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The nuclear channel effect in the isomeric ratio of the reaction products

Tran Duc Thiep[1*], Truong Thi An[1], Bui Minh Hue[1], Phan Viet Cuong[2]
A. G. Belov[3] and S. Mitrofanov[3]

[1]*Institute of Physics, VAST, 10 Dao Tan St., Ba Dinh Dist., Hanoi, Vietnam*
[2]*Vietnam Institute of Atomic Energy, 59 Ly Thuong Kiet, Hoan Kiem Dist., Hanoi, VN*
[3]*Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Moscow Region, Russia*
[*]*Email: tdthiep@iop.vast.ac.vn*

Abstract This work presents the experimental study of the isomeric ratio of ^{115m}Cd to ^{115g}Cd produced in ^{116}Cd(γ, n)^{115m,g}Cd photonuclear reaction and ^{116}Cd(n, γ)^{115m,g}Cd neutron capture reaction by thermal, epithermal and mixed thermal and epithermal neutrons. The investigated samples were natural cadmium irradiated at the bremsstrahlung photon flux, in the neutron source constructed at the electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reaction, Joint Institute for Nuclear Research, Dubna, Russia. The results were analyzed, discussed, compared and combined with those of other authors in the existing literature to examine the role of the nuclear channel effect in the isomeric ratio and provide the nuclear data for theoretical model interpretation of nuclear reactions and applied research.

Keywords: *Photonuclear reaction - neutron capture reaction - isomeric ratio - nuclear channel effect - nuclear reaction mechanism.*

I. INTRODUCTION

The structure of nuclear excited levels can be obtained from two sources, namely natural radioactive decay and nuclear reactions. The first source is very limited while the second one is very rich and provides not only the information about the nuclear structure but also about nuclear reaction mechanism as well. In nuclear reactions induced by different projectiles, usually the reaction products are existed in the isomeric and ground states. The ratio of the yields of forming these states, the so called isomeric ratio *IR* has become a diverse source of information about nuclear structure and reaction mechanism. It has been used for studying reactions with photon, neutrons, proton [1- 4], deuterium, tritium, alpha, heavy ions [5-7]; nuclear fission [8-10], or nucleon transfer, and complete and incomplete fusion reactions [11, 12]. The *IR* is connected to different nuclear effects as the excitation energy, momentum transfer, spin dependence, nucleon configuration, intermediate state structure, nuclear channel effect, contributions of direct and pre-equilibrium processes and so on. N. Tsoneva et al [13] shows that in the isotone nuclei, the *IRs* depend on the mass numbers. In refs. [15, 16] the authors by studying the *IRs* in photonuclear reaction of different isotopes led to conclusion that the *IR* decreases with the increase of neutron number. The dependence of *IR* on masses of isotones and isotopes is called the effect on nucleon configuration. F. Cserpak et al [17], S. M. Qaim et al [18] and C. D. Nesaraja [19] investigated the *IR* of the same nucleus produced from different reaction

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channels and show the influence of the reaction channel on the *IR*. The excitation energy, momentum transfer effects can be found in refs. [15, 16] and [20]. M. Huber et al [21] and J. J. Carroll et al [22] show the important role of intermediate state structure on the mechanism of population of the isomeric and ground states. The contributions of direct and pre-equilibrium processes can be found in ref. [23]. It is well known that the isomeric and ground states are formed simultaneously during nuclear reaction process in the same experimental conditions. Therefore, the *IR* can be determined with high accuracy. By fitting the *IRs* calculated on the basis of a definite theoretical model to the experimental ones, it is possible to obtain information about the nuclear structure, namely the spin dependence of the nuclear level density, in particular, the spin cut-off parameter σ and the level density parameter a as well as nuclear reaction mechanism.

The aim of this work is to study the *IRs* of isomeric pair ^{115m,g}Cd produced in ^{116}Cd(γ, n)^{115m,g}Cd photonuclear reaction and in ^{114}Cd(n, γ)^{115m,g}Cd neutron capture reaction by the activation method. The reason is that up to now the data for these reactions in existing literature are very rare. On the other hand, the model calculation of nuclear reactions needs not only one but a big number of nuclear data. The results of this investigation will be used to examine the role of the nuclear channel effect and they also can provide the nuclear data for theoretical interpretation of nuclear reactions as well as for applied research.

