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EXCITATION CROSS-SECTION FOR THE ISOMERIC STATE OF ^{127}Te NUCLEUS IN THE (γ, n) REACTION IN THE (9–20)-MeV ENERGY INTERVAL

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The energy dependences of the cross-sections and the isomeric yield ratios for the reaction $^{128}Te(\gamma, \mathrm{n})^{127}Te$ in the (9–20)-MeV interval have been studied. The obtained experimental data are compared with the results of theoretical calculations carried out with the use of the TALYS-1.2 software package.

K e y w o r d s: isomeric yield ratio, Hauser–Feschbach mechanism, giant dipole resonance

1. Introduction

Nowadays, the development of experimental researches concerning the properties of giant E1-resonance revealing themselves in the cross-sections of gamma quantum absorption by nuclei is associated, to a great extent, with studying different channels of its decay, first of all, those which enable the study of the population for certain selected states of daughter nuclei. The probability distribution for the population of excited states in a final nucleus is governed by both the characteristics of a combined parent nucleus and the spectrum of emitted particles. If the daughter nucleus possesses isomeric states with the spins J_m substantially different from that in the ground state, J_g, the probability of the population of those states is governed by both the spin distribution in the spectrum of emitted particles and the spin and energy distributions over higher levels. Therefore, the measurements of isomeric ratios – i.e. the ratios between the cross-sections of nucleus formation in the isomeric, σ_m, and ground, σ_g, states – allow the estimation of parameters describing the energy and spin dependences of the level density to be done and the probability of radiative transitions into the isomeric and ground states to be evaluated. All that composes a sensitive test for the adequacy of theoretical approaches, including the statistical theory, when they are used for the description of the decay mechanism for high-energy collective states.

This work aimed at studying the relative population of the isomeric state with $J_m = 11/2^-$ and its dependence on the gamma quantum energy in the reaction $^{128}\mathrm{Te}(\gamma, \mathrm{n})^{127m,g}\mathrm{Te}$ in the energy range 9–20 MeV. A peculiarity of photonuclear experiments carried out with the use of bremsstrahlung gamma quanta consists in that it is the photonuclear reaction yield $Y(E_{\gamma\max})$ – in our case, it is the ratio between the isomeric yields $d = Y_m/Y_g$, where Y_m and Y_g are the yields of reactions that populate the isomeric and ground states, respectively–rather than its cross-section that is directly determined in the course of measurements. A considerable attention has been paid to the measurements of the isomeric yield ratios for nuclei with the atomic numbers $A = 110 \div 130$ [1–3]. However, the dependence $d = f(E_{\gamma\max})$ for ^{127}Te nucleus has not been studied till now. In this work, this task was solved for the first time. The isomeric state of tellurium-127 is characterized by the spin-parity $J_m = 11/2^-$, which is determined by the $1h_{11/2^-}$ subshell, and its ground state has the spin-parity $J_g = 3/2^+$ and is formed by the $2d_{3/2}$ subshell.

2. Experimental Technique

In our experiment, we used the activation technique. Research was carried out with the use of a bremsstrahlung beam obtained from an electron accelerator, an M-30 microtron, at the Department of

