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NUCLEI
Experiment

Excitation of Isomeric $1h_{11/2}$ States in Nuclear Reactions Induced by γ Rays and Neutrons and in Beta Decay

A. G. Belov, Yu. P. Gangrsky, L. M. Melnikova, V. Yu. Ponomarev, N. Tsoneva[1], Ch. Stoyanov[1], A. Tonchev[2], and N. Balabanov[3]

Joint Institute for Nuclear Research, Dubna, Moscow oblast, 141980 Russia

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Abstract—Isomeric ratios were measured for $N = 81$ isotones (^{135}Xe, ^{137}Ba, ^{139}Ce, ^{141}Nd, ^{143}Sm). In the experiment reported here, $J^\pi = 11/2^-$ isomers were excited in (n, γ) and (γ, n) reactions and in the β^+ decay of ^{139}Pr and ^{141}Pm. In order to determine the reaction yields, use was made of the activation method involving measurement of the gamma-ray spectra of reaction products. It is found that, in the same reactions, isomeric ratios are different for isotones characterized by different atomic numbers Z. Isomeric ratios were calculated with the spectra of low-lying levels and radiative-transition probabilities established on the basis of the quasiparticle–phonon model. Good agreement between the experimental and calculated values of isomeric ratios is obtained for all isotopes invesigated here. The dependence of isomeric ratios on the atomic number Z of a nucleus is explained by the difference of reaction energies, which leads to different probabilities of excitation of activation levels through which the isomers being considered are populated.

INTRODUCTION

Investigation of nuclear reactions leading to the production of isomeric states is an efficient method for obtaining data on the features of nuclei at low excitation energies. The system of levels through which an isomeric state is populated is one of such features. As a rule, such levels have not yet received adequate study, since they are weakly manifested in the majority of nuclear reactions.

Measurement of isomeric ratios—i.e., ratios of the cross sections for reactions (yields from reactions) leading to the production of a nucleus in an isomeric and in the ground state—that is followed by a comparison of the results of such a measurement with the results of a relevant calculation is the most popular method for studying reactions that involve isomer production. In such calculations, use is made of specific ideas of the properties of nuclear levels, and the degree of agreement between the experimental and calculated values of isomeric ratios is a measure of correctness of these ideas. Usually, the calculations in question rely on the statistical model of the nucleus [1–3] and comply well with experimental data (see, for example, [4–6]) for a number of reactions. It is important that this agreement can be achieved with the level-density parameter a and the spin-cutoff parameter σ (which specify, respectively, the energy and the angular-momentum dependence of the level density) set to values adopted in the model or deduced from independent experimental data.

It is well known that the statistical model faithfully reproduces the spectrum of nuclear levels that occur above the neutron binding energy. At the same time, isomeric ratios are substantially, and even sometimes crucially, affected by lower levels through which gamma-ray cascades populate an isomeric state. However, data on the properties of such levels (specifically, on their spectrum, nucleonic configurations, and wave function) are by far insufficient, so that a correct calculation of this stage of the isomer-production process is often impossible. Obviously, this is one of the reasons behind a noticeable discrepancy between experimental and calculated data. Such a discrepancy is exemplified by the isomeric ratio in the reaction ^{180}Ta(γ, γ'), where the spin difference between the ground-state and the isomeric level is as large as $\Delta J = 8$ and where the measured isomeric ratio is 0.3 [7] (according to statistical-model calculations, it should not exceed 0.001).

It seems natural to calculate isomeric ratios on the basis of a model that would describe well the proper-

[1]Institute for Nuclear Research and Nuclear Energy, Blvd. Tsarigradsko chausse 72, BG-1784 Sofia, Bulgaria.

[2]State University of Idaho, USA.

[3]Hilendarski University, Plovdiv, Bulgaria.

Table 1. Spectroscopic features of nuclei under study

Nucleus	Ground state				Isomeric state			
	$T_{1/2}$	E_γ, keV	I_γ, %	α	$T_{1/2}$	E_γ, keV	I_γ, %	α
^{135}Xe	9.1 h	249.8	93	0.076	15.3 min	526.6	81	0.24
^{137}Ba	Stable				2.55 min	661.6	90	0.11
^{139}Ce	138 d	165.8	80	0.25	56.8 c	754.2	93	0.08
^{141}Nd	2.5 h	1127	0.75	0.002	62.0 d	756.7	92	0.09
^{143}Sm	8.8 min	1056	2.0	0.003	66.0 d	754.0	90	0.11

ties of levels in the excitation-energy range between the isomeric state and the neutron binding energy. For one, this is the quasiparticle–phonon model that was developed by V.G. Soloviev and his colleagues [8–12] and which was successfully used to describe the spectroscopic properties of a wide range of nuclei and nuclear reactions, including those that lead to the excitation of isomeric states [13, 14].