II. EXPERIMENTAL

A. Irradiation sources

The irradiation sources which consisted of the bremsstrahlung photon, the thermal and epithermal neutrons were created at the electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions at JINR, Dubna**.** The Microtron MT-25 produces 10 to 25 MeV electron beam with 1 MeV energy step and its description is presented in [24].

1. Bremsstrahlung photon source

The bremsstrahlung photon flux is produced through an electron-photon converter made of 3 mm thickness W disk and cooled by water. To absorb low energy electrons passing the converter in the irradiation sample, an Al absorber of 20 mm thickness was placed behind the converter. The energy spread of the accelerated electrons is small (30- 40 keV for up to 600 W of average beam power) allows the measurement of the *IR* at strictly defined bremsstrahlung end-point energy. To completely avoid the contribution of the neutron background from reactions on the accelerating structure or the breaking target itself, the sample was covered by cadmium foil of 2 mm thickness.

2. Thermal and epithermal neutron source

Production of the thermal and epithermal neutron source is shown in Fig. 1. The bremsstrahlung photon flux was obtained when the electron beam was directed to a uranium electron-photon converter with cylinder form (diameter and length of 10 mm) surrounded by beryllium. The neutron beam was produced by (γ, n) photonuclear and (γ, f) fission reactions of uranium with high energy part and by (γ, n) photonuclear reaction of beryllium with low energy part of the bremsstrahlung photon flux. Beryllium also generated neutrons at the interaction with the photons scattered by uranium and served as a neutron moderator. The simultaneous use of uranium and beryllium as photon-neutron converter provided a higher neutron flux than uranium converter. This uranium-beryllium converter was placed within a 120x120x120 cm^3 graphite cube, which served as a main neutron moderator to thermal and epithermal energy neutrons. The thermal neutron flux at the center of the cube was 4.10^8 neutrons/s.cm^2 at an electron energy of 25 MeV and a current of 20 μA. The detailed construction of this neutron source can be found in ref. [25, 26].

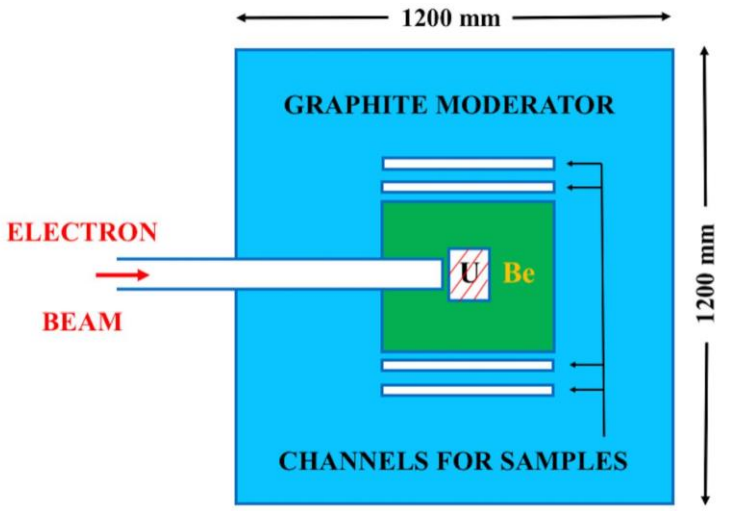

Fig. 1. The scheme for production of thermal and epithermal neutron source

B. Sample preparation and irradiation

The sample for investigation was prepared from a foil of the 99.99 % purity natural cadmium, in disk shape with diameter of 1.0 cm and mass of 0.7143 g. The sample for the ^{116}Cd(γ, n)^{115m,g}Cd photonuclear reaction investigation was irradiated by the bremsstrahlung flux of 24 MeV end-point energy for 1 hour. The irradiation place was 2 cm from the aluminum absorber and at the axis of the electron beam. For the ^{114}Cd(n, γ)^{115m,g}Cd reaction, the sample was uncovered and covered in Cd foil of 2 mm thickness. The irradiation was performed in the graphite cube presented in Fig. 1 for 2 hours at the place of 40 cm from the uranium converter where the Cd ratio is 2.5. The average electron current for both bremsstrahlung and neutron irradiations was about 15 μA.

