ISOMER RATIOS AND MEAN ANGULAR MOMENTA OF PHOTONUCLEAR REACTION PRODUCTS

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Isomer ratios and mean angular momenta are obtained both for photofission products of ^{237}Np, ^{238}U and for nuclei ^{122,120m,g}Sb and ^{117m,g}In. Photonuclear reactions ^{121}Sb(γ,n)^{120m,g}Sb, ^{123}Sb(γ,n)^{122m,g}Sb, ^{118}Sn(γ,p)^{117m,g}In were studied in the last cases. The technique of gamma-ray spectrometry for isomeric ratio determination was used. Target nuclei were irradiated by bremsstrahlung spectrum of microtron M-30. Comparison of isomer ratios calculated by Empire II code with experimental data was performed. Effects of the nuclear structure model parameters on values of isomer ratios are discussed.

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1. INTRODUCTION

Study of mean angular momenta of the fission fragments is useful for investigation of a configuration of fissionable system near scission point [1,6-9]. The various experimental techniques are used to obtain such information on mean angular momenta: measurements of anisotropy [2] and number of emitted gamma rays [3]; ground state band populations in even-even fission products [4]; investigation of isomer ratios [7]. Isomer ratio is one of the most simple and rather reliable method to deduce information on spin distribution and on value of mean angular momenta. It is based on investigations of independent yield of isomer states with different spin (isomer ratio) in evaporation residues of primary fission products. Values of isomer ratio are rather sensitive to parameters of nuclear models. Therefore it is important to investigate such dependencies for more accurate estimation of mean angular momenta of photonuclear reaction products. Note that angular momentum of compound nucleus which formed in photonuclear reaction has a relatively small value. So the effects of rotation of the compound nucleus are expected to be small in photonuclear reactions.

In this contribution we present a study of isomeric yield ratios and primary angular momenta for two groups of nuclei. First group of fragments ^{84}Br, ^{130}Sb, ^{131,133}Te, ^{132}Sb, ^{134}I, ^{135}Xe is produced in the photofission of ^{238}U and ^{237}Np by bremsstrahlung with maximum energy of 16 MeV. The isomer ratios for nuclei ^{122,120m,g}Sb and ^{117m,g}In are obtained from reactions ^{121}Sb(γ,n)^{120m,g}Sb, ^{123}Sb(γ,n)^{122m,g}Sb, ^{118}Sn(γ,p)^{117m,g}In. Bremsstrahlung spectrum of microtron M-30 with electrons energy 15 and 16 MeV was used for irradiation.

2. EXPERIMENTAL TECHNIQUE AND RESULTS

The uranium and neptunium targets were irradiated by bremsstrahlung of microtron M-30 with maximum energy of electrons 16 MeV to obtain photofission products. Bremsstrahlung spectrum of microtron M-30 with electrons energies 15 and 16 MeV was used for irradiation of stibium and tin targets.

The targets with ^{237}Np consisted of thin aluminium foil with deposited thin layer of neptunium; ^{238}U targets consisted of a set of aluminium plates with thin layers of depleted uranium on the both sides of plates; distance between plates was fixed. Thin foils (about ten pieces) were inserted between plates. Some part of the fission fragments with high kinetic energy was driven in the foils. After irradiation the foils were removed for subsequent measurements of gamma spectra.

The HPGe spectrometer with energy resolution 2.0 keV at 1332 keV (gamma energy of ^{60}Co) was used. Gamma-ray spectra of photonuclear reaction products were analyzed at different time intervals to perform correct identification of the products. The time of measurement was varied (from 1 min in the beginning to

10 min in the end of a measurement) to have optimal conditions for data acquisition.

The examples of gamma spectra for fission products of ^{238}U and ^{237}Np are shown on Figs. 1 and 2, as well as some gamma-peaks used to determine isomer ratios. The examples of gamma spectra of ^{122}Sb, ^{120}Sb, $^{117m,g}In$ are shown on Fig. 3. One can see that spectra are rather complex and consist of several hundred of gamma-peaks. The special code was developed to process spectra in manual and semi-automatic way.

