STUDY OF THE EFFECTIVE EXCITATION CROSS SECTION OF THE ^{115}In ISOMERIC STATE IN THE (γ,γ') REACTION

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Braking radiation of a betatron and a microtrone at the Chair of Nuclear Physics of the Faculty of Physics of the Uzhgorod National University was used to obtain the yield curve of the $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ reaction in the energy interval 7—25 MeV with a step of 0.5—1 MeV. This curve was used to calculate the effective cross section of the reaction, and a second maximum in the reaction cross section at the energy of 22 MeV was revealed.

1. Introduction

In order to explain the appearance of the giant dipole resonance (GDR) of atomic nuclei and to describe its physical characteristics, a number of theoretical models (both one-particle and collective ones) has been developed, but the available experimental data are insufficient to give preference to one of them. The further progress in the experimental studies of the GDR is substantially associated with the consideration of various channels of its decay; first of all, the channels which give rise to the population of isomeric nuclear states. A relatively long lifetime of nuclei in such a state considerably facilitates the research of their quantum characteristics and allows the direct measurements of the probabilities of radiative transitions from these states to be fulfilled.

A comparison between the values of the effective excitation cross sections of isomeric nucleus states measured in absolute units in photonuclear reactions and those calculated in the framework of the corresponding theoretical models can be used to improve and develop these models further. It can also provide a valuable information concerning the structure of energy levels in isomeric nuclei and the mechanism of their population.

The body of experimental data on the channels of population of the isomeric states of final nuclei owing to photonuclear reactions remains scanty. The only decay channels for the nuclear states that have been excited below the nucleon escape threshold are the channels of elastic and inelastic scattering of gamma-quanta by relevant nuclei. Provided that gamma-quanta with the energies in the GDR range and above are absorbed, the discharge of the excited nucleus is accompanied by the emission of particles of various types. For example, for the energies above the neutron escape threshold, the most probable reaction is (γ,n); therefore, the effective cross section of isomer excitation through the (γ,γ') reaction would fall down quickly as the energy grows beyond the threshold. However, in a number of works [1–5], an increase of the effective cross sections of isomer state excitation in the (γ,γ') reaction has been registered experimentally for some nuclei above their neutron escape threshold. In particular, the measurements of the effective cross sections of the reaction $(\gamma,\gamma')^m$, which were fulfilled in the 1960s on various experimental installations for ^{89}Y [2], ^{103}Rh [3], ^{115}In [1], ^{109}Ag [4], and ^{107}Ag [5] nuclei within the energy interval 5—25 MeV, revealed the existence of two maxima in the energy dependences of the effective cross sections of the $(\gamma,\gamma')^m$ reaction with the participation of these nuclei: the first being located below the corresponding (γ,n)-reaction threshold and the second at the energy of 14—20 MeV.

The experimental measurements of the effective cross section of the $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ reaction, which were carried out in 1986—1987 [6,7], found only one maximum at 8—9 MeV in the energy dependence of the effective cross section of this reaction, with the magnitude of the cross section in the maximum being equal to 1–2 mb. Above the (γ,n)-reaction threshold, the effective cross section of the $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ reaction abruptly falls down and does not grow until the energy of 30 MeV. Thus, the data of works [6, 7] testify to the absence of the second maximum in the effective cross section of the $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ reaction in the GDR energy range.