C. Measurement of gamma-ray activity

The γ-ray activities of the investigated samples were measured with a spectroscopic system consisting of a coaxial p-type HPGe detector with a diameter of 60.5 mm and length of 31 mm, connected to a PC based 8192 channel analyzer (CANBERRA) for the data processing [15 - 26]. The resolution of the detector system was 1.8 keV FWHM at the 1332.5 keV γ-ray photo-peak of ^{60}Co. The efficiencies of the detector were determined with a set of standard single gamma ray sources calibrated to 1 - 2 %. Fig. 2 shows the efficiency of the detector measured at a distance of 5 cm. The measured efficiency curve consists of two parts from two sides of a maximum. The left part for lower energies was fitted with the function (1) while the right one for higher energies with function (2) as follows:

$$ln(\varepsilon) = \sum_{i=0}^{2} a_i (lnE)^i \quad (1)$$

$$ln(\varepsilon) = \sum_{i=0}^{4} a_i (lnE)^i \quad (2)$$

where ε is the detection efficiency, a_i represents the fitting parameters and E is the energy of gamma ray.

In our experiment, the measurements were performed with count statistics less than 0.3 - 2% for all the interested gamma rays.

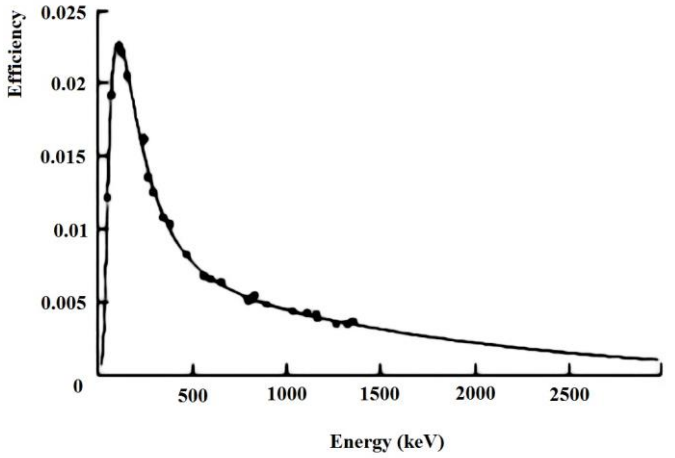

Fig. 2. The efficiency of HPGe semiconductor detector measured at a distance of 5 cm

D. Data analysis and isomeric ratio determination

1. Data analysis and gamma ray selection for the IR calculation

The isomeric pair ^{115m,g}Cd is formed through ^{116}Cd(γ, n)^{115m,g}Cd photonuclear reaction and ^{116}Cd(n, γ)^{115m,g}Cd neutron capture reaction. Fig. 3 depicts the simplified decay schemes of isomeric and ground states ^{115m}Cd and ^{115g}Cd. The isomeric state ^{115m}Cd ($T_{1/2}$ = 44.6 d) decays to ^{115}In by β$^-$ 100% following by 484.5, 933.8 and 1290.6 keV gamma rays with intensities of 0.029, 2.0 and 0.890% respectively. Therefore 933.8 keV gamma ray was chosen for calculation of *IR* as most intense. The ground state ^{115g}Cd ($T_{1/2}$ = 53.46 h) decays to ^{115}In by β$^-$ 100% following by 527.9, 492.3 and 336.2 keV gamma rays with intensities of 27.45, 8.03 and 45.9% respectively. The 336.2, 492.3 and 525.9 keV gamma rays are intense and were chosen for *IR* calculation. Table 1 shows the decay characteristics and gamma rays, which were taken from [27, 28] used in the isomeric ratio calculation of the isomeric pair ^{115m,g}Cd.

