EXCITATION OF ISOMERIC STATES IN $(n,2n)$ AND (γ,n) REACTIONS ON ^{198,200}Hg NUCLEI*

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The production cross sections and isomeric ratios of the cross sections of $(n,2n)$ reactions on ^{198,200}Hg nuclei at a neutron energy of 14.1 MeV have been measured by the induced activity method. The isomeric ratios of the photo-neutron reaction yields (γ,n) were also measured at the maximum bremsstrahlung energies of 25, 30, and 35 MeV. The experimental isomeric ratios are compared with the results of other works and the calculated results using the statistical model of the nucleus.

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1. Introduction

The study of isomeric ratios is one of the most actual issues that gives the possibility of obtaining useful information about the reaction mechanism, in particular, on the moment of inertia of the nucleus, the spin dependence of the level density, and the character of transitions between highly excited nuclear states. Moreover, it can also be helpful in getting data from the isomeric ratios of the yields of nuclear reactions which are necessary for replenishing nuclear data in this area and optimizing experiments in analytical and numerical studies using methods of activation analysis [1]. In this work, the isomeric ratios of the cross sections for the $(n,2n)$ reaction on ^{198,200}Hg nuclei were studied by the induced activity method. The isomeric ratios of

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the yields of the (γ, n) reaction on the ^{198}Hg nucleus were also determined. In the bremsstrahlung energy range of 25–35 MeV, the isomeric ratios of reaction yields were obtained for the first time.

2. Experimental technique

The studies were carried out on a high-current betatron SB-50 of the Research Institute of Applied Physics of the National University of Uzbekistan and a neutron generator NG-150 of the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan [2]. The neutron generator NG-150 realizes fluxes of fast neutrons with energies ~ 2.4 and 14 MeV from the $D + d \to\ ^{3}\mathrm{He} + n$ or $T + d \to\ \alpha + n$ reactions using deuterium and tritium targets. In this case, the neutron fluxes are $\sim 10^8$ and 10^{10} n/sec, respectively. The time of exposure to a neutron flux with the energy of 14 MeV is 50 min. The neutron flux is monitored using a natural isotopic aluminum plate, where it has been irradiated together with the targets. Samples of mercury oxide (HgO) weighing 2–3 g in the form of a disk of 15 mm in diameter are used as targets. Experiments on the (γ, n) reaction were carried out on the bremsstrahlung γ-beam of the SB-50 betatron in the energy range of 12–35 MeV with a step of 1 MeV.

The induced γ-activity of the targets was measured on a Canberra γ-spectrometer, consisting of an HPGe germanium detector (with a relative efficiency of 15%, a resolution for the ^{60}Co 1332 keV line — 1.8 keV), a DSA 1000 digital analyzer and a personal computer with the Genie 2000 software package for acquisition and processing of gamma spectra. The energy scale of the detector was set by commercially used reference sources of ^{54}Mn, ^{57}Co, ^{60}Co, ^{109}Cd, ^{133}Ba, ^{137}Cs, ^{152}Eu, ^{210}Pb, and ^{241}Am. The measurements were performed in standard geometry, in which the detector was calibrated in terms of efficiency.

The population of the isomeric and basic levels was identified by γ-lines. The spectroscopic characteristics of the nuclei products of the $(n, 2n)$ reaction, necessary for processing the results of measurements, are taken from [3, 4] and given in Table 1, where Q is the reaction energy, I^π is the spin and parity of the level, $T_{1/2}$ is the half-life of the nucleus, E_γ is the energy of γ-quanta, I_γ is the intensity of γ-quanta of a given energy for decay, and p is the branching factor of the γ-transition.

To identify the isomeric state, γ-lines were used, which appear as a result of the transition between levels with an energy of 298.9 keV $(13/2^+) \to$ 133.9 keV $(5/2^-) \to 0$ keV $(1/2^-)$. To identify the ground states, we used the γ-line with an energy of 191.5 keV, which results from the e-capture of ^{197}Hg.

Table 1. Spectroscopic characteristics of the nuclei under study.

