MECHANISM OF TELLURIUM ISOMERS EXCITATION IN (γ, n) REACTIONS

V. M. Mazur, D. M. Symochko, Z. M. Bigan, T. V. Poltorzhytska, P. S. Derechkey

Institute of Electron Physics, National Academy of Sciences of Ukraine, Uzhgorod, Ukraine

Isomeric yield ratios for the ^{119}Te, ^{121}Te, ^{123}Te, ^{127}Te, ^{129}Te nuclei were obtained in (γ, n) reactions with bremsstrahlung end point energies ranging 10 - 22 MeV with ΔE = 0.5 MeV step. Experimental isomeric ratios were used to calculate the cross-sections of $(\gamma, n)^m$ reactions, that were further compared with TALYS-1.4 calculations.

1. Introduction

Gamma beams are an accurate tool for investigating different processes in nuclear physics and astrophysics. Photons with energies of tens MeV bring relatively small changes to nuclei and due to the pure electromagnetic character of photonuclear reactions can be used to obtain information on nucleon-nucleon interactions [1], collective motions of the nuclear matter (giant dipole resonance, pygmy dipole resonance etc) [2], mechanism of the particular nuclear states excitation [3, 4], etc. Photonuclear reactions are also important for understanding the processes of elements creation in a stellar environment. Particularly to explain the abundances of p-nuclei which are mainly synthesized through the chain of photonuclear reactions on r- or s-precursors [5]. ^{120}Te is one of these p-process nuclei and the reaction ^{120}Te(γ, n)^{119}Te partly determines the cross-section of its photodisintegration. Moreover, in view of the fact that ^{120}Te is produced by photodisintegration of the s-only nucleus ^{122}Te followed by that of ^{121}Te, cross-sections of ^{122}Te(γ, n)^{121}Te can be treated as part of the production cross-section of the p-nucleus. To determine p-abundances a database that includes exact values for thousands of reaction cross-sections is needed. As the experimental information on reactions involved in the p-process is very scarce, reaction rates based on Hauser - Feshbach calculations [6] are used for modeling of the p-process flow. One of the methods to check the conformity of the statistical model based on compound nucleus assumption is to compare its results with experimental data on isomeric states population

The isomeric ratios and cross-sections of $(\gamma, n)^m$ reactions on Te isotopes in the GDR energy region were not sufficiently studied previously. There are only two published works [7, 8] that contains complex studies of Te isomeric yields ratios, but measured for the particular energies up to $E_{\gamma max}$ = 25 MeV. At the same time, Te isotopes are remarkable because they could allow for the investigation of the evolution of isomeric ratios with the change of neutron subshell population through a wide mass range (A = 119 - 130).

2. Experiment

The activation technique was used in the experiment. Samples were irradiated with a bremsstrahlung beam from electron accelerator Microtron M-30 of the Institute of Electron Physics of NAS of Ukraine [9] within the 10 - 18 MeV endpoint energy range in △E = 0.5 MeV steps. The electron beam extracted from the accelerator was converted into bremsstrahlung with a 0.5 mm thick tantalum radiator. The intensity of the magnetic field was measured by the NMR method and it allowed achieving less than 50 keV uncertainties in the electron beam energy spread determination. The mean current of beam electrons was 5 μA and was controlled by a secondary-emission monitor with the 1.2 s timestep. For the energies 20 - 22 MeV the bremsstrahlung beam from betatron B25/30 of Uzhhorod National University was used. Tellurium targets were placed on the beam axis at a distance of 30 cm from Tantalum radiator. Targets were made from glass-like TeO_2 of natural isotopic composition (99.99 % chemical purity) in the form of disks (25 mm diameter, 2.5 mm thickness).Follow the irradiations and cooling period, the residual activity in the samples was measured in a low-background environment by an ORTEC spectroscopic system consisting of the calibrated 175 cm^3 HPGe-detector and a multichannel analyzer. The detector was screened from background radiation by the combined Pb-Cd-Cu shield. The energy resolution was 2 keV for ^{60}Co gammas.