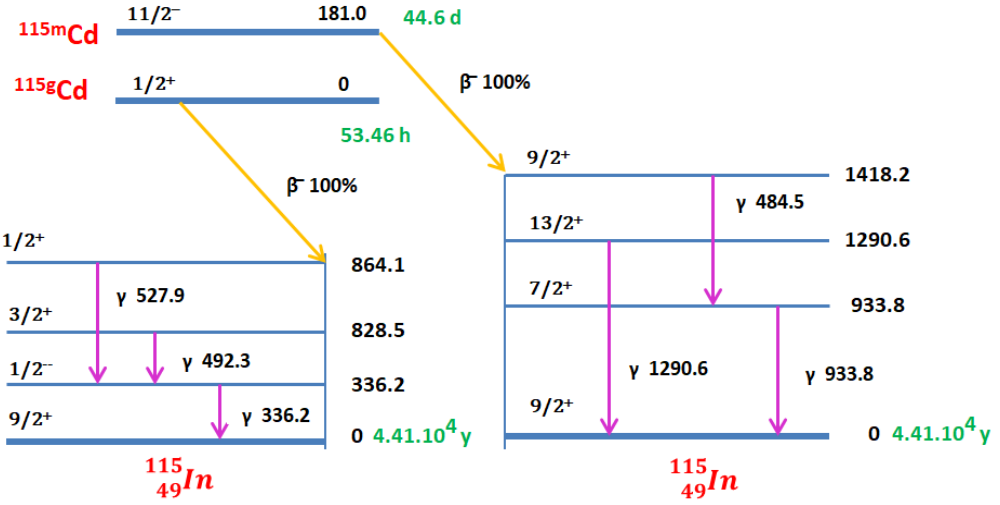

Fig. 3. The simplified decay schemes of isomeric and ground states ^{115m}Cd and ^{115g}Cd

2. The IR calculation

The *IR* was calculated based on the counts of γ-rays characterizing the isomeric and ground states measured for the definite times of irradiation, cooling and counting. The calculation procedure is the same, which has been presented in refs. [15, 26] by using the following expression:

$$\frac{1}{IR} = \frac{\frac{S_g \varepsilon_m I_m}{S_m \varepsilon_g I_g} \Lambda_3\Lambda_6\Lambda_9 - \Lambda_1\Lambda_5\Lambda_8 - \Lambda_3\Lambda_5\Lambda_8 - \Lambda_3\Lambda_6\Lambda_7}{\Lambda_2\Lambda_5\Lambda_8} \quad (3)$$

Where m and g - the isomeric and ground states; *S*, ε and *I* - the counts, the efficiencies and the intensities of the interested gamma rays and Λ_i (i = 1 ~ 9) are expressions related to the irradiation, cooling and measurement times.

Table I. The decay characteristics and gamma rays used in the isomeric ratio calculation of the isomeric pair ^{115m,g}Cd

Nuclear Reactions	Abun. [%]	Reaction Product	Spin [ħ]	Half life	γ-ray energy, [KeV] and intensity, [%]
^{116}Cd(γ, n)^{115m,g}Cd	7.49	^{115m}Cd	$11^-/2$	44.6 d.	933.8(2.00)
^{114}Cd(n, γ)^{115m,g}Cd	28.73	^{115g}Cd	$1^+/2$	53.46 h.	336.2(45.9)
					492.3(8.03)
					527.9(27.45)

E. Uncertainty sources and corrections

The total uncertainty of the isomeric ratio determination comes from two sources. The first one is related to the systematics, including those from the distance from the detector to sample, the gamma ray selection, the electron beam variation, the irradiation and cooling times, which were estimated to be of 1, 1, 1.5, 15 and 1.5%, respectively. The second one is related to the *IR* calculation, which was calculated with the help of the error propagation principle for the expression (3). The total uncertainty of the isomeric ratio determination was estimated to be of 10%. In order to improve the accuracy of the *IR* determination, the losses of the counts of the characteristic gamma rays of the isomeric and ground states due to the effects of coincidence summing and self- absorption were taken into account.

The coincidence summing for cascades 527.9 - 336.2 keV; 492.3 - 336.2 and 484.5 - 933.7 keV was estimated by the method presented in ref. [29] using the formula below:

$$C_c = \frac{1}{1 - \sum_{i=1}^{i=j} f_i \cdot \varepsilon_t(i)} \quad (4)$$

Where f_i - the fraction of coincidence photons of energy *i* in coincidence with the gamma ray of interest and ε_t (*i*) - the total efficiency of the coincidence photon of energy *i* and C_c - the correction factor. In our experiment C_c was found to be 1.08, 1.11 and 1.11 and 1.0 for 336.2, 492.3, 527.9 and 933.7 keV at the distance 0 cm from detector, respectively.

The self-absorption was estimated by the following formula as in ref. [30]:

$$F_g = \frac{\mu t}{1 - e^{-\mu \cdot t}} \quad (5)$$

Where μ - the linear attenuation coefficient, *t* - the sample thickness and F_g is defined as the ratio of the true and measured counts of the interested gamma rays. This coefficient was calculated to be 1.065, 1.050, 1.041 and 1.011 for the gamma rays of 336.2,

492.3, 527.9 and 933.7 keV respectively. The data for μ was taken from ref. [31].

