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RESEARCH ON PHOTONUCLEAR REACTIONS CREATING ISOMERIC PAIRS ON TARGERTS ^{113}In, ^{107}Ag, ^{195}Pt, ^{138}Ce và ^{151,153}Eu USING THE MT-25 ELECTRON ACCELERATOR

Major: Atom and nuclear physics

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OVERVIEW

1. The reason for choosing the thesis topic

Nuclear isomeric states, also known as metastable states, were discovered by Otto Hahn in 1921 [92]. At that time all nuclear excited states were considered to have lifetimes less than 10^{-13} seconds, so there was much speculation about the origin of isomeric states. Nuclei in this quasi-stable state can de-excite back to a lower excited state or ground state by emitting gamma radiation or undergoing a decay process (eg β-decay). -…) and turns into another nucleus.

The isomeric ratio can give us important information about the energy level structure of the nucleus as well as the reaction mechanism, important information about the spin dependence of the nuclear level density, information about the role of the angular moment of the entrance channel, the role of incoming and outgoing particles, in other words the role of the effect reaction channels [15-21].

In experimental research on isomer ratios, photonuclear reactions has an important role because the characteristics of the electromagnetic field in interaction with nucleons are well known [22]. Therefore, investigating the isomer ratio formed in photonuclear reactions is an effective tool to clarify the reaction mechanism, especially when the role of angular moment becomes important [23]. Experimentally, studying the rate ratio of isomeric pair formation in photonuclear reactions often uses beams of bremsstrahlung radiation with maximum energy end-point in the giant dipole resonance (GDR) region that changes in the range from 8-30 MeV. In this energy region, corresponding to the superposition of the levels of the component nuclei, the photonuclear reaction cross section reaches its maximum and has a Gaussian shape called giant resonance. Due to the above urgent requirements, I carried out the project "Research on some photonuclear reactions creating isomeric pairs on targets ^{113}In, ^{107}Ag, ^{195}Pt, ^{138}Ce and ^{151,153}Eu using electron accelerator MT-25".

2. Purpose of this study

To research and develop experimental methods and theoretical calculations to determine the isomeric ratio of photonuclear reactions in the giant dipole resonance energy region (8-30 MeV).

Experimentally determine the isomer ratio in some photonuclear reactions on targets ^{113}In, ^{107}Ag, ^{195}Pt, ^{138}Ce and ^{151,153}Eu caused by a photon beam with Emax from 14 to 24 MeV.

Theoretical calculation of differential cross-section and isomerism ratio of some photonuclear reactions in the giant dipole resonance energy region.

3. Main research contents, layout of the thesis

i) Learn an overview of photonuclear reactions, the structure of isomeric nuclear states; ii) Research and develop experimental methods. Presenting the activation method in isomer ratio research, measurement recording system and spectrum analysis; iii) Research and develop theoretical calculation methods to determine the isomeric ratio of photonuclear reactions in the giant dipole resonance energy region; iv) Experimental determination of isomerism ratio in photonuclear reactions ^{113}In(γ,2n)^{111m,g}In, ^{113}In(γ,n)^{112m,g}In, ^{107}Ag(γ,n)^{106m,g}Ag, ^{195}Pt(γ,p)^{194m,g}Ir; ^{198}Pt(γ,n)^{197m,g}Pt and ^{138}Ce(γ,n)^{137m,g}Ce caused by photon beam with maximum energy from 14 to 24 MeV; v) Theoretical calculation of differential cross-section and isomerism ratio of photonuclear reactions $^{151}Eu(\gamma,n)^{150m,g}Eu$ and $^{153}Eu(\gamma, n)^{152m,g}Eu$ in the giant dipole resonance energy region giant.

4. Layout of the thesis

The thesis includes 110 pages of content, 15 tables, 42 images, 05 published works (4 ISI articles and 1 Scopus article), 125 references distributed as follows:

The introduction introduces the reason for choosing the topic, purpose, objectives, subjects and scope of research as well as the scientific and practical significance of the thesis topic; Chapter 1: Overview of photonuclear reactions, nuclear structure and isomerism; Chapter 2: Experimental research methods and theoretical calculations of isomerism ratios of photonuclear reactions; Chapter 3: Experimental results and theoretical calculations of isomer ratios in some photonuclear reactions. Conclusion and recommendations on future research directions; Finally, there is a list of published works related to the thesis and reference documents.

CHAPTER 1: OVERVIEW OF PHOTO-NUCLEAR REACTIONS, NUCLEAR STRUCTURE AND ISOMERIC STATES

1.1. Photonuclear reaction

1.1.1. Concept of photonuclear reaction

Photonuclear reaction is a nuclear reaction that occurs when there is an interaction between a gamma quantum, also known as a photon, and a nucleus. After the nuclear interaction, neutrons, protons or other types of particles/radiation can be emitted. Photonuclear reactions are energy-absorbing reactions, so the condition for a reaction to occur is that the photon energy ($E\gamma$) must be greater than the threshold energy (Eth).

1.1.2. Conservation laws in photonuclear reactions

Like other nuclear reactions, photonuclear reactions are governed by conservation laws, see [4,13].

1.1.3. Cross section and yield of photonuclear reactions

Nuclear reaction cross section (σ) is the probability of a reaction occurring on a target nucleus in one second when the flux of the radiation beam/incident particle is equal to 1 particle/s.

The rate of reaction is the number of reactions occurring on the target per unit of time. In the case of an incident particle beam with a continuous energy spectrum, let $\varphi(E)$ be the radiation beam flux in the energy region E, and $\sigma(E)$ is the reaction cross section at energy E. Particle reaction energy multiplied by Y, determined by the formula:

$$Y = N_0 \int_{E_{th}}^{E_{max}} \sigma(E).\varphi(E)dE \tag{1.12}$$

Eth and Emax are the threshold energy of the reaction and the maximum energy of bremsstrahlung radiation.

