EXCITATION OF ISOMER IN $^{115}In(\gamma,\gamma')^{115m}In$ REACTION

O.S. Shevchenko, A.N. Dovbnja, E.L. Kuplennikov, A.A. Nemashkalo, V.I. Noga, Y.N. Ranyuk

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

Activation yield measurements of the $^{115}In(\gamma,\gamma')^{115m}In$ reaction were performed with bremsstrahlung of endpoint energies in the range of $E_{\gamma max} \leq 0.8…3.0$ MeV. The integrated cross sections for some intermediate states (*IS*) were deduced from the measured yield curve. It is shown, that increased of the reaction yield at the energy range of 1.6 … 3.0 MeV can be connected with existence of strong intermediate levels at the energy of 1999 and 2420 keV.

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1. INTRODUCTION

One of the important problems in nuclear structure physics and nuclear-reaction mechanisms are investigation of metastable nuclear states, known as isomers. Of special interest is a study of the excited levels with a rather big lifetime**.** In this case separation in time both process of irradiation and measurement give the opportunity to avoid of the intense γ-quanta background and essential increase experimental sensitivity.

Usually study of mentioned above states have been performed in reaction induced by nucleons, deuterons, α-particles and heavy ions but their study in (γ,γ') reactions, however, is of great interest. In part, the (γ,γ') process attract attention as there are not Coulomb barrier and binding energy for γ- quanta; one can obtain excited nuclei both in the region above nucleon threshold and below it; the momentum being introduced into nucleus by γ-quanta 1ħ (contribution of other moments as a rule ≤ 1% [1]) is not varied with energy increase; both the excitation (photoabsorption) and deexcitation (electromagnetic decays) processes proceed via the well-known electromagnetic interaction. In spite of referred advantages, the study of (γ,γ') reactions at photon energies below the particle threshold suffered in the past from the small cross-sections, discrete nature of the photon absorption by nuclei and lack of γ-sources of high spectral intensity. As it was stressed in [2] the reputation of the photoactivation technique was somewhat damage due to contradictory conclusions drawn from experiments with radioactive γ-ray sources.

During last decade considerable interest has been shown again in the field of photo-induced reactions. It was caused by the experimental progress achieved and manifold physical motivations. For example, theory has predicted low-lying collective magnetic dipole transitions in heavy deformed nuclei, the so-called "scissors" mode [3,4], and electric dipole excitation mode known as "Pygmy" resonance [5]. Besides that the attention in such process is also motivated by the possible innovating applications. Specific energy stored by some isomers for long period of time is much higher as compared to the standard sources of energy. For instance, the four-quasiparticle, long-lived (31 years), high-spin 16^{+} $^{178m2}Hf$ isomeric state stores a specific energy of about 1.3 MJ/mg [6] (for comparison the same value for the famous explosive nitroglycerine is of only $6.3 \cdot 10^{-6}$ MJ/mg [7]) So, the triggered release of the energy is promising for creation of powerful pulsed sources of γ-radiation. The investigation of astrophysical aspects can help to understand of the nucleo-synthesis of several isotopes and test of stellar models [8]. In addition to fundamental aspects, the isomeric states investigations of the (γ,γ') reactions are of practical interest as approximately 80% of radionuclides, using in medicine, and 40% in activation analysis are isomers.

The experiment presented in this work is focused on the study of $^{115}In(\gamma,\gamma')^{115m}In$ reaction. ^{115}In is the odd-even nucleus that contains 49 protons and 66 neutrons. The ground state (g.s.) with spin and parity $J_g^{\pi} = 9/2^{+}$ is practically stable with a half-life of $T_{1/2} = 4.4 \cdot 10^{14}$ years. The relevant param eters of the isomeric state are: excitation energy $E_{iso} = 336.2$ keV, $T_{1/2} = 4.49$ h, $J_{iso}^{\pi} = 1/2^{-}$. Spin difference between ground and isomeric state $\Delta J = |J_g - J_{iso}| = 4$. The isomer decays to the g.s. owing to a M4 γ-transition with relative probability (γ-line intensity) of $I_{\gamma} = 45.8\%$.

During the last decades a series of detail experiments [1,2,9] has been performed on the photoactivation of ^{115m}In. In these studies the electron energies, which were measured with an accuracy of ~ 30 keV, were varied from 0.5 to 4.3 MeV with step in size of 40…250 keV. The aim of our systematic investigations is to obtain additional experimental data over the range of $1.0 \leq E_{\gamma max} \leq 3.0$ MeV in a completely different geometry and new bremsstrahlung source.