The objective of the present study is to measure isomeric ratios in nuclei having similar properties but in strongly different reactions and to calculate isomeric ratios on the basis of the quasiparticle–phonon model. Our investigation was performed for nuclei that have one hole in the filled neutron shell $N = 82$ (^{135}Xe, ^{137}Ba, ^{139}Ce, ^{141}Nd, ^{143}Sm) and which are produced in the relevant reactions of radiative thermal-neutron capture, (n, γ); photonuclear reactions involving the emission of one neutron, (γ, n), in the giant-dipole-resonance region; and in β^+ decay.

Available experimental data on the isomeric ratios for these nuclei show sizable scatter in the (γ, n) reactions, although these reactions have similar properties. Specifically, the isomeric ratios are much less for ^{141}Nd and especially for ^{143}Sm than for ^{137}Ba and ^{139}Ce [15, 16]. These distinctions are at odds with the results of the calculations according to the statistical model with the values adopted there for the parameters a and σ. In order to achieve agreement, one has to use strongly different values of these parameters for each group of nuclei, but this cannot be reasonably explained.

A totally different type of variation in isomeric ratios is observed for the (n, γ) reactions as one goes over from one nucleus to another: the lightest nucleus ^{135}Xe has the smallest isomeric ratio, and the isomeric ratio grows with increasing atomic number Z [17].

In order to study more comprehensively the behavior of isomeric ratios in the aforementioned region of nuclei, the accuracy of previous measurements was considerably improved: the uncertainties were reduced to 10% for all absolute values of the isomeric ratios and to 5% the for relative ones. This was achieved by using samples enriched in the isotope under study, by more thoroughly calibrating the efficiency of the gamma-radiation detector, and by performing all measurements under identical conditions with a reduced background level.

In addition to measuring isomeric ratios in (n, γ) and (γ, n) reactions, we have also determined the probabilities of isomeric-state excitation in β^+ decay. In the heavy nuclei ^{139}Ce, ^{141}Nd, and ^{143}Sm, there are no direct beta transitions to isomeric states. At the same time, a high beta-decay energy leads to the population of a wide set of nuclei that is comparable with its analog in the (γ, n) reactions. It is the cascade of gamma transitions from these levels that leads to the population of the isomeric state.

SPECTROSCOPIC FEATURES OF THE NUCLEI UNDER INVESTIGATION

The nuclei under investigation have a comparatively simple and nearly identical spectrum of low-lying excitations. All single-particle states following from the shell model ($2d_{3/2}$, $3s_{1/2}$, $2h_{11/2}$, $2d_{5/2}$, $1g_{7/2}$) [8, 18] lie in the energy region extending up to 1.4 MeV. The spin–parity of these nuclei in the ground state is $3/2^+$, while the spin–parity in the first excited state is $1/2^+$. As to $J^\pi = 5/2^+$ and $7/2^+$ single-particle states, they lie much higher (in the energy range 1.1–1.3 MeV). Radiative transitions from all these levels (of the $M1$ or the $E2$ type) lead only to the ground state—they do not populate the isomeric level. It is populated from higher states of spin–parity $J^\pi = 7/2^-, 9/2^-$, or $9/2^+$.

There are $J^\pi = 11/2^-$ isomeric states in a large number (more than 50) of nuclei from Zr ($Z = 40$) to Yb ($Z = 70$). All these states have close values of the magnetic moment (about half the value computed on the basis of the Schmidt model [19]) and of the reduced probabilities of $M4$ radiative transitions from the isomeric level to the $3/2^+$ ground state (1 to 2 Weisskopf single-particle units). All this suggests the presence of small admixtures of other configurations, although the nuclei involving isomers are

substantially different (ranging from nuclei having a closed proton shell and a nearly closed neutron shell to nuclei from the transition region between spherical nuclei and deformed ones). In the nuclei under investigation, isomeric levels lie comparatively high—from 527 keV in ^{135}Xe to 757 keV in ^{141}Nd. The energies of the isomeric states in question correspond to the energies of gamma rays emitted in their deexcitation (see Table 1).