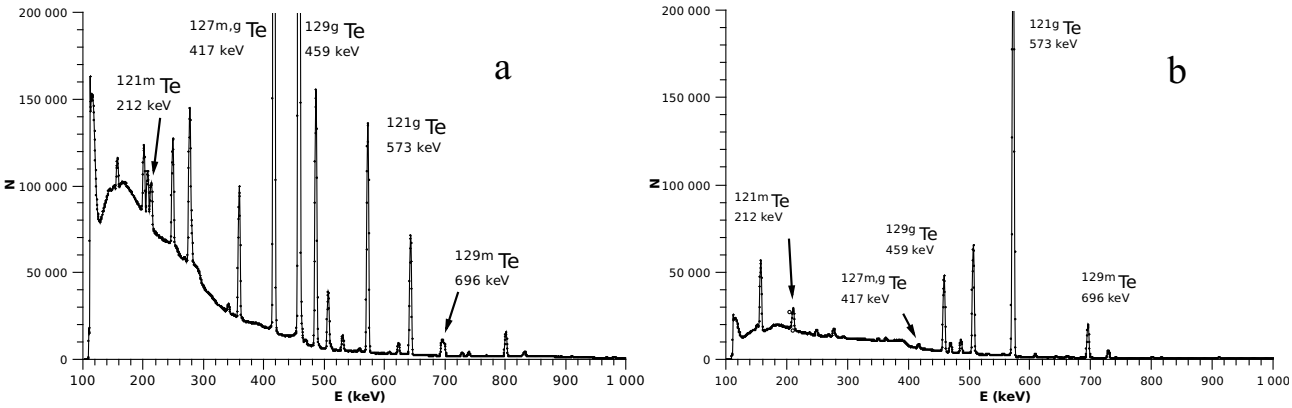

Fig. 1. Sections of the apparatus spectrum from an irradiated tellurium target: (a) the cooling time is 3.5 h, and the measurement time is 20 h; (b) the cooling time is 7 days and the measurement time is 44.7 h

photonuclear processes of the Institute of Electron Physics of the NAS of Ukraine [4]. The energy of accelerated electrons was changed in two ways: in a wide range, by changing waveguide inserts, i.e. by varying the number of orbits passed by the electron beam; and in the range allowed by a single waveguide insert, by varying the magnitude of a driving magnetic field. The strength of the magnetic field in the accelerator was monitored with the use of the nuclear magnetic resonance method. The energy spread of the electronic beam did not exceed 30–50 keV. The current of accelerated electrons extracted from the microtron was measured by a secondary emission monitor preliminarily calibrated by a Faraday cup. Every 1.2 s, the registered current value was stored in the PC memory. The average current of accelerated electrons was 5 μA. The beam of accelerated electrons was used as a source of bremsstrahlung gamma quanta. As a bremsstrahlung target, we used a tantalic plate 0.5 mm in thickness. The specimen to study was arranged across the beam axis at a distance of 30 cm behind the plate.

The examined targets were fabricated from glassy tellurium oxide (TeO_2, a purity of 99.99%) in the form of disks 25 mm in diameter and 2 mm in thickness. The experimental targets were irradiated in the energy range 9–20 MeV with the increment $\Delta E = 0.5$ MeV.

The gamma radiation spectra obtained owing to the induced activity of tellurium targets were measured on a high-resolution gamma spectrometer created on the basis of an HPGe-detector 175 cm^3 in volume and an 8192-channel ORTEC analyzer connected with a computer for data accumulation. The photoefficiency of a detector was determined with the use of standard monochromatic gamma sources. The detector resolution was about 2 keV for the 1332-keV line of cobalt-60. The typical apparatus spectra of induced activity for a TeO_2 target irradiated at $E_{\gamma\max} = 16$ MeV are depicted in Fig. 1. The curves demonstrate the dependences of the number of gamma quanta, N, registered in the analyzer on their energy. The irradiation time was 40 min. The spectrum in Fig. 1,a was obtained when the cooling time was 3.5 h, and the measurement time was 20 h. For the spectrum in Fig. 1,b, the cooling time was 7 days, and the measurement time was 44.7 h. The spectroscopic parameters of the examined nucleus were taken from works [5, 6]. The energy of the isomeric level is 88.26 keV, and it decays into the ground state with the probability $p = 97.6\%$. However, the intensity of the corresponding gamma line is extremely weak (0.084%). Even weaker is the intensity of another possible analytical line at 659 keV (0.013%). At the same time, the intensity of the 417-keV gamma line related to the ground state decay amounts to 0.993%, so that this line can be reliably registered.