2. PHOTOACTIVATION EXPERIMENTS

Different investigations [1,2] have confirmed that direct resonant excitation of the isomeric levels is negligible because of very small width (ΔE_{iso}) of them (at $T_{1/2} > 1$ s $\Delta E_{iso} = \hbar/\tau < 10^{-14}$ eV, where τ is averaged isomer life-time). The population of isomers by (γ,γ') reactions at excitation energies below the photoneutron threshold proceeds by the process depicted schematically in Fig. 1. The figure identifies the relevant parameters including the natural width of the intermediate level *Γ*, which is the sum of all partial widths for transitions on all levels, lying between the excited and g.s. and the branching ratios b_0 and b_{iso} for decay from the *IS* directly to the g.s. and by unknown cascade to the isomer.

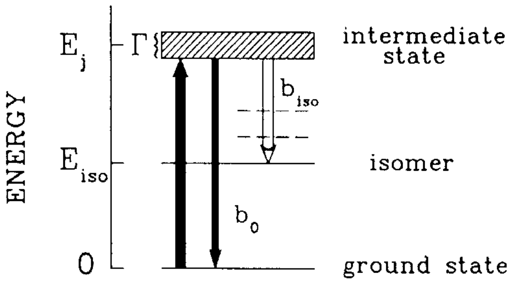

Fig. 1. *Mechanism of an isomer population*

As it is known [1,2] the level scheme of ^{115}In is well studied in the low-energy part and all possible intermediate states are available [11]. The decay diagram of the Indium isomer and spectroscopic characteristics are given in Fig. 2. Everyone can see that the decay is practically dominated by the 336.2 keV γ transition to the g.s. The diagonal downward arrows indicate beta decay. A weak line at 497 keV is a γ transition in ^{115}Sn nucleus. The corresponding level is populated with a probability of only $4.7\cdot10^{-4}$ in the β^- decay of the ^{115}In isomer.

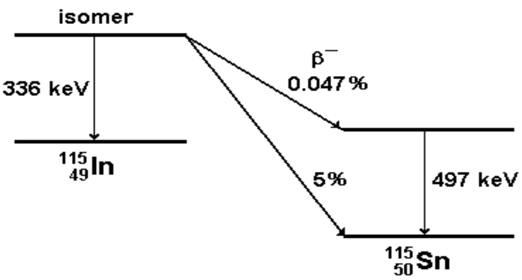

Fig. 2. *Decay scheme of ^{115}In isomeric state*

Present experiment was performed at the electrostatic electron accelerator ELIAS. Main parameters of the accelerator are presented in Table 1:

***Table 1**. The main parameters of ELIAS accelerator*

Parameter	Mean
Energy of accelerated electrons	0.5 - 3.2 MeV
Deviation for energy	< 1%
Electron current without scanning	0.5 – 150 μA
Maximum electron current with scanning	> 500 μA
Dispersion of electron beam	10^{-4} rad
Vacuum in accelerated and electron tubes	10^{-7} mbar
Diameter of the beam (without focusing)	1.0 cm
Diameter of the beam (with focusing)	< 1 mm

Bremsstrahlungs spectra with $E_{\gamma max} \leq 3.0$ MeV were generated by irradiating Ta converter with thickness of 0.5 mm. The fluent of water under pressure of 2.5 bars is used for cooling the radiator during the experiments. Natural abundance Indium target (95.6% ^{115}In and 4.4% ^{113}In) by thick of 0.2 mm and diameter of 15 mm was placed in the photon beam just behind the converter. Typical irradiation time was 60 min and averaged electron current varied from 50 to 200 μA. The endpoint energy changed with step in size of 200 keV. Gamma rays of the isomeric transition were detected by a well-shielded Ge(Li) detector with sensitive volume of 40 cm^3 and energy resolution 2.5 keV for 1332 keV of ^{60}Co isotope, coupled to a 4096 multichannel analyzer. The γ-spectra were processed by means of the BALTISPECTR-3.02 program [10].