1.1.4. Photonuclear reactions in the giant dipole resonance region

Giant dipole resonance (GDR) is the most common form of giant dipole resonance excitation. The photon absorption cross section that excites the nucleus to the giant resonance state is represented by the Lorentz function:

$$\sigma_{GDR}(E_\gamma) = \sum_i \sigma_i \frac{(E_\gamma \Gamma_i)^2}{(E_\gamma^2 - E_i^2)^2 + (E_\gamma \Gamma_i)^2} \tag{1.13}$$

σ_i, E_i , Γ_i are the GDR resonance peak cross-section, energy and peak width, respectively. The sum will be limited to i = 1 for spherical nuclei, whereas for deformed nuclei the resonance is split and i=1.2

1.2. Nuclear structure and isomeric state

1.2.1. Gamma shift

Gamma shift is the process by which a nucleus moves from a high-energy excited state to a low-energy excited state or ground state by emitting electromagnetic radiation called gamma radiation. Depending on the process occurring inside the nucleus related to gamma shift, gamma shift is divided into electric shift and magnetic shift. Or the emitted radiation is divided into electric radiation and magnetic radiation. The probability of moving P from the initial state described by the wave function ψf to the final state described by the wave function ψi is determined by the formula [95]:

$$P = \frac{2\pi}{\hbar}|M|2\frac{dn}{dE} \qquad (1.25)$$

$M = \int \psi_f^* H \psi_i dt$ is the displacement matrix element of the Hamiltonian operator H, which is the interaction operator of the electromagnetic field with the nucleons participating in the displacement; dn/dE is the density of the final state; ψf and ψi are the wave functions of the final and initial states of the nucleus, respectively.

Gamma shift must obey the rules of conservation of total angular momentum and conservation of parity.

1.2.2. Isomeric state

The simultaneous combination of large spin changes and small energy transitions between two states in the nucleus can lead to long decay times, forming excited states with relatively long lifetimes. (≥ 10-9 seconds) are called pseudostable states or isomeric states. In some cases, the nucleus can have two pseudostable states. The pseudostable state can also be observed in β-stable nuclei. At that time, the semistable state is de-excited by gamma quantum emission and electron conversion

1.2.3. Nuclear structure and isomeric state

According to experimental data, the region where isomeric states are often found is the region of nuclei with medium mass numbers to heavy nuclei close to the closed shell according to the shell model theory, in this region there is the formation of states. cutting many particles with high spin at low energy.

Nuclear isomeric states are states with high spin, these states are formed in many different ways such as from electromagnetic stimulation, from nuclear reactions, in addition to inelastic collisions of e-, p, α and d particles can also excite the nucleus to similar states. In most cases, the formation of nuclear isomeric states occurs in two steps: first, the formation of highly excited nuclear states and then the decay from these states to other states. Pseudo-stable state by cascading decay process.

1.3. Isomeric yield ratio

The isomeric ratio is the ratio of the cross-sections forming the isomeric state (σ_m) and the unstable ground state (σ_g). In the case of a non-monoenergetic incident particle beam when determining the ratio of isomeric cross-sections, instead of measuring the cross-sections, it is possible to measure the ratio of the energy forming an isomeric state (Y_m) and an unstable ground state (Y_g).). Thus it can also be called isomerism ratio.

$$\mathrm{IR} = \frac{Y_m}{Y_g} \tag{1.35}$$

Yi is determined according to formula (1.12)

For bremsstrahlung beams, due to the continuity of the energy spectrum, the isomer stoichiometry ratio is expressed as follows [4]:

$$\mathrm{IR}(E_{\mathrm{max}}) = \frac{Y_{\mathrm{hs}}(E_{max})}{Y_{\mathrm{ls}}(E_{max})} \tag{1.37}$$

This ratio can be determined by experimental measurements as well as theoretical calculations. Theoretical calculations are based on the Huizenga – Vandenbosch statistical model based on the compound nuclear mechanism..

CHAPTER 2: EXPERIMENTAL METHODS AND THEORETICAL CALCULATIONS

2.1. Activation method in isomeric ratio research

In the activation method, research sample targets are irradiated by particle/radiation beams of appropriate energy and intensity, through nuclear reactions that create radioactive isotopes. Reaction product isotopes are identified based on the energy of their gamma spectral lines and their half-lives. Their activities provide information about the cross-section and yield of the reaction. For photonuclear reactions caused by beams of bremsstrahlung radiation, the partial stoichiometry ratio can be determined through solving the activation and decay equations corresponding to the formation and decay of daughter nuclei. in the isomeric and ground states in three different stages: (1) activation, (2) decay, and (3) gamma spectroscopy.

2.2. Determine the isomer ratio in photonuclear reactions

For photonuclear reactions forming isomeric pairs, the formation of isomeric pairs and their decay can be described by the corresponding system of activation and decay equations.

