https://doi.org/10.46813/2025-157-021

STUDY OF THE PHOTONUCLEAR REACTION CROSS-SECTION ^{165}Ho(γ,n)^{164m,g}Ho ON THE M-30 MICROTRON AT THE ENERGY OF 10…18 MeV

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The study results of the isomeric yield ratios in the reaction ^{165}Ho(γ,n)^{164m,g}Ho in the region of giant dipole resonance (GDR) energies of 10…18 MeV are presented. The experimental values of the isomeric yield ratios as a function of the maximum energy of the gamma quanta of the braking spectrum are presented. The obtained data are used to get the excitation cross-section of the ^{164m}Ho isomeric nucleus state using the inverse matrix method with a step of ΔE = 0.5 MeV. It is shown that this cross section has a two-humped shape with a maximum of σ_m=100.93 mb at 12.5 MeV and σ_m=108.79 mb at 14.5 MeV. The results of comparing experimental and theoretical data obtained with different models of the TALYS-1.6 software package are discussed.

PACS: 25.20.DC

INTRODUCTION

Nuclear reactions involving lanthanide isotopes under the influence of gamma quanta are an essential source of information on the structure of their energy levels and the characteristics of the accompanying nuclear radiation. The growing interest in measuring the photonuclear reaction cross sections of rare earth metals (REEs) is due to their importance in various fields, from nuclear energy, including fusion laser technology, to elucidating astrophysical phenomena of nucleosynthesis [1–5].

Their chemical elements, which are low in the Earth's crust, are known to be of high strategic value. That is why developing effective nuclear schemes for simulating their excitation and transformations to probe the energy characteristics of nuclear isomers is of great importance in modern nuclear physics [6–8]. Today, the main problem is the study of nuclear isotopes available in small quantities as REMs and investigating their main parameters. Holmium stands out among the lanthanides as containing a significant number of isomers: ^{158m,159m,160m,161m,162m,163m,164m,166m}Ho, and the ^{165}Ho isotope is the dominant one in the composition of the natural chemical element.

It is known that the nuclei of holmium isotopes belong to the group of deformed axially symmetric nuclei, which are promising for the study of photonuclear reactions with the formation of both its excited states and daughter nuclei in specific quantum states after the emission of nuclear particles. One such task is to study the excitation of isomeric states of holmium isotopes in (γ, n) reactions [9]. For 165Ho isotopes, the daughter isomer nuclei produced in the (γ, n) reaction are short-lived and unstable. The photoabsorption cross-sections of their nuclei have double-humped curves, typical for such deformed nuclei [10, 11]. The study results of their isomeric states are most fully described in [12, 13].

This work aims to study the isomeric states of the heavily deformed 165Ho nucleus in the region of giant dipole resonance (GDR) energies of 10…18 MeV.

EXPERIMENT

The studies used a beam of braking gamma rays from the M-30 microtron of the Institute of Electron Physics of the National Academy of Sciences of Ukraine in the GDR energy range. The beam of electrons was removed from the accelerator and directed to a 1 mm thick tantalum brake target. The beam of generated brake gamma-quanta was monitored by establishing the spatial distribution of intensity and directed to the target under study.

The energy of the accelerated electrons was changed in two ways: by changing the number of orbits of the accelerated electrons by changing the internal waveguide inserts, which led to a change in energy with a significant step ΔE=2…3 MeV. Within these limits, the energy was changed smoothly, with a small step of 0.2…0.5 MeV, by changing the accelerator magnetic field. The nuclear magnetic resonance method monitored the accelerator's leading magnetic field. The uncertainty of the energy of the accelerated electrons was no more than 50 keV, and the current was ≈ 5 μA.

A natural holmium weighing 2 g and 20 mm in diameter was used as the test target. After irradiation, the target was delivered to the spectroscopic laboratory, where the induced activity was measured under good background conditions. The cooling time of the targets after irradiation was chosen so that the recording equipment's miscalculations (dead time) did not exceed 5%. The measurement time and cooling time were selected from the optimality condition, considering the half-lives of the formed isomers. A gamma spectrometer based on a 175 cm^2 semiconductor HPGe detector from ORTEC measured the gamma spectra with high resolution. The detector was placed in a lead shield, and the inner walls were covered with copper and cadmium sheets. The signals from the detector were fed to an 8192-channel CANBERRA analyzer connected to a computer for data storage and processing. The detector resolution was ~ two keV for the 1332 keV cobalt-60 line.