In the case of isotope ^{127}Te, the half-life periods in the isomeric, T_m, and ground, T_g, states differ from each other by more than two orders of magnitude; in particular, $T_m = 109$ days and $T_g = 9.35$ h. This circumstance was used as follows. Right after the irradiation of the target, the duration of which was varied from 20 min to 2 h depending on the maximum energy of bremsstrahlung gamma, $E_{\gamma\max}$, and the cooling of the irradiated target for 1–2 h, the yield of the ground-state population was measured for 16–20 h. Since $T_m \gg T_g$ and $\lambda_m \ll \lambda_g$, we adopted–with an accuracy not worse than 0.5%–that the number of

pulses, N_g, in the photopeak of the 417-keV gamma line corresponded to the decay of the ground state only, whereas the possible contribution to the ground state population owing to the decay of the isomeric state was neglected.

The measurements were repeated in 7–10 days after irradiation. Within this time interval, the number of nuclei, N_g, formed in the $^{128}\mathrm{Te}(\gamma,\mathrm{n})^{127g}\mathrm{Te}$ reaction in the course of irradiation became 10^5–10^6 times smaller. Therefore, we may assert with a high confidence that the total population of the ground state at the time of a measurement was a result of the isomeric state decay. In other words, we can adopt that, at the initial moment $t = 0$, the parameter $N_g = 0$, and the number of isomeric nuclei equaled $N_m(0)$. Then, the decay is described by the following equations:

$$\frac{dN_m}{dt} = -\lambda_m N_m, \quad \frac{dN_g}{dt} = \lambda_m N_m - \lambda_g N_g. \tag{1}$$

Since $\lambda_m \ll \lambda_g$ and $e^{-\lambda_m t} \gg e^{-\lambda_g t}$, we have

$$N_g(t) = \frac{\lambda_m}{\lambda_g - \lambda_m} N_m(0) e^{-\lambda_m t}.$$

Taking into account that $N_m(t) = N_m(0)e^{-\lambda_m t}$, the ratio between the numbers of nuclei in the transient equilibrium state equals

$$\frac{N_g}{N_m} = \frac{\lambda_m}{\lambda_g - \lambda_m} \approx \frac{\lambda_m}{\lambda_g} = \mathrm{const},$$

$$\lambda_g N_g(t) = \lambda_m N_m(t) = \frac{-dN_m}{dt}. \tag{2}$$

One can see that the ground state decays with the period of the isomeric state. Therefore, by registering the 417-keV gamma line (i.e. by measuring the ground state decay), we can determine the number of isomeric nuclei formed during irradiation. Hence, taking the aforesaid into account, the isomeric ratio d can be found as the isomeric ratio between independent yields,

$$d = \frac{Y_m}{Y_g} = \frac{N_m}{N_g}\frac{c_g}{c_m}\frac{\phi_g}{\phi_m}\frac{\lambda_m}{\lambda_g}\frac{f_g(t)}{p f_m(t)}. \tag{3}$$

Here, N_m and N_g are the numbers of pulses in the photopeaks of the gamma line, which are associated with the decay of the isomeric and ground states, respectively; $\phi_{m,g} = \xi_{m,g} k_{m,g} \alpha_{m,g}$; $\xi_{m,g}$ is the registration photoefficiencies of gamma lines emerging owing to the decay of the isomeric (m) and ground (g) states; $k_{m,g}$ are the corrections for the self-absorption

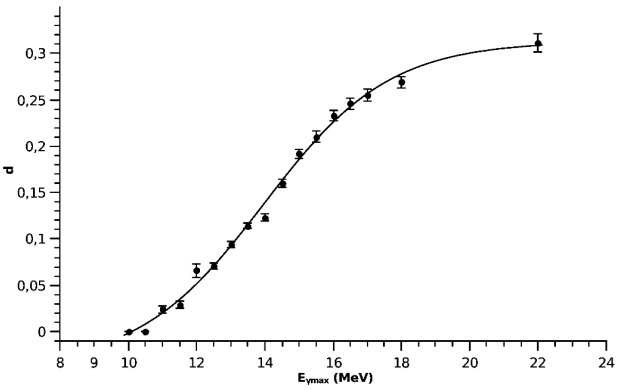

Fig. 2. Dependence of the isomeric yield ratio on the maximum energy of the bremsstrahlung gamma spectrum

of corresponding lines; $c_{m,g}$ are the correction coefficients for pulse summing (random or coincident) and dead-time losses, respectively; $\lambda_{m,g}$ are the decay constants of the isomeric (m) and ground (g) states; and p is the branching factor.

