α, β, and γ transitions accompanied by changes in the nuclear shape

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The probabilities of α, β, and γ transitions accompanied by changes of the nuclear shape are analyzed. Three regions in which such transitions can occur are considered: transitional nuclei, rotational bands in spherical nuclei, and spontaneously fissile isomers. In the first two regions, the change in the deformation of the nucleus has a weak influence on the transition probability, whereas these transitions are strongly forbidden in the decay and population of spontaneouly fissile isomers.

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INTRODUCTION

A nucleus has a complicated shape of the distribution of charge and nuclear matter. The majority of nuclei have nonzero quadrupole moments; elastic and inelastic scattering of particles on nuclei can be described correctly only with a complicated nuclear potential. The shape of such nuclei can be described by means of the expression

$$R(\vartheta)=R_0(1+\beta_2Y_2(\vartheta)+\beta_4Y_4(\vartheta)+\ldots), \quad (1)$$

where R_0 is the radius of the spherical nucleus; $Y_n(\vartheta)$ are spherical harmonics; β_n is the deformation parameter of n-th order.

For the majority of nuclei, the quadrupole deformation parameter is decisive, reaching values of 0.2-0.3. However, the deformation parameters of higher orders have nonzero values. For example, for the isotope ^{238}U experiments on the inelastic scattering of α particles have yielded $\beta_2=0.23$, $\beta_4=0.055$, and $\beta_6=-0.018$ (Ref. 1). In some cases, to describe the spectra of excited states it is necessary to assume a departure of the nuclear shape from axial symmetry.

The shape of a nucleus may change when the numbers of protons and neutrons change, and also as a result of excitation. Transitions between states with different nuclear shapes will have a number of particular features. Because the wave functions of the initial and final states overlap less strongly, the transitions will be hindered. One will expect this effect to be the greater, the greater is the difference in shape of the two states. However, the actual situation in a nucleus may be much more complicated. As a rule, states with different shapes also have different structures. These changes of the structure accompanying the transitions lead to various selection rules. The best known are those associated with a change of the orbital angular momentum, the number and position of unpaired quasiparticles, the quantum number K (the projection of the spin onto the symmetry axis of the nucleus), and other asymptotic quantum numbers. Virtually all transitions associated with a change in the nuclear shape are subject to corresponding hindrance factors. For a definite transition, it is usually impossible to separate clearly the hindrances associated with the change in the shape of the nucleus from other factors. It is necessary to analyze a large body of experimental material in order to distinguish the effects.

Hitherto, quadrupole deformation of nuclei has been the best studied. There is much experimental material on the quadrupole moments of the ground and excited states of nuclei.[2-5] From inelastic scattering experiments one can also obtain fairly definite information about the sign and value of the quadrupole deformation of a nucleus.[6] There are entire regions of nuclei whose shape can be represented as an ellipsoid with semi-axis ratio 2:3. The lowest excited states correspond to rotation of such a nucleus, and the probabilities of transitions between the rotational states are determined by the intrinsic quadrupole moment of the nucleus.

At the same time, information on the deformation parameters of higher order is much sparser. Only a comparatively small number of nuclei have had their hexadecapole deformation parameters determined (through the inelastic scattering of charged particles,[7-9] and also by measurement of the transition energies in μ-mesic atoms[10]). Therefore, in the present review we give experimental data on α, β and γ transitions associated with a change in the quadrupole deformation of the nucleus. We consider three regions of nuclei in which there are such transitions:

1) the transitional nuclei between those that are definitely deformed and the spherical nuclei;

2) rotational bands in spherical nuclei;

3) spontaneously fissile isomers.

We analyze the dependence of the reduced transition probability (or the reduced width), which does not depend on the transition energy, on the change in the quadrupole deformation parameter β_2 of the nucleus. This last can be determined from the intrinsic quadrupole moment Q_0 under the assumption that the nucleus is an ellipsoid of revolution:

$$Q_0=\frac{3}{\sqrt{5\pi}}ZR_0^2\beta_2(1+0.16\beta_2+\ldots), \quad (2)$$

where Z and R_0 are the charge and radius of the nucleus. This assumption means that in the expression (1) that describes the shape of the nucleus all the β_n except β_2 are zero.

