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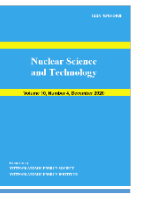

Investigation of the same isomeric pair, produced from different nuclear reactions

Tran Duc Thiep[1, 2*], Truong Thi An[1], Bui Minh Hue[1, 2**], Phan Viet Cuong[3], Nguyen Hong Ha[1], A. G. Belov[4], S. Mitrofanov[4]

[1]*Institute of Physics, VAST, 10 Dao Tan St., Ba Dinh Dist., Hanoi, Vietnam*
[2]*Grad. University of Science and Technology, VAST, 18 H. Q. Viet, Hanoi, Vietnam*
[3]*Danang Irradiation Center, VINATOM, Danang City, Vietnam*
[4]*Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Moscow, Russia*

[*]Corresponding author: <tdthiep@iop.vast.ac.vn>

[**]First author: bmhue@iop.vast.ac.vn

Abstract The isomeric ratio (IR) of isomeric pair ^{109m,g}Pd, produced in ^{110}Pd(γ, n)^{109m,g}Cd reaction and ^{108}Pd(n, γ)^{109m,g}Pd neutron capture reactions, induced by thermal, epithermal and mixed thermal-epithermal neutrons have been determined. The off-line activation technique using a spectroscopic system consisting of a HPGe semiconductor detector with high energy resolution and a PC based 8192 channel analyzer (CANBERRA) was applied. The investigated samples were prepared from the 99.99 % purity PdO and irradiated at the electron accelerator Microtron MT-25 of the Joint Institute for Nuclear Research Dubna, Russia. The data analysis and necessary corrections were made to upgrade the precision of the experimental method. The obtained results were discussed, compared and combined with those from other authors to point out the role of the reaction channels in nuclear reactions.

Keywords: *Photonuclear reaction - neutron capture reactions - isomeric ratio – isomeric pair ^{109m,g}Pd – intake impulse – transfer momentum - reaction channel effect.*

I. INTRODUCTION

The product of a nuclear reaction can exist in the isomeric or ground states. The ratio of the cross sections or the yields (in the case of continuous excitation energy spectrum) of these two states is the so called isomeric ratio (IR), which furnishes important information on nuclear level structure, level density, namely the spin cut-off parameter σ and the level density parameter a as well as nuclear reaction mechanism. In fact this ratio is connected to different nuclear effects as the excitation energy, momentum transfer, spins of the isomeric and ground states and their dependence, nucleon configuration, intermediate state structure, nuclear channel effect, the contributions of direct and pre-equilibrium processes and so on [1 - 16]. N. Tsoneva et al [3] measured the IRs in (γ, n) reactions in N = 81 isotone nuclei (^{137}Ba, ^{139}Ce, ^{141}Ba and ^{143}Ba) and showed that in the isotone nuclei, the IRs depend on the mass numbers. This is the so called nucleon configuration effect and was also observed in [3 - 6]. In ref. [4] we have studied the IRs of (γ, n) nuclear reactions in Z = 56 isotopes of Ba and the

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isomeric pairs ^{129m,g}Ba, ^{131m,g}Ba and ^{133}Ba were formed with the same spin ground state $1^+/2$ and isomeric states of spins $7^+/2$, $9^-/2$ and $11^-/2$, respectively. The results showed that the IR decreases with the increase of the isomeric state spin. This effect is the so called isomeric state spin dependence. The other effect, which is also concerned the spins is that the higher the isomeric state spin, the smaller the IR can be found in [7, 8]. M. Huber et al [9] and J. J Carroll et al [10] pointed out the important role of intermediate states on the mechanism of population of the isomeric and ground states. Up to now the famous statistical model of Huizenga and Vandenbosch [1, 2] has been applied to consider the IR in nuclear reactions induced by different projectiles. S. Mukherjee et al [11] studied the nuclear reaction induced by α particle on ^{93}Nb nucleus and came to the conclusion that the angular momentum removal in the pre-equilibrium emission play a major role in the formation of the isomers and hence in the measurement of IR. S. Sudar and S. M. Qaim in [12] used the STAPRE code in a combination of the Hauser-Feshbach (statistical model) and exciton model (pre-equilibrium effects) formalisms to consider their experimental results for the excitation functions and IRs in nuclear reactions, induced by α and ^{3}He particles. They showed that the level density parameters and the spin of residual nucleus play important role in the calculated IRs as well as in formation of the isomeric states. All most the researches in photonuclear reactions in the giant dipole resonant (GDR) region show that the IR of high spin state to that of low spin state increases with the increase of end-point bremsstrahlung energy [3 - 6, 13 - 16].