3. DATA ANALYSIS

The number of nuclei activated through *IS* by a beam of bremsstrahlung equals:

$$N_f = \frac{\lambda S_\gamma t_{irr}}{\varepsilon_D I_\gamma (1-e^{-\lambda t_m})(1-e^{-\lambda t_{irr}})e^{-\lambda t_c}}, \quad (1)$$

where λ- constant decay, connected with $T_{1/2}$ and τ by the ratio of $T_{1/2} = \ln2/\lambda = \ln2\tau$, S_γ- number of γ-quanta in the photopeak area, t_{irr}, t_c, t_m - time of irradiation, cooling and measuring respectively. ε_D- detector efficiency, which usually takes from a calibration curve obtained beforehand for standard set of monochromatic sources.

Following the formalism reported earlier [2] another formula could be used for finding of the activated nuclei number:

$$N_f = N_T \int_{E_{th}}^{E_{\gamma\max}} \sigma(E_\gamma)\frac{d\Phi(E_\gamma, E_{\gamma\max})}{dE_\gamma} dE_\gamma, \quad (2)$$

where N_T describes the number of target nuclei per cm^2, $\sigma(E_\gamma)$ is resonant absorption cross section, $d\Phi(E_\gamma, E_{\gamma max})/dE_\gamma$ represents the spectral intensity per energy of photon field for an $E_{\gamma max}$, the lower integral limit in Eq. (2) E_{th} is a threshold energy – minimal energy for the population of the isomer.

If the *IS* widths are small (for example, for ^{115}In in the investigated region $E_{\gamma max} \leq 3.0$ MeV $\Delta E_{IS} \leq 10^{-3}$ eV) the $d\Phi(E_\gamma, E_{\gamma max})/dE_\gamma$ can be considered as constant $N(E_j, E_{\gamma max})$ over each resonance. Then Eq. (2) is simplified [2]:

$$N_f = N_T \sum_j (\sigma\Gamma)^j_{iso} N(E_j, E_{\gamma\max}), \quad (3)$$

where $(\sigma\Gamma)^j_{iso}$ and E_j is the isomer excitation integrated cross section through the *j*- level and *IS* energy. A description of the photons number with energy E_j per the solitary energy interval of the bremsstrahlung continuum $N(E_j, E_{\gamma max})$ is usually obtained from Monte-Carlo simulations.

The theoretical expression for integrated cross section of the isomer population through the *j*-th *IS* evaluated on a base of the Breit-Wigner formula [2]:

$$(\sigma\Gamma)^{j(t)}_{iso} = \pi^2 \left(\frac{\hbar c}{E_j}\right)^2 \frac{2J_j+1}{2J_g+1} b_g b_{iso}\Gamma, \quad (4)$$

where $\hbar c = 1.973\cdot10^{-11}$ MeV·cm.

If the properties of corresponding *IS* are known, the integrated cross sections can be derived.

4. RESULTS AND DISCUSSION

A typical experimental γ-spectrum of the activated natural In sample is depicted in Fig. 3.

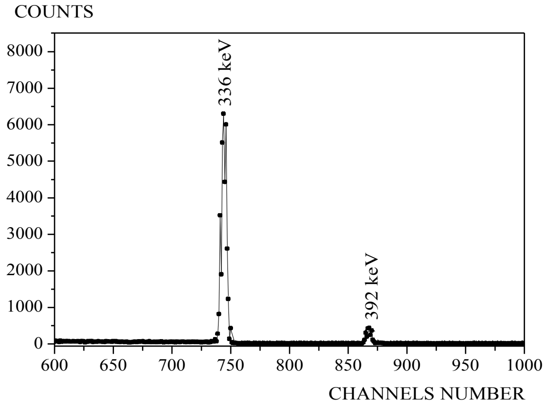

Fig. 3. *γ-ray spectrum after irradiation of In target by the 3.0 MeV bremsstrahlang. Electron current $I = 48\ \mu A$, $t_{irr} = 60$ min, $t_c = 50$ min, $t_m = 41$ min*

First photopeak at 336 keV is connected with ^{115}In isomer decay. Second one at 392 keV is associated with the corresponding M4 transition from the 99.5 min $J^{\pi}_{iso} = 1/2^-$ metastable state in ^{113}In to the g.s. with relative probability of 64.2%. Note that sensitivity of our experimental facility was not enough to clearly distinguish the peak at 497 keV from decay of the isomer to ^{115}Sn.