Table 1 displays the features of the radiative decays of the nuclei under investigation in the ground and isomeric states: the half-lives $T_{1/2}$, the energies $E\gamma$ and the intensities $I\gamma$ of the gamma lines, and the total internal-conversion coefficients α [18]. These data were used to identify product nuclei and to determine their yields.

Data on the statistical properties of the excited states of the nuclei being discussed are much more scanty. By analogy with neighboring nuclei for which the mean spacings between neutron resonances were measured, we can assume that the level-density parameter a and the spin-cutoff parameter σ are about 15 to 20 and 4 to 5, respectively.

EXPERIMENTAL PROCEDURE

Measurements of isomeric ratios in (n, γ) and (γ, n) reactions were performed at the MT-25 microtron installed at the Flerov Laboratory of Nuclear Reactions (Joint Institute for Nuclear Research, Dubna). The description of the microtron and its basic parameters can be found in [20, 21]. An accelerated electron beam served as a source of both bremsstrahlung photons and neutrons.

For a braking target, we used a tungsten disk 2 mm thick followed by a 30-mm-thick aluminum absorber of electrons. A typical electron current during the experiment was 20 μA, the corresponding intensity of bremsstrahlung that had an energy above the (γ, n) threshold and which was incident on a target being about 10^{13} s^{-1}. The maximum energy of the accelerated electrons was 25 MeV; it could be reduced by implementing a transition to a different orbit or by changing a magnetic field. The bremsstrahlung spectrum had a typical shape; its calculation for the conditions of the present experiment (tungsten-disk thickness, solid angle covered by the irradiated sample) is described in [22].

In order to obtain neutrons, an electron beam was directed onto a cylindrical converter made from uranium and surrounded by beryllium. This converter was arranged within a graphite cube of side length 120 cm that served as a moderator for neutrons. The (γ, n) and (γ, f) reactions on uranium and the (γ, n) and $(n, 2n)$ reactions on beryllium were used to produce neutrons. At an electron energy of 25 MeV and an electron current of 20 μA, the thermal-neutron flux at the cube center was 4×10^8 s^{-1} cm^{-2}, the cadmium ratio being 1.8.

The samples subjected to irradiation consisted of the oxides of the elements being investigated (BaO, Ce_2O_3, Nd_2O_3, Sm_2O_3). They had a weight of 200 mg and an area of 1.5×1.5 cm and were packed in thin envelopes of Dacron (20 μm thick). Use was made of both samples of natural isotopic composition and samples enriched in the isotopes being studied (^{136}Ba enriched to 95%, ^{138}Ce enriched to 60%, and ^{144}Sm enriched to 90%). When irradiated, noble gases enriched in the isotopes ^{134}Xe (to 90%) and ^{136}Xe (to 95%) were in quartz-glass ampules of volume about 1 cm^3 at a pressure of 1 atm.

The time of sample irradiation was determined by the half-lives of reaction products. It was about three half-lives for $T_{1/2} < 1$ h and 3 to 4 h for $T_{1/2} > 1$ h. After irradiation, the samples were transported to a room shielded from the radiation of the accelerator, where their gamma-ray spectra were measured. For these measurements, we used a Ge(Li) detector having a volume of 60 cm^3 and a resolution of 2.8 keV for the 1332-keV γ line of ^{60}Co. The measured spectra were processed with the aid of the ACTIV code [23], which makes it possible to separate, in a complex spectrum, γ lines close in energy. The reaction products were identified on the basis of the energies of the γ lines and the time dependence of their intensities (these features of radioactive decay are quoted in Table 1). The absolute intensities of these γ lines (more precisely, their absolute values corrected for the efficiency ε of gamma-radiation detection, the internal-conversion coefficient α, the fraction k of a given γ line in the spectrum, accumulation over the irradiation time t_1, and decay over the time interval t_2 prior to measurements) make it possible to determine the reaction yield

$$Y = \frac{S\lambda(1+\alpha)(1-e^{-\lambda t_1})e^{-\lambda t_2}}{t_3 \varepsilon k}, \qquad (1)$$

where S is the area of the γ line after the background subtraction, λ is the radioactive-decay constant ($\lambda = 0.69/T_{1/2}$), and t_3 is the measurement time. This yield is related to the reaction cross section Σ by the equation

$$Y = A\Sigma I, \qquad (2)$$

where A is the number of atoms of the isotope under investigation in the irradiated sample and I is the flux of bombarding particles (neutrons or photons) that is integrated over the irradiation time. An isomeric ratio (IR) measured experimentally, which is defined as the ratio of the cross sections for the production of