Recently, the study of IR has been an effective tool to check different models of nuclear reaction by computation programs, in which it is worth mentioning the Talys program [17] and its applications [18 - 21]. Talys code is a nuclear reaction program, which simulates nuclear reactions that involve neutrons, gamma-rays, protons, deuterons, tritons, helions, and alpha-particles, in the 1 keV - 200 MeV energy range. This work aims at studying the isomeric pair ^{109m,g}Pd, produced from ^{110}Pd(γ, n)^{109m,g}Pd photonuclear reaction and ^{108}Pd(n, γ)^{109m,g}Pd neutron capture reaction, induced by thermal, epithermal and mixed thermal-epithermal neutrons. The obtained experimental results could provide the data for the nuclear model test as well as for practical applications of nuclear technology.

II. EXPERIMENTAL

A. Irradiation sources and sample preparation

In this study, the bremsstrahlung photon flux, produced by the electron accelerator Microtron MT-25 of the Flerov Laboratory of Nuclear Reactions, JINR Dubna, Russia [22] was used for performing the photonuclear reaction. This accelerator produces 10 to 25 MeV electron beam with 1 MeV energy step and 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 end-point energy bremsstrahlung.

The source of thermal, epithermal and mixed thermal-resonant neutrons was constructed at the Microtron MT-25 by using a graphite cub as depicted in Fig. 1. The neutron beam was obtained by (γ, n) reactions with Be and U and (γ, f) fission reaction of U when the electron beam was directed to a uranium electron-photon converter. The uranium-beryllium converter was also 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 with an electron energy of 25 MeV and a current of 20 μA. The detailed construction of this neutron source can be found in refs. [23, 24].

The investigated samples were prepared from the 99.99 % purity PdO, packed in polyethylene wrap in disk shape with diameter of 1.0 cm. The sample mass was chosen to be of 0.3230 g, which was proper for the study of both (γ, n) and (n, γ) capture reactions.

B. Sample irradiation and measurement

For ^{110}Pd(γ, n)^{109m,g}Pd reaction investigation, the sample was placed at the axis of the electron beam with 2 cm from the aluminum absorber of MT-25 and irradiated by the bremsstrahlung flux of 24 MeV end-point energy for 30 minutes. To avoid the interference from (n, γ) capture reactions, caused by 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. In the case of neutron capture reactions with thermal, resonant and thermal-resonant mixed neutrons, the sample was uncovered or covered in Cd foil of 2 mm thickness and placed at 40 cm distance from the center of the graphite cube, where the Cd ratio was 2.5. In both bremsstrahlung and neutron irradiations, the average electron current was of 15 μA and the irradiation time – 90 min., which were estimated so that the counts of the interested gamma rays of the isomeric and ground states to ensure a good count statistics.

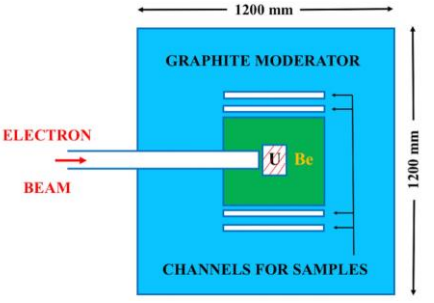

Fig. 1. The scheme for production of thermal and epithermal neutron source.

After a definite cooling time, 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 a length of 31 mm, connected to a PC based 8192 channel analyzer (CANBERRA) for the data processing. 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 %. The detailed information of the measuring system can be found in [4 - 5].

III. DATA ANALYSIS AND ISOMERIC RATIO DETERMINATION

The ^{110}Pd(γ, n) reaction, excited by bremsstrahlung and ^{108}Pd(n, γ) reactions, induced by thermal, resonant and thermal-resonant mixed neutrons produce the same isomeric pair ^{109m,g}Pd. Fig. 2 depicts the simplified decay schemes of isomeric and ground states ^{109m}Pd and ^{109g}Pd.

