Isomeric yield ratios in nuclei ^{190}Ir and ^{150,152}Eu

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Isomeric yield ratios ^{190}Ir$^{m2,m1+g}$, ^{150}Eu^{m,g}, ^{152}Eu^{m1,m2} have been measured in (γ,n)-reactions for the end point energies of bremmsstrahlung photons about 12, 12.5, and 16 MeV for ^{190}Ir$^{m2,m1+g}$ and 12 MeV for ^{150}Eu^{m,g}, ^{152}Eu^{m1,m2}. Experimental values of the isomeric yield ratios have been compared with the theoretical values, which were calculated by using codes TALYS and MCEM. The low influence of nonstatistical effects has been observed for all these energies.

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I. INTRODUCTION

Studies of nuclear reactions with different projectiles are important sources of information both about nuclear reactions mechanism and about properties of excited states of nuclei. Such information has been obtained using a variety of experimental methods over many years. A common type of investigation is to measure isomeric ratios (IRs); that is, the measurement of the cross-sections ratio (or yields) for the reactions resulting in the production of residual nuclei in isomeric and ground states. These ratios depend on many factors: spin of the target, the angular momentum added to the system by the projectile, the reaction mechanism, and the properties of excited states in continuous and discrete excited regions of the energy level spectrum [1]. The angular momentum of the projectile is determined from its mass and energy. Using information about IRs enables one to investigate both nuclear reaction mechanisms and statistical properties of excited states of atomic nuclei.

Measurements of simple nuclear reactions, such as (γ, n), (n, γ), (γ, p), and (p, γ), provide data that can be interpreted with less ambiguity than hadron-induced reactions with particle decay channels. In all these reactions the low angular momentum (1/2 to 1) $\hbar$ is entered, the momentum variance is changing in the range of (1 to 2) $\hbar$ after escape of the particle.

Among these reactions, photonuclear reactions have special place, because determined angular momentum (1$\hbar$) is added to system. Also, the interaction γ-rays with nuclei is only electromagnetic and so we have choosen for our investigation only photonuclear reactions.

It is known that most nuclei in the region $150 \leqslant A \leqslant 190$ are deformed with the rotary spectrum for low-energy excitations. Two transient mass regions with $A \sim 150$ and $A \sim 190$ between spherical and deformed nuclei are attached to the region of the deformed nuclei. The change of the level structure at the low excitation energies is characteristic in these transient regions. The isotopes of ^{190}Ir, ^{150,152}Eu are in these transient regions and they will be the subject of our investigations. We have choosen these odd-odd nuclei also because of the high level density in the low excitation energy region, which allows the use of the statistical model in calculating the isomeric yields ratio. The level density and its dependence from angular momentum and the energy of the excitation are known to define IR in the statistical model. Consequently, it is possible to conclude about the change of the properties of the excited levels which have the excitation high-energy, analysing calculated isomeric yields ratio.

The nuclei of ^{190}Ir and ^{152}Eu have isomeric states with the high spins, ($I^\pi = 11^-$) for ^{190}Ir and ($I^\pi = 8^-$) for ^{152}Eu. The population of these states may be forbidden by statistical channel, when the energy of the projectiles is around to threshold. Therefore, the investigation of the excitation of these isomeric states on the low spin target, irradiated by the projectiles, which entered with low angular momentum, allows us to estimate more appropriately the role of the nonstatistical processes. By studying nuclear reactions in the energy threshold region of the projectiles we can choose the little range of the excitation energy of the residual nucleus. It permits us to simplify the analysis of the isomeric yields ratio and to determine more unambiguous nuclear parameters of the statistical model.

In contrast to the ^{190}Ir and ^{152}Eu, the nucleus of ^{150}Eu is interesting because there a is large difference between half-lives of the isomeric and ground states ($t_{1/2} = 12.8$ h for ^{150m}Eu and 35.8 yr for ^{150g}Eu), having smaller difference between spins of the isomeric and ground states ($I^\pi = 0^-$ for ^{150m}Eu and $I^\pi = 5^-$ for ^{150g}Eu).