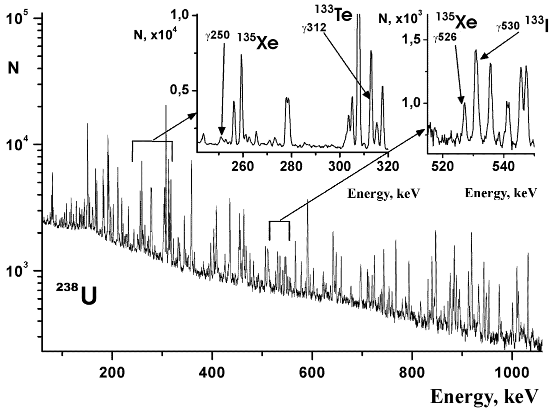

Fig. 1. Typical gamma spectra of photofission fragments of ^{238}U

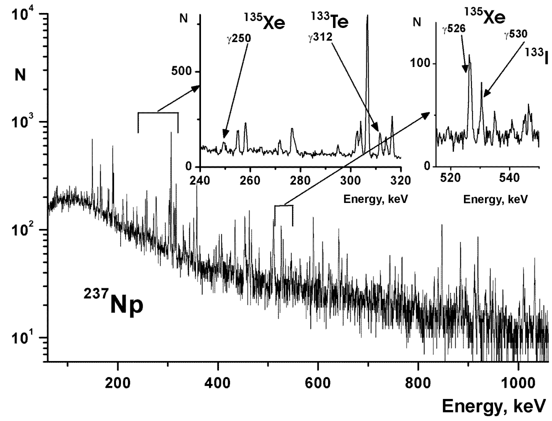

Fig. 2. Typical gamma spectra of photofission fragments of ^{237}Np

The contributions of genealogically related β-decay branches to yield of investigated nuclei were taken into account for correct calculation of the experimental values of isomer ratios [8]. Input information on gamma transitions, their absolute yields, nuclear structure, which are needed for calculation of isomer ratios, was used from Ref. [9]. The table contains the obtained experimental values of isomer ratios.

The following isomer yield ratios for reactions $^{123}Sb(\gamma,n)^{122m,g}Sb$ and $^{118}Sn(\gamma,p)^{117m,g}In$ were obtained:

^{120}Sb: $Y_m/Y_g=(7.1\pm0.7)\cdot10^{-2}$; $E_\gamma=16$ MeV;

^{122}Sb: $Y_m/Y_g=(15\pm1)\cdot10^{-2}$; $E_\gamma=16$ MeV;

^{117}In : $Y_m/Y_g=(24\pm2)\cdot10^{-2}$; $E_\gamma=16$ MeV;

^{117}In : $Y_m/Y_g=(9\pm7)\cdot10^{-2}$; $E_\gamma=15$ MeV.