Solving the above system of equations for the three stages of projection, decay and measurement with the initial conditions, we derive the formula for calculating the isomerism ratio as follows:

$$IR = \left[\frac{S_g C_m \varepsilon_m I_m}{S_m C_g \varepsilon_g I_g} - \frac{\Lambda_1\Lambda_5\Lambda_8 + \Lambda_3\Lambda_4\Lambda_8 + \Lambda_3\Lambda_6\Lambda_7}{\Lambda_3\Lambda_6\Lambda_9}\right].\frac{\Lambda_3\Lambda_6\Lambda_9}{\Lambda_2\Lambda_5\Lambda_8} \qquad (2.3)$$

Here, Si is the peak area of the gamma spectrum of the nucleus in the ground state or isomer (with i = m,g), Ci includes correction for self-absorption, real coincidence effect and other effects. Another effect, ε_i is the recording efficiency of the gamma spectrometer system corresponding to the energy of the characteristic gamma ray, Ii is the intensity of gamma ray emission; coefficients số Λ_j, j = 1 ÷ 9 are functions depending on the time ti, tc, tm are the projection time, decay time and measurement time, respectively [6, 7, 15]

2. 3. Microtron MT-25 electron accelerator

Within the framework of the thesis, photonuclear reactions on research sample targets are caused by a beam of braking photons created from the Microtron MT-25 electron accelerator at the JINR Institute, Dubna, Russia, with the following main parameters: : Maximum electron energy: 25 MeV; Electron beam energy range: 4 - 25 MeV; Average current: 20 µA; Pulse current duration: 2.2×10^{-6} seconds; Beam diameter: 5mm; Brake target: W; Absorbent plate after braking target: Al**.**

2.4. Gamma spectrometer is used to experimentals

In the study, we used a gamma spectrometer with an ultra-pure germanium semiconductor detector HPGe model 2002CSL (CANBERA), volume 100 cm3, energy resolution 1.80 keV at peak 1332.5 keV (60Co) combined with The functional electronic components are as shown in Figure 2.5 and are connected to the computer. Recording and processing of gamma spectrum through Genie 2000 software.

2.5. Analyze gamma spectrum and calibrate experimental data

Gamma spectrum analysis is to determine the energy and area of spectral peaks as a basis for identifying radioactive isotopes and determining its radioactive activity. In experiment, the energy of gamma radiation corresponding to the total absorption peaks can be determined by energy calibration. Radioactivity was determined based on the area of the spectral peaks. Some corrections to improve the accuracy of experimental results have also been performed.

2.6. Calculation of isomer ratio theory in photonuclear reactions using a combination of Talys and Geant4 software

2.6.1. Talys code in calculating photonuclear reaction cross-section

Talys software began to be developed in 1998 with the purpose of analyzing and predicting the cross section of nuclear reactions caused by light particles (gamma, neutrons, protons,... up to 4He) with energies within ranges from 1 keV to 200 MeV. During the calculation process, the influence of level density parameters and gamma ray force function was studied and appropriate calculation models were selected.

2.6.2. Introducing Geant4

Geant4 is a Monte-Carlo simulation tool developed by the European Nuclear Research Agency (CERN) using the object-oriented programming language C++. In the field of nuclear physics, the use of Geant4 allows them to We can simulate various nuclear physics experiments such as: Geant4 has a definition of all particles "participating" in the reaction process,... Simulates orbits and interactions of particles with matter. Geant4 allows programmers to write simulation code based on Geant4's available classes, allowing "interaction" with other software,...

2.6.3. Combining TALYS and Monte-Carlo simulation using Geant4

In this thesis, we have implemented the differential cross section calculated by TALYS 1.8 into Geant4, or in other words, developed the simulation code based on Geant4 using the differential cross section as the calculation result of TALYS 1.8. to simulate the entire process by simulating the bremsstrahlung radiation spectrum emitted from the MT-25 accelerator corresponding to electron beams with different energies and the photonuclear reaction process. To simulate the bremsstrahlung radiation spectrum that is a consequence of the interaction of the electron beam with the W stimulant target in the MT-25 accelerator, the entire electromagnetic interaction process between the electron beam and secondary particles can create into the target nucleus considered in the Geant4 simulation code. To simulate the photonuclear reaction process, we can use the G4PhotoNuclearProcess class available in Geant4 or another class based on the G4GammaNuclearReaction model.

CHAPTER 3. EXPERIMENTAL AND THEORETICAL RESULTS OF ISOMERIC RATIOS

3.1. The nuclear structure corresponds to in the studied nuclei

In this chapter we will present the results of experimental research on determining isomer ratios in photonuclear reactions: $^{107}Ag(\gamma, n)^{106m,g}Ag$, $^{113}In(\gamma, 2n)^{111m,g}In$, $^{113}In(\gamma,n)^{112m,g}In$, $^{195}Pt(\gamma, p)^{194m,g}Ir$, $^{198}Pt(\gamma, n)^{197m,g}Pt$ and $^{138}Ce(\gamma, n)^{137m,g}Ce$. In addition, theoretical calculation results of isomer ratios in the photonuclear reactions $^{151}Eu(\gamma,n)^{150m,g}Eu$ and $^{153}Eu(\gamma, n)^{152m,g}Eu$ using the combined Talys method and Monte - simulation Carlo uses Geant4. The results of theoretical calculations and comparison with experiments will be presented in part 3 of this chapter.

Table 3.1. Photonuclear reactions form isomeric pairs

Nucl. reactions	**Nucleus**	**Spin**	**$T^{1/2}$**
$^{107}Ag(\gamma, n)$	^{106m}Ag	6^+	8,28 d
	^{106g}Ag	1^+	24,0 min
$^{113}In(\gamma, 2n)$	^{111m}In	$1/2^-$	7,6 min
	^{111g}In	$9/2^+$	2,83 d
$^{113}In(\gamma, n)$	^{112m}In	4^+	20,56 min
	^{112g}In	1^+	14,97 min
$^{195}Pt(\gamma, p)$	^{194m}Ir	11^+	171,55 d
	^{194g}Ir	1^-	19,15 h
$^{198}Pt(\gamma, n)$	^{197m}Pt	$13/2^+$	95,4 min
	^{197g}Pt	$1/2^-$	19,89 h
$^{138}Ce(\gamma, n)$	^{137m}Ce	11/2-	34,4 h
	^{137g}Ce	$3/2^-$	9,0 h

3.2. Experiments and results of determination of isomerism ratio

The research samples were excited on a photon beam from the MT-25 accelerator with different exposure times, calculated to match the half-life of the product nuclei**.**

3.2.1. Experiment to determine the isomer ratio in the photonuclear reaction of $^{107}Ag(\gamma, n)^{106m,g}Ag$

In this experiment 11 high purity natural silver (Ag) samples were used. Characteristics of the samples are presented in detail in the thesis. The samples were excited using the bremsstrahlung photon beam of a Microtron MT 25 electron accelerator with peak energies varied from 14 MeV to 24 MeV with an exposure time of 60 minutes, with an average electron current intensity of 14 μA for Eγmax: 14-19 MeV; 12μA for Eγmax from 20 - 24 MeV. The results of the experimental research are presented in Figure 3.5.