Notwithstanding all abovementioned properties, the given nuclei have not been investigated much. The nuclear reaction ^{191}Ir (γ, n) ^{190}Ir^{m1,m2,g} was studied only in the work [2] for the end point energy of bremmsstrahlung photons about 22 MeV. The Russian group carried out the ^{150}Eu for the discrete values of the end point energy of bremmsstrahlung photons in the region 13 to 22 MeV [3]. The nucleus of the ^{152}Eu has two isomeric states and it has been studied earlier [4–6], but both ^{152}Eu and ^{150}Eu are not investigated for the end point energy of bremmsstrahlung photons about 12 MeV.

Considering all above-mentioned points, the purpose of this work is as follows:

(i) To determine the isomeric yields ratio in ^{190}Ir$^{m2,m1+g}$, ^{152}Eu^{m1,m2}, and ^{150}Eu^{m,g} in (γ, n)-reactions for the end point energies of bremmsstrahlung photons about 12, 12.5, and 16 MeV.

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(ii) To calculate the isomeric yield ratios using codes TALYS and MCEM for these energies.
(iii) Comparing experimental values of the isomeric yield ratios with the results of the nuclear model calculations, with particular attention given to the mechanism of the nuclear reactions.

II. EXPERIMENT

Isomeric yield ratios were measured by activation and identification of the radioactive products. This technique is very suitable for investigation low-yield reaction products and closely spaced low-lying isomeric states, provided their lifetimes are not too short. The isomeric and nonstable ground states are formed simultaneously during nuclear reaction process in the same experimental conditions, so the isomeric ratios can be determined with high accuracy.

A. Samples and irradiation

The measurement of isomeric yield ratios in (γ, n)-reactions was done by using the electron beams extracted from both the M-30 microtron of the Laboratory of Photonuclear Reactions at IEP, Uzhgorod and B-25 betatron of the Uzhgorod university [7]. These electron beams were sources of the bremmsstrahlung photons. A cooled tantalum disk, 2-mm thick, served as a bremmsstrahlung producing target for the both beams.

Exposures to bremsstrahlung photons were performed for the end point energies: 12, 12.5, and 16 MeV. The mean electron current was around 3μA at each energy. Targets were made of metallic foils of Ir and Eu with the natural isotopic composition. All samples were in the form of right-angled stripes and had a weight around 1 g and a surface area around 1 cm^2. There were a few series of the irradiations. Exposure times from 1.5 h to 4 h ensured sufficient induced activity of the decay both for the ground and for the isomeric states. The distance from bremsstrahlung producing target to samples was 9 cm.

B. The measurement of the activity

After irradiation the studied samples were transfered to a separate laboratory. In the laboratory a spectroscopic system was equiped.

The γ-spectra of the reaction products were measured by this system, consisting of HPGe detectors made by CANBERRA and ORTEC, amplifier 2024 and multichannel analyzer 8192, connected to computer for data processing. The detectors have energy resolution 2 keV for the 1332-keV γ-line of ^{60}Co and detection efficiency of 30% in comparison with a 3 in. × 3 in. NaI(Tl)-detector.

The nucleus of ^{190}Ir has two isomeric states [8]. The population of the first isomeric state has not been measured. The spin and parity of the second isomeric state of ^{190}Ir is $I^{\pi} = 11^{-}$and that of the ground state is $I^{\pi} = 4^{+}$ [8]. In order to get the yield of the population for the isomeric state with $I^{\pi} = 11^{-}$, we determined the intensities of the transitions 502 and 616 keV, which follow the decay of the ^{190}Os levels populated only after of the isomeric state decay ($t_{1/2} =$ 3.25 h) [8] (see Fig. 1).

The yield of the population of the ground state together with the first isomeric state was determined by using the intensity of the γ-ray 371 keV from the decay of the 558-keV level in ^{190}Os, which was populated following electron capture on the ground state (see Fig. 1).

