ISOMER RATIOS OF PHOTONUCLEAR REACTION PRODUCTS ON SILVER AND INDIUM ISOTOPES FOR BREMSSTRAHLUNG ENERGIES ABOVE $35\,MeV$

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Isomer ratios were obtained for nuclei ^{104m,g}Ag and ^{110m,g}In-products of reactions ^{107}Ag(γ,3n)^{104m,g}Ag and ^{113}In(γ,3n)^{110m,g}In after bremsstrahlung irradiation with maximum energies 35 and 36 MeV, respectively. Linear electron accelerator LU-40 with tantalum target was used as bremsstrahlung source. Experimental data are compared with theoretical predictions calculated with TALYS code.

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1. INTRODUCTION

Using of high energy gamma-quanta as projectiles in nuclear reactions has some essential advantages for studying nuclear structure and nuclear reactions mechanisms. Thus gamma-quanta don't introduce large angular momentum into compound nucleus and additional contribution to excitation energy of compound nucleus due binding energy of projectile is absent. Besides that precise stepless control of gamma-quanta energy is possible.

As a rule, characteristics of photonuclear reactions are well studied in the energy region of Giant Dipole Resonance (GDR) and energies over pion-producing threshold (PPT). The energy region over GDR and less than PPT (within nearly 30 and 100 MeV) is studied much less both with theoretical and experimental techniques. Such a situation is due to small photonuclear reaction cross section values and limited availability of highly intensive quasi monoenergetic gamma ray sources with fine control of gamma-quanta energy.

During last several years an essential progress is observable in a development of new and upgrading existing theoretical models for photonuclear reactions in the energy region considered. The quasi-deuteron model was enhanced [1], some new pre-equilibrium models have been developed for description of multiparticle emission [2, 3]. The constantly growing interest to Accelerator Driven Systems and progress in the design of the highly intensive quasimonoenergetic gamma-quanta sources [4] also stimulates the study of photonuclear reactions over GDR energies. Very limited experimental data for photonuclear reactions in the energy range 30...100 MeV to testing newly developed and available theoretical models is a reason to conduct our and similar research.

The main purpose of this paper was to obtain the isomer ratios experimentally for two nuclei ^{104m,g}Ag, ^{110m,g}In as products of ^{107}Ag(γ,3n)^{104m,g}Ag, ^{113}In(γ,3n)^{110m,g}In reactions, respectively, and comparison with calculation results gained with modern theoretical models.

2. EXPERIMENTAL METHOD

Transition times between levels during deexcitation of nuclei by γ-cascade, as a rule, do not exceed value 10^{-13}. In some cases these transitions are suppressed due to large difference of angular momenta of transition levels. As a rule, these isomeric levels have not large excitation energy and its angular momentum differ from spin of ground level on a few Planck's constants.

Isomer or ground levels with large values of spin in exited nuclei are populated mainly from highly excited states with large values of spins. Deexcitation to isomer or ground levels with smaller values of spin is happened in the main from highly excited states with small values of spins. Investigations of relative populations of isomer and ground states for isomer nuclei [5, 6] can be useful to derive spins of highly excited levels and to study deexcitation mechanisms via gamma-quanta emission.

For monoenergetic gamma beam with energy E

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the isomer ratio is defined as a cross sections ratio $\sigma_m(E)/\sigma_g(E)$, where $\sigma_g(E)$ - cross section for nucleus (product of photonuclear reaction) in the ground state, $\sigma_m(E)$ - cross section of the same nucleus in the isomer state. Also isomer ratio often is defined as ratio of cross section σ_H for state with high spin to cross section σ_L for state with low spin:

$$\xi = \frac{\sigma_H(E)}{\sigma_L(E)}\,. \tag{1}$$

When spectrum of gamma-quanta projectiles is nonmonoenergetic (for experiments with bremsstrahlung sources) the isomeric yield ratio is being determined as:

$$d(E_{max}) = \frac{Y_m(E)}{Y_g(E)}\,, \tag{2}$$

where yield of reaction is

$$Y_{m,g} = N_t \int_{E_{por}^{m,g}}^{E_{max}} \sigma_{m,g}(E)\, W(E, E_{max})\, dE\,, \tag{3}$$

N_t - number of target nuclei, $Y_{m,g}$ - reaction yield for nucleus in isomer (m) or ground (g) state, E_{max}-maximum energy of gamma projectiles, $W(E, E_{max})$-gamma-quanta energy spectrum, $\sigma_i(E)$, $i = g, m$ - reaction cross section for nucleus to be formed in metastable (ground) state for projectile energy E, E^i_{por} - reaction energy threshold when nucleus-reaction product is formed in the metastable (ground) state.