Gamma lines from the decay of ^{164m}Ho produced in the reaction ^{165}Ho(γ, n)^{164m,g}Ho were measured in the energy range $E_{\gamma max}$=10.0…18.0 MeV, i.e., in the range of GDR energies. The measurement step was ΔE=0.5 MeV.

RESULTS

The ground state term of the initial ^{165}Ho is $^4J_{15/2}$, and the spin of the nucleus is J=7/2. It is known that the isomeric state of the ^{164}Ho daughter nucleus obtained in the reaction ^{165}Ho(γ, n)^{164m,g}Ho is characterized by spin parity J^{π}=6$^-$, energy 139.8 keV and half-life $T_{1/2}$=37.0 min. Since the nucleus of the ^{164}Ho isotope is unstable, the population intensity of the isomeric state in the experiment is determined by the gamma line E_m = 37.5 keV, and the ground state is defined as the average of the intensities of two lines E_g = 73.5 and 91.5 keV.

Spectroscopic characteristics

Core	J^{π}	$T_{1/2}$, min	E_m, keV	E_{γ}, keV	I_{γ},%	B_n, MeV
Ho^{164m}	6$^-$	37.0	139.8	37.5	11.7	8.0
$Ho^{164g}{}_1$	1$^+$	29.0	–	73.5	1.9	–
$Ho^{164g}{}_1$	1$^+$	29.0		91.5	2.7	–

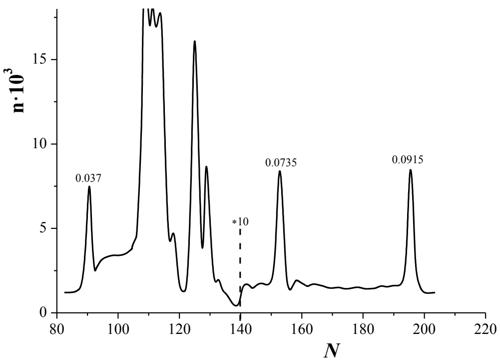


Fig. 1. A fragment of the spectrum obtained in the reaction ^{165}Ho(γ, n)^{164m,g}Ho, the energy of the γ-quanta of the characteristic radiation is given in MeV

The main spectroscopic characteristics of the studied ^{164}Ho nucleus: spin-pairing of the ground J_g^{π} and isomeric states J_m^{π}, their half-lives $T_{1/2}$, energy of the isomeric level E_m, energy of the recorded gamma transition E_{γ}, number of gamma quanta per decay I_{γ}, threshold energy (γ, n) of the reaction for the parent nucleus B_n are taken from [13–17] and are given in the Table.

A fragment of the hardware gamma spectrum in the range of channels N is shown in Fig. 1. As can be seen, although the characteristic line of the ^{164m}Ho isomer is in the low-energy y emission range, it is identifiable.

The decay level diagrams for the ^{164}Ho daughter nucleus, Fig. 2, were taken from the NuDat system [18].