To extract optimal amount of data from the decay of the residual nuclei the measurement process was organized as following. After the irradiation and 1 - 2 h cooling time (to reduce dead-time of the detector) the decay of the ^{129}Te^g ground state was measured. Gamma-spectra obtained during next 24 h were used to obtain data on the decay of ^{119}Te^m, ^{119}Te^g, ^{127}Te^g, ^{129}Te^m states. Measurements of long-lived reaction products were done during 1 - 3 days after 7-20 days of cooling. We used spectroscopic data for the investigated nuclei from ENSDF data base [10].

In the general case isomeric yields ratios d are determined as [11]:

$$d = {}^{Y_m}\!\big/_{Y_g} = \left[\frac{\lambda_g}{\lambda_m} \cdot \frac{f_m(t)}{f_g(t)} \left(c \cdot \frac{N_g}{N_m} \cdot \frac{\phi_m}{\phi_g} - p \frac{\lambda_g}{\lambda_g - \lambda_m} \right) + p \frac{\lambda_m}{\lambda_g - \lambda_m} \right]^{-1}, \qquad (1),$$

where $N_{m,g}$ are the counts in photopeaks associated with isomer and ground sates decay; $\varphi_{m,g}$ – coefficient which includes detector efficiency ε, self-absorption in the targets μ and gamma-lines intensity α; p – branching ratio; c – correction factor for detector "dead-time" and pulse overlapping; $f_{m,g}$ – time functions expressed in following way:

$$f_{m,g} = \left[1 - \exp\left(-\lambda_{m,g} \cdot t_{irr}\right)\right] \cdot \exp\left(-\lambda_{m,g} \cdot t_{cool}\right) \left[1 - \exp\left(-\lambda_{m,g} \cdot t_{meas}\right)\right], \qquad (2)$$

where $\lambda_{m,g}$ denote decay constants of isomeric and ground states, t_{irr}, t_{cool}, t_{meas} – intervals of irradiation, cooling and measurements.

Obtained experimental isomeric yields ratios $d = f(E_{\gamma max})$ with standard errors are shown as dots in Fig. 1. Essentially, dependences $d = f(E_{\gamma max})$ grow from the $(\gamma, n)^m$ reactions thresholds for all presented cases and reach the plateau within 20 - 22 MeV energy range.