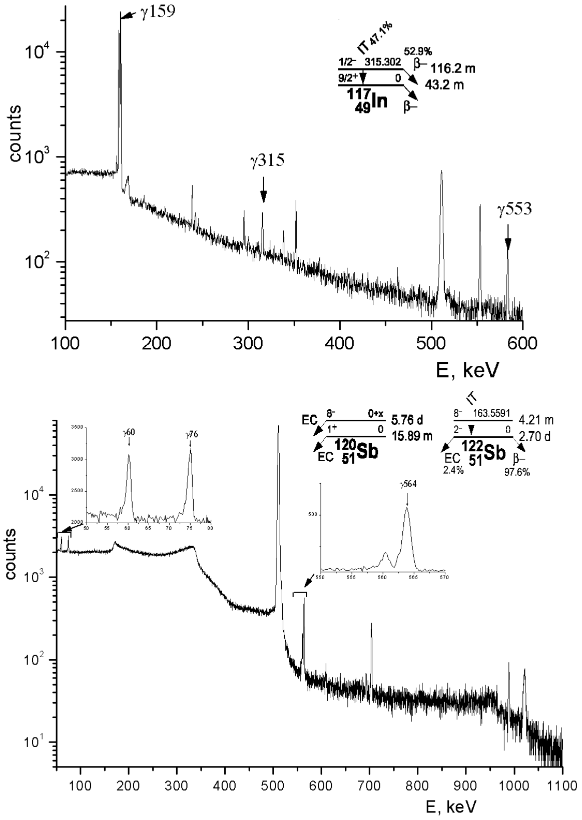

Fig. 3. Typical gamma spectra of $^{120m,g}Sb$, $^{122m,g}Sb$, $^{117m,g}In$

3. CALCULATION OF MEAN ANGULAR MOMENTA AND ISOMER RATIOS

The code Empire-II [10] was used to obtain spin distributions and mean angular momenta of primary photofission products using experimental values of isomeric yield ratios. This code was modified and extended for analysis of photonuclear reactions and for investigations of both dependences of angular momenta and energy of primary fission fragments on isomer ratio values [11,12].

The procedure of isomer ratio calculations is automatized. Initial population of discrete nuclear levels after escape of all neutrons is calculated by Empire-II code within Hauser-Feshbach model. The probabilities of deexcitation and population of discrete levels were taken from the experimental data and from RIPL-2 library of evaluated data. Isomer ratio is calculated as a ratio of populations of metastable and ground states.

Isomer ratios and mean angular momenta of photofission fragments

Target Nucleus	Isomer Nucleus – Product of Photofission	Isomer Ratio σ_H/σ_L	Mean Angular Momentum $<J>$
^{238}U	^{84m,g}Br	$\sigma(5^-)/\sigma(2^-)$ =0.44 ± 0.04	4.4 ± 0.2
^{238}U	^{130m,g}Sb	$\sigma(8^-)/\sigma(5^+)$ =1.2 ± 0.2	6.8 ± 0.4
^{238}U	^{131m,g}Te	$\sigma(11/2^-)/\sigma(3/2^+)$ =1.38 ± 0.21	5.2 ± 0.4
^{238}U	^{132m,g}Sb	$\sigma(8^-)/\sigma(4^+)$ =0.79 ± 0.13	7.4 ± 0.4
^{238}U	^{133m,g}Te	$\sigma(11/2^-)/\sigma(3/2^+)$ =1.44 ± 0.15	6.8 ± 0.3
^{238}U	^{134m,g}I	$\sigma(8^-)/\sigma(4^+)$ = 0.67 ± 0.13	7.0 ± 0.5
^{238}U	^{135m,g}Xe	$\sigma(11/2^-)/\sigma(3/2^+)$ =0.22 ± 0.03	2.8 ± 0.15
^{237}Np	^{134m,g}I	$\sigma(8^-)/\sigma(4^+)$ = 2.4 ± 0.2	11.0 ± 0.4
^{237}Np	^{135m,g}Xe	$\sigma(11/2^-)/\sigma(3/2^+)$ =0.61 ± 0.06	4.2 ± 0.2

The following information is needed for unambiguous extraction of value of mean angular momentum of initial primary fission fragment from isomer ratio: total excitation energy of fragments after scission point; distribution of this energy among the fragments; distribution of mean angular momenta and relative yield of initial primary fission fragments. We assumed that total excitation energy is distributed among fragments proportionally to their masses (this conclusion is consequence of assumption on equality temperature in fissionable nucleus and fission fragments). The distribution of mean angular momenta J is taken in form of delta function or by the expression $P(J)\approx(2J+1)\cdot exp(-J\cdot(J+1)/B^2)$ where B is parameter of distribution. The yields of fragments with equal charge Z and number of neutrons $N\pm1$ is considered as the same. The mean angular momenta for these fragments are assumed to be equal. Detail calculation procedure is described in [13].