III. RESULTS AND DISCUSSION

Natural cadmium consists of 8 isotopes Cd-106, Cd-108, Cd-110, Cd-111, Cd-112, Cd-113, Cd-114 and Cd-116 with abundances of 1.25, 0.89, 12.49, 12.80, 24.13, 12.22, 28.73 and 7.49%, respectively [32]. Therefore when irradiated by 24 MeV bremsstrahlung, gamma rays of the isomeric pair ^{115m,g}Cd as product ^{116}Cd(γ, n)^{115m}Cd reaction are seen very clearly (see Fig. 4). Other gamma rays on this spectrum come from different products of the interaction beetwen the bremsstrahlung and cadmium isotopes.

In case of irradiation with thermal and epithermal neutrons, as a result of neutron capture reactions two isomeric pairs ^{115m,g}Cd and ^{117m,g}Cd appear as products of ^{114}Cd(n, γ)^{115m,g}Cd and ^{116}Cd(n, γ)^{117m,g}Cd reactions. Under our measurement condition only gamma rays of isomeric pair ^{115m,g}Cd are seen very clearly on the spectrum, presented in Fig. 5. The isomeric pair ^{117m,g}Cd was not observed because the half-lives of its isomeric and ground states are much shorter in comparison with the cooling time. The *IR* of ^{115m,g}Cd was calculated for different times of cooling and measurement using formula (3).

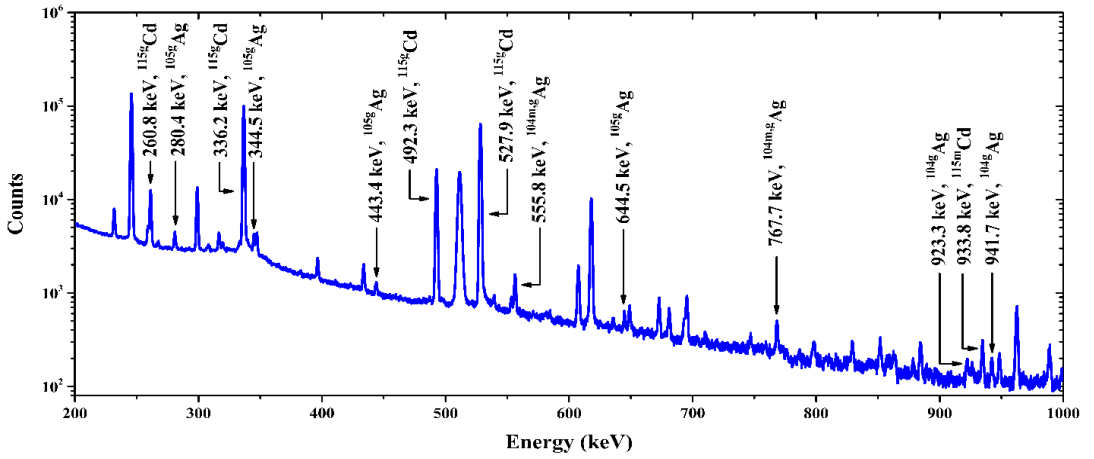

Fig. 4. Spectrum of $^{Nat.}$Cd irradiated by 24 MeV bremsstrahlung for 60 min, measured for 20 min with cooling time of 275.5 min. at the distance of 5 cm from the detector

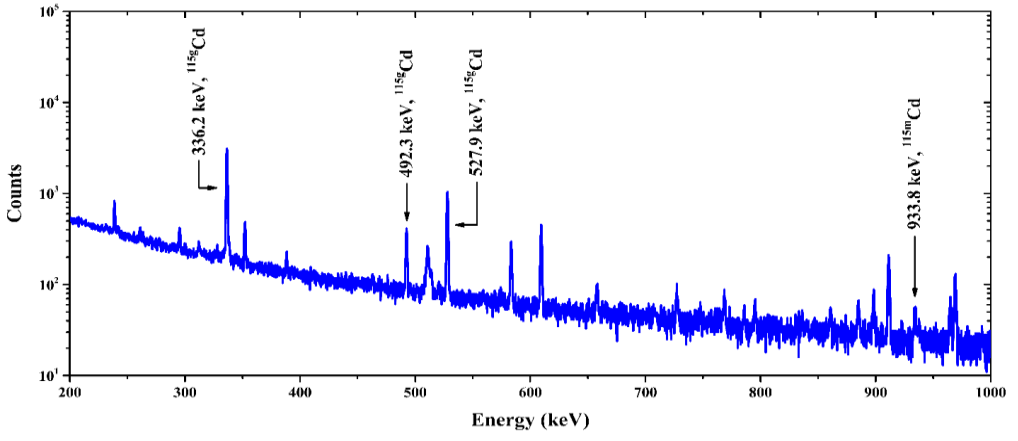

Fig. 5. Spectrum of $^{Nat.}$Cd covered by Cd irradiated in neutron source for 2 h, measured for 17 h with 14.2 d cooling time at the distance of 0 cm from the detector.