1. TRANSITIONAL NUCLEI

There are well known regions (for example, $A\geqslant 220$ or $150\leqslant A\leqslant 190$) in which the nuclei have a static equil-

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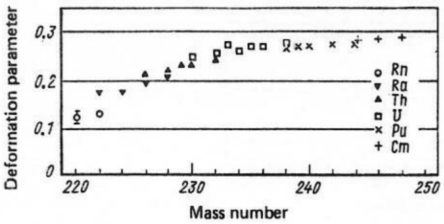

FIG. 1. Quadrupole deformation parameter as function of the mass number for nuclei with $A = 220–248$.

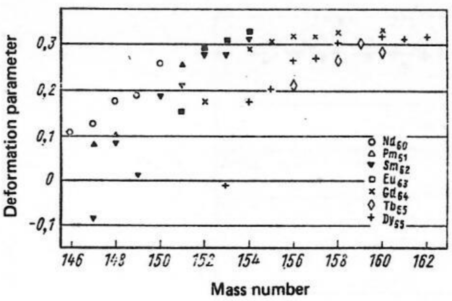

FIG. 3. Quadrupole deformation parameter as function of the mass number for nuclei with $A = 146–162$.

ibrium deformation. The transition from the deformed shape to spherical shape occurs in some cases rather abruptly (for example, at the neutron number 90), but in other cases more smoothly. In Figs. 1–3, we have plotted the quadrupole deformation parameter β_2 as a function of the mass number for nuclei on the boundaries of the above regions. The values of β_2 were obtained by means of the expression (2). For the majority of nuclei, the intrinsic quadrupole moments were determined by the experimentally measured reduced probabilities of transitions between levels of the rotational band:

$$B(E2I_i \to I_f) = \frac{5}{16\pi} e^2 Q_0^2 \langle I_i K 20 \mid I_f K \rangle, \quad (3)$$

where I_i and I_f are the spins of the initial and the final state; K is the spin projection onto the symmetry axis of the nucleus. In some odd nuclei, in which it is impossible to distinguish the levels of the rotational band, the spectroscopic quadrupole moment, which is determined by the interaction of the nucleus with the gradient of an external electric field, was used. The spectroscopic moment is related to the intrinsic moment by

$$Q_s = Q_0 I (2I-1)/[(I+1)(2I+3)]. \quad (4)$$

For a number of the nuclei in Figs. 1–3 the hexadecapole deformation parameter β_4 is known. Allowance for it slightly changes the value of β_2 (up to 10%). However, to be specific, we determined all of the β_2 values under the assumption $\beta_4 = 0$.

Nuclei in the region of $A = 220$ and 190 can undergo α decay; those in the region of $A = 150$, β decay. It can be seen from Figs. 1–3 that there is a whole series of α and β transitions for which the change in β_2 reaches ~0.1, i.e., 30–50% of its total value. It should be noted that the change in the static deformation may be even greater since the intrinsic quadrupole moment determined by the expression (3) may also reflect dynamical deformation of the nucleus. In Fig. 4 we represent the values of β_2 obtained from measurements of the lifetime of the first levels of even-even nuclei[4] and the spectroscopic moments (from an investigation of the reorientation effect in Coulomb excitation[5]). Whereas the two values of β_2 are equal for deformed nuclei (the deformation of the nucleus is static), on the transition to spherical nuclei the difference between the parameters is increased. This means that in transitional nuclei the static deformation is only part of the total.

α Decay. The probability of α decay is characterized by the reduced width δ_α^2, which does not depend on the energy of the α transition.[15] The dependence of the α width on the mass number for Rn, Ra, Th, Pu, U, and Cm isotopes (both even and odd) is shown in Fig. 5. The values of δ_α^2 were taken from Ref. 12 or calculated in accordance with the method described in this paper. It can be seen from Fig. 5 that for transitions without change of spin and parity the reduced α width is virtually the same for the Pu and Cm isotopes, in which there is no change in the deformation, as well as for the Th and Ra isotopes, for which the deformation parameter is reduced by 0.04–0.06 as a result of α decay. The situation is the same for odd-Z nuclei, which are not represented in Fig. 5. We conclude that these changes in the deformation of the nucleus do not significantly lower the reduced α width.