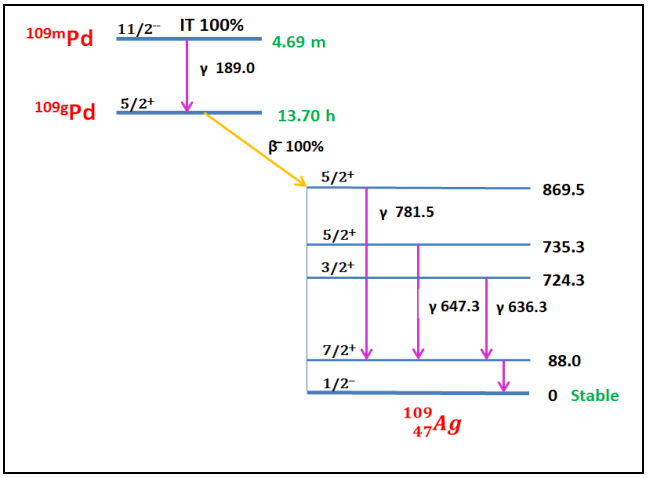

Fig. 2. The simplified schemes of the isomeric and ground states of ^{109m,g}Pd.

Table I. The decay characteristics and gamma rays used in the isomeric ratio calculation of the isomeric pair ^{109m,g}Pd.

Nuclear Reaction	Target Spin, Parity [Jπ]	Nuclear state	Spin Parity [Jπ]	Decay Mode [%]	Half Life	γ-ray Energy [keV]	Intensity [%]
^{108}Pd(n, γ) ^{109m}Pd	0^+	^{109m}Pd	$11/2^-$	IT: 100	4.69 m	189.0	55.9
^{108}Pd(n, γ) ^{109g}Pd	0^+	^{109g}Pd	$5/2^+$	β^- : 100	13.7 h	88.04	3.6

Table I shows the decay characteristics and **γ**-rays used for the IR calculation of isomeric pairs ^{109m,g}Pd and ^{111m,g}Pd. The criterion for choosing the gamma rays in this table were the followings: a/ Their intensities are higher than that of other gamma rays, b/ They are separated in the gamma spectra and c/ They are free of the contributions from the products of other nuclear reactions with natural palladium. The data in this table were taken from [25, 26].

The losses of gamma ray activities due to the self-absorption and coincident summing effects, which lead to the error in the isomeric ratio determination, were corrected by formulas (1) and (2), taken from refs. [27, 28], respectively as below:

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

$$F_g = \frac{\mu t}{1 - e^{-\mu \cdot t}} \quad (2)$$

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; 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. In our experiment C_c was found to be 1.0 and 1.0; and F_g were 1.26 and 1.05 for 88.0 and 189.0 keV, respectively at the distance of 0 and 5 cm from the detector.

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. [16, 27] 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.

The total uncertainty of the isomeric ratio determination was estimated to be 10%. It consists of the systematic errors, including those from the distance from the detector to sample, the gamma ray selection, the electron beam variation, the irradiation and cooling times and that, calculated by the error propagation principle of the expression (3).

IV. RESULTS AND DISCUSSION

Fig. 3 shows a typical spectrum of natural Pd, irradiated with 24 MeV bremsstrahlung for 20 min. and measured for 10 min. after 40 min cooling time. Fig. 4 presents a spectrum of natural Pd irradiated by neutron for 1.5 h, measured for 30 min and cooling time of 11 min., measured at 0 cm distance from the detector.