Since, in our case, $\phi_m = \phi_g$, the isomeric yield ratio equals

$$d = \frac{N_m}{N_g}\frac{c_g}{c_m}\frac{\lambda_m}{\lambda_g}\frac{f_g(t)}{p f_m(t)}, \tag{4}$$

where

$$f_{m,g}(t) = (1 - e^{-\lambda_{m,g} t_{\mathrm{irr}}}) e^{-\lambda_{m,g} t^{m,g}_{\mathrm{cool}}} (1 - e^{-\lambda_{m,g} t^{m,g}_{\mathrm{meas}}}).$$

Here, t_{irr} is the irradiation time; and $t^{m,g}_{\mathrm{cool}}$ and $t^{m,g}_{\mathrm{meas}}$ are the cooling and measurement times, respectively, at the registration of decays of the isomeric (m) and ground (g) states.

3. Discussion of Results

Points in Fig. 2 present the experimental isomeric yield ratio for the reaction $^{128}\mathrm{Te}(\gamma,\mathrm{n})^{127m,g}\mathrm{Te}$ calculated by relation (4). In the figure, we also showed the corresponding root-mean-square errors. One can see that the curve describing the dependence of the isomeric ratio on the gamma quantum energy, $d = f(E_{\gamma\max})$, rapidly increases above the threshold energy and, in an interval of 18–20 MeV, saturates at the level $d = 0.31 \pm 0.01$. The solid curve in Fig. 2 corresponds to the Boltzmann dependence

$$d = A - \frac{B - A}{1 - \exp[\frac{E - E_0}{\Delta E}]},$$

where A, B, E_0, and ΔE are fitting parameters. The experimental points obtained for the reaction

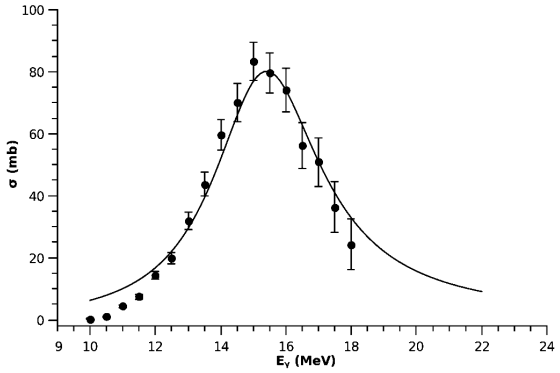

Fig. 3. Cross-section of the ^{128}Te$(\gamma, \mathrm{n})^{127m}$Te reaction. The solid curve exhibits the Lorentzian dependence

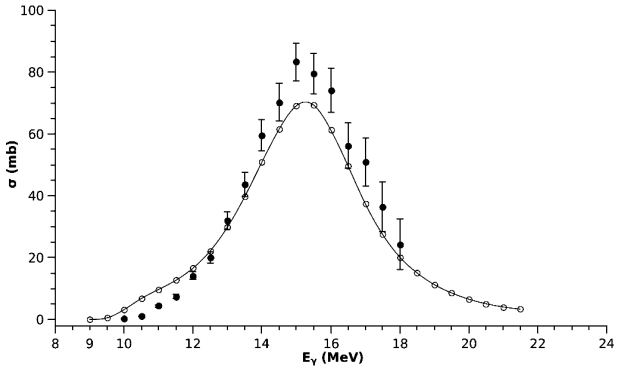

Fig. 4. Comparison between theoretical (○) and experimental (●) cross-sections of the ^{128}Te$(\gamma, \mathrm{n})^{127m}$Te reaction

^{128}Te$(\gamma, \mathrm{n})^{127m,g}$Te were approximated by the Boltzmann dependence with the use of the least square method. The fitting procedure gave the following parameters: $A = 0.315 \pm 0.020$, $B = 0.0496 \pm 0.020$, $E = 13.92 \pm 0.19$ MeV, and $\Delta E = 1.97 \pm \pm 0.08$ MeV.