Our results show that the isomer ratio in the reaction $^{107}Ag(\gamma,n)^{106m,g}Ag$ in the GDR region decreases as the maximum energy of the bremsstrahlung radiation beam increases, reaching a minimum value at the end of this region (21 MeV) and varies slightly for higher energies (23, 24 MeV). This is as expected from formula (1) as mentioned above. On the other hand, it can also be seen that the isomer ratio changes insignificantly in the giant dipole resonance region.

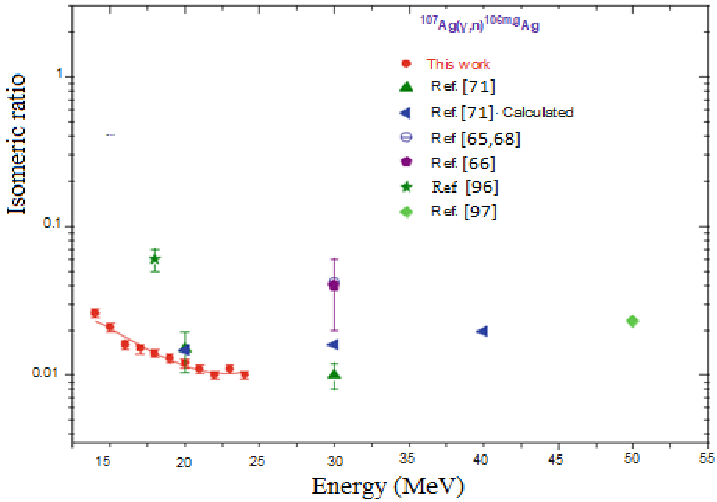

Figure 3.5. Dependence of the isomer ratio in the reaction $^{107}Ag(\gamma,n)^{106m,g}Ag$ *on the Emax of the bremsstrahlung beam*

3.2.2. Experiment to determine the isomer ratio in the photonuclear reaction $^{113}In(\gamma, n)^{112m,g}In$ ***and*** $^{113}In(\gamma,2n)^{111m,g}In$

In this experiment, 11 samples of high purity natural Indium (99.99%) in disc form with a diameter of 1cm were prepared. The samples were activated by a beam of bremsstrahlung radiation from the Microtron MT-25 accelerator with a maximum energy of 14-25 MeV with an average current of 14-15 μA, activation time for all samples was 15 minutes (details are presented in table 3.6 of the thesis). The results of isomer ratios in the photonuclear reactions $^{113}In(\gamma, n)^{112m,g}In$ and $^{113}In(\gamma,2n)^{111m,g}In$ are shown in Figure 3.9 and Figure 3.10.

From the results of this experiment, we can see: up to now, there is very little data on the isomer ratio in the nuclear reaction of natural indium caused by bremsstrahlung radiation beams in the

GDR energy region as well as higher energy range. For the isomeric pair 112m,gIn formed via photonuclear reaction in the GDR region, the isomeric ratio increases with the increase of the maximum energy (end point), reaching a maximum value at the end of this region (20 – 21 MeV) and does not change much at higher energies.

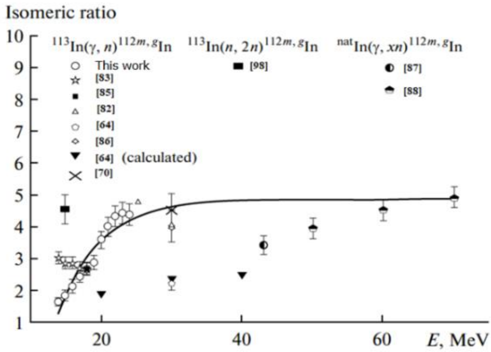

Figure 3.9. Isomeric ratio in photonuclear reactions

$^{113}In(\gamma, n)^{112m,g}In$

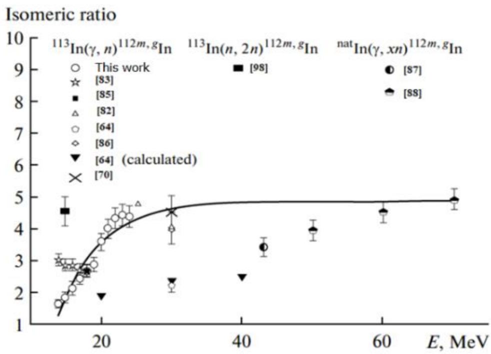

Figure 3.10. Isomeric ratio in photonuclear reactions

For the isomeric pair 111m,gIn, so far there is no experimental data or theoretical calculations. Therefore, it can be confirmed that the experimental results on the isomeric ratio 111m,gIn in the GDR region in our study **are new data**.