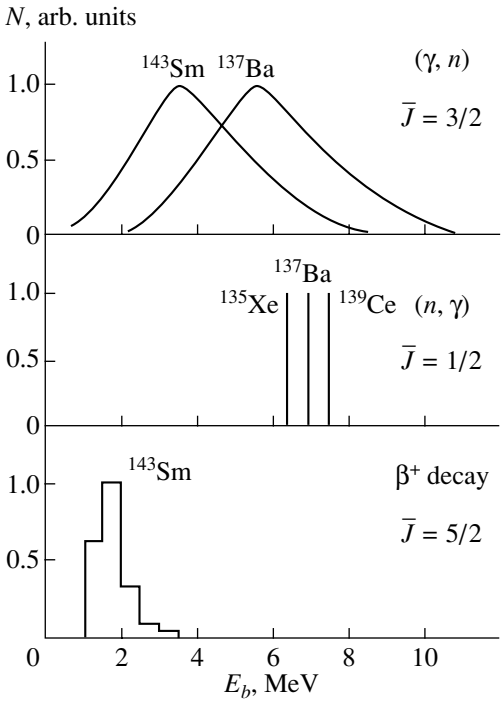

Fig. 1. Excitation-energy distributions of nuclei prior to the gamma-ray cascade in (γ, n) and (n, γ) reactions and in β^+ decay.

a nucleus in the isomeric and in the ground state, can be replaced by the ratio of the corresponding yields, since the measurements were performed for same target and within the same irradiation run; that is,

$$\mathrm{IR} = \frac{\Sigma_i}{\Sigma_g} = \frac{Y_i}{Y_g}, \qquad (3)$$

where the subscripts i and g label quantities referring to the isomeric and the ground state, respectively.

EXPERIMENTAL RESULTS

On the basis of the measurement and data-processing procedures outlined above, we determined isomeric ratios in reactions of three types.

(i) In the reactions of radiative thermal-neutron capture by ^{134}Xe, ^{136}Ba, and ^{138}Ce isotopes, compound nuclei had an excitation energy equal to the corresponding neutron binding energy (see Table 2) and the spin–parity of $J_c^\pi = 1/2^+$. The isomeric states were populated by a gamma-ray cascade, while the isomeric ratios are given by expression (3). The ground-state nucleus produced in the reaction ^{136}Ba$(n, \gamma)^{137}$Ba is stable. In order to obtain the relevant isomeric ratio, we therefore used the value of Σ_g known from [17] and determined Σ_i from a comparison with the well-known cross section for the reaction ^{65}Cu$(n, \gamma)^{66}$Cu [17].

(ii) For photonuclear reactions involving the emission of one neutron at the electron energy (endpoint energy of the bremsstrahlung spectrum) of 25 MeV, we have measured the isomeric ratios for all five nuclei quoted in Table 1. In these reactions, compound nuclei are produced with the spin–parity of $J_c^\pi = 1^-$ and the energy equal to the absorbed-photon energy. Since the bremsstrahlung spectrum and the spectrum of emitted neutrons are both continuous, the product nuclei are characterized by a rather wide excitation-energy distribution, which is given by

$$Y(E_b) = \int_0^{E_0} \int_0^{E_0 - B_n} \sigma(E_\gamma) N(E_\gamma) W(E_n) dE_\gamma dE_n, \quad (4)$$

where E_b is the excitation energy of the final nucleus, B_n is the neutron binding energy in the compound nucleus, $\sigma(E_\gamma)$ is the cross section for the absorption of a photon of energy E_γ, $N(E_\gamma)$ is the number of photons of energy E_γ in the bremsstrahlung spectrum with endpoint energy E_0, and $W(E_n)$ is the probability of the emission of a neutron of kinetic energy E_n from the compound nucleus. In order to calculate these distributions, we used the energy dependences of the cross sections for monochromatic-photon absorption from [24], the kinetic-energy spectra of neutrons from [25], and the bremsstrahlung spectrum computed in [22] for the conditions of the present experiment. Some examples of these distributions are presented in Fig. 1, while the mean excitation energies of the final nuclei for all reactions considered here are quoted in Table 2.

