХ РЕАКЦІЙ НА ЛЕГКИХ ІЗОТОПАХ ТЕЛУРУ В ОБЛАСТІ 10–18 МеВ

В інтервалі енергії гамма-квантів 10–18 МеВ проведено вимірювання виходу і розраховано переріз реакції ^{122}Te(γ, n)^{121}Te. Одержаний переріз співставляється з перерізом реакції ^{120}Te(γ, n)^{119}Te. Експериментальні результати порівнюються з теоретичними розрахунками, проведеними в рамках програмного пакета TALYS-1.9. Установлено домінування статистичного механізму для (γ, n) реакцій на досліджуваних ядрах.

Ключові слова: гігантський дипольний резонанс, атомне ядро, ядерні реакції, переріз, гальмівний гамма-спектр, ізомерне відношення.