When gamma-quanta fluence is time invariable, a contribution from interfering reaction may be considered as negligible, and for simple decay scheme of isomer level to be discharged to ground state with competitive γ-decay, and similar γ-decay of ground state the following differential equation system may be written:

$$\begin{aligned} \frac{dN_m}{dt} &= Y_m - \lambda_m N_m\,, \\ \frac{dN_g}{dt} &= Y_g - \lambda_g\, N_g + p\,\lambda_m N_m\,, \end{aligned} \tag{4}$$

where N_i-level population (m-isomer level, g-ground level), Y_i-reaction yield according to (3), λ_m, λ_g - decay constants for isomer and ground state, p - branch factor (transition probability from isomer to ground state, divided on full probability of isomer level gamma decay [7, 8]). The solution of system (4) is as follows:

$$\begin{aligned} \frac{S_m}{C\,\epsilon\,f_m} &= Y_m \Lambda_3 \Lambda_6 \Lambda_9\,, \\ \frac{S_g}{C\,\epsilon\,f_g} &= Y_g \Lambda_2 \Lambda_5 \Lambda_8 + \\ &\quad Y_g(\Lambda_1\Lambda_5\Lambda_8 + \Lambda_3\Lambda_4\Lambda_8 + \Lambda_3\Lambda_6\Lambda_7)\,, \end{aligned} \tag{5}$$

where S_i, $i = g, m$ - photopeak area (in gamma spectrum of activation products), coefficient C includes the effectiveness of gamma-quanta detection for gamma-line energy, transition probability for this line and self-absorption factor, ϵ-full effectiveness of gamma-quanta detection for gamma-line energy E; f_i, $i = g$, m-percentage of γ-line for i-state decay; coefficients Λ_j, j=1,9 are defined by t_1, t_2, t_3, - irradiation time, cooling time and measurement time, respectively:

$$\Lambda_1 = \frac{p}{\lambda_g}\left[1 - \frac{\lambda_m\lambda_g}{\lambda_m - \lambda_g}\left(\frac{e^{-\lambda_g t_1}}{\lambda_g} - \frac{e^{-\lambda_m t_1}}{\lambda_m}\right)\right],$$

$$\Lambda_2 = \frac{1}{\lambda_g}\left(1 - e^{-\lambda_g t_1}\right), \quad \Lambda_3 = \frac{1}{\lambda_m}\left(1 - e^{-\lambda_m t_1}\right),$$

$$\Lambda_4 = p\frac{\lambda_m}{\lambda_m - \lambda_g}\left(e^{-\lambda_g t_2} - e^{-\lambda_m t_2}\right),$$

$$\Lambda_5 = e^{-\lambda_g t_2}, \quad \Lambda_6 = e^{-\lambda_m t_2},$$

$$\Lambda_7 = p\left[1 - \frac{\lambda_m\lambda_g}{\lambda_m - \lambda_g}\left(\frac{e^{-\lambda_g t_3}}{\lambda_g} - \frac{e^{-\lambda_m t_3}}{\lambda_m}\right)\right],$$

$$\Lambda_8 = 1 - e^{-\lambda_g t_3}, \quad \Lambda_9 = 1 - e^{-\lambda_m t_3}.$$

As a result, the following expression was obtained

$$F = Y'_m X + Y'_g\,, \tag{6}$$

where F and X are defined as

$$F = \frac{S}{\epsilon f_g \Lambda_2 \Lambda_5 \Lambda_8}\,,$$

$$X = \frac{(\Lambda_1\Lambda_5\Lambda_8 + \Lambda_3\Lambda_4\Lambda_8 + \Lambda_3\Lambda_6\Lambda_7) + \frac{f_m}{f_g}\Lambda_3\Lambda_6\Lambda_9}{\Lambda_2\Lambda_5\Lambda_8}\,,$$

where $S = S_m + S_g$ peak area sum, $Y'_{m,g} = CY_{m,g}$ - values, proportional to reaction yields. Isomer yield ratio was calculated with expression (6) by fitting experimental data (X, F).