Nuclear reaction	Q [MeV]	I^π	$T_{1/2}$	E_γ [keV]	I_γ [%]	p
$^{198}Hg(n,2n)^{197m}Hg$	−8.56	$13/2^+$	23.8 h	133.9	30.2	0.93
$^{198}Hg(n,2n)^{197,g}Hg$	−8.49	$1/2^-$	64.1 h	191.5	0.55	
$^{200}Hg(n,2n)^{199m}Hg$	−8.03	$13/2^+$	42.6 m	158	58	1

3. Results and discussion

To obtain the absolute values of the cross sections of the ground and isomeric states, some methods were used to compare the yields of the studied and monitor reactions. $^{27}Al(n,\alpha)^{24}Na$ ($T_{1/2} = 15$ h, $E_\gamma = 1368$ keV) was used as a monitor reaction, the cross section of which is: $\sigma_m = 114 \pm 6$ mb at $E_n = 14.6 \pm 0.3$ MeV [5].

The obtained experimental results on the isomeric ratios of the yields and cross sections of the $(n, 2n)$ and (γ, n) reactions on $^{198,200}Hg$ nuclei are shown in Fig. 1 and Tables 2 and 3.

Table 2. Cross sections for the $(n, 2n)$ reactions on $^{198,200}Hg$ nuclei.

Nuclear reaction	E_n [MeV]	σ [mb]		σ_m/σ_g	Ref.
		m	g		
$^{198}Hg(n,2n)^{197}Hg$	14.0*	1130	853	1.32	This work
	14.5*	1186	835	1.41	This work
	14.1	900 ± 70	940 ± 75	0.96 ± 0.11	This work
	14.1	—	—	0.80 ± 0.10	[6]
	14.4	885 ± 80	1125 ± 100	0.79 ± 0.10	[7]
	14.7	910 ± 85	1010 ± 140	0.90 ± 0.15	[8]
	14.02	930 ± 60	1110 ± 110	0.84 ± 0.10	[9]
$^{200}Hg(n,2n)^{199m}Hg$	14.0*	932	1934**	0.48	This work
	14.5*	978	1965**	0.50	This work
	14.1	820 ± 100	—	0.39 ± 0.05	This work
	14.4	789 ± 120	—	0.37 ± 0.06	[7]

* The cross sections were calculated using the TALYS-1.6 program.

** Total cross section.

As can be seen from Table 2, the data of all works are consistent within the measurement errors. The absolute error of the isomeric ratios of reaction cross sections is determined by the statistical error of counting in the photopeak of the measured γ-line, the efficiency of registration of γ-radiation, and the error in the values of the monitors' cross sections. It is also seen from the data given in the table that in the case of the ^{200}Hg$(n, 2n)^{199m}$Hg reaction, there are only two works.

The obtained experimental results on the isomeric ratios of the reaction yields (γ, n) in the energy range of 12–35 MeV with a step of 1 MeV are shown in Fig. 1. The results of the measurements showed that the value of the Y_m/Y_g isomeric yield ratios increases from the reaction threshold to the energy corresponding to the position of the maximum of the giant dipole resonance E_m. At energies above E_m, the function $d(E_{\gamma\,\max}) = Y_m/Y_g$ has the form of a saturation curve.

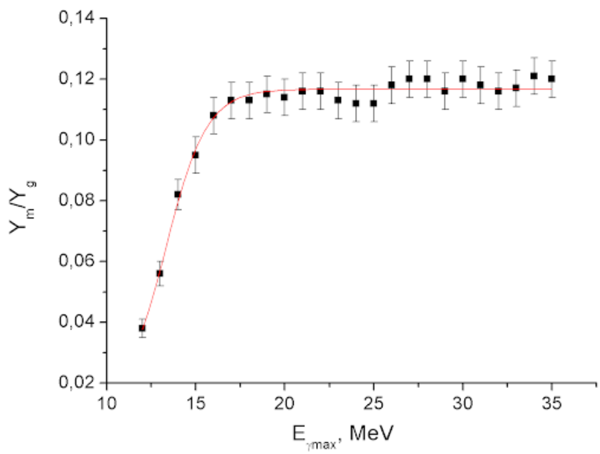

Fig. 1. Energy dependence of the isomeric ratio of the yields of the ^{198}Hg$(\gamma, n)^{197m,g}$Hg reaction.