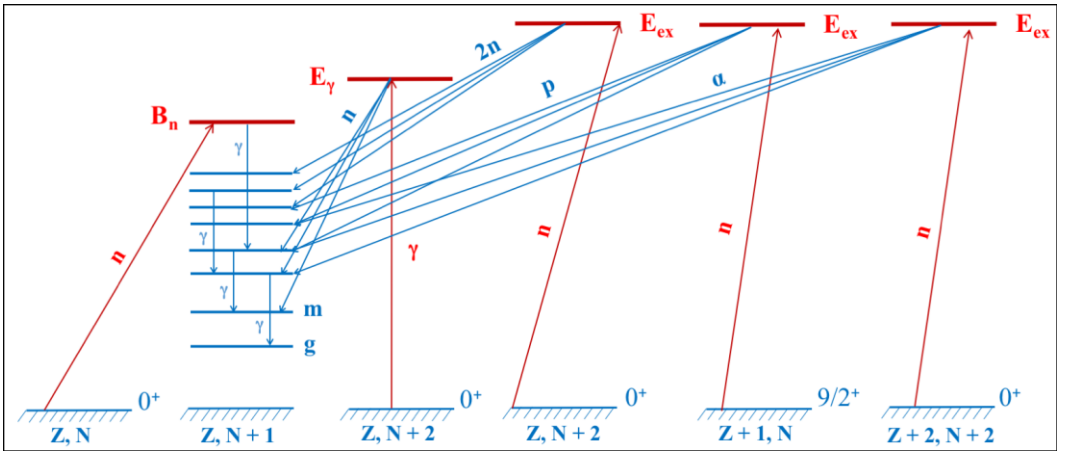

Fig. 6. The simplified schemes of ^{116}Cd(n, γ)^{115m,g}Cd, ^{116}Cd(n, γ)^{115m,g}Cd, ^{116}Cd(n, 2n)^{115m,g}Cd, ^{115}In(n, p)^{115m,g}Cd and ^{118}Sn(n, α)^{115m,g}Cd reactions

Fig. 6 depicts the simplified schemes of ^{114}Cd(n, γ)^{115m,g}Cd, ^{116}Cd(γ, n)^{115m,g}Cd, ^{116}Cd(n, 2n)^{115m,g}Cd, ^{115}In(n, p)^{115m,g}Cd and ^{118}Sn(n, α)^{115m,g}Cd reactions, which lead to the same isomeric pair ^{115m,g}Cd. The characteristics of the investigated reactions are shown in Table 2. In practice 24 MeV bremsstrahlung is equivalent to a mean value of excitation energy E_{ex} of about 15.7 MeV and the effective excitation energy E_{eff} of the reaction product ^{115}Cd is about 6.0 MeV. The values E_{eff} and E_{ex} were calculated by the following formulas:

$$E_{eff} = E_{ex} - B_n - \mathcal{E}_n \quad (4)$$

$$E_{ex} = \frac{\int_{E_{th}}^{E_0} E\sigma(E)\phi(E,E_0)dE}{\int_{E_{th}}^{E_0} \sigma(E)\phi(E,E_0)dE} \quad (5)$$

where B_n - The binding energy of neutron, taken from [27], $\mathcal{E}_n$ – the mean kinetic energy of photo-neutrons, taken from [33], $\sigma(E)$ - the excitation function taken from [34] with assumption that the excitation functions of ^{116}Cd(γ, n)^{115m,g}Cd and ^{116}Sn(γ, n)^{115m,g}Sn reactions have the same form due to the mass number is the same and $\phi(E, E_0)$ - the Schiff formula for the bremsstrahlung photon flux described in ref. [35], E_0 - the electron energy and E_{th} - the reaction threshold energy taken from ref. [27].