In the case of α transitions with a change in the spin and parity, the reduced α widths are naturally smaller. In Fig. 5, we show the α widths for transitions with $\Delta I = 2$ (without change of parity) and $\Delta I = 1$ (with change of parity). It can be seen that in this case, as one would expect, the α width is 100–1000 times smaller than for α transitions in even-even nuclei, and this ratio remains virtually the same for the whole of the considered region (irrespective of the change in the

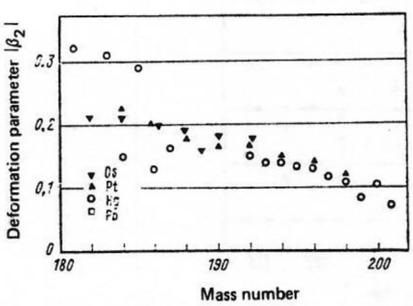

FIG. 2. Quadrupole deformation parameter as function of the mass number for nuclei with $A = 174–200$.

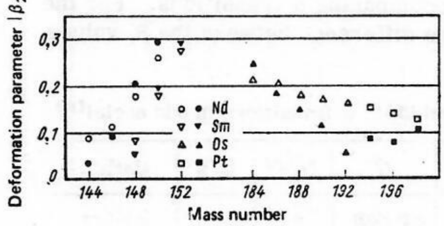

FIG. 4. Deformation parameters determined from level lifetimes (open points) and the effect of reorientation accompanying Coulomb excitation (solid points) for Nd, Sm, Pt, and Os isotopes.

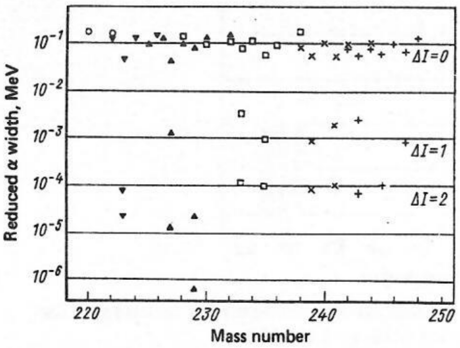

FIG. 5. Reduced α width as function of the mass number for nuclei with $A = 220-248$. The notation is the same as in Fig. 1.

deformation). However, for some nuclei, α transitions with $\Delta I=1$ or 2 have anomalously low (by 10^4-10^5 times) values of δ_α^2. All these transitions (attention was drawn to some of them by Geĭlikman[13]) are shown in Table I. Although the deformation parameters of some of the initial and all of the final states are unknown, it may be assumed that they correspond to the systematics of β_2 in Fig. 1. In this case, the change in β_2, as we have noted above, is 0.04–0.06, and it does not lead to an appreciable reduction in δ_α^2. The anomalously large suppression for the transitions in Table I is either due to the unusual shape of the final states or to the fact that the change in the deformation leads to an appreciable change in the structure of the final states. The latter is the more probable since an unusual shape of the states would also hinder transitions from these states, which is not observed (such states are not isomeric states).

The α width is shown as a function of the mass number for Pb, Hg, and Pt isotopes in Fig. 6. For this region of nuclei, there are fewer experimental results,[14,15] and therefore we consider only even-even nuclei. In contrast to the nuclei considered above with $Z=86-96$, in this region there is a much larger change in δ_α^2 (from 0.004 MeV for ^{186}Pb to 0.27 MeV for ^{174}Pt). At the same time, the behavior of the reduced α width is different for these elements: With decreasing A, the values of δ_α^2 decrease for the Pb isotopes, remain constant for the Hg isotopes, and increase for the Pt isotopes. This behavior of δ_α^2 can be explained by a change in the quadrupole deformation in this region of nuclei:

1) In the whole of the region of A, the Pb isotopes evidently have spherical shape. At the same time, the deformation increases in the Hg isotopes with decreasing A, and so therefore so does the difference in the deformations accompaning α transitions. For the α decay of ^{186}Pb, the difference between the β_2 values