The isomer yield excitation function of the (γ,γ′) reaction with the metastable state excitation $Y(E_{\gamma max})$ is defined as the number of activated nuclei N_f normalized on the number of target nuclei N_T and the number of incident electrons N_e [1,2]. Then, the experimental isomer yield can be expressed as:

$$Y\left(E_{\gamma\,\max}\right) = \frac{\lambda S_{\gamma} t_{irr}}{N_T N_e \varepsilon_D I_{\gamma} (1 - e^{-\lambda t_m})(1 - e^{-\lambda t_{irr}}) e^{-\lambda t_c}}. \quad (5)$$

The accuracy of the reaction yield depends on uncertainties in the determination of photopeak area, quantity of investigated nuclei in the target, number of incident electrons, detector efficiency, conditions of the irradiation, cooling and measuring times. The full errors are the sum of systematic and statistical uncertainties. Note, that statistical errors were small. In typical cases a counting time of 1 hour gave better than 3% statistical accuracy in the photopeak area. The main contribution to the full error comes from the efficiency calibration of the Ge(Li) detector.

The experimental reaction yield is shown in Fig. 4. As it can be seen the onset of the yield curve is given by excitation energy of the first *IS* 934 keV that decays to the isomer with probability 0.5%. The reaction yield doesn't practically change in $1.0 \le E_{\gamma\,max} \le 1.5$ MeV region. It means that contributions of *IS* to the isomer within this energy range are small. With increasing $E_{\gamma\,max}$ the reaction yield becomes by a rather strong function of the endpoint energy. It is probably a consequence of powerful contributions of further *IS* with [1] $E_j = 1497$, 1608, 1999 and 2950 keV. Unfortunately, the breaks of the yield curve are not clearly visible. It creates a certain difficulties as each kink in the yield curve corresponds to the excitation energy of a further *IS*.

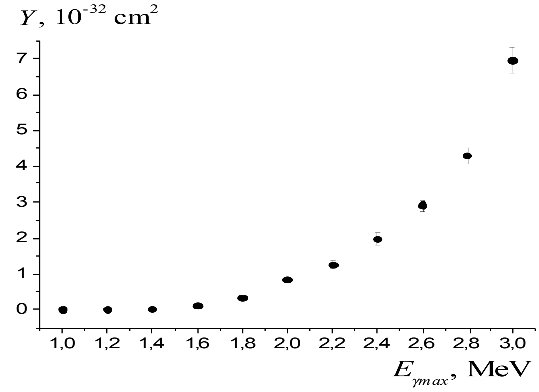

Fig. 4. *Isomer yield excitation function versus of endpoint energy*

Knowing [1,2] that the yield curve for a single *IS* must be of linear function of the $E_{\gamma\,max}$ and change of slope is proportional to the excitation strength of the respective state [2] it is possible to extract the $(\sigma\Gamma)^j_{iso}$ from the measured isomer yield. Following the procedure proposed in [1,2] we restored $(\sigma\Gamma)^j_{iso}$, defining them as parameters of a system of equations (6) when fitting to the experimental $Y(E_{\gamma max})$:

$$Y_i\left(E_{\gamma\,\max}\right) = \frac{N_f}{N_T N_e^{eff}} = \sum_j (\sigma\Gamma)^j_{iso} \frac{N_i\left(E_j, E_{\gamma\,\max}\right)}{E_e^{eff}}, \quad (6)$$

where $Y_i(E_j, E_{\gamma\,max})$ is the reaction yield at the *i*-th point of measurement. $N_i(E_j, E_{\gamma\,max})$ was calculated with the program GEANT3.21. The following parameters were used: the statistics was of $E_e^{eff} = 10^7$ triggers, the grouping interval equaled of 1 keV, the cut-off energy was of $E_{th} = 0.5$ MeV. The angular dependence of the spectral distribution is included in the definition of the target geometry in calculations. Properties of the intermediate states contributing to the population of the isomer for $E_{\gamma max} \le 3$ MeV [1,2], extracted $(\sigma\Gamma)^j_{iso}$ together with results [1,2,9] and calculated integrated cross sections are summarized in Table 2. The b_o, b_{iso}, and $(\sigma\Gamma)^{j(t)}_{iso}$ were counted using Eq. (4) and spectroscopic data [11]. Unfortunately we could not calculate above mentioned values for levels of 1999, 2420 and 2950 keV because of absence of corresponding parameters in [11].