For ^{114}Cd(n, γ)^{115m,g}Cd reaction with thermal neutron, epithermal and mixed thermal and epithermal, it is easy to find that the excitation product energy is the binding energy of neutron in the compound nucleus. The product excitation energy for ^{116}Cd(n, 2n)^{115m,g}Cd, ^{115}In(n, p)^{115m,g}Cd and ^{118}Sn(n, α)^{115m,g}Cd were calculated by a conventional method, in which the Coulomb potentials of proton and alpha were taken into account.

The results of our experiment and the data from other authors in refs. [36 - 41] for the ^{116}Cd(γ, n)^{115m,g}Cd, ^{114}Cd(n, γ)^{115m,g}Cd, ^{116}Cd(n, 2n)^{115m,g}Cd, ^{115}In(n, p)^{115m,g}Cd and ^{118}Sn(n, α)^{115m,g}Cd reactions, which lead to the same isomeric pair ^{115m,g}Cd are presented in Table 2. There are very rare data in the existing literature, including only one paper for each of ^{116}Cd(γ, n)^{115m,g}Cd and ^{114}Cd(n, γ)^{115m,g}Cd reactions. One can see that our data and that from ref. [36] for ^{116}Cd(γ, n)^{115m,g}Cd reaction are in agreement. The difference between our data and the data from A. Gicking [37] for ^{114}Cd(n, γ)^{115m,g}Cd reaction may come from the fact that the *IR* in this case is determined as the

ratio of the cross-sections of the isomeric and ground states, while our result was obtained directly by calculation using formula (3) and doesn't depend on experimental conditions. On other hand, the author used the Oregon State University TRIGA reactor as neutron source and we used the neutron source shown in Fig. 1, where the neutron energy spectra are different. For ^{114}Cd(n, γ)^{115m,g}Cd reaction induced by epithermal neutron, our result and that in ref. [38] in the error limit are in agreement.

Table II. The isomeric ratio of ^{137m}Ce to ^{137g}Ce produced in different nuclear reactions

Nuclear Reaction and Product	Target Spin [ħ]	Type of Projectile	Product Exc. Energy, MeV	Isomeric Ratio *IR*
^{116}Cd(γ, n)^{115m,g}Cd	0^+	24 MeV-Bremsstrahlung	6.0	0.165 ± 0.016 0.168 ± 0.020 /36/
$^{1\ 114}$Cd(n, γ)^{115m,g}Cd	0^+	Thermal neutron	6.1	0.116 ± 0.012 0.099 ± 0.033 [37]
^{114}Cd(n, γ)^{115m,g}Cd	0^+	Epitherm. neutron	6.1	0.137 ± 0.014 0.079 ± 0.028 [37] 0.122 ± 0.031 [38] (cal.)
^{114}Cd(n, γ)^{115m,g}Cd	0^+	Thermal and Epitherm. neutron	6.1	0.112 ± 0.011 0.080 ± 0.028 [37]
^{116}Cd(n, 2n)^{115m,g}Cd	0^+	14.1 MeV neutron 14.4 MeV neutron 14.8 MeV neutron	5.4 5.7 6.1	0.921 ± 0.130 [39] 0.694 ± 0.074 [40] 0.710 ± 0.131 [41]
^{115}In(n, p)^{115m,g}Cd	$9/2^+$	14.9 MeV neutron	3.5	0.616 ± 0.118 [42]
^{118}Sn(n, α)^{115m,g}Cd	0^+	14.9 MeV neutron	1.4	0.261 ± 0.090 [42]

According to the statistical model of Huizenga and Vandenbosch [43 - 45], a nuclear reaction, which leads to formation of the isomeric and ground states occurs in the following three stages: • Formation of compound nucleus; • Evaporation of nucleons (neutron, proton …) from the compound nucleus; • Cascade transition of gamma rays. The *IR* is defined as the relative probability for the population of the isomeric pair is calculated by the following procedure: one calculates "center of spins" (*COS*) of the isomeric state with high spin J_h and ground state with low spin J_l as $COS = (J_h + J_l)/2$. All states with spin < *COS* feed the ground state, all states with spin > *COS* feed the isomeric state and states with spin = *COS* feed both states in equal parts. This means that the *IR* strongly depends on the probabilities of population for the isomeric and ground states in each reaction, i.e. on the reaction mechanisms. In the neutron capture reaction, the above second stage is absent and formation of the isomeric and ground states starts upon the transitions of primary and intermediate levels of the excited compound nucleus (see Fig. 6). For photonuclear reactions in the GDR region, the momentum transferred to the target nucleus after absorbing an E1 gamma quantum is 1 ħ, which is independent from the gamma quantum energy. This leads the target nucleus with spin J_0 to excited states in the compound nucleus with spins $J_C = J_0, J_0 \pm 1$. In neutron capture reaction by thermal and resonant neutron, it is assumed that only s-