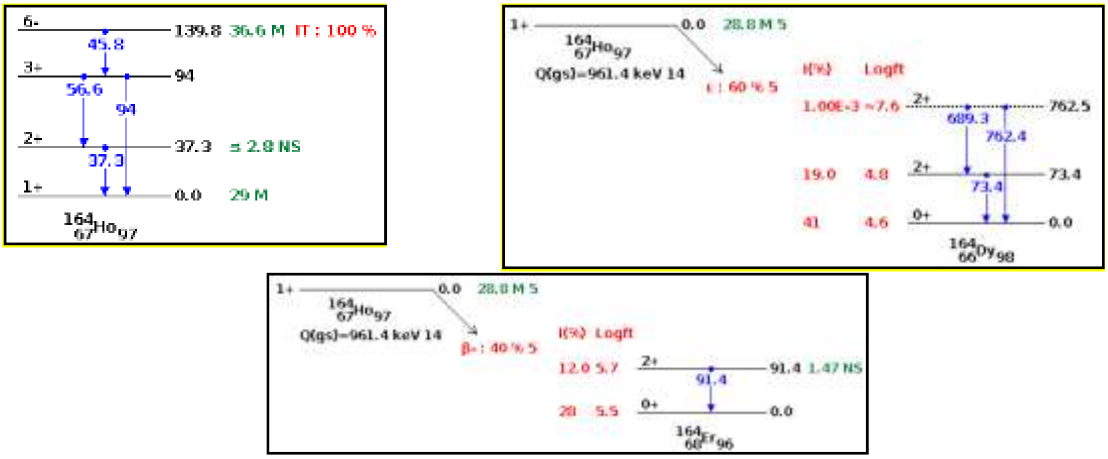


Fig. 2. Diagrams of decay levels of the isomeric and ground states of the ^{164}Ho isotope

According to the number of registered pulses in photopeaks responsible for the decay of the isomeric and ground states as a result of the (γ, n) reaction during irradiation in the beam of brake gamma rays, isomeric ratios were calculated using formula (1) [19]:

$$d = Y_m / Y_g = \left[\frac{\lambda_g}{\lambda_m} \frac{F_m(t)}{F_g(t)} \left(C \cdot \frac{N_g}{N_m} \cdot \frac{\phi_m}{\phi_g} - p \frac{\lambda_g}{\lambda_g - \lambda_m} \right) + p \frac{\lambda_g}{\lambda_g - \lambda_m} \right]^{-1}, \quad (1)$$

where Y_m, Y_g are the excitation outputs of the isomeric and ground states; N_m and N_g are the intensities of the isomeric and ground state lines; C is a coefficient that takes into account miscalculations and pulse overlap; $\varphi_{m,g} = I_{m,g} \cdot \xi_{m,g} \cdot k_{m,g}$ ($I_{m,g}$ is the intensity of gamma transitions populating the isomeric and ground states, which falls on the decay of the activated nucleus, $\xi_{m,g}$ is the efficiency of registration of the corresponding gamma lines, $k_{m,g}$ is the self-absorption coefficients of gamma quanta in the target); $F_{m,g}$ is the time function:

$$F_{m,g} = [1 - \exp(\lambda_{m,g} \cdot t_{irr})] \cdot \exp(\lambda_{m,g} \cdot t_{cool}) \cdot [1 - \exp(\lambda_{m,g} \cdot t_{meas})],$$

where t_{irr}, t_{cool}, t_{meas} are the irradiation, cooling and measurement times. Using the formula

$$\eta = Y_m/Y_{tot} = Y_m/(Y_m + Y_g) = 1/(1+1/d),$$

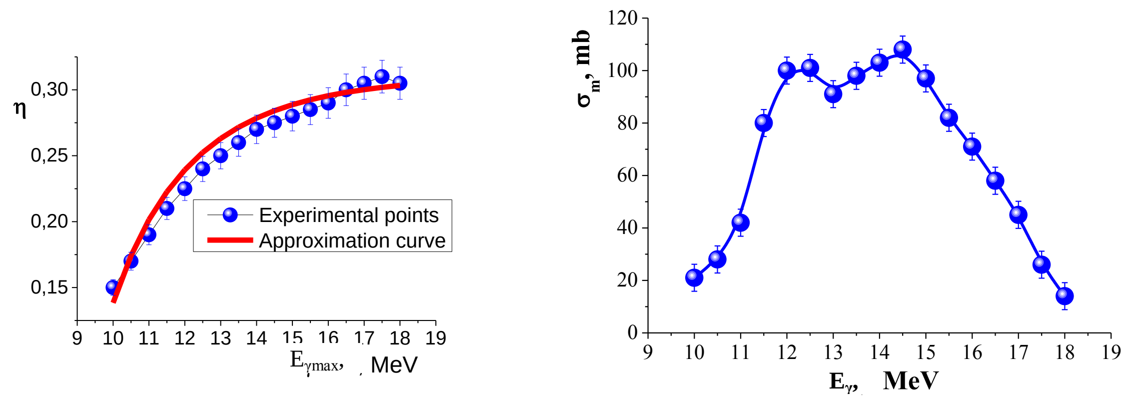
where Y_{tot} is the reaction's total excitation yield (γ, n) (Y_{tot}=Y_m,+Y_g), we obtain the experimental isomeric yield ratios γ. Fig. 3,a shows the dependence of η on the energy of gamma quanta $E_{\gamma max}$.