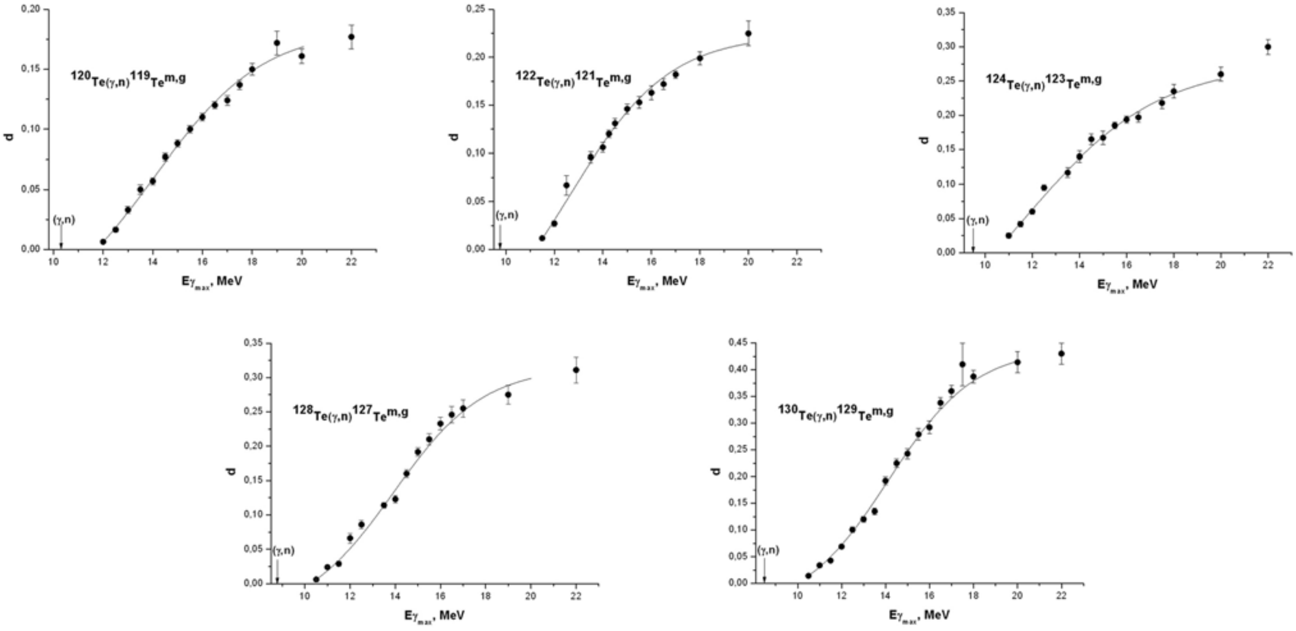

Fig. 1. Experimental isomeric yields ratios for the ^{120}Te(γ, n)^{119}Te^{m,g}, ^{122}Te(γ, n)^{121}Te^{m,g}, ^{124}Te(γ, n) ^{123}Te^{m,g}, ^{128}Te(γ, n)^{127}Te^{m,g}, ^{130}Te (γ, n) ^{129}Te^{m,g} reactions.
Dots – experimental values, solid line – approximation of experimental results.

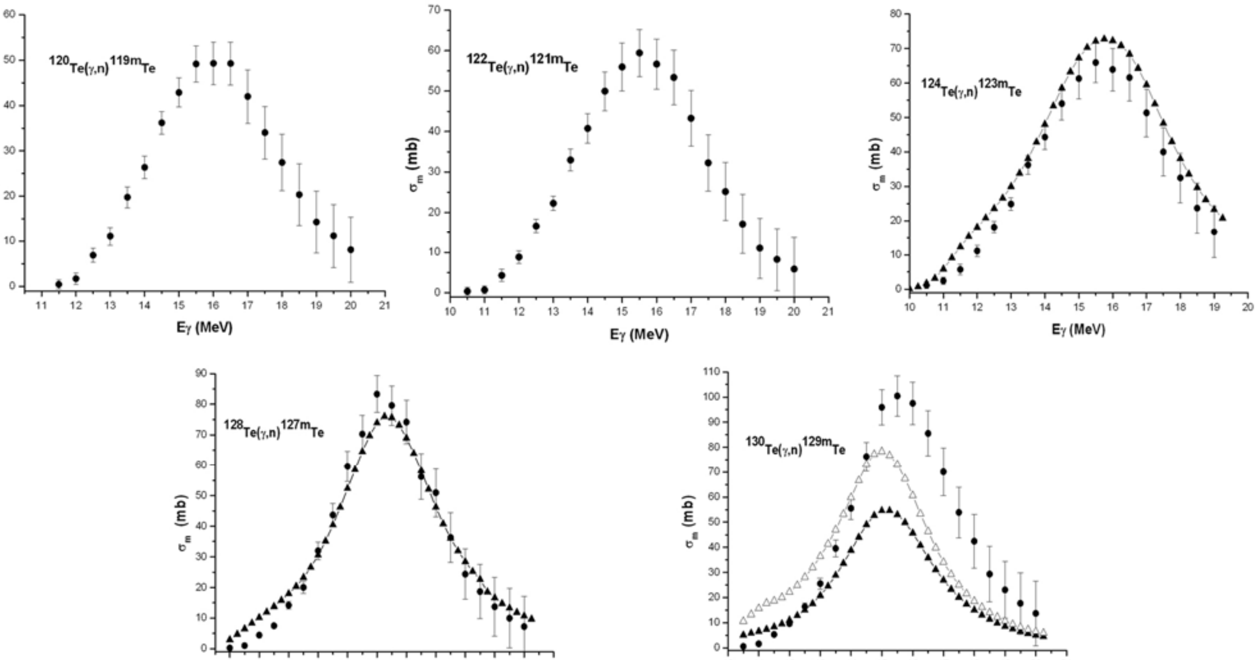

Fig. 2. The cross-sections of the ^{120}Te(γ, n)^{119}Te^{m}, ^{122}Te(γ, n)^{121}Te^{m}, ^{124}Te(γ, n) ^{123}Te^{m}, ^{128}Te(γ, n)^{127}Te^{m}, ^{130}Te (γ, n) ^{129}Te^{m}. Dots – experimental values, filled triangles- TALYS-1.4 calculations with RIPL-3 standard level structure, open triangles - TALYS-1.4 calculations with modified level structure.