wave neutrons are captured. Therefore the spins of excited states in the compound nucleus are $J_C = J_0 \pm ½$, where J_0 is the target nucleus spin. These effects restrict the spin range of excited levels or with other words, they restrict the excitation of high spin states making the value of *IR* in the photonuclear and thermal and resonant neutron capture reactions lower in comparison with that of other reactions (see Table II).

The ^{116}Cd(n, 2n)^{115m,g}Cd, ^{115}In(n, p)^{115m,g}Cd and ^{118}Sn(n, α)^{115m,g}Cd reactions are induced by fast neutrons of nearly the same energy. Therefore the momentum transferred to the target nuclei is nearly the same. However the value of *IR* is different for three reactions and highest in ^{116}Cd(n, 2n)^{115m,g}Cd and lowest in ^{118}Sn(n, α)^{115m,g}Cd. This fact can be explained with the difference of the product excitation energies. As it is seen in Table 3, the excitation of the reaction product is highest in ^{116}Cd(n, 2n)^{115m,g}Cd reaction and lower in ^{115}In(n, p)^{115m,g}Cd and ^{118}Sn(n, α)^{115m,g}Cd reactions due to the Coulomb barrier of proton and α particles. As a reason the probability to excite high spin states become lower, which leads to lower value of *IR*. On other hand, it is worth noting that in (γ, n), (n, 2n), (n, p) and (n, α) reactions, especially for nuclear reactions, accompanying emission of charge particles, the direct and pre-equilibrium processes play important role in suppressing the formation of high spin states [17 - 19, 23].

In general, the *IR* of isomeric pair ^{115m,g}Cd produced from different nuclear reactions is different. This is the so called the nuclear channel effect on the *IR*. From the experimental data [17-19, 46, 50], it was concluded that this effect affects the *IR* considerably, particularly when the reaction channels differ each other widely. Other examples for the channel effect in the *IR* can be found for ^{135m,g}Xe from ^{134}Xe(n, γ)^{135m,g}Xe, ^{136}Xe(γ, n)^{135m,g}Xe , ^{136}Xe(n, 2n)^{135m,g}Xe reactions and photo-fission of ^{232}Th, ^{233}U and ^{237}Np in ref. [46] , ^{58m,g}Co for ^{58}Fe(p, n) ^{58m,g}Co, ^{Natural}Fe(d, xn)^{58m,g}Co, ^{55}Mn(α, n) ^{58m,g}Co and ^{59}Co (n, 2n)^{58m,g}Co reactions from the respective thresholds to 14.12 MeV with protons, 12.97 MeV with deuterons, 13 MeV with neutrons and 25.52 MeV with alpha particles in ref. [47]; ^{75m,g}Ge through (n, 2n), (n, p) and (n, *α*) reactions measured over 13.73 MeV to 14.77 MeV in ref. [48]; ^{87m,g}Y produced from the ^{93}Nb(γ, α2n) and ^{Natural}Zr(γ, pxn) reactions with the end-point bremsstrahlung energy of 45 - 70 MeV in ref. [49] and ^{137m,g}Ce produced in ^{138}Ce(γ, n)^{137m,g}Ce photonuclear reaction, in neutron capture reaction and in the two simultaneous ^{138}Ce(γ, n)^{137m,g}Ce and ^{136}Ce(n, γ)^{137m,g}Ce reactions in the mixed photon – neutron field in ref. [50].

IV. CONCLUSIONS

From the above discussion, the following conclusions can be drawn:

a/ The *IR* of the same isomeric pair produced from different reactions by different projectiles (i.e. different nuclear reaction channels) is different. This is the so called the channel effect in *IR*.

b/ For interpretation of this effect, this needs different nuclear reaction models, which combine all nuclear reaction mechanisms as statistical, direct and pre-equilibrium processes.

c/ Our results in this paper for (γ, n) and (n, γ) reactions can provide new data for nuclear reaction interpretation as well as for applied research.

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