TABLE I. Strongly forbidden α transitions in odd nuclei[10]

α transition	I_i^π	I_f^π	E_f, keV	I_α, %	$\delta_\alpha^2/(\delta_\alpha^2)_{r-r}$
^{229}Pa → ^{225}Ac	5/2+ [642]	3/2− [532]	0	<0.5	$<5\cdot10^{-4}$
	5/2+ [642]	3/2+ [651]	40	0.2	$3\cdot10^{-4}$
^{229}Th → ^{225}Ra	5/2+ [633]	3/2+	0	0.01	$6\cdot10^{-6}$
	5/2+ [633]	3/2+	42.8	0.24	$2\cdot10^{-4}$
^{227}Th → ^{233}Ra	3/2+ [631]	3/2−	50.2	$2.5\cdot10^{-3}$	10^{-4}
^{223}Ra → ^{219}Rn	7/2+	5/2+—9/2+	0	$8\cdot10^{-3}$	$5\cdot10^{-4}$
	7/2+	5/2+—9/2+	14.4	$3.2\cdot10^{-3}$	$1.5\cdot10^{-4}$

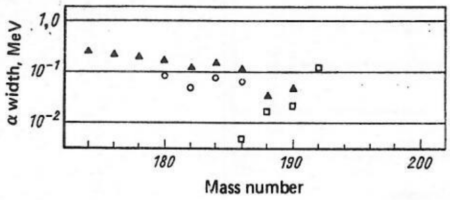

FIG. 6. Reduced α width as function of mass number for nuclei with $A = 174-200$. The notation is the same as in Fig. 2.

already reaches 0.20–0.25, and this may explain the reduced values of δ_α^2;

2) in the Pt isotopes, the deformation increases with decreasing A, as in the Hg isotopes. The difference of the deformations between the Pt and Hg isotopes changes little, and this leads to similar values of δ_α^2 for different A;

3) the Pt isotopes with $A=188$ and 190 have a smaller deformation than the Os isotopes, which are deformed nuclei. At $A=186$, there is a transition in the Pt isotopes to spheroidal shape, and therefore for $A \leqslant 186$ the difference of the deformations between the Pt and Os isotopes becomes small and this leads to an increase in the δ_α^2 values.

According to the theoretical calculations of Ref. 16, the Pt and Hg isotopes for $A > 186$ have oblate shape; for $A \leqslant 186$, prolate. At the same time, in the Pb and Os isotopes the sign of the deformation in this range of A does not change. If this is really the case, then the α decay of the Pb isotopes ($A \geqslant 190$) and Pt isotopes ($A \geqslant 188$) is accompanied by not only a change in the value of the deformation but also of its sign. However, it can be seen from Fig. 6 that at these values of A there is no appreciable change of the reduced α width.

Thus, despite the appreciable change in the quadrupole deformation parameter in this region of nuclei (by up to 0.20–0.25), the changes in δ_α^2 do not exceed 10–20.

β Decay. In nuclei with $A=145-155$, β decay may be accompanied by a change in the deformation. It can be seen from Fig. 3 that in some cases the quadrupole deformation parameters of neighboring nuclei between which the β transitions take place differ by 0.05–0.1. Berlovich[19] has already noted that such changes in β_2 may hinder β and γ transitions in this region of nuclei,

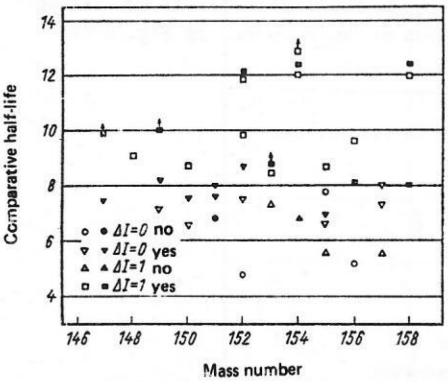

FIG. 7. Comparative half-life against β decay as a function of the mass number for nuclei with $A = 146-162$. The solid points correspond to $\Delta\beta_2 > 0.05$; the open, to $\Delta\beta_2 < 0.05$.