Table 1 shows our experimental results obtained from the isomeric yield ratios $d = Y_m/Y_g$ for the (γ, n) reaction on ^{198}Hg nuclei at energies of 25, 30, and 35 MeV. Data from other works are also presented. Earlier in [10], the ratios of the Y_m/Y_g isomeric yields of the (γ, n) reaction on the ^{198}Hg nucleus were measured in the energy range of 10–17 MeV with a step of 0.5 MeV, the results of which agree with our results within errors. In [11], the isomeric ratios of the cross sections were determined at the maximum bremsstrahlung energy of 25 MeV, the results of which, within the measurement error, agree with the data of other works. The results of [12] differ from the results of other works. The data [12] were obtained on a scintillation spectrometer, the energy resolution of which is worse than that of the modern semiconductor detectors. The relative probability of the formation of ^{197m,g}Hg isomeric states in the $(n, 2n)$ reaction is greater (~ 8 times) than in the (γ, n) photonuclear reaction. This is probably due to the momentum introduced into the nucleus, which is greater in the case of the $(n, 2n)$ reaction than in the case of the (γ, n) reaction.

Table 3. Isomeric ratios of the yields of the (γ, n) reaction on the ^{198}Hg nucleus.

Reaction	$E_{\gamma\,\max}$ [MeV]	Y_m/Y_g	Ref.
$^{198}\mathrm{Hg}(\gamma, n)^{197m,g}\mathrm{Hg}$	25	0.114 ± 0.006	This work
	30	0.113 ± 0.006	This work
	35	0.112 ± 0.006	This work
	17	0.112 ± 0.055	[10]
	25*	0.11 ± 0.01	[11]
	30	0.05 ± 0.01	[12]

* Value given is $r_{\mathrm{int}} = \sigma^m_{\mathrm{int}}/\sigma^g_{\mathrm{int}}$.

In order to calculate the theoretical isomeric ratios of yields, we have used the TALYS-1.0 software package [13]. The program has several variants of model approaches to the description of the level density. Discrete-level schemes are taken into account automatically. The complexity of calculations in this energy region is due to the fact that the energy spectrum of bremsstrahlung γ-rays shows a continuous behavior with a decrease from maximum values to zero. In the betatron, the bremsstrahlung target has been considered in order to be a thin target, and therefore the Schiff formula [14] was used to calculate the bremsstrahlung spectrum. The general scheme of the reaction is assumed to be the same as in [12], namely, first, the dipole γ-rays is absorbed on the nucleus with the formation of a compound nucleus, then the neutron is evaporated with the formation of the excited state of the final nucleus. The excitation of the daughter nucleus is removed by cascade emission of γ-rays, resulting in the formation of the ground or isomeric state of the final nucleus.

The density of nuclear levels was calculated using the Beta–Bloch formula [14], the spin part of which has the form of

$$\rho(J) = (2J+1)\exp\left[-\left(J+1/2\right)^2/2\sigma^2\right] .$$

It was possible to improve the quantitative agreement between calculations and experiment by fixing the spin confinement parameter σ. In this case, the satisfactory agreement is reached at $\sigma = 3.2\hbar$.

4. Conclusion

It is observed from an analysis of the data given in Table 3 that experimental studies of the excitation of isomeric states in photonuclear reactions of the (γ, n)-type have been carried out mainly in the range of energies 10–17 MeV which corresponds to the range of giant dipole resonance. In the range of energies, the above-mentioned giant resonance dependence of isomeric ratios on its energy has been poorly understood. The studies allow for the possibilities of obtaining information about the nuclear density levels and contributions of direct processes to the photonuclear reaction mechanism in the energy range.

The experimental results obtained in this work can be used to assess the analytical capabilities of activation analysis, for planning a new type of such experiments in studies of isomeric ratios in nuclear reactions, and to explain physical mechanisms reactions.

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