In work [8] which has been published recently, the increase of the effective cross section of the $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ reaction above the (γ,n)-reaction

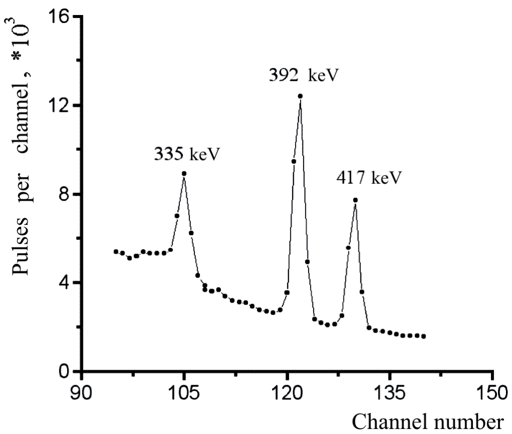

Fig. 1. Instrument gamma-radiation spectrum of an indium specimen irradiated at the energy of 22 MeV

threshold, in particular, within the interval of 9—30 MeV, has been revealed. Therefore, further experimental and theoretical researches dealing with the behavior of the effective excitation cross sections of the isomeric states of some nuclei in the (γ,γ') reaction in a wide energy interval, which covers the GDR one, seem actual.

The data reported in works [1, 6–8] are inconsistent. Hence, in this work, we measured the yield of the ^{115}In$(\gamma,\gamma')^{115m}$In reaction and, on its basis, calculated the effective cross section of this reaction in the energy interval 7—25 MeV.

2. Measurement Method and Results

The yield of the reaction concerned was measured following the activation method on experimental installations built on the basis of an M-10 microtrone and a B-25 betatron accelerator at the Chair of Nuclear Physics. The betatron braking radiation intensity amounted to 25 R/min at a distance of 1 m from the brake target and the maximal energy of 23 MeV, the gamma-quantum pulse duration was 7 μs, and the pulse-repetition rate was 50 Hz. The average output current of the electron beam produced by the microtrone was 10—20 μA, the pulse current 10—20 mA, the pulse-repetition rate of electron emission 400 Hz, and the energy of accelerated electrons can be varied within the limits 4—9 MeV.

The gamma-emission of irradiated specimens was measured making use of a Ge(Li) detector with the chamber volume of 80 cm^3 and the resolution of 6 keV for the 1332-keV line. Metallic indium disks, 3 cm in diameter and 1—1.2 mm in thickness, composed of the natural mixture of isotopes were used for measurements.

If indium specimens are irradiated by gamma-quanta with the energy more than 10 MeV, six radioactive indium isotopes emerge owing to the (γ,γ') and $(\gamma$,n) reaction. These include ^{112}In, ^{112m}In, ^{113m}In, ^{114}In, ^{114m}In, and ^{115m}In, the half-life periods of which are within the scope from 72 s to 50 days; and they emit gamma-quanta, beta particles, and positrons.

The table quotes the data concerning the nuclear-physical characteristics of indium isotopes, radioactive isotopes, and isomeric states which are formed in the course of the irradiation of stable indium isotopes with gamma-quanta and neutrons, owing to the reactions (γ,γ'), $(\gamma$,n), and (n,γ). The irradiation types and energies, the intensities of some gamma-lines, and the reaction energy thresholds are also indicated in the table.

Taking the long half-life period of isomer ^{115m}In into account, ten specimens were fabricated for measurements. During the irradiation, the specimens were arranged at a distance of 25 cm from the betatron's brake target on the front surface of the absolute ionization chamber.

Figure 1 shows an example of the instrument gamma-emission spectrum of a specimen after its irradiation at the energy of 22 MeV. Three maxima related to the isomeric transitions for ^{116m}In, ^{113m}In, and ^{116m}In isotopes are observed.

To verify our betatron-based method, we measured the absolute yield of the reaction ^{63}Cu$(\gamma$,n$)^{62}$Cu and calculated its differential cross section. Our results agree well with the data of work [9], where the reaction cross