The solid lines in Fig. 1 resulted from approximation of experimental isomeric ratios with Boltzmann curves:

$$d = A + (B - A) \Big/ \left[1 + \exp\left(\frac{E - E_0}{\Delta E} \right) \right], \tag{3}$$

where A, B, E0 and ΔE – parameters. Approximation was carried out by a least square method in the range from reactions thresholds up to 20 MeV.

Experimental dependence of the isomeric yields ratios on the bremsstrahlung endpoint energy $d = f(E_{\gamma max})$ allows to calculate the experimental isomeric state population cross-sections σ_m using known total (γ, n) reaction cross-sections [12]. The calculation was carried out by the reverse matrix method [13]. The yield curves were smoothed before used as an input for the calculations. Obtained cross-sections of isomers population are presented via dots in the Fig. 2. Figs. 1 and 2 reveal that isomeric yields ratios and cross-sections are increasing with growth of isotopes mass from A = 119 to A = 129. It correlates with population of outer subshell $1h_{11/2}$, which starts to fill from ^{122}Te and reach 8 neutrons in ^{130}Te.

3. Model calculations

For the purpose of comparing the experimental and theoretical data on isomeric excitation we performed the calculations of the reaction cross-sections with the help of TALYS-1.4 code [14]. The following scheme was used in calculations. Dipole monochromatic gamma with E_γ energy interacts with nuclear target (Z_i, N_i) and the compound state (J_c, π_c) is formed with excitation energy E_c equal to the energy of incident gamma. Total photoabsorption cross-section σ_{tot} is calculated with the use of experimental GR parameters (if available) or from semiempirical systematics. Both statistical and preequlibrium mechanism contribute to the decay process of the residual nuclei. The main contribution in the investigated energy region belongs to Hauser - Feshbach statistical mechanism. But with increasing energy the part of preequilibrium processes simulated with exciton model [15] becomes more significant. After the gamma absorption the particle-hole pair (exciton) is created. The system evolves through the steps and on each of them the number of excitons is increased by one. Particle emission is possible from every stage of the process. After 6 steps the process is no longer treated as preequilibrium and further reaction flow is simulated with statistical model. Calculations show that statistical mechanism dominates for the GR region and its contribution to the total (γ,n) cross-sections even for higher energies is more than 80 %. After the neutron emission the population of the particular residual nucleus levels is calculated using the transmission coefficients T_l obtained from optical model. RIPL-3 database [16] was used to obtain information on first 80 discreet levels. At higher energies excited states spectrum was treated as continuous and described by the level density ρ(E, J, π) divided into 40 equidistant energy bins. For simulation of the continuous spectra we used the Back-shifted Fermi gas model [17].

The calculated cross-sections are plotted in Fig. 2 with black triangles. We are not presenting results of calculations for ^{120}Te(γ, n)^{119}Te^{m} and ^{122}Te(γ, n)^{121}Te^{m} reactions as there is no published experimental data on total (γ, n) cross-sections for this isotopes and this can serve as source of errors in calculations on the stage of photoabsorption cross-section determination. Calculated values are significantly consistent with experimental data for ^{124m}Te, ^{127m}Te, but at the same time we can see very poor agreement in case of ^{129m}Te. Notable disagreement (more than 50 % at the maximum) for the reaction ^{130}Te(γ, n)^{129}Te^{m} motivated us for additional research. We found that information on discreet levels for the ^{129}Te used in RIPL-3 database originated from the ENSDF evaluation [18] which was not updated from 1996. However, the detailed study of ^{129}Te structure was published in 2003 [19]. This paper introduces the 1221 keV level with $J^\pi = 5/2^-$ which can be the key to understanding the strong population of the ^{129}Te^{m} isomer. This level effectively accumulates the intensity from higher lying $3/2^-$ states, which can be easily excited in (γ, n) reactions. The substantial part of neutrons will be emitted with L = 0 moment after the decay of 1^- state of giant dipole resonance via photoneutron chanel and it leads to the direct excitation of $3/2^-$ levels in the residual nuclei. Similar mechanisms of the isomer population were found in others Te isotopes [19, 20]. We modified the level structure file according to the information published in the paper [19] and performed additional calculations (open triangles in Fig. 2). We can see that calculations with updated data lead to significantly better agreement with experimental cross-section.