3.2.3. Experiment to determine the isomerism ratio in the reaction $^{195}Pt(\gamma,p)^{194m,g}Ir$ and $^{198m,g}Pt(\gamma, n)^{197}Pt$

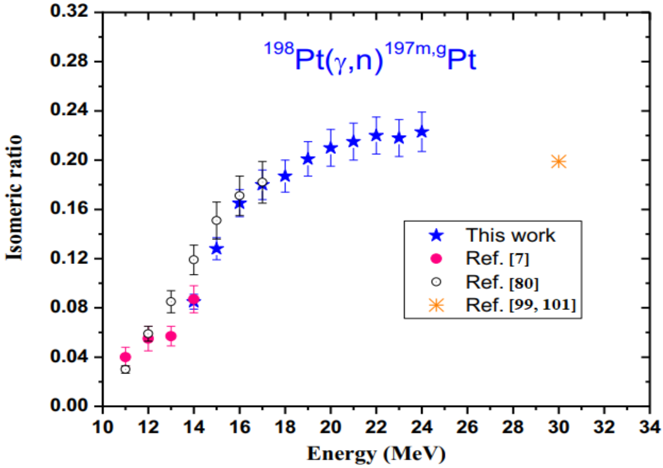

Figure 3.12. Isomeric ratio of the isomeric pair $^{197m,g}Pt$ in the photonuclear reaction $^{198}Pt\ (\gamma,n)^{197m,g}Pt$

Experimental data on the rate of production of isomeric pairs $^{194m,g}Ir$ and $^{197m,g}Pt$ in this study with bremsstrahlung radiation beams with energies from 19 to 23 MeV for $^{194m,\ g}Ir$ and from 18 to 24 MeV for $^{197m\ ,\ g}Pt$ is the new experimental data. The results are shown in Figures 3.12 and 3.13.

From the results in Figures 3.12 and 3.13, we can see: there is very little data on the isomerism ratio of the reaction $^{198}Pt(\gamma,n)^{197m,g}Pt$. The isomeric ratio in the reaction $^{195}Pt(\gamma,p)^{194m,g}Ir$

increases with increasing bremsstrahlung radiation energy and remains almost unchanged at the end of the GDR region.

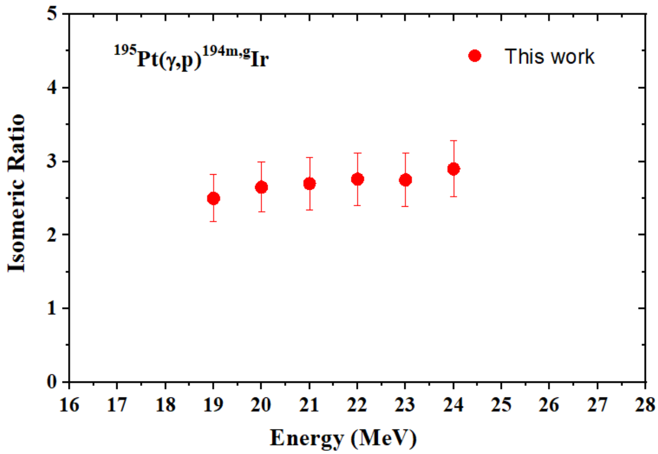

Figure 3.13. IR in photonuclear reactions $^{195}Pt\ (\gamma,p)\ ^{194m,g}Ir$

It is worth noting that in the $^{195}Pt(\gamma,p)^{194m,g}Ir$ reaction, the proton must overcome the Coulomb barrier of about 14.07 MeV. Therefore, it can be seen that the role of direct and pre-equilibrium processes in this reaction is significant when taking into account the Coulomb barrier for protons ejected from the ^{195}Pt nucleus.

3.2.4. Experiment to determine the isomer ratio in the photonuclear reaction of $^{138}Ce(\gamma,n)^{137m,g}Ce$

In this experiment, we determine the rate of formation of the isomeric pair $^{137m,g}Ce$ by the photonuclear reaction of $^{138}Ce(\gamma, n)^{137m,g}Ce$ with a beam of bremsstrahlung radiation with maximum energy from 14 MeV to 17 MeV with exposure time of 90 minutes; from 21 to 23 MeV and 19 MeV, exposure time 60 minutes; e- beam intensity is 14μA; sample diameter 1cm, and sample weight from 0.8560 - 0.8586 g. The results are analyzed, discussed and compared with published data to consider the role of excitation energy and the difference in spin of the isomeric state and the ground state. Figure 3.16 depicts the IR dependence of the $^{137m,\,g}Ce$ isomer pair on the peak energies in and above the GDR region taken from our data and those of other authors. We can see that there are incomplete and discrepant experimental data of IRs in the GDR region, **the results in this study can be considered new data.**

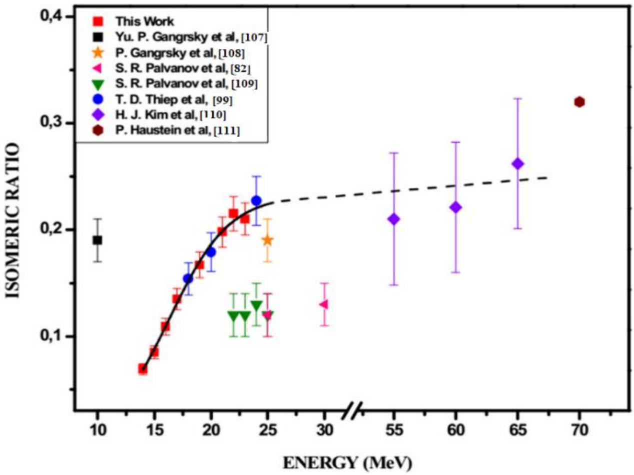

Figure 3.16. *IR in the reaction 138Ce(γ, n)137m,gCe induced by bremsstrahlung photon beams with different maximum energies*

The 137Ce daughter nucleus of the $^{138}Ce\ (\gamma,n)^{137m,g}Ce$ reaction is an even-odd, isomeric and ground state nucleus formed with spins of 11/2- and 3/2+, respectively. The GDR region for the nuclear reaction $^{138}Ce(\gamma,\ n)^{137m,g}Ce$ is from about 8.7 to about 23 MeV [119]. In this experiment, we obtained the isomeric ratio values of the reaction $^{138}Ce\ (\gamma,n)^{137m,g}Ce$ corresponding to different maximum energy levels of the bremsstrahlung radiation beam from 14-23 MeV. The results were compared with published data by authors Gangrsky and colleagues [107, 108], Palvanov and colleagues [82,109] and previous results of our group [21].