Since, for the relevant (γ, n) reactions, it is not the cross section but the yield integrated over the bremsstrahlung spectrum that is measured experimentally, the isomeric ratio is determined as the yield ratio

$$\mathrm{IR} = \frac{\int_{E_1}^{E_0} \sigma_i(E_\gamma) N(E_\gamma) dE_\gamma}{\int_{E_1}^{E_0} \sigma_g(E_\gamma) N(E_\gamma) dE_\gamma}, \qquad (5)$$

where E_1 is the threshold for the reaction leading to the production of a nucleus in the ground or in the isomeric state. We have $E_1 = B_n$ for the ground state and $E_1 = B_n + E_i$ for the isomeric state.

Just as in the case of (n, γ), a direct measurement of the yield of the stable final nucleus ^{137}Ba was impossible. For this reason, the relevant isomeric ratio was determined from a comparison of the yields of the ^{137}Ba and ^{139}Ce isomers and the known ^{138}Ba(γ, n) and ^{140}Ce(γ, n) cross sections integrated over the bremsstrahlung spectrum [24].

Table 2. Experimental and calculated values of the isomeric ratios for (γ, n) and (n, γ) reactions and for beta decay

Reaction	$\bar{E}_b$, MeV	$\bar{J}$, $\hbar$	Isomeric ratios	
			experiment	calculation
^{134}Xe$(n, \gamma)^{135}$Xe	6.45	1/2	0.013(2)	0.023*
^{136}Xe$(\gamma, n)^{135}$Xe	6.1	3/2	0.110(9)	0.11**
^{136}Ba$(n, \gamma)^{137}$Ba	6.90	1/2	0.022(3)	0.024*
^{138}Ba$(\gamma, n)^{137}$Ba	5.4	3/2	0.120(8)	0.10**
^{138}Ce$(n, \gamma)^{139}$Ce	7.47	1/2	0.025(3)	0.027*
^{140}Ce$(\gamma, n)^{139}$Ce	4.8	3/2	0.130(8)	0.11**
$^{139}\mathrm{Pr} \xrightarrow{\beta^+} {}^{139}\mathrm{Ce}$	1.6	5/2	0.008(2)	0.007**
^{142}Nd$(\gamma, n)^{141}$Nd	4.2	3/2	0.060(6)	0.05**
$^{141}\mathrm{Pm} \xrightarrow{\beta^+} {}^{141}\mathrm{Nd}$	2.1	5/2	0.009(2)	0.010**
^{144}Sm$(\gamma, n)^{143}$Sm	3.5	3/2	0.046(5)	0.05**
$^{143}\mathrm{Eu} \xrightarrow{\beta^+} {}^{143}\mathrm{Sm}$	2.2	5/2	0.007(2)	0.007**

* Calculations according to the statistical model.
** Calculations according to the quasiparticle–phonon model.

(iii) In determining the isomeric ratios for the β^+ decay of and for electron capture by ^{139}Pr ($T_{1/2} = 4.4$ h, $Q_\beta = 2.80$ MeV, $J^\pi = 5/2^+$) and ^{141}Pm ($T_{1/2} = 20.9$ min, $Q_\beta = 4.56$ MeV, $J^\pi = 5/2^+$) nuclei, we obtained them in the reactions ^{141}Pr$(\gamma, 2n)^{139}$Pr ($E_{\gamma 0} = 25$ MeV) and ^{141}Pr$(\alpha, 4n)^{141}$Pm ($E_\alpha = 38$ MeV), respectively, at the MT-25 microtron and the U-200 isochronous cyclotron of the Flerov Laboratory of Nuclear Reactions (JINR, Dubna). By using the experimental facility described above, we have measured the spectra of gamma radiation emitted in the beta decay of ^{139}Pr and ^{141}Pm nuclei. The by-products of the photon- and alpha-particle-induced reactions (^{140}Pr, ^{142}Pm, ^{143}Pm) had significantly different half-lives, and their gamma radiation could easily be discriminated.