Fig. 3,a shows that the isomeric yield ratio η above 10 MeV of ^{165}Ho(γ,n)^{164m,g}Ho increases, and in the region > 18 MeV reaches saturation and is ~ 0.3. The experimental isomeric yield ratios η are shown by squares in Fig. 3, and the solid curve shows the result approximation of the experimental results by the Boltzmann curve, which describes the probability of occupation of states of a two-level nuclear system depending on their energy, temperature, and density of states:

$$y = A + (B - A)/[1 - \exp(-\frac{E-E_0}{\Delta E_1})], \quad (2)$$

where *A, B*, E_0, ΔE_1 are the parameters. A sufficient degree of agreement was achieved for the following values of the fitting parameters: A=0.63803±0.25482, B=0.31901±0.00276, E_0=(5.96688±1.118) MeV i ΔE_1= (2.66851±0.185) MeV. The deviations are explained by the significant deformation of the ^{164}Ho nucleus and two resonant GR frequencies associated with the possibility of longitudinal and transverse nucleon vibrations. The measured experimental dependences of the isomer ratios allow us to calculate the partial cross sections for the excitation of isomeric states in the ^{165}Ho(γ,n)^{164m,g}Ho reaction using the available full cross sections of the ^{165}Ho(γ,n)^{164}Ho reaction [20]. The cross-section σ_m was calculated using the inverse matrix method [21] with a step ΔE = 0.5 MeV. In calculating the cross-section $\sigma_m(E_\gamma)$, the curve $\eta(E_{\gamma max})$ was used, which was obtained as a result of fitting the experimental data with the Boltzmann curve. Fig. 3,b shows the calculated cross-sections $\sigma_m(E_\gamma)$ for the formation of the isomeric state of the ^{164}Ho isotope (see Fig. 3,a). The cross-section has a two-humped shape with maxima: σ_m=100.93 mb at 12.5 MeV and σ_m=108.79 mb at 14.5 MeV.

Fig. 4 shows a comparison of these experimental data with the results of modeling the cross-section of the ^{165}Ho(γ,n)^{164m,g}Ho reaction using the TALYS-1.9 software package, which is widely used in calculations of the astrophysical nuclear reaction grid. For the problems of atomic nucleus isomerism, the TALYS package has six models that use different representations of the level density: (i) ldmodel1: Constant temperature model + Fermi Gas model (default); (ii) ldmodel2: Back-Shifted Fermi Gas model; (iii) ldmodel3: Generalised Superfluid Model (iv); ldmodel4: Goriely microscopic model based on Hartree Fock calculations (v); ldmodel5: Microscopic Combinatorial model of S. Goriely-S. Hilaire and (vi) ldmodel6: Microscopic level density based on temparature-dependent Hartree-Fock-Bogoliubov calculations using the D1M Gogny force [22]. The basis of these models is the idea of the excitation of the nucleus and the two-stage decay process through pre-equilibrium processes and the statistical decay of the Hauser-Feshbach compound nucleus.



a *b*

Fig. 3. Results of the study of the isomeric state of the ^{164}Ho isotope: a – experimental isomeric yield ratios η=Y_m/Y_{tot}, solid line – approximation by the Boltzmann curve (1); b – calculated excitation cross sections of isomeric states in the reaction ^{165}Ho(γ,n)^{164m,g}Ho

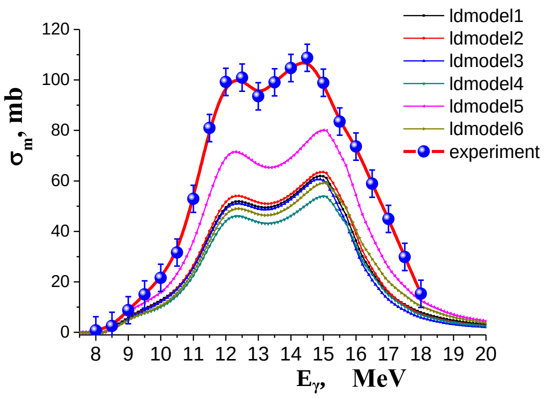


Fig. 4. Comparison of experimental and calculated cross sections of the ^{165}Ho(γ,n)^{164m,g}Ho reaction using different models of excited nucleus decay of the TALYS-1.9 package

In Fig. 4, the black circles show the calculated experimental cross sections $\sigma_m(E_\gamma)$ for the ^{164}Ho isotope and the results of calculations with the TALYS-1.9 software package using different models.