3. EXPERIMENTAL PROCEDURES

The method of induced activity measurement was applied to obtain isomer ratios. Irradiations of Ag and In targets have been carried out with 35 and 36 MeV bremsstrahlung correspondingly. Linear accelerator LU-40 (Research and Development Complex "Accelerator" NSC KIPT) was used as a source of fast electrons (see Fig.1).

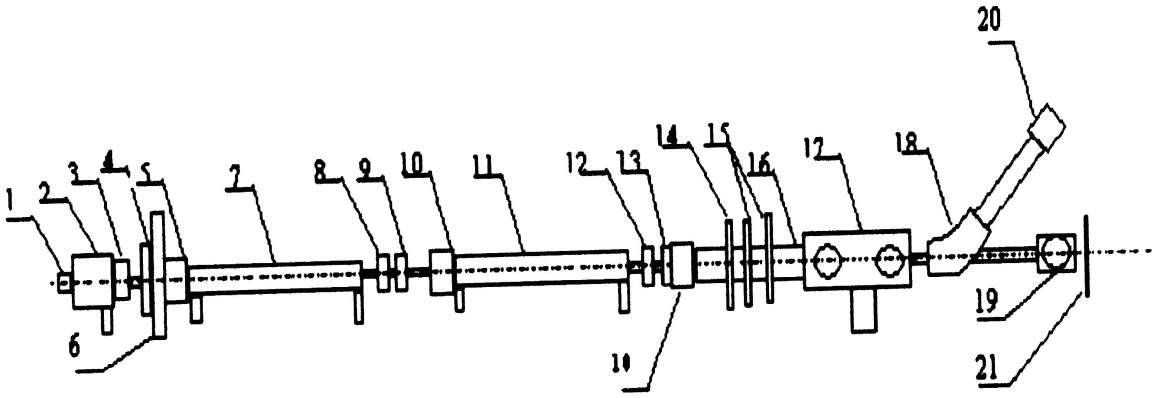

Fig.1. *Structural layout of the accelerator. 1-electron gun, 2-resonator system of the injector, 3,9, 13-current transformers, 4-axial lens, 5, 10-valves, 6-adjustable collimator, 7, 11-accelerating sections, 8, 12-beam position monitors, 14, 15-quadrupoles, 16-beam pipe, 17-unit of slot collimators and Faraday cup, 18-magnetic analyzer, 19-Faraday cup with an exit window, 20-Faraday cup of the magnetic analyzer, 21-tantalum converter*

Instability of electron beam intensity was within 2%. At the exit window of accelerator facility the tantalum converter with 1.05 mm thickness was placed, close to which a cylindrical aluminum gamma absorber with 5.5 cm height and 9.5 cm diameter was installed. A distance between tantalum converter and absorber was 4 cm, between tantalum converter and target - 30 cm.

The cylindrical targets with isotopes natural abundance were of 2 mm thickness and 10 mm diameter. Each sample was irradiated during 20 min. Then within 3 seconds the irradiated sample was moved with pneumatic transfer system to measurement area.

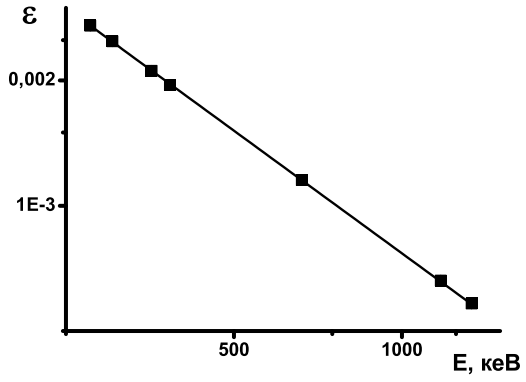

Fig.2. *Linear range in the double logarithmic scale of efficiency calibration dependency. HPGe detector GC2019 with Canberra multichannel analyzer In-Spector was used. Sample-detector distance-15 cm*

HPGe detector with energy resolution $< 2.0\,keV$ for ^{60}Co γ-line 1332 keV was used to acquire instrumental gamma-ray spectra of activation products as a set of serial measurements in various time periods. Cooling times varied for silver from 5 seconds to few hours and for indium - up to dozens of hours. Measurement time for every spectrum was 900 seconds.