In the statistical model, because of averaging by the large number of overlapped states, we can neglect the matrix elements features that describe the decay of particular states. It results in a similarity of transition matrix elements, i.e. the final levels for the decay of a particular state are equal. Thus, the probability of particular transition is proportional to the final density of states and depends on the transitions multipolarity. In TALYS–1.4 calculations of the γ-transitions probabilities are derived from the gamma-ray strength functions. For E1 transitions the generalized Lorentzian form of Kopecky-Uhl was used, while for the transitions of other multipolarities -standard Lorentzian (Brink-Axel form). It should be noted that E1 transitions are dominating in calculated gamma-cascade (~90 %) with little admixture of E2 and M1 radiation

The situation is different in the low energy part of the spectra where the microscopic calculations of level structure can be performed. In paper [19] it was mentioned that all states in ^{129}Te of negative parity lower 1100 keV are only weakly populated in (d, p) which can serve as a sign for their complicated structure. The interacting boson-fermion model (IBFM) describes states $3/2^-$ and $5/2^-$ of ^{129}Te as a mixture of the $1h_{11/2}$ neutron wavefunction as a main part with a small $3p$ component, coupled to the first 4+ state of the core [20]. The IBFM calculations reproduce well the energy of the states and confirm the enhanced E2 transitions between the levels of negative parity due to the admixed quadrupole phonons. According to the analysis of the γ-transitions between low-energy levels [18] we can see that the part of E1 transitions is extremely low. States of positive parity decay by M1 and E2 transitions and do not populate levels of negative parity. Their decay path leads to final level $J^\pi = 3/2^+$ and practically do not contribute to the population of $J^\pi = 11/2^-$ isomer. As mentioned above, the enhanced E2 transitions are observed between negative parity states. Therefore the transitions probabilities are mainly defined by their microscopic nature. It is highly possible that same is true for the higher energies described in the calculations as continuous spectra.

As it was mentioned before, the main part of Te isomers excitation cross-section belongs to the statistical mechanism. But the growth of isomeric population and cross-section of $(\gamma, n)^m$ reactions with isotopes mass increasing cannot be explained in the framework of the statistical model. It would be natural to suggest that the increasing contribution of preequilibrium processes can be responsible for that, but calculations showed that their share is too low to explain this effect. Experimental data on nuclear structure of Tellurium isotopes [18 - 20] (including ^{129}Te) suggest that growth is rather caused by redistribution of transitions between low-lying nuclear levels connected with their microscopic nature.

4. Conclusions

Isomeric yields ratio dependence on bremsstrahlung end point energy has been measured for the reactions: ^{120}Te(γ, n)^{119}Te^{m,g}, ^{122}Te(γ, n)^{121}Te^{m,g}, ^{124}Te(γ, n)^{123}Te^{m,g}, ^{128}Te(γ, n)^{127}Te^{m,g}, ^{130}Te(γ, n)^{129}Te^{m,g} in the energy region 10 - 22 MeV. The values of isomeric ratios are increasing with the filling of the subshell $1h_{11/2}$ and are highest for the ^{129}Te. The observed effect of correlation between increasing possibility of isomers $J^\pi = 11/2^-$ excitation and growing of the neutrons number on subshell $1h_{11/2}$ cannot be associated with contribution of statistical or preequilibrium mechanisms, but rather is a consequence the non-statistical distribution of gamma transition probabilities resulted from peculiarities in level structure.

The cross-sections of isomers population in all investigated reactions have been calculated with inverse matrix method. Results were compared with TALYS-1.4 calculations. Theoretical calculations revealed the dominating role of the statistical model based on Hauser - Feshbach formalism in the (γ, n) reactions In most cases calculation reproduce the cross-section and this can serve as evidence of statistical theory adequacy. But the case of ^{130}Te(γ, n)^{129}Te^m reaction showed that results of calculations significantly depends on properties of low-energy levels and transitions between them. Thus, without precise knowledge on nuclear structure, calculations of isomers excitation can produce misleading results.