The nucleus of ^{152}Eu also has two isomeric states. The yield of the population for the ground state has not been measured. The spin and parity of the second isomeric state of ^{152}Eu is $I^{\pi} = 8^{-}$and that of the first isomeric state is $I^{\pi} = 0^{-}$ [8]. To obtain the yield of the population for the second isomeric state with $I^{\pi} = 8^{-}$, we determined the intensity of the 90-keV γ-ray

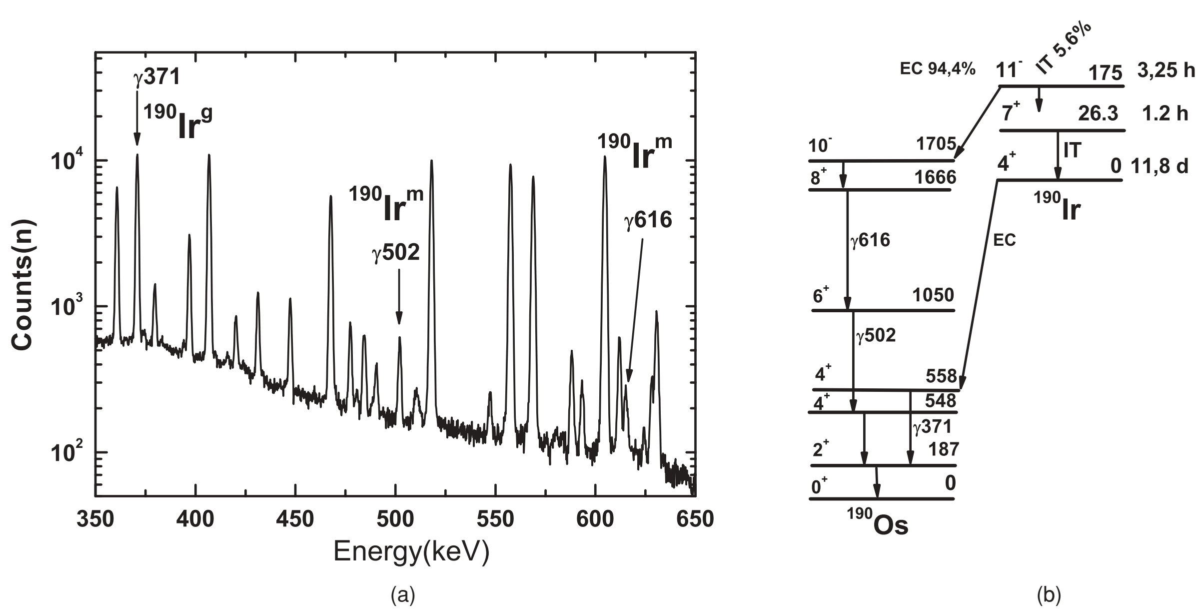

FIG. 1. Spectrum of the ^{190}Ir$^{m2,m1+g}$ (a) and the fragmented decay chain of this nucleus (b).