Detector to sample distances (dozens centimeters just after irradiation and few centimeters at the end of measurements) were chosen to optimize both statistics and time restrictions when large contribution of interfering reactions took place.

Efficiency calibration was carried out for every detector to sample distance used. The efficiency-energy dependency in double logarithmic scale was found as good quality and linear one in energy range of interest and presented Fig.2. Deviations between experimental data and linear fitting values do not exceed 2%.

Example of gamma-spectrum and corresponding gamma peaks, which were used for calculation of isomer ratios are shown in Fig.3 and Fig.4.

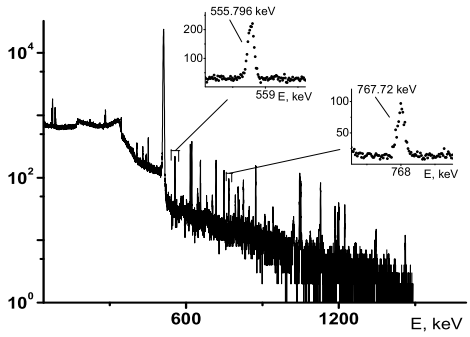

Fig.3. *Gamma-ray spectrum resulting from induced activities in the silver target after cooling time about* 100 min

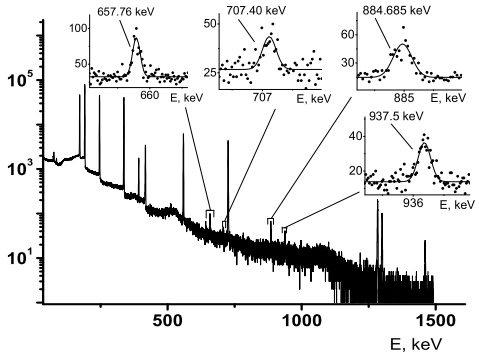

Fig.4. *Gamma-ray spectrum resulting from induced activities in the indium target after cooling time about* 19 *hours*

4. RESULTS

Isomer ratio was obtained as

$$IR(E_\gamma) = \frac{Y_H(E_\gamma)}{Y_L(E_\gamma)},$$

where $Y_H(E_\gamma)$ - reaction yield for case of creation of final nucleus with larger angular momentum (ground state), $Y_L(E_\gamma)$ - reaction yield for case of creation of final nucleus with lesser angular momentum (metastable state). Simplified decay scheme for ^{104m,g}Ag nucleus (without all levels of ^{104}Ph nucleus) is shown in the Fig.5.

One can see fitting line for experimental points (X, F) of silver nucleus in Fig.6.

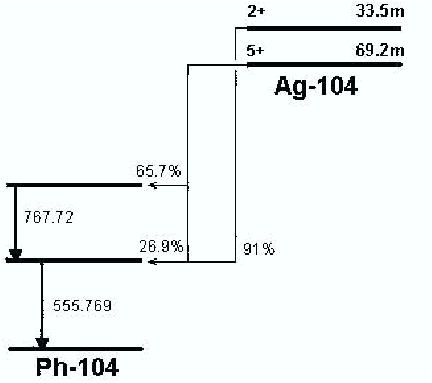

Fig.5. *Simplified decay scheme for* $^{104m,g}Ag$

Gamma-transitions and corresponding lines with energies 767.7 keV (β^+ decay of ground state) and 555.8 keV (common line for decay of ground and isomer level) were used to calculate isomer ratio for $^{104m,g}Ag$ (see Fig.4) and resulted in the following final value: $IR(E_\gamma) = (0.88 \pm 0.14)$.

By analogy, the gamma-lines 884.7 keV, 937.5 keV, 707.4 keV (β^+ decay of ground state) and 657.8 keV (common line for decay of ground and isomer level) were used to obtain isomer ratio for $^{110m,g}In$ (see Fig.5). As result isomer yield ratio for nucleus $^{110m,g}In$ was calculated as $IR(E_\gamma) = (0.36 \pm 0.07)$.