3. 3. Theoretical calculation results of differential cross-section and isomerism ratio in photonuclear reactions $^{151}Eu(\gamma,n)^{150m,g}Eu$ and $^{153}Eu(\gamma, n)^{152m,g}Eu$

In this section, we will present the results of theoretical calculations of differential cross sections using Talys and the results of calculating the isomer ratio in the photonuclear $^{151}Eu(\gamma, n)^{150m,g}Eu$ and $^{153}Eu(\gamma, n)^{152m,g}Eu$ uses a combination of simulation of the braking spectrum with Geant4 and the results of calculating the differential cross section with Talys. The calculation method has been presented in chapter 2. The calculation results are compared with our experimental data as well as those of other authors. In particular, the results of calculating differential section theory using Talys 1.8 with 06 different models, including: Constant temperature model with Fermi gas model (CFM), Fermi gas model (BFM) , Generalized Superfluid Model (GSM), Skyme-mG Force Model, Skyme-mH Force Model and Gogny-mH Force Model. In Figure 3.17 is an example of the excitation function of the $^{153}Eu(\gamma, n)^{152m,g}Eu$ photonuclear reaction calculated using the CFM model. It can be seen that in the giant dipole resonance region, the The main contributing reaction mechanism is the component mechanism. The cross-section of the formation of isomeric and ground states of the reaction 153Eu(□, n)152m,gEu is shown in Figure 3.20.

For the reaction $^{153}Eu(\gamma, n)^{152m,g}Eu$, the results of calculating the cross-section for the formation of state 152gEu (0-) using 6 different models of Talys 1.8 are very coincident, the state $^{152m2}Eu$(3-) gives quite similar results, however with the state $^{152m1}Eu$(8-) there is a large difference between the results when using different models.

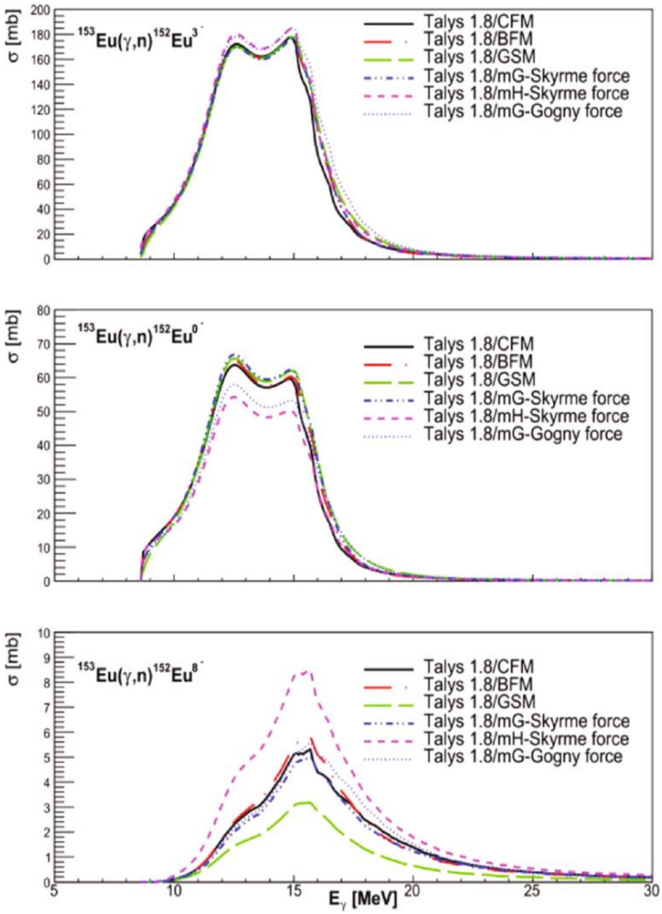

Figure 3.20. *Differential cross sections form states* $^{152m1}Eu(8^-)$, $^{152m2}Eu(0^-)$ *và* $^{152g}Eu(3^-)$