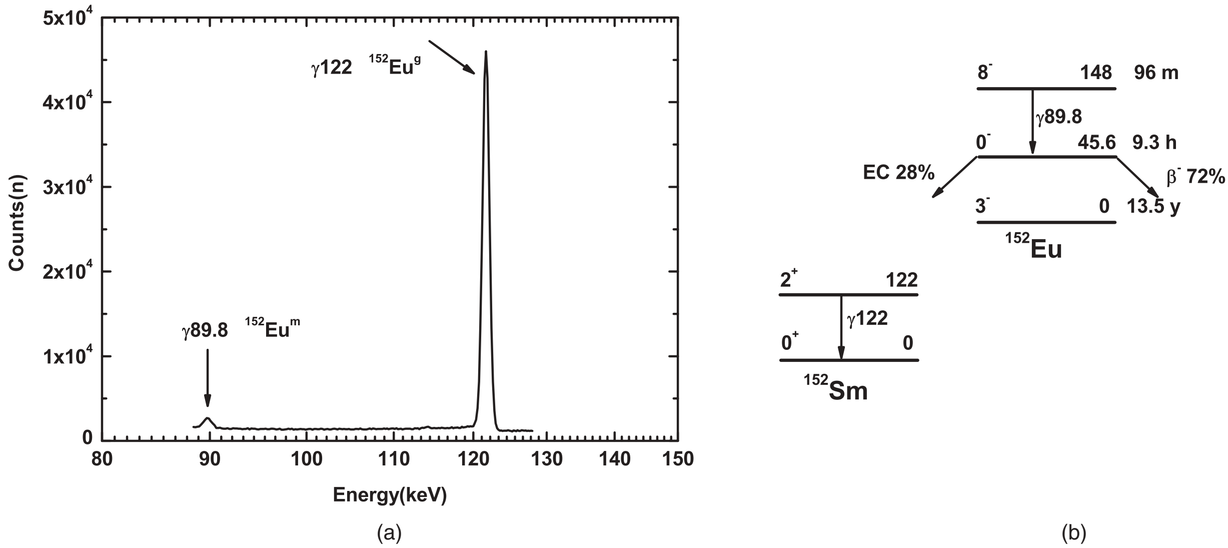

FIG. 2. Spectrum of the ^{152}Eu^{m2,m1} (a) and the fragmented decay chain of this nucleus (b).

transition, which follows the decay of the second isomeric state ^{152}Eu ($t_{1/2} = 96$ min) [8] (see Fig. 2).

In order to obtain the yield of the population for the first isomeric state of ^{152}Eu with $I^{\pi} = 0^{-}$, we determined the intensity of the 122-keV γ-ray transition, which follows the decay of the first excited state of ^{152}Sm that is populated after electron capture on the first isomeric state of ^{152}Eu ($t_{1/2} =$ 9.3 h) [8] (see Fig. 2).

The nucleus of ^{150}Eu has one isomeric state and ground state with very long half-life. The main complication of the measurement of the isomeric yield ratios in ^{150}Eu is the very large difference in the half-lives of the isomeric ($t_{1/2} = 12.8$ h) and ground ($t_{1/2} = 35.8$ yr) levels. The yield of the population of both the ground and the isomeric states was determined by using the intensity of the 334-keV γ-ray line from the decay of the first excited state of ^{150}Sm, which was populated following the electron capture on both the ground and isomeric states of ^{150}Eu (see Fig. 3).

The intensity of the 334-keV γ-ray line from the decay of the isomeric state of ^{150}Eu was measured immediately after of the irradiation.

The decay of the ground state of ^{150}Eu was measured within 30 days after the irradiation. To get the necessary statistical accuracy, the counting measurements continued for one month.

III. THE RESULTS

Using the experimental spectrums we determined the isomeric yield ratios Y_m/Y_g for ^{190}Ir$^{m2,m1+g}$, ^{152}Eu^{m1,m2}, and ^{150}Eu^{m,g} using as follows [9]:

$$d(E_{\gamma\,\max}) = \frac{Y_m}{Y_g} = \left[\frac{\lambda_g}{\lambda_m}\cdot\frac{f_m(t)}{f_{g(t)}}\left(\frac{\xi_m k_m \alpha_m}{\xi_g k_g \alpha_g}\cdot\frac{N_g}{N_m} - p\frac{\lambda_g}{\lambda_g-\lambda_m}\right) + p\frac{\lambda_m}{\lambda_g-\lambda_m}\right]^{-1}, \quad (1)$$