Derived values of mean angular momentum $<J>$ are given in the table, where σ_H is cross-section of population of high spin level and σ_L is cross-section of population of low spin level. The results for photofission products are in rather good agreement with data of other authors, for example from Ref. [14]. Calculated values of isomer ratios for (γ,n) reactions rather poorly agree with experimental data. Calculated isomer ratios for ^{117m,g}In are 0.21 for energy 16 MeV and 0.14 for energy 15 MeV. Isomer ratios for set of nuclei in reactions (γ,n) and (n,γ) were calculated to compare with experimental data and calculations of other authors [15]. The following conclusions can be made from these comparisons. A consistent using of statistical Hauser-Feshbach model of nuclear reactions with taking into account escape of all particles, gamma cascades, angular momentum conservation low by Empire II code can not explain the high population values of levels with high spins for nuclei with initial small spin of compound nucleus. The description becomes especially problematic when difference between spin of isomer and ground level is larger than four. Influence of the spin cut-off factor on the isomer ratio is not very important. Calculations with the use of Empire II code and base of experimental characteristics of levels show that widely used Huizenga-Vandenbosh assumption [7] of final decisive transition is rather poor approximation for many nuclei.

Mean number of quanta in gamma cascade (multiplicity) is very important for determination of isomer ratio in such approaches. In many cases this value is free parameter to fit isomer ratios to the experiment. Note that gamma multiplicity first of all depends on the nuclear level density and radiative strength function in the low energy region. Experimental information on radiative strength function in the region of gamma quanta energies near 1…2 MeV is very fragmentary. Characteristics of the low lying levels and decay probabilities can be very important for population of levels with high enough spins. In many cases these effects are not statistical and it is necessary to exclude such contribution for correct study of statistical mechanisms. The agreements of calculations by Empire II with experimental data for some nuclei with large difference of isomer and ground spins is only provided by peculiar properties of nuclear level scheme. In general the theoretical isomer ratios are as a rule smaller than experimental values in the range of medium and heavy weight nuclei near the beta-stability line.

4. CONCLUSIONS

Isomer ratios and mean angular momenta for photofission products of ^{237}Np and ^{238}U for nuclei ^{122,120m,g}Sb and ^{117m,g}In are obtained. Influence of the nuclear structure model parameters on value of isomer ratio was discussed. Consistent using of statistical Hauser-Feshbach model of nuclear reactions with taking into account escape of all particles, gamma cascades, angular momentum conservation low without fitting critical parameters can not explain the high population values of levels with high spins for nuclei with initial small spin of compound nucleus. Study of gamma quanta multiplicity, radiative strength function in the low energy region, multipolarity factors is necessary for more precise calculations with use of isomer ratio method. The authors (V.A.P., O.A.B., I.M.K.) are very thankful for support in part by the IAEA (Vienna) under IAEA Research Contract № 12492.1.

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ИЗОМЕРНЫЕ ОТНОШЕНИЯ И СРЕДНИЕ УГЛОВЫЕ МОМЕНТЫ ПРОДУКТОВ ФОТОЯДЕРНЫХ РЕАКЦИЙ

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Измерены изомерные отношения и извлечены средние угловые моменты для продуктов фотоделения ядер ^{238}U и ^{237}Np, а также измерены изомерные отношения для ядер ^{120,122m,g}Sb и ^{117m,g}In в реакциях (γ,n) и (γ,p). Облучение проводилось тормозными γ-квантами микротрона М-30 с максимальной энергией спектра 16 и 15 МэВ. Исследованы зависимости изомерных отношений от угловых моментов возбужденных ядер с использованием программы Empire II для расчета характеристик ядерных реакций.

ІЗОМЕРНІ ВІДНОШЕННЯ ТА СЕРЕДНІ КУТОВІ МОМЕНТИ ПРОДУКТІВ ФОТОЯДЕРНИХ РЕАКЦІЙ

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Досліджено ізомерні відношення та визначено середні кутові моменти для продуктів фотоділення ядер ^{238}U і ^{237}Np, а також виміряні ізомерні відношення для ядер ^{120,122m,g}Sb и ^{117m,g}In в реакціях (γ,n) та (γ,p). Опромінення проводилося гальмівними γ-квантами мікротрону М-30 з максимальною енергією спектру 16 та 15 МеВ. Досліджено залежності ізомерних відношень від кутових моментів збуджених ядер з використанням програми Empire II для розрахунку характеристик ядерних реакцій.