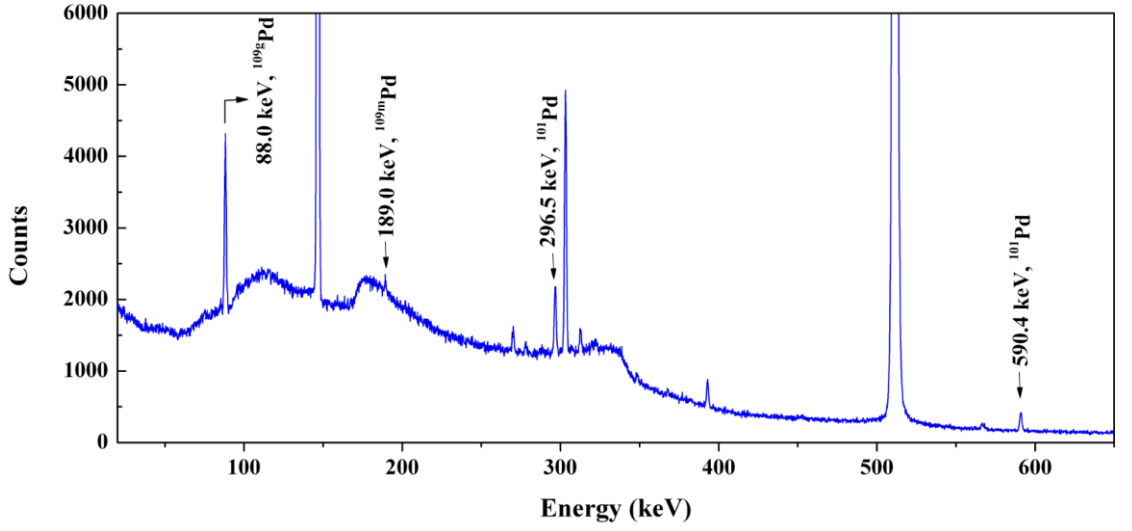

Fig. 3. A typical spectrum of natural Pd, irradiated with 24 MeV bremsstrahlung for 20 min. and measured for 10 min. after 40 min cooling time, measured at 5 cm from the detector.

Natural palladium consists of ^{102}Pd, ^{104}Pd, ^{105}Pd, ^{106}Pd, ^{108}Pd and ^{110}Pd with the abundances of 1.020, 11.14, 22.33, 27.33, 26.46 and 11.72%, respectively. Through photonuclear reactions, only one isomeric pair ^{109m,g}Pd was formed in ^{110}Pd(γ, n)^{109}Pd reaction, while two isomeric pairs ^{109m,g}Pd and ^{111m,g}Pd were produced in ^{108}Pd(n, γ)^{109m,g}Pd and ^{110}Pd(n, γ)^{111m,g}Pd neutron capture reactions. One can see that the characteristic gamma rays of the isomeric and ground states of the isomeric pairs ^{109m,g}Pd are seen very clearly in the spectra. Table II presents the IRs in ^{110}Pd(γ, n)^{109m,g}Pd reaction, ^{108}Pd(n,

γ)^{109m,g}Pd capture reactions induced by thermal, resonant and mixed thermal-resonant neutrons, obtained in our experiments and from other authors in refs. [29 - 30]. For the interpretation, the IRs for ^{110}Pd(n, 2n)^{109}Pd reactions are also shown hereby [14, 31]. In Table II are also presented the reaction product excitation energies.

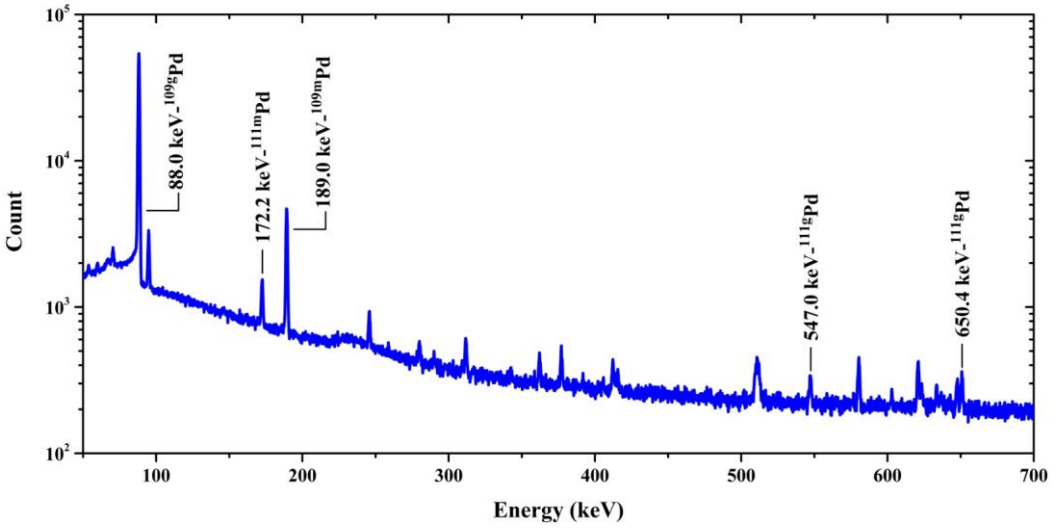

Fig. 4. Spectrum of natural Pd irradiated by neutron for 1.5 h, electron current-15 μA, measured for 30 min and cooling time -11 min., at 0 cm distance from the detector.