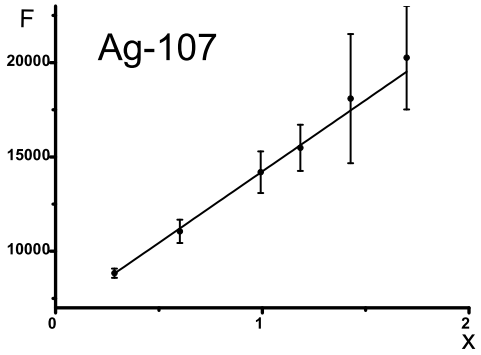

Fig.6. *Fitting line to experimental points* (X, F) *of silver nucleus* $^{104m,g}Ag$ *(reaction* $^{107}Ag(\gamma, 3n)^{104m,g}Ag$*)*

Based on new theoretical approaches and experimental data available very power codes for calculation of nuclear reaction characteristics are developed [2,3]. Some of them are open source codes. One of these codes-TALYS code [9]. It allows also to derive isomer ratios for variety of nuclear reactions. We performed theoretical calculations using this code and made a comparison with experimental data. Standard set of parameters and also additionally preequilibrium models have been used for calculations. For ^{104m,g}Ag nucleus and bremsstrahlung energy 35 MeV the calculated model isomeric yield ratio was equal 0.38. For nucleus $^{110m,g}In$ and bremsstrahlung energy 36 MeV the calculated model isomeric yield ratio was obtained as 0.44. The agreement for $^{110m,g}In$ may be considered as quite acceptable and for $^{104m,g}Ag$ there is 2.3 times difference which is much higher than experimental uncertainties.

5. CONCLUSIONS

Experimental values of isomer ratio are obtained for $^{104m,g}Ag$ and $^{110m,g}In$ nuclei-products of photonuclear reactions $^{107}Ag(\gamma, 3n)^{104m,g}Ag$, $^{113}In(\gamma, 3n)^{110m,g}In$. These data are compared with model theoretical calculations with using code TALYS. Good correspondence was found for $^{110m,g}In$ case between experimental results and theoretical calculations. The experimental value of isomeric yield ratio for $^{104m,g}Ag$ nucleus exceeds theoretical calculation result more then two times. This work is supported partly by grant of NAS Ukraine "NMRT X-9-535"

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ИЗОМЕРНЫЕ ОТНОШЕНИЯ ПРОДУКТОВ ФОТОЯДЕРНЫХ РЕАКЦИЙ НА ЯДРАХ СЕРЕБРА И ИНДИЯ ДЛЯ ЭНЕРГИЙ ГАММА-КВАНТОВ ВЫШЕ 35 МэВ

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В работе приведены результаты измерений и расчетов изомерных отношений продуктов фотоядерных реакций с множественным вылетом частиц на ядрах серебра и индия для энергий гамма-квантов выше энергий гигантского дипольного резонанса. Для определения изомерных отношений использовалась методика измерения наведенной активности облученных образцов спектрометром на базе полупроводникового детектора из сверхчистого германия. Для анализа согласованности теоретических расчетов с экспериментально полученными данными был использован код TALYS.

ІЗОМЕРНІ ВІДНОШЕННЯ ПРОДУКТІВ ФОТОЯДЕРНИХ РЕАКЦІЙ НА ЯДРАХ СРІБЛА ТА ІНДІЮ ДЛЯ ЕНЕРГІЙ ГАММА-КВАНТІВ ВИЩЕ 35 МеВ

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У роботі наведені результати вимірювань та розрахунків ізомерних відношень продуктів фотоядерних реакцій з множинним вильотом частинок на ядрах срібла та індію за енергій гамма-квантів вище енергій гігантського дипольного резонансу. Для визначення ізомерних відношень використовувалась методика вимірювання наведеної активності зразків, що опромінювалися, спектрометром на базі напівпровідникового детектору з надчистого германію. Для аналізу відповідності теоретичних розрахунків та експериментально отриманих даних використовувався код TALYS.