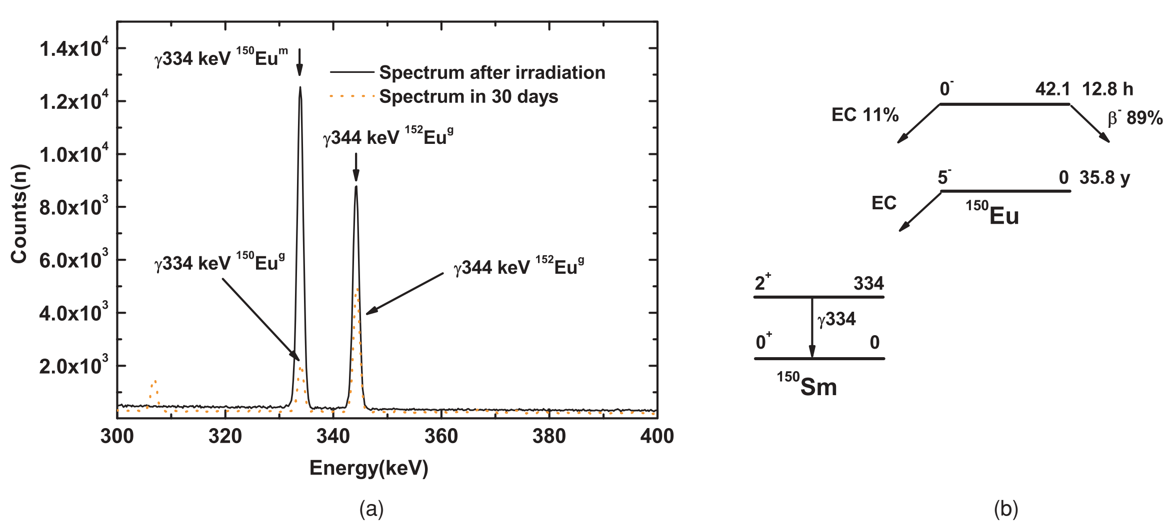

FIG. 3. Spectrum of the ^{150}Eu^{m,g} (a) and the fragmented decay chain of this nucleus (b).

TABLE I. Experimental and calculated values of the isomeric yields ratios. E^* is the excitation energy of the residual nucleus. Y_h is the yield of the population of the high-spin isomer. Y_l is the yield of the population of the low-spin isomer.

Reaction	Energy MeV	E^* MeV	Experiment	Y_h/Y_l Calculation MCEM	Calculation TALYS
^{191}Ir $(\gamma,n)^{190}$Ir$^{m2,g+m1}$	12	3.75	$(5.3\pm1.0)\times10^{-5}$	3.1×10^{-5}	2.5×10^{-7}
	12.5	4.25	$(5.2\pm0.4)\times10^{-5}$	3.6×10^{-5}	8×10^{-7}
	16	7.75	$(61\pm5)\times10^{-5}$	55×10^{-5}	5.0×10^{-5}
^{153}Eu$(\gamma,n)^{152}$Eu^{m2,m1}	12	3.4	$(1.2\pm0.1)\times10^{-3}$	2×10^{-4}	$(1.47\pm0.1)\times10^{-3}$
^{151}Eu$(\gamma,n)^{150}$Eu^{m,g}	12	4	$(1.5\pm0.1)\times10^{-1}$	6.5×10^{-2}	$(3.5\pm0.1)\times10^{-1}$

where

$$f_m(t) = [1-\exp(-\lambda_m\cdot t_{\mathrm{irr}})] \times \exp(-\lambda_m\cdot t_{\mathrm{cool}})[1-\exp(-\lambda_m\cdot t_{\mathrm{meas}})], \quad (2)$$

$$f_g(t) = [1-\exp(-\lambda_g\cdot t_{\mathrm{irr}})] \times \exp(-\lambda_g\cdot t_{\mathrm{cool}})\cdot[1-\exp(-\lambda_g\cdot t_{\mathrm{meas}})], \quad (3)$$

N_g, N_m—quantity of the counts under the peaks, which follow the decay of daughter nuclei in the isomeric (m) and ground (g) states; $\alpha_{m,g}$—yield of γ-rays from the decay of the isomeric and ground states; $\xi_{m,g}$—the registration efficiency of the γ-rays; t_{irr}, t_{cool}, t_{meas}—the time of the irradiation, cooling and measurement, properly; $k_{m,g}$—the self-absorption coefficient of γ-rays; p—the branching coefficient (it is the probability ratio of the transition from isomeric state to the ground state to full probability of decay for the isomeric state); λ_m, λ_g—constants of decay for isomeric and ground states.

An adaptation of the experimental spectra was done using the Winspectrum program [10]. This program permits the user to write the spectra in a defined time periods. Therefore, enabling the identification of the isotope from the energies of the γ-rays and the half-lives.

To determine the absolute efficiency of the spectrometer, we used a set of single γ-ray lines from the decay of the calibration sources of ^{152,154}Eu and of ^{133}Ba. To calibrate the absolute efficiency of the spectrometer, we used GEANT4 [11], which performs calculations based on the method Monte Carlo techniques. The results of the modeling agreed with experimental values of the calibration in the boundary of the experiment error.

The numerical values $\lambda_m, \lambda_g, p, k_{m,g}, \alpha_{m,g}$, were taken from [8]. Shown in Table I are the data obtained for the isomeric yield ratios for end point energies of about 12, 12.5, and 16 MeV using the (γ,n)-reaction. The isomeric yield ratios in the nuclei of ^{190}Ir, ^{152}Eu, and ^{150}Eu have been obtained for the first time at these energies.