TABLE II. Comparative half-lives for β transitions to levels of the rotational band of even–even nuclei.

β transitions	I_i^π	β_2^i	β_2^f	lg $f\tau$		
				0+	2+	4+
$^{150}Eu \rightarrow ^{150}Sm$	(0−, 1−)	(0.15)	0.180±0.005	7.5	8.5	—
$^{150}Eu \rightarrow ^{150}Gd$			0.10±0.01	6.5	9.2	—
$^{152}Pm \rightarrow ^{152}Nd$	1+	(0.30)	(0.30)	4.8	—	—
$^{152}Pm \rightarrow ^{152}Sm$			0.285±0.005	6.5	—	—
$^{152}Eu \rightarrow ^{152}Sm$	3−	0.29±0.02	0.285±0.005	—	11.9	11.5
$^{152}Eu \rightarrow ^{152}Gd$			0.17±0.01	—	12.1	12.3
$^{152}Eu \rightarrow ^{152}Sm$	0−	(0.20)	0.285±0.005	8.6	8.5	—
$^{152}Eu \rightarrow ^{152}Gd$			0.17±0.01	7.5	8.4	—
$^{154}Eu \rightarrow ^{154}Sm$	3−	0.33±0.04	0.315±0.005	—	12.4	13.7
$^{154}Eu \rightarrow ^{154}Gd$			0.290±0.005	—	> 12.9	12.5
$^{158}Tb \rightarrow ^{158}Gd$	3−	0.26±0.04	0.325±0.005	—	12.4	12.1
$^{158}Tb \rightarrow ^{158}Dy$			0.295±0.006	—	12.0	12.7

Note. The values of β_2 estimated from the systematics (see Fig. 2) are given in parentheses.

as can be judged on the basis of Fig. 7. In it, we have systematized the values of the comparative half lives $f\tau$ in the range 146–160 of mass numbers[18-20] The complete set of $f\tau$ values is divided into two groups: In one, the change in the deformation parameter accompanying the β transition is greater than 0.05; in the other, it is less. In the cases when the deformation parameter is unknown, it was found by interpolating the known data (see Fig. 3) under the assumption of a smooth dependence of β_2 on A. This assumption may not be satisfied (especially for excited states), which lowers the reliability of the assignment of the $f\tau$ values to the one group or the other. However, there are few such cases and they cannot distort the general picture. It can be seen from Fig. 7 that β transitions accompanied by large changes in the deformation (solid points) have large values of $f\tau$. On the average, this excess for transitions with the same change in the spin and parity is about 10. At the same time, the $f\tau$ spread for transitions of one type exceeds this value. This may mean that the various selection rules associated with the change in the structure of the states influence the probability of β transitions more strongly than a change in the deformation of the nucleus.

The values of $\log f\tau$ for β decay of odd-odd nuclei to levels of the ground-state rotational band of two neighboring even-even nuclei having different deformations are given in Table II. In this case, the initial state is the same and the final states have nearly the same structure. Therefore, the influence of deformation on the probability of the β transition must be here more clearly manifested. It can be seen that for the β decay of the ^{152}Eu ground state to the 2^+ and 4^+ states of ^{152}Gd, when $\Delta\beta_2=0.12$, the values of $\log f\tau$ are higher respectively by 0.2 and 0.8 than for β transitions to the same levels of ^{152}Sm (in this case, β_2 is hardly changed). The opposite situation occurs for the β decay of the isomeric state of ^{152}Eu, which has a much smaller deformation. The values of $\log f\tau$ for transitions to the 0^+ and 2^+ levels of the strongly deformed nucleus ^{152}Sm are higher, respectively, by 1.1 and 0.1 than for transitions to the levels of the weakly deformed nucleus ^{152}Gd. However, it can be seen from Table II that similar differences of $\log f\tau$ are also observed in the cases when the β transitions to both nuclei are accompanied by a small (~0.03) change in the deformation parameter. This means that the change in the deformation of the nucleus has a small influence on the probability of β decay in the transitional nuclei.