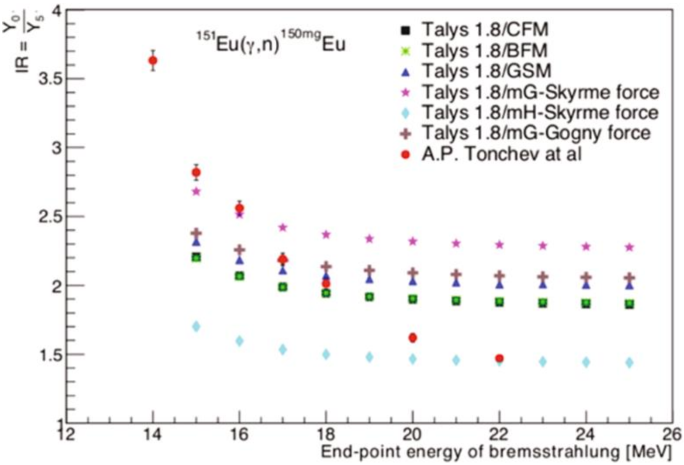

Figure 3.22. IR in photonuclear reactions $^{151}Eu(\gamma, n)^{150mg}Eu$

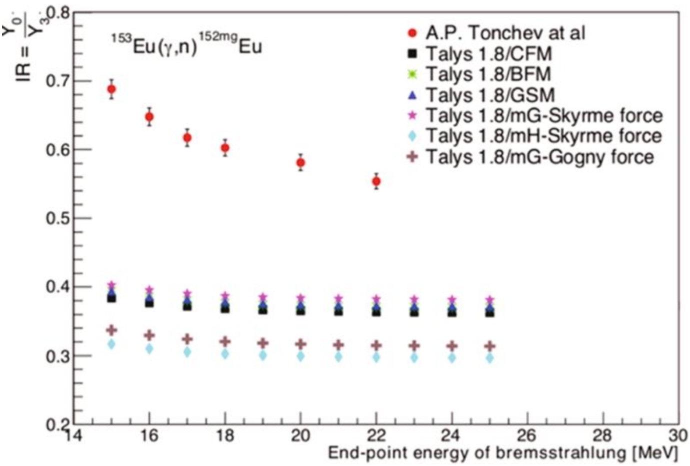

Figure 3.23. Isomeric rate ratio *$^{152m2}Eu(0^-)$ và $^{152g}Eu(3^-)$*

Figure 3.22 shows the results of calculating the isomer ratio in the reaction $^{151}Eu(\gamma, n)^{150m,g}Eu$ and experimental data of A. P. Tonchev and colleagues [4]. We can see that with the reaction

$^{151}Eu(\gamma,n)^{150m,g}Eu$ in the low energy region (<16 MeV), theoretical calculations with Talys 1.8mG-Skyrme force can describe the experimental data well; with the energy range from 17-19 MeV, Talys 1.8/CFM, Talys 1.8/BMF, Talys 1.8/GSM and Talys 1.8/mG-Gogny describe the experimental data well while with the energy range from 20 MeV to the end giant dipole resonance region, Talys 1.8/mH-Skyrme suitable for calculating isomerism ratios.

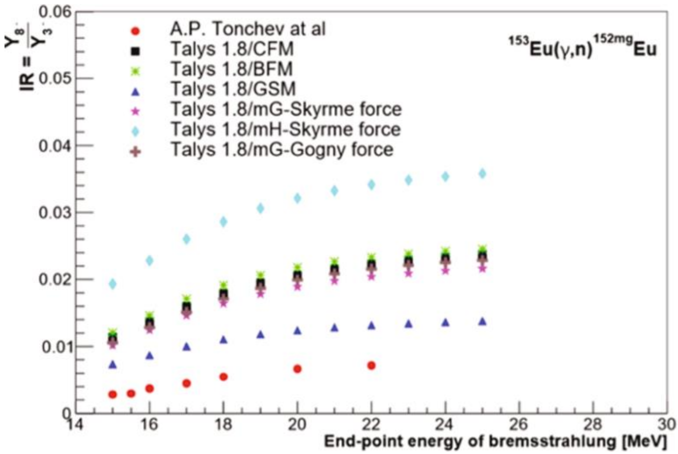

Figure 3.24. *Isomeric rate ratio $^{152m1}Eu(8^-)$ và $^{152g}Eu(3^-)$*

For the reaction $^{153}Eu(\gamma, n)^{152m,g}Eu$, the isomer ratio was calculated using Talys 1.8 and compared with experiment for the pairs $^{152m2}Eu(0^-)$ and ^{152g}Eu (3^-); $^{152m1}Eu(8^-)$ and ^{152g}Eu (3^-) ; $^{152m1}Eu(8^-)$ and $^{152m2}Eu$ (0^-) are presented in Figures 3.23. Here, the experimental data are taken from the publication of A. P. Tonchev and colleagues [4] and from our experimental results.

Figures 3.24 and 3.25 show that Talys 1.8/GSM describes the experimental data better than other models for the pairs $^{152m1}Eu(8)$,

^{152g}Eu(3$^-$) và cặp ^{152m1}Eu(8$^-$), ^{152m2}Eu(0$^-$). However, theoretical calculations describe well the changing trend of the isomer ratio in the reactions ^{151}Eu(γ,n)^{150m,g}Eu and ^{153}Eu(γ,n)^{152m,g}Eu, which means the stoichiometry ratio The formation of a high spin/low spin state increases as the maximum energy of the bremsstrahlung beam increases.

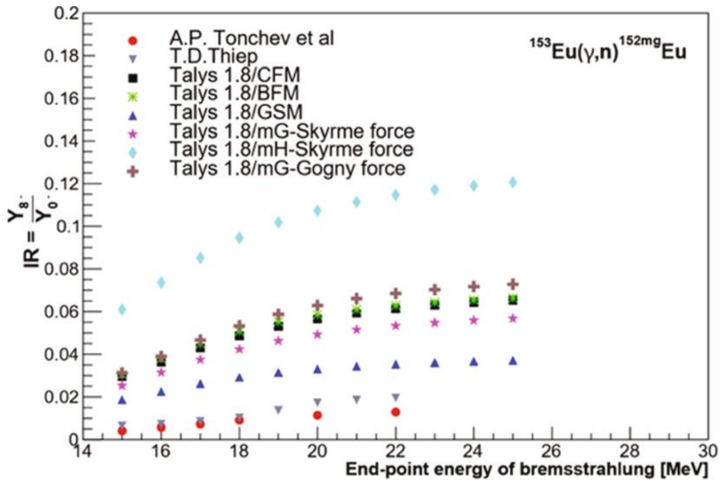

Figure 3.25. *IR of pair creation rate ^{152m1}Eu(8$^-$) và^{152m2}Eu(0$^-$)*

CONCLUDE

The thesis has achieved the set research objectives and content, and the main results obtained include:

1. Overview of photonuclear reactions, nuclear structure and isomeric nuclear states.

2. Research and develop experimental methods and theoretical calculations to determine the isomeric ratio of photonuclear reactions in the GDR energy range (8-30 MeV).