REFERENCES

1. *Skibinski R. et al.* Search for three-nucleon force effects in two-body photodisintegration of ^{3}He (^{3}H) and in the time reversed proton-deuteron radiative capture process // Phys. Rev. C. - 2003. - Vol. 67. - P. 054002 (8 pages).
2. *Varlamov A.V. e.al.* Atlas of Giant Dipole Resonances. - Vienna: IAEA, 1999. - 311 p.
3. *Mazur V.M.* Excitation of Nuclear Isomeric States in Photoneutron Reactions in the Giant E1 Resonance Region // Phys. Part. Nucl. - 2000. - Vol. 31. - P. 188 - 221.
4. *Gangrsky Ju.P., Mazur V.M.* Scattering of γ-Rays from Nuclei and Excitation of Isomeric States // Phys. Part. Nucl. - 2002. - Vol. 33. - P. 158 - 196.
5. *Mohr P. et al.* Photon-induced Nucleosynthesis: Current Problems and Experimental Approaches // Eur. Phys. J. A. - 2007. - Vol. 3. - P. 357 - 269.
6. *Hauser W., Feshbach H.* The Inelastic Scattering of Neutrons // Phys. Rev. - 1952. - Vol. 87. - P. 336 - 373.
7. *Belov A.G.et al.* Excitation of Isomeric $1h_{11/2}$ States in the Reactions (γ, n) // Phys. Atomic Nuclei. - 1996. - Vol. 59**.** - P. 553 - 562.
8. *Thiep T.D. et al.* The isomeric ratios in photonuclear reactions of natural tellurium induced by bremsstrahlungs with endpoint energies in the giant dipole resonance region // J. Radioanal. Nucl. Chem. - 2011. - Vol. 289. - P. 637 - 645.
9. *Kapica S.P., V.N.Melechin.* The Microtron. - London: Harwood Academic, 1978. - 256 p.
10. *ENSDF* - Evaluated Nuclear Structure Data File. http://www.nndc.bnl.gov/ensdf/
11. *Vanska R., Rieppo R.* The Experimental Isomeric Cross-Section Ratio in the Nuclear Activation Technique // Nucl. Instr. And Meth. - 1981. - Vol. 179. - P. 525 - 532.
12. *Lepretre A. et al.* A Study of the Giant Dipole Resonance of Vibrational Nuclei in the $103 < A < 133$ Mass Region // Nucl. Phys. - 1974. - Vol. A219. - P. 39 - 60.
13. *Bogdankevich O.V., Nikolaev F.A.* Methods in Bremsstrahlung Research. - NY: Academic Press, 1996. - 198 p.
14. *Koning A.J. et al.* TALYS-1.0 // Proc. of the Int. Conf. on Nuclear Data for Science and Technology / Ed. by O. Bersillon, F. Gunsing et al. - EDP Science, 2008. - P. 211 - 214.
15. *Gadioli E., Hodgson P.E.* Pre-equilibrium Nuclear Reaction. - Oxford: Oxford University Press, 1992. - 211 p.
16. *Capote P. et al.* RIPL - Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations // Nucl. Data Sheets. - 2009. - Vol. 110. - P. 3107 - 3214.

17. *Dilg W. et al.* Level density parameters for the back-shifted Fermi gas model in the mass range 40<A<250 // Nucl. Phys. - 1973. - Vol. A217. - P. 269 - 298.
18. *Tendow Y.* Nuclear Data Sheets for A = 129 // Nucl. Data Sheets. - 1996. - Vol. 77. - P. 631 - 770.
19. *Wirth H.F. et al.* Nuclear structure of ^{129}Te studied with (n, γ), (d, p) and (d, t) reactions // Nucl. Phys. -2003. - Vol. A726. - P. 3 - 54.
20. *Bondarenko V. et al.* Origin of the anomalous population of long-lived isomers in odd-*A* Te isotopes // Phys. Rev. C. - 1999. - Vol. 60. - P. 027302 (4 pages).