IV. NUCLEAR MODEL CALCULATIONS AND DISCUSSION

A. TALYS calculations

The calculation of the cross sections was done using the code TALYS [12]. There are several mechanisms of the nuclear reactions in this code. The main contribution in the cross sections of population both of the isomeric and the ground states gives a statistical mechanism of the nuclear reactions for all used energies of the γ-rays. It is based on Hauser-Feshbach theory [13]. Little contribution in total cross section is entered also by the preequilibrium mechanism which is based on the exiton model [14].

Each evaporation step is treated in the framework of the statistical model, taking into consideration the angular momentum and parity conservation, as well as the preequilibrium decay in the neutron emission.

The exiton model [14–16] assumes that after the initial interaction between the incident particle and the target nucleus, the excited system can pass through a series of stages of increasing complexity before equilibrium is reached. Neutron emission may occur from these states yielding the preequlibrium neutrons. The contribution of the preequilibrium components in total cross sections was lower by 10%.

The excited state of the compound nucleus deexcites either by neutron emissions to another isotope or by γ-ray cascade to the ground state or to the isomeric state of the residual nuclei. The particle transmission coefficients were generated via the spherical optical model using the computer code ECIS03 and the default set of global parameters: for neutrons and protons from [17]. The transmission coefficients of photons are also of considerable significance in calculations on isomeric cross sections. They were derived from the γ-ray strength function. For the $E1$ transition, the generalized Lorentzian form of Kopecky and Uhl [18] was applied; while for the $M1$, $E2$, and $M2$ radiation, the so-called Brink-Axel option [19] was used.

TALYS has been compiled and 50 of the discrete low levels are allowed for in the automatic regime. The spectroscopic characteristics of the levels and nuclei and their charts of the decay are taken from the library RIPL-2 [20].

There are five variants of models to describe of the levels density in TALYS. The choice of these variants is determined by an entered parameter "ldmodel." Calculating with TALYS, we used a back-shift Fermi gas model (BFM) [21] for describing the level density in the continuum energies region. In BFM, the pairing energy is treated as an adjustable parameter and the Fermi gas expression is used all the way down to the energy, which agreed with the energy of the 51 discrete level. The range from the maximal excitation energy till the energy of the 51 discrete level was devided on the ecvidistant energy intervals (bins). There are two adjustable parameters for the BFM, a—the energy parameter levels density and δ—an adjustable parameter for odd-even effects. The calculations of the IRs were done for the various energies of the γ-rays. For the reaction ^{191}Ir (γ,n) ^{190}Ir$^{m2,g+m1}$, the modeling of IRs was done starting from the threshold and till to 16 MeV with the step 1 MeV.

For the reactions ^{153}Eu (γ, n) ^{152}Eu^{m2,m1} and ^{151}Eu (γ, n) ^{150}Eu^{m,g}, the modeling of IRs was done starting from the threshold and till to 12 MeV with the step 1 MeV for both reactions.

The results of modeling allowed us to do the following conclusions.

For the reaction ^{191}Ir (γ, n) ^{190}Ir$^{m2,g+m1}$, the IRs are changed from $\sigma_{m2}/(\sigma_g + \sigma_{m1}) = 0.5 \times 10^{-5}$ for $E^{\gamma\,\max} =$ 14 MeV to $\sigma_{m2}/(\sigma_g + \sigma_{m1}) = 0.5 \times 10^{-4}$ for $E^{\gamma\,\max} =$ 16 MeV, it is being increased, when the energy is rising. The same tendency appeared also in the experiment, but the theoretic IRs understate approximately by order of magnitude as against experimental IRs. From this information, we concluded, that the model level densities with low spins overstates approximately by order of magnitude for the nuclei of ^{190}Ir, when the energy of the excitation for the residual nucleus is 7–8 MeV.

For the reaction ^{153}Eu (γ, n) ^{152}Eu^{m2,m1} the agreement between experiment and calculation was reached for such values of the parameters: $a = 10; \delta = 0$. For the reaction ^{151}Eu (γ, n) ^{150}Eu^{m,g}the agreement between experiment and calculation was not reached by rational variation a and δ. The agreement between experiment and calculation is worse, when the other models for describing the level density are used.