3. Experimentally determine the isomerism ratio in the reactions $^{113}In(\gamma,2n)^{111m,g}In$, $^{113}In(\gamma,n)^{112m,g}In$, $^{107}Ag(\gamma,n)^{106m,g}Ag$, $^{195}Pt(\gamma,p)^{194m,g}Ir$; $^{198}Pt(\gamma,n)^{197m,g}Pt$ and $^{138}Ce(\gamma,n)^{137m,g}Ce$ are caused by photon beams with maximum energy from 14 to 24 MeV. Obtained 11 IR ratio data for $^{111m,g}In$; 6 data for $^{112m,g}In$; 11 data for $^{106m,g}Ag$; 6 data for $^{194m,g}Ir$, 11 data for $^{197m,g}Pt$ and 8 data for $^{137m,g}Ce$.

4. Theoretical calculation of differential cross-section and isomerism ratio of photonuclear reactions $^{151}Eu(\gamma,n)^{150m,g}Eu$ and $^{153}Eu(\gamma, n)^{152m,g}Eu$ in the GDR energy region.

The results obtained many new data on the yield ratio of forming isomeric nuclear pairs. Provides a complete view of the changing trend of the isomer ratio with energy in the GDR region. The results were compared and evaluated with published data showing good agreement. This is the basis for confirming the reliability of the results obtained.

In addition to experimental studies, the thesis has developed a new approach combining Talys and Monte-Carlo simulation using Geant4 in calculating the rate of formation of ground states and isomers, thereby calculating Calculate the isomerism ratio and compare with experimental data. This approach allows simulating the entire reaction process from the generation of bremsstrahlung spectra, the electromagnetic interaction of bremsstrahlung radiation with the target nucleus, and the process of photonuclear reactions. The differential cross section of the photonuclear reaction was calculated using Talys. The simulation program developed by us allows simultaneous simulation of isomeric and ground state formation reactions, so the competing process is fully considered in each event. Therefore, similar conditions when comparing theory and experiment are guaranteed. Our method has been applied to calculate the isomerism ratio in the photonuclear reactions $^{151}Eu(\gamma,n)^{150m,g}Eu$ and $^{153}Eu(\gamma,n)^{152m,g}Eu$. It can be concluded that theoretical calculations using Talys combined with Geant4 describe well the trend of experimental isomeric ratios. For the $^{151}Eu(\gamma,n)$ reaction that produces spherical nuclei of $^{150m,g}Eu$, the theoretical calculation results with different models in Talys describe well the experimental data on isomer ratios in each energy region. quantity. However, in the remaining reaction, the nuclei formed are strongly deformed nuclei, the theoretical calculated data are lower than the experimental ones. Thus, it can be said that the theoretical models of nuclear structure in Talys need to be further improved to be able to well describe the structure of the ^{152}Eu deformation nucleus.

In this thesis, analysis of the nuclear structure corresponding to the isomeric and ground states was conducted. However, analysis and evaluation of the correlation between experimental data on isomer ratios and nuclear structure as well as spin or spin difference between isomeric and ground states have not been conducted. In the future, analysis and systematization of experimental data on isomerism ratios according to the above parameters and factors need to be carried out. In addition, the evaluation and systematization of the dependence of the isomerism ratio on the mass number of the target nucleus and the resulting nucleus also needs to be considered. In addition, with the successful development of the above theoretical calculation approach, we will extend the calculation of reaction stoichiometry and isomerism ratio to many different photonuclear reactions with radiation beams. brake has maximum energy in the giant dipole resonance region and above the giant dipole resonance region and compared with experiments from reliable databases around the world so that recommendations can be made. reports help improve theoretical models in Talys.

LIST OF PUBLISHED WORKS RELATED TO THE THESIS

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2. T. D. Thiep, T.T.An, P.V.Cuong, N.T.Vinh , B. Hue, A. Belov, O. D. Maslov. "*Study of isomeric ratios in* $^{107}Ag(\gamma,n)^{106m,g}Ag$ *reaction of natural silver induced by bremsstrahlungs with endpoint energies in the giant dipole resonance region".* Journal of Radioanalytical and Nuclear Chemistry, 299 (2014) 477-484. DOI: 10.1007/s10967-013-2727-0. ISI.
3. Tran Duc Thiep, Truong Thi An, Phan Viet Cuong, Nguyen The Vinh, A. G. Belov & O. D. Maslov. *"Study of the isomeric ratios in photonuclear reactions of natural Platinum induced by end-point bremsstrahlung energies in the giant dipole resonance region".* Journal of Radioanalytical and Nuclear Chemistry, 303 (2015)1857-1864. DOI: 10.1007/ s10967-014-3701-1. ISI.
4. Tran duc Thiep,Tran Duc Thiep, Truong Thi An, Phan Viet Cuong, Nguyen The Vinh, Bui Minh Hue, A. G. Belov, O. D. Maslov, M. V. Gustova,, *"Isomeric Ratio of* ^{137m}Ce *to* ^{137g}Ce *Produced in* $^{138}Ce(\gamma, n)^{137m,g}Ce$ *Photonuclear Reaction Induced by End-point Bremsstrahlung Energies from 14 to 17; 21 to 23 and at 19 MeV".* Journal of Radioanalytical and Nuclear Chemistry, 311 (2017) 887-892. DOI: 10.1007/s10967-016-5064-2. ISI.
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