An analysis of the spectra of gamma radiation from ^{139}Pr and ^{141}Pm enabled us to determine the probabilities of the population of isomers in the daughter nuclei ^{139}Ce and ^{141}Nd. In this analysis, we also used data on the β^+ decay of these isotopes [18] and of ^{143}Eu, the isomer in the ^{143}Sm nucleus being excited in the last case [26]. By analogy with the (n, γ) and (γ, n) reactions considered above, we also evaluated isomeric ratios in beta decay, determining them as the ratios of the numbers of nuclei produced in the isomeric state to the number of beta transitions to all levels above the isomer:

$$\mathrm{IR} = \frac{N_i}{\sum N_\beta(E_b > E_i)}. \qquad (6)$$

By way of example, one excitation-energy distribution of nuclei originating from β^+ decay (for ^{143}Sm) is displayed in Fig. 1. Because of a finite and comparatively small number of beta transitions, a histogram is presented here instead of a continuous distribution. For the remaining nuclei (^{139}Ce, ^{141}Nd), the analogous distributions have a similar shape. In relation to the corresponding distributions for the relevant (γ, n) reactions, the distributions being discussed are narrower and are shifted toward lower energies.

The isomeric-ratio values measured in this way for all reactions studied here are presented in Table 2, along with the features of final nuclei (mean excitation energies $\bar{E}_b$ and mean angular momenta $\bar{J}$) before the gamma-ray cascade leading to the isomeric or the ground state. Within the combined errors, these isomeric-ratio values agree with the known data from [15–17], but, as was noted above, the former are characterized by a higher accuracy; as a result, we can now draw more reliable conclusions about the distinctions between the isomeric ratios for different nuclei and different reactions for their production.

DISCUSSION OF THE RESULTS

From Table 2 and from Fig. 1, we can see that the conditions of isomer excitation are different in different processes. In beta-decay processes, the cascade of gamma rays begins from a comparatively narrow range of low-lying levels (1.5–3.0 MeV), whose mean angular momentum (5/2) is higher than in other processes. The situation is totally different in the relevant (n, γ) reactions—the excitation energy is the highest

(6.5–7.5 MeV), while the angular momentum is the lowest (1/2). In this respect, the (γ, n) reactions in question occupy an intermediate position—they are characterized by the greatest scatter of excitation energies and angular momenta. This variety of nuclear features leads to considerable distinctions between isomeric ratios and makes it possible to obtain comprehensive information about the spectrum of levels through which the isomers are populated.

An analysis of the spectrum of gamma radiation emitted in the beta decay of ^{139}Pr, ^{141}Pm, and ^{143}Eu revealed that, in all cases, the isomers are populated by radiative $E2$ transitions through $J^\pi = 7/2^-$ levels that are excited immediately after the relevant beta transitions. In the ^{139}Ce (^{141}Nd) nucleus, the isomer is populated through the single $7/2^-$ level at 1.578 (1.420) MeV, while, in the ^{143}Sm nucleus, this occurs through three levels at 1.310, 2.886, and 3.325 MeV. In these three nuclei, the isomeric ratios have close values and are determined primarily by the probabilities of the beta transitions to the $7/2^-$ levels involved.

In the (n, γ) reactions, a sufficiently long cascade of gamma transitions (not less than three) is required for populating the isomer because the spin difference between the compound nucleus and the isomer is large ($\Delta J = 5$). A wide energy gap between the initial level and the isomer (more than 6 MeV) favors the development of such a cascade and makes it possible to calculate the isomeric ratios on the basis of the statistical model. The calculations for this case were performed with the aid of the EMPIRE code [27]. At the parameter values of $a = 18$ and $\sigma = 4.5$, the isomeric ratios calculated in this way are presented in Table 2. Good agreement is seen to be obtained for ^{137}Ba and ^{139}Ce, whence we conclude that, in the (n, γ) reactions, the statistical model is applicable to these nuclei. However, an analysis of gamma radiation emitted in thermal-neutron capture by a ^{136}Ba nucleus [28] has revealed that about half of the contribution to the relevant isomeric ratio comes from a single gamma-ray cascade through ^{137}Ba levels:

$$6.605\ \text{MeV}(1/2^+) \xrightarrow{E1} 2.182\ \text{MeV}(3/2^-)$$
$$\xrightarrow{E2} 1.798\ \text{MeV}(7/2^-) \xrightarrow{E2} 0.661\ \text{MeV}(11/2^-).$$

This gamma-ray cascade indicates that specific states through which the isomer is populated may play an important role in the (n, γ) reactions, as they do in beta decay.

In the (γ, n) reactions, spin-1/2 to spin-9/2 levels that lie in a broad range of excitation energies (Fig. 1) are populated following neutron evaporation. It is the properties of these levels that determine the probability of isomer excitation. They have a complicated structure—their single-particle and collective components are fragmented over a wide energy interval and undergo strong fluctuations. To describe them, it is therefore desirable to use some effective approach. We will invoke an approach based on the aforementioned quasiparticle–phonon model [8–12], which was successfully used to describe a number of nuclear phenomena.