B. MCEM calculations

We decided to analyze the obtained results by using the modificated cascading-evaporating model (MCEM) [1], because the agreement between the experiment and calculation IRs was not reached for all nuclei.

The properties of the MCEM are as follows:

(i) The population of the isomeric pair occured taking into consideration the chart of the decay of the discrete low levels, which are known from the experiment [22].

(ii) The possibility of the yrast-trap passing taking into consideration from the states around of the yrast-line, when the angular momentums of these states are higher than the spin of the metastable state.

(iii) Only the statistical mehanism of the nuclear reactions is taken into consideration, which is also based on Hauser-Feshbach theory [13].

For our low energy excitations, the possibility of the yrast-trap passing is not takes into consideration.

We used an back-shift Fermi gas model (BFM) [23] for describing the level density in the continuum energies region. The particle transmission coefficients were generated from the set of global parameters for neutrons and protons [24]. The transmission coefficients of photons were derived from the γ-ray strength function [25]. In MCEM 30 of the discrete low levels are allowed for in the automatic regime. We used the average energy of the γ-rays in the residual nucleus in the next manner [26]:

$$\bar{E}_\gamma = 4 \times \sqrt{\frac{E^*}{a} - \frac{\sigma}{a^2}}, \qquad (4)$$

where E^* is the excitation energy of the residual nucleus, which was calculated from the energy balance of the nuclear reaction; a is the one-particle level density; σ is the spin cutoff. The parameters a and σ have been obtained from systematics and theoretical calculations [27]. Obtained results were shown in the table.

As shown, the experimental and theoretical isomeric yield ratios for ^{190}Ir$^{m2,g+m1}$ are close in the energy threshold region of the projectiles, but the theoretic IR is understated approximately twice as little against experimental IRs. The agreement between experiment and calculation was not reached by rational variation a and σ. We think it can be caused by an admixture of the $E2$-component in the statistical $E1$-transitions. The percent of the admixture is the third independent parameter in the MCEM. The calculation of isomeric yield ratios for average energy of the γ-rays obtained using Eq. (4) with an admixture of the $E2$-component 0.1% shows total agreement between theoretical and experimental IRs for ^{190}Ir$^{m2,g+m1}$ and ^{150}Eu for investigated energies of the projectiles.

It should be noted that in case of irradiation by the projectiles with higher energy, the theoretical results agreed with measured data within error limits. This information agreed qualitativly with the conclusion, that it is necessary to allow for $E2$-multipolarity in more degrees for low energy of the projectiles, when the relative role of the $E2$-multipolarity is significant higher.

V. CONCLUSIONS

Isomeric yield ratios^{190}Ir$^{m2,m1+g}$, ^{150}Eu^{m,g}, ^{152}Eu^{m1,m2} have been measured in (γ, n)-reactions for the end point energies of bremmsstrahlung photons about 12, 12.5, and 16 MeV for ^{190}Ir $^{m2,m1+g}$ and 12 MeV for ^{150}Eu^{m,g}, ^{152}Eu^{m1,m2}.

Used in our investigation for the theoretical calculations were the codes both the modificated cascading-evaporating model (MCEM) and TALYS based on Hauser-Feshbach theory. These models based on the statistical mechanism of nuclear reactions.

In addition, there is a contribution of the pre-equlibrium mechanism for these end-point energies of bremmsstrahlung photons in TALYS. This mechanism based on the exciton model. It is shown that the contribution of the pre-equilibrium model not exceeding 5–10%.

Despite the relatively high difference between spins the metastable and ground states, the isomeric yield ratios are relatively high for all pairs at low excitation energies. This implies, that the statistical mechanism of (γ, n)-nuclear reactions dominates even when the energy of the projectiles is around to threshold. The average energy of the statistical γ-rays is 300–400 keV (4) in this region. But, the agreement between experiment and calculation was reached by rational variation of the statistical model parameters only for ^{152}Eu^{m1,m2}. Therefore we were induced to introduce a third free parameter in the MCEM. This parameter is a percent of the admixture of the $E2$-component in the statistical E1-transitions. The calculation using the MCEM subject 0.1 of the percent of the

$E2$-multipolarity permit to agree theoretical and experimental values of the isomeric yields ratios for $^{190}\mathrm{Ir}^{m2,m1+g}$ and $^{150}\mathrm{Eu}^{m,g}$. In the general case, the TALYS operates better for $^{150,152}\mathrm{Eu}$ when the MCEM for $^{190}\mathrm{Ir}$.