For the ^{108}Pd(n, γ)^{109m,g}Pd neutron capture reactions, the product excitation energy is equal to the binding energy of ^{109}Pd, taken from [25]. The product excitation energy of ^{110}Pd(γ, n)^{109}Pd reaction is an effective value E_{eff} due to the reaction with bremsstrahlung and was calculated as following:

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

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

Where B_n - The binding energy of neutron, taken from [25], $\mathcal{E}_n$ – the mean kinetic energy of photo-neutrons, taken from [32], $\sigma(E)$ - the excitation function taken from [14] and $\phi(E, E_0)$ - the Schiff formula for the bremsstrahlung photon flux described in ref. [33], E_0 - the electron energy and E_{th} - the reaction threshold energy taken from ref. [25].

For (n, 2n) reaction, the product excitation energy is as following:

$$E_{prod.ex} = E_{ex} - S_{2n} \quad (6)$$

Where $E_{prod.ex}$, E_{ex} and S_{2n} - the product, the target excitation energies and the two neutrons separation energy of the compound nucleus, which were taken from ref. [25].

From the Table II one can make the following comments:

a/ For the neutron capture reactions, our results are insignificantly lower than that in ref. [29] and higher than the data in refs. [30]. This may be since in the previous works, the authors used scintillation detector [29, 30], while in this work we used high resolution HPGe semiconductor detector and the advanced data processing program.

b/ The product excitation energies in (γ. n) and (n, γ) reaction are insignificantly

different, but the IRs in (γ, n) reactions are much higher than that in (n, γ) reactions because the intake impulses in the (γ, n) reactions are higher in the (n, γ) reactions. This fact can be used to explain why the IRs in the (n, 2n) reactions strongly exceed that in the (n, γ) and (γ, n) reactions.

c/ In photonuclear reactions in the GDR region and nuclear capture reactions by thermal and resonant neutrons, the transfer momenta to the target nuclei are very low, namely L = 1 and 1/2 ħ, respectively. Therefore, the compound nuclei in both reaction kinds are with spins $J_C = J_0$, $J_0 \pm 1$ and $J_0 \pm 1/2$ respectively. These effects restrict the spin range of excited levels or in 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.

d/ The investigated results show that the IRs in different nuclear reactions are different and depend on the projectile type, intake impulse, excitation energy, spins of the isomeric and ground states as well as the nuclear reaction mechanisms. This is the channel effect in nuclear reactions.

e/ The Talys computation program [17] has been applied to study many problems of nuclear physics, in which study of the cross sections and isomeric ratios in nuclear reactions, produced by different projectiles is one important research direction, for example [17 - 21, 34 - 40] and for test any model it is needed to carried not one, but a series of measurements. Therefore, in this meaning we do hope that our results as additional data can be used for the test of nuclear reaction models by the mentioned program.

Table II. The IRs of ^{109m,g}Pd in photonuclear reaction, in neutron capture reactions with thermal, resonant and mixed thermal-resonant neutrons and in other reactions.

Nuclear Reaction and Product	**Type of Projectile**	**Product Exc. Energy, MeV**	**Isomeric Ratio *IR***
^{108}Pd(n, γ)^{109m,g}Pd	Thermal neutron	6.15	0.023 ± 0.002 [This work] 0.028 ± 0.005 [29] 0.018 ± 0.005 [30]
^{108}Pd(n, γ)^{109m,g}Pd	Resonant neutron	6.15	0.023 ± 0.002 [This work] 0.028 ± 0.005 [29]
^{108}Pd(n, γ)^{109m,g}Pd	Mixed Thermal-Resonant neutron	6.15	0.023 ± 0.002 [This work]
^{110}Pd(γ, n)^{109m,g}Pd	24 MeV Bremstrahlung 25 MeV Bremsstrahlung	6.50 6.93	0.069 ± 0.007 [This work] 0.065 ± 0.003 [14]
^{110}Pd(n, 2n)^{109m,g}Pd	14.1 MeV neutron	5.28	0.410 ± 0.039 [14] 0.41 ± 0.03 [31]

V. CONCLUSIONS

We have studied the IRs of the same isomeric pair ^{109m,g}Pd, formed from the photonuclear reaction, neutron capture reactions, induced by thermal, resonant and mixed thermal-resonant neutrons. The obtained results show the nuclear reaction

channel effect in IRs and could provide the data to the Nuclear Data Bank for test of nuclear reaction models as well as for nuclear application uses. For interpretation of this effect, this needs different nuclear reaction models, which combine all nuclear reaction mechanisms as statistical, direct and pre-equilibrium processes.

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