CALCULATION OF ISOMERIC RATIOS WITHIN THE QUASIPARTICLE–PHONON MODEL

For many nuclei, the spectra of excited states in a broad range of excitation energies and their reduced the widths with respect to the radiative transitions from them to the isomeric and the ground state in each nucleus being considered have been calculated within this model; in addition, so-called activation states—that is, states from which isomeric levels are populated as the result of gamma decay—have been singled out on the same basis. In these calculations, both the ground state and excited states characterized by an angular momentum J and its projection M were described in terms of the wave function

$$\Psi^\nu_{JM} = C^\nu_J\{\alpha^+_{JM} + \sum_{\lambda JM} D^{\lambda i}_j(J\nu)[\alpha^+_{jm}Q^+_{\lambda\mu i}]_{JM}\Psi_0\}, \quad (7)$$

where α^+_{jm} is the creation operator for a quasiparticle having the shell quantum numbers j and m; $Q^+_{\lambda\mu i}$ is the creation operator for a phonon having an angular momentum λ, its projection μ, and a number i; Ψ_0 is the wave function for the neighboring even nucleus; and ν is the ordinal number of an excited state in the sequence of states characterized by given J^π. The coefficients C^λ_j and $D^{\lambda i}_j$ are the quasiparticle and the quasiparticle–phonon amplitudes for ν states. The calculations performed with the wave functions (7) are described in detail elsewhere [12, 29].

In the calculations described below, the Woods–Saxon potential with the parameters set to the values from [30, 31] was used for that part of the Hamiltonian which describes the mean field. The strength of the residual interaction was chosen in such a way as to reproduce, in the one-phonon approximation, the experimental values of the energies and reduced probabilities of low-lying collective states in the neighboring even–even nuclei [32]. The wave functions used in our calculations took into account the $\lambda^\pi = 1^\pm$, 2^+, 3^-, 4^+, and 5^- phonons. We employed the effective charges $e_p = (N/A)e$ and $e_n = -(Z/A)e$ for $E1$ transitions and the effective charges $e_p = e$ and $e_n = 0$ for $E2$ transitions. The contribution of electromagnetic transitions of other multipole orders to the processes being considered is negligible.

We have calculated the spectrum of $J^\pi = 1/2^\pm$, $3/2^\pm$, $5/2^\pm$, $7/2^\pm$, $9/2^\pm$, and $11/2^\pm$ excited states up to the excitation energy of 6.5 MeV and their structure. The $1h_{11/2}$ isomeric state is faithfully reproduced in these calculations for all isotones being considered: the deviations from the experimental energy values did not exceed 40 keV. The wave functions are dominated by the single-quasiparticle component (its weight is above 80%).

In calculating the isomeric ratios, we assumed that the isomers are populated by radiative transitions from the $J_i^\pi = 7/2^-$ ($E2$ transitions), $9/2^+$ ($E1$ transitions), and $9/2^-$ ($M1$ transitions) levels. The spectrum of activated levels, together with the calculated reduced widths, is presented in Fig. 2 for the ^{139}Ce nucleus. For the other $N = 81$ isotones being considered, the corresponding spectra are very similar. The ground state is predominantly populated by transitions proceeding from $J_i \leq 5/2$ levels.

Since, following beta decay, the nuclear excitation energy does not exceed 3.0 MeV (Table 2), the population of the isomer in this reaction is due exclusively to the $J_i^\pi = 7/2^-$ excited state at an excitation energy of about 1.5 MeV (Fig. 2). Here, the absolute value of the isomeric ratio is determined, to a considerable extent, by the probability of the population of levels in the daughter nucleus formed upon beta decay. These probabilities were computed by using the initial- and final-state wave functions. Since, in the nuclei being considered, beta decay populates predominantly $J_i^\pi \leq 5/2^+$ levels, which then decay into the ground state, the absolute value of the isomeric ratio is quite modest (see Table 2). Small variations in its magnitude in the ^{139}Ce, ^{141}Nd, and ^{143}Sm nuclei are associated with the details of the nuclear-structure calculations.