This comparison allows us to validate the theoretical approaches underlying models 1–6 of the TALYS package. As can be seen, a common characteristic of all cross sections obtained as a result of the calculation is the underestimation of the excitation cross sections of the isomeric states in the ^{165}Ho(γ,n)^{164m,g}Ho reaction by about 30…40% compared to the experiment and a satisfactory reproduction of the two-hump structure of the cross-section in terms of energy. The difficulty of modeling the decay of excited states of medium-heavy nuclei as ^{164}Ho is their significant deformation, peculiarities of the frequency spectrum as for anisotropic structures, and the conventionality of using a statistical method that is more adapted to nuclei with atomic masses of 200…300 units. The best approximation of the cross-sectional size, Fig. 4, was obtained with idmodel5, which operates on the values of nuclear level densities improved by the Hartree-Fock-Bogolyubov microscopic approach and the combinatorial method, represented by grey circles in Fig. 4 [23, 24]. It can be seen that when comparing the experimental and theoretically calculated cross sections of the ^{165}Ho(γ, n)^{164m,g}Ho reaction, an unsatisfactory agreement in their magnitude is observed, but a satisfactory agreement in the energy maxima is observed.

CONCLUSIONS

Thus, the experimental study of the ^{165}Ho (γ,n) ^{164m,g}Ho reaction at the brake beam of the M-30 microtron in the range of gamma-ray energies of 10…18 MeV allows us to establish the dependence of the reaction cross sections on the gamma-ray energy. The ratio of isomeric and ground state yields for the ^{165}Ho (γ,n) ^{164m,g}Ho reaction was determined for the first time. It was found that the isomeric yield ratio η increases above the threshold of the ^{165}Ho (γ,n)^{164m,g}Ho reaction, and in the region > 18 MeV, it reaches saturation and is ~ 0.3. It is shown that the experimental cross-section of the formation of the ^{164}No isomeric state has a two-humped shape with two maxima: σ_m=100.93 mb at 12.5 MeV and σ_m=108.79 mb at 14.5 MeV. Given that the ^{164}Ho isotope belongs to the class of deformed nuclei with spin parity $J^\pi=6^-$, it is better to use models that detail the vibrational structure of the nucleus and the excitation of the nucleus phonon system to explain these features of the reaction cross-section.

The authors are grateful to V.M. Mazur for consultations on the topic of this publication.

The work was carried out within the framework of the project supported by the National Research Foundation of Ukraine. State registration number – 2023.04/0083.

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Article received 14.04.2025

ДОСЛІДЖЕННЯ ПЕРЕРІЗУ ФОТОЯДЕРНОЇ РЕАКЦІЇ ^{165}Ho(γ,n)^{164m,g}Ho НА МІКРОТРОНІ М-30 ПРИ ЕНЕРГІЇ 10…18 МеВ

П.С. Деречкей, З.М. Біган, О.М. Поп, П.П. Пуга

Представлено результати дослідження ізомерних відношень виходів у реакції ^{165}Ho(γ,n)^{164m,g}Ho у районі енергій гігантського дипольного резонансу (ГДР) 10…18 МеВ. Приведено експериментальні значення ізомерних відношень виходів від максимальної енергії гамма-квантів гальмівного спектра. Отримані дані використано для отримання перерізу збудження ізомерного стану ядра ^{164m}Ho із використанням методу оберненої матриці з кроком ΔE=0,5 МеВ. Показано, що такий переріз має двогорбу форму із максимумом σ_m=100.93 мб при енергії 12,5 МеВ та σ_m=108,79 мб при енергії 14,5 МеВ. Обговорюються результати порівняння експериментальних та теоретичних даних, отриманих у рамках різних моделей програмного пакета TALYS-1.6.