Nuclear-physical characteristics of indium isotopes

Isotope	Natural Occurrence, %	$T_{1/2}$	E_γ, keV	E_β, keV	Reaction (Energy threshold, MeV)
^{112}In	—	14.4 min	119	β^+1500, β^-650	^{113}In(γ, n)^{112}In (9.58)
^{112m}In	—	20.9 min	157	—	^{113}In(γ, n)^{112m}In(9.58)
^{113}In	4.3	1015 years			
^{113m}In	—	99.4 min	392		^{113}In(γ,γ')^{113m}In (0.39)
^{114m}In	—	49.5 days	190	—	^{115}In(γ, n)^{114m}In (9.23)
^{115}In	95.7	$5{\cdot}10^{14}$ years		495 (46%)	
^{115m}In	—	4.486 h	336 (45,9%);	β^-830	^{115}In(γ,γ')^{115m}In (0.33)
^{116m}In		54.1 min	138 (3.3%); 417	1000	^{115}In(n, γ)^{116m}In

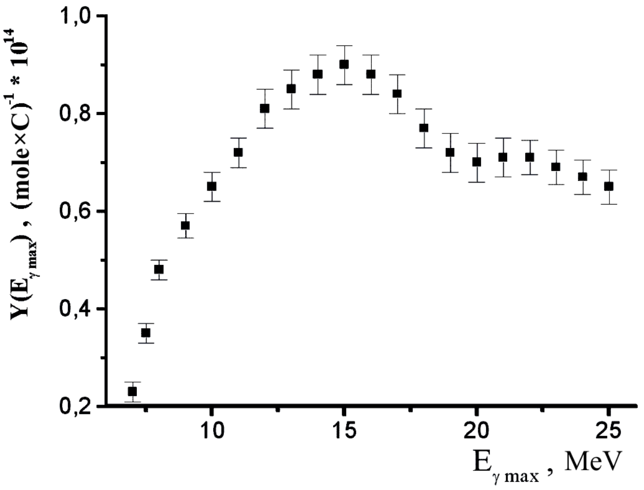

Fig. 2. Dependence of the absolute yield of the ^{115}In$(\gamma,\gamma')^{115m}$In reaction on the maximal energy of braking radiation

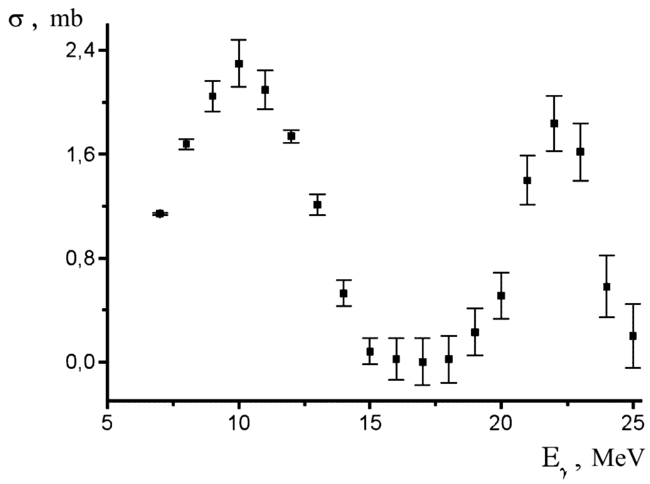

Fig. 3. Dependence of the effective cross section of the ^{115}In$(\gamma,\gamma')^{115m}$In reaction on the gamma-quantum energy

section was measured taking advantage of quasimonochromatic gamma-quanta, which is a certain evidence for the absence of systematic errors in our measurement technique.

Isotope ^{115m}In can be formed in the (n,n′) reaction as well. Background neutrons (fast and slow photoneutrons) can be formed in the betatron's brake target and other constructive elements. The spatial distribution of those neutrons is isotropic. In order to compare the influences of the neutron background and the ^{115}In(n,n′)^{115m}In reaction, we also irradiated an indium specimen beyond the braking radiation beam; but, in this case, only gamma-emission with the energy of 417 keV, i.e. emitted owing to the reaction ^{115}In(n,γ)^{116m}In, was observed.

3. Cross Section of the ^{115}In$(\gamma,\gamma')^{115m}$In Reaction

The measurement data on the induced radioactivity were used to plot the sections of the instrument spectrum, which, in turn, were used to find the area under the photopeak associated with 336-keV gamma-quanta.