Consideration of all above-stated we can do conclusion that there is a low contribution direct and preequilibrium processes in the mechanisms of nuclear reactions in the investigated region of the energies of the bremmsstrahlung photons.

[1] E. A. Bogila and V. M. Kolomietz, Ukr. Phys. J, **34**, 7 (1989).
[2] Yu. P. Gangrski, M. N. Kolesnikov, V. G. Lukashik, and L. M. Melnikova, Izv. Acad. Nauk. Ser. Fiz. **68**, 167 (2004).
[3] A. P. Tonchev, Yu. P. Gangrsky, A. G. Belov, and V. E. Zhuchko, Phys. Rev. C **58**, 2851 (1998).
[4] A. G. Belov, Yu. P. Gangrsky, A. P. Tonchev, and V. E. Zhuchko, Phys. At. Nucl. **60**, 1773 (1997).
[5] I. N. Vishnevsky, V. A. Zheltonozhsky, V. M. Mazur, and M. V. Hoshovsky, Phys. At. Nucl. **62**, 941 (1999).
[6] V. M. Mazur, Z. M. Bigan, M. V. Hoshovsky *et al.*, *Scientific Proceeding IEP-96, IEP NS Ukraine, Uzhgorod, 1996,* p. 219.
[7] D. M. Symochko, AIP Conf. Proc. **958**, 248 (2007).
[8] R. B. Firestone, *Table of Isotopes,* 8th ed. (Wiley Interscience, New York, 1996).
[9] R. Vanska and R. Rieppo, Nucl. Instrum. Methods **179**, 525 (1981).
[10] I. N. Vishnevsky, V. A Zheltonozhsky, A. G. Zelinsky *et al.*, Collected Scientific articles Kiev Institute for Nuclear Research 60 (1999).
[11] GEANT4-a simulation toolkit, S. Agstinelli *et al.*, Nucl. Instrum. Methods Phys. Res. A **506**, 250 (2003).
[12] A. J. Koning, S. Hilaire, and M. C. Duijvestijn, *Proceedings of the International Conference on Nuclear Data for Science and Technology, 2005,* p. 1154.
[13] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[14] A. J. Koning and M. C. Duijvestijn, Nucl. Phys. **A744**, 15 (2004).
[15] H. Gruppelaar, P. Nagel, and P. E. Hodgson, Riv. Nuovo Cimento **9**, 1 (1986).
[16] E. Gadioli and P. E. Hodgson, *Pre-equilibrium Nuclear Reactions* (Oxford University Press, Oxford, 1992); W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).
[17] A. J. Koning and J. P. Delaroche, Nucl. Phys. **A713**, 231 (2003).
[18] J. Kopecky and M. Uhl, Phys. Rev. C **41**, 1941 (1990).
[19] D. M. Brink, Nucl. Phys. **4**, 215 (1957); P. Axel, Phys. Rev. **126**, 671 (1962).
[20] Handbook for calculations of nuclear reaction data: reference input parameter library, http://www-nds.iaea.or.at/RIPL-2/.
[21] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. **A217**, 269 (1973).
[22] N. M. Lederer and U. S. Shirey, *Table of Isotopes,* 7th ed. (J. Wiley, New York, 1978).
[23] A. V. Ignatuk, *Statistical Properties of the Excited Atomic Nuclei* (Energoatomizdat, Moscow, 1983).
[24] K. H. Murthy, S. K. Gupta, and A. Chatterjee, Z. Phys. A **305**, 73 (1982).
[25] P. Decowski, W. Grochulski, and A. Marcinkowski, Nucl. Phys. **A194**, 380 (1972).
[26] V. A. Zheltonozhsky, V. M. Mazur, and Z. M. Bigan, Phys. At. Nucl. **67**, 899 (2004).
[27] L. Ya. Arifov, B. S. Masitov, and V. G. Ulanov, Yad. Fiz. **34**, 1028 (1981).