The obtained experimental dependence of the isomeric yield ratio d on the maximum gamma spectrum energy $E_{\gamma\max}$ in the interval from the threshold of the (γ, n) reaction to 20 MeV allowed us, using the available data for the total cross-sections of (γ, n) reactions [7, 8], to calculate the excitation cross-sections for isomeric states, σ_m. Our calculations were carried out with the use of the inverse matrix method [9]. The calculation procedure included the smoothing of yield curves. The obtained cross-section of the ^{128}Te$(\gamma,\mathrm{n})^{127m}$Te reaction is shown in Fig. 3. The cross-section has a one-peak shape with a maximum at the energy $E = 15.5$ MeV. The solid curve exhibits the cross-section approximation by the Lorentzian dependence

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

The approximation was carried out with the use of the least square method. The following values of fitting parameters were obtained: $\sigma_0 = 80.2 \pm 0.84$ mb, $E = 15.41 \pm 0.03$ MeV, and $\Gamma_0 = 4.01 \pm 0.12$ MeV.

In order to analyze the obtained experimental results theoretically, we calculated the excitation cross-section for the isomeric state $J^\pi = 11/2^-$ in the ^{128}Te$(\gamma, \mathrm{n})^{127m}$Te reaction taking advantage of the TALYS-1.2 software package [10]. The following scenario was used at calculations: the examined target nucleus with the proton and neutron numbers (Z_i, N_i) and the spin-parity (J_i, π_i) absorbs a gamma quantum with the energy E_γ to form a compound nucleus with the excitation energy $E_c = E_\gamma$ and the spectrum of possible spin-parity values (J_c, π_c). The total cross-section of photoabsorption, σ_{tot}, was calculated. The excited nucleus decay was simulated according to either the statistical mechanism or the mechanism of semidirect processes. In our case, the fraction of semidirect processes was 1% at $E_\gamma = 12$ MeV, 7.5% at $E_\gamma = 16$ MeV, and 11% at $E_\gamma = 18$ MeV. The statistical decay was calculated in the framework of the Hauser–Feshbach mechanism [11]. Neutron emission was calculated for specific levels (bands) of the daughter nucleus and with the use of the transmission coefficients T_l determined in the framework of the optical model [12]. In so doing, if the excitation energy of the daughter nucleus did not exceed 3 MeV, the parameters of actual discrete levels were taken from the RIPL-3 database. At higher excitation energies, the spectrum of daughter nucleus states was regarded to be continuous, and it was described by the level density function $\rho(E, J, \pi)$. This spectrum of levels was divided into a certain number of energy bands (50, in our case). If a nucleus decayed into a band belonging to the continuous spectrum, the effective transmission coefficient T_l^{eff} was used. For the description of the level density, we used the model of energy-shifted Fermi gas in our calculations [13]. The results of calculations are depicted in Fig. 4 by hollow circles and the solid curve. The solid points correspond to experimental data.

A comparison of the calculated cross-section with the experimental one testifies to their satisfactory agreement, which evidences, in turn, a dominant role of the statistical mechanism in the population of the isomeric state in the ^{128}Te$(\gamma, \mathrm{n})^{127m}$Te reaction.

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ПЕРЕРІЗ ЗБУДЖЕННЯ ІЗОМЕРНОГО СТАНУ ЯДРА ^{127}Te В РЕАКЦІЇ (γ, n) В ІНТЕРВАЛІ ЕНЕРГІЙ 9–20 МЕВ

Р е з ю м е

В інтервалі 9–20 МеВ досліджено залежність ізомерних відношень виходів та перерізу в реакції $^{128}\mathrm{Te}(\gamma, \mathrm{n})^{127}\mathrm{Te}$ від енергії гамма-квантів. Одержані експериментальні дані порівнюються з теоретичними розрахунками, проведеними за допомогою програмного пакета TALYS-1.2.