The reaction yield $Y(E_m)$ was calculated by the formula

$$Y(E_m) = \frac{S(E_m)\lambda}{n\varepsilon\eta D(1-e^{-\lambda t_{\rm irr}})e^{-\lambda t_{\rm cool}}(1-e^{-\lambda t_{\rm meas}})}, \quad (1)$$

where λ is the constant of the isomeric nucleus decay, $S(E_m)$ the area under the 336-keV photopeak in the instrument spectrum of gamma-emission of the investigated isomer after the specimen having been irradiated at the energy E_m, ε the efficiency of the isomer gamma-emission registration, η the coefficient which takes the quantum yield of the isomer line into account, D the dose of braking radiation expressed in terms of a current through the thick-wall ionization chamber, $t_{\rm irr}$ the irradiation time interval, $t_{\rm cool}$ the specimen cooling time interval, and $t_{\rm meas}$ the measurement time interval.

Since the braking radiation intensity did not remain stable during the irradiation of the specimens, the radiation dose was measured with the help of the absolute ionization chamber and a device, the measuring capacity of which was connected with resistors. The resistances of the latter were selected to provide exponential, not linear, growth of the output voltage, with the power exponent equal to the decay constant of isomer ^{115m}In. In such a way, the ripple of the betatron gamma-emission intensity during specimen irradiation was taken into account automatically.

In Fig. 2, the dependence of the absolute reaction yield on the maximal energy of braking radiation is shown. The root-mean-square statistical errors over 3 to 4 series of measurements are also indicated.

The resulted reaction yield curve was used to calculate the effective cross section of the reaction in the energy interval 7—25 MeV. cross sections were calculated in the framework of the inverse matrix method (the Penfold–Leiss method) making use of the computer program developed at the Kharkiv Physical and Technical Institute and adapted to our conditions. In Fig. 3, the results of our calculations are depicted. From this figure, one can see that there exists a second maximum in the energy dependence of the cross section at about 22 MeV. The yield data were measured with a statistical error of 3%. Therefore, our cross section data confirm the conclusion made in works [1–5] that the cross section of inelastic scattering of gamma-quanta by nuclei increases above 15 MeV and has a second maximum. This conclusion contradicts that of works [6, 7], where the authors assert that the cross section decreases after reaching the first maximum and, above 12 MeV, becomes zero within the measurement errors.

In works [10–13] dealing with the photoexcitation of isomeric states in the reaction of inelastic scattering of gamma-quanta by nuclei, a possibility for two maxima in the $(\gamma,\gamma')^m$-reaction cross section to coexist was considered. In particular, the mechanism for a second maximum to appear in the effective cross section of the $(\gamma,\gamma')^m$ reaction was discussed in the framework of the available model approaches; however, no quantitative estimations were quoted. The experimental results obtained in the presented work allowed us to reveal the existence of a second maximum in the effective cross section of the $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ reaction at the energy of 22 MeV. The further researches concerning the energy dependence of the effective cross section of the isomeric state population in the $(\gamma,\gamma')^m$ reaction with some other nuclei seem actual.

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ДОСЛІДЖЕННЯ ЕФЕКТИВНОГО ПЕРЕРІЗУ ЗБУДЖЕННЯ ІЗОМЕРНОГО СТАНУ ЯДРА ^{115}In В РЕАКЦІЇ (γ,γ')

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Р е з ю м е

На гальмівному пучку бетатрона та мікротрона кафедри ядерної фізики Ужгородського національного університету одержано криву виходу реакції $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$ в інтервалі енергій 7—25 МеВ з кроком 0,5—1 МеВ. З одержаної кривої виходу розраховано ефективний переріз реакції. Виявлено, що при енергії 22 МеВ спостерігається другий максимум в ефективному перерізі реакції $^{115}\mathrm{In}(\gamma,\gamma')^{115m}\mathrm{In}$.