Our analysis has shown that the obtained results are in reasonable agreement with other data and that increasing of the ^{115}In(γ,γ′)^{115m}In reaction yield at the interval of $1.6 \le E_{\gamma max} \le 3.0$ MeV can be connected with existence of intensive *IS* at the $E_j = 1999$ and 2420 keV.

Table 2. *Spectroscopic characteristics of the* ^{115m}*In and integrated cross sections*

[11] E_j, keV	[11] J_j^{π}	This work $(\sigma\Gamma)_{iso}^{j}$, $eV\cdot b$	[1] $(\sigma\Gamma)_{iso}^{j}$, $eV\cdot b$	[2] $(\sigma\Gamma)_{iso}^{j}$, $eV\cdot b$	[9] $(\sigma\Gamma)_{iso}^{j}$, $eV\cdot b$	$T_{1/2}$, psec	b_o, %	b_{iso}, %	Theory $(\sigma\Gamma)_{iso}^{j(t)}$, $eV\cdot b$
934	7/2+				0.0085(40)	57(5)	99.8(3)	0.2(1)	0.00006(1)
941	5/2+		0.008(3)			15.1(1.4)	89.8(6)	10.2(2)	0.0072(8)
1078	5/2+	0.10(4)			0.115(4)	0.99(5)	83.4(6)	15.7(4)	0.119(8)
1449	9/2+		0.140(41)			0.35(4)	85.0(7)	0.14(7)	0.0028(5)
1463	7/2+					0.063(10)	94.2(7)	0.9(1)	0.087(15)
1487	9/2+					0.44(6)	79.8(6)	0.4(1)	0.005(1)
1497	7/2+	0.62(25)	0.78(27)		0.59(20)	0.20(2)	78.1(8)	21.9(8)	0.626(75)
1608	7/2+	0.25 (15)	0.25(12)		0.25(15)	0.113(9)	69.2(7)	4.9(2)	0.166(30)
1999	7/2+	0.96(40)	1.12(39)						
2420		1.70(60)	1.83(63)						
2950			3.1(13)	5.7(11)					

5. CONCLUSIONS

Isomer yield excitation function has been measured in ^{115}In(γ,γ′)^{115m}In reaction by activation method at the irradiation facility of the electrostatic electron accelerator ELIAS. The bremsstrahlung with endpoint energy range of 1.0…3.0 MeV was used. The integrated photoactivation cross sections for some intermediate states have been extracted. The integrated cross sections results are analyzed in combination with data from low-energy photon scattering (γ,γ′) reaction. It is shown, that ^{115m}In excitation function is sharply grow up at the endpoint energy range of 1.6…3.0 MeV and such increase can be connected with existence of intensive activating levels at the energy of 1999 and 2420 keV.

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ВОЗБУЖДЕНИЕ ИЗОМЕРА В РЕАКЦИИ ^{115}In(γ,γ′)^{115m}In

О.С. Шевченко, А.Н. Довбня, Э.Л. Купленников, А.А. Немашкало, В.И. Нога, Ю.Н. Ранюк

Измерения активационного выхода ^{115}In(γ,γ′)^{115m}In реакции проведены на тормозном пучке в области граничных энергий $E_{\Upsilon max} \leq$ 0.8…3.0 МэВ. Интегральные сечения для ряда промежуточных состояний получены из анализа кривой выхода. Показано, что рост выхода реакции в интервале 1.6…3.0 МэВ может быть связан с существованием сильных промежуточных уровней с энергией 1999 и 2420 кэВ.

ЗБУДЖЕННЯ ІЗОМЕРА В РЕАКЦІЇ ^{115}In(γ,γ′)^{115m}In

О.С. Шевченко, А.М. Довбня, Е.Л. Купленніков, А.А. Немашкало, В.І. Нога, Ю.М. Ранюк

Вимірювання активаційного виходу ^{115}In(γ,γ′)^{115m}In реакції проведені на гальмовому випромінюванні в області граничних енергій $E_{\Upsilon max} \leq$ 0.8…3.0 МеВ. Інтегральні перерізи для кількох проміжних станів отримані з аналізу кривої вихода. Доведено, що зростання виходу в інтервалі 1.6…3.0 МеВ може бути пов'язано з існуванням сильних проміжних рівнів з енергією 1999 та 2420 кеВ.