The number of activation states involved in the population of the isomer in the (γ, n) reaction, where the daughter nucleus formed upon the decay of the giant dipole resonance has an excitation energy of up to about 6 MeV, is much greater (Fig. 2). The mechanism of ground-state and isomer population in this reaction was considered in detail elsewhere [33]. The isomeric ratio is given by

$$\mathrm{IR} = \frac{\sum\limits_{J_i^\pi}(2J_i+1)T_{l_j}(\varepsilon)\sum\limits_\nu (C^\nu_{J_i^\pi})\Gamma^\nu_{J_i^\pi\to\mathrm{is}}}{\sum\limits_{J_i^\pi}(2J_i+1)T_{l_j}(\varepsilon)\sum\limits_\nu (C^\nu_{J_i^\pi})\Gamma^\nu_{J_i^\pi\to\mathrm{gs}}}, \qquad (8)$$

where T_{l_j} is the transmission coefficient for a neutron of orbital angular momentum l_j; J is the total angular momentum of the nucleus following neutron emission; $C^\nu_{J^\pi}$ are the spectroscopic factors for the states of spin–parity J^π; and $\Gamma_{J^\pi\to\mathrm{is}}$ and $\Gamma_{J^\pi\to\mathrm{gs}}$ are the partial widths of intermediate-energy states with respect to gamma decay into, respectively, the isomeric and the ground state. In the calculations, it was assumed that an emitted neutron of medium energy can carry away angular momenta of 0, 1, 2, and 3 (this determines the set of final-nucleus spins). The isomeric ratios calculated in this way are displayed in Table 2. The agreement with experimental data is seen to be good. A drop in the isomeric ratio when we go over to ^{143}Sm and ^{141}Nd is explained by the fact that, because of a higher neutron binding energy in the initial nucleus in heavier isotones, a smaller number of $7/2^-$, $9/2^+$, and $9/2^-$ activation levels are populated in the final nucleus.

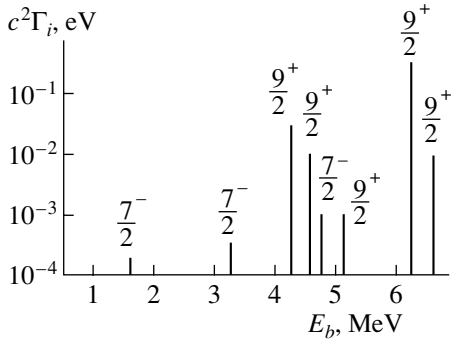

Fig. 2. Calculated reduced widths of ^{139}Ce nuclear levels from which radiative transitions lead to the isomeric state.

The above calculations were performed under the assumption that the direct decay of intermediate-energy states into the ground and the isomeric state dominates over cascade transitions. This assumption is justified at modest excitation energies of the nucleus, in which case the density of excited levels is low and the phase space for possible cascades is severely constrained. That the calculated isomeric ratios are in good agreement with experimental data obtained in the (γ, n) reactions proves the applicability of this assumption up to excitation energies of about 6 MeV. However, the population of isomers in the $N = 81$ isotones in the (n, γ) reactions cannot be explained without taking into account cascade transitions. In these reactions, the spin of the daughter nucleus formed upon thermal-neutron capture is 1/2, and isomer generation requires an angular-momentum transfer of 5—that is, a cascade of not less than three to four gamma transitions. This is the reason why, in particular, the isomeric ratios obtained in the (n, γ) reactions for the set of nuclei under investigation are much less than in the (γ, n) reactions, where the averaged angular momentum of states populated in dipole-resonance decay is 3/2 and where the $7/2^-$, $9/2^+$, and $9/2^-$ levels can be populated upon neutron emission as well.

If one aims at considering cascade transitions within a microscopic approach, the requirements for

the accuracy in describing the details of the structure of excited states at intermediate excitation energies are much more stringent than those for direct transitions to the ground and to the isomeric state. In this case, the description of excited states up to the neutron-separation energy in terms of the wave function (7) is by far insufficient—it must additionally include at least *quasiparticle plus two phonons* and *quasiparticle plus three phonons* terms, and the calculations must be performed without a radical truncation of the basis. Fulfillment of these requirements leads to a configuration space where a diagonalization of the model Hamiltonian presents, at the moment, serious technical difficulties. For the sake of comparison, the isomeric ratios computed for the (n, γ) reactions within the statistical approach at the above values of the parameters a and σ are therefore quoted in Table 2. The calculated isomeric ratio for the ^{135}Xe nucleus below the experimental value admits a natural explanation, because the neutron binding energy is lower in this nucleus. As can be seen from the calculations based on the quasiparticle–phonon model, a smaller number of activation states is therefore involved in the population of the isomeric state.

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