γ Decay. In transitional nuclei, one observes a whole series of excited states whose deformation differs significantly from that of the ground state. In some cases, this deformation is measured, for example, in ^{149}Sm, by the spectroscopic quadrupole moment,[2] while in ^{151}Eu it is measured from the isomeric shift in a μ-mesic atom.[24] In the remaining cases, the change in the deformation can be deduced from indirect data: the cross sections of the (t, p) or (p, t) reactions, the moment of inertia of the nucleus in an excited state (these data were obtained for the ^{150}Sm and ^{152}Sm isotopes[2,22] and the ^{151}Eu isotopes[23]). The quadrupole deformation parameters for the ground and excited states of such nuclei and the reduced probabilities of transitions between these states (in Weisskopf single-particle units) are given in Table III. It can be seen from Table III that although the changes in β_2 accompanying the γ transitions are in all cases about the same (~0.1) the values of $B(\lambda)$ exhibit a large spread: from the enhanced

TABLE III. Radiative transitions between states with different deformation of the nucleus[20]

Nucleus	I_i^π	β_2^i	E_f, keV	I_f^π	$T_{1/2}$, sec	β_2^f	$E\lambda+M\lambda$	$B(\lambda)$, W.u
^{149}Sm	7/2−	0.01	22	5/2−	$7.1\cdot10^{-9}$	0.1	$E2+M1$	27
^{150}Sm	0+	0.19	1255	0+	$<10^{-8}$	(0.25)	$E2$	$>10^{-3}$
^{152}Sm	0+	0.28	1083	0+	$<10^{-8}$	(0.21)	$E2$	$>10^{-3}$
^{151}Eu	5/2+	0.16	196	3/2+	$2.4\cdot10^{-10}$	0.22	$E2+M1$	2.5
			261	5/2+	10^{-8}	(0.25)	$E2+M1$	10^{-2}
^{152}Eu	3+	0.29	49	0−	$>1.5\cdot10^{10}$	(0.20)	$M3$	$<10^{-6}$

$E2$ transition in ^{149}Sm (27 Weisskopf units) to the strongly suppressed $M3$ transition in ^{152}Eu ($<10^{-6}$ Weisskopf units). This spread of the $B(\lambda)$ values is obviously due to the different nature of the γ transitions and the different changes in the structure of the states. These factors evidently have a greater influence on the transition probability than the change in the deformation of the nucleus.

More complete data are available for γ transitions from the $11/2^-$ isomeric state. In deformed nuclei, this is the well known single-particle state [505]. However, it is also present in transitional nuclei. The rotational band based on it indicates that the nucleus is strongly deformed in this state. The deformation parameter can be estimated from the well known relation

$$\beta_2 = (1255/[6(\hbar^2/2J)\, A^{7/3}])^{1/2}, \qquad (5)$$

where J is the moment of inertia of the nucleus for the given rotational band. From the $11/2^-$ level there is an $E2$ transition to one of the lower excited states (with spin $7/2^-$). The quantum numbers of the $11/2^-$ levels in Sm, Gd, Dy, and Er isotopes with neutron number between 87 and 93, the deformation parameters of the ground state and the excited state, and also the reduced probabilities of the $E2$ transitions from the isomeric level are given in Table IV. It can be seen that the $E2$ transitions are suppressed and with increasing A, when the deformation of the nucleus in the ground state increases and the difference between the deformation of the ground and the excited states decreases, the suppression increases. This hindrance for the transitions is explained by the known selection rule with respect to the quantum number K. Indeed, the nuclei in Table IV with $N \geqslant 89$ have large quadrupole deformation, and their lowest levels form a rotational band with $K = 3/2^-$. For $E2$ transition from the isomeric level ($K = 11/2^-$) to the $7/2^-$ level of this rotational band, $\Delta K = 4$, and $\Delta K - \lambda = 2$ (λ is the multipolarity of the transition). It is known from the systematics of $E2$ transitions that such a change of $\Delta K - \lambda$ leads to a suppression by 10^4 times. The values of $B(E2)$ given in the table can be explained in this way. With decreasing deformation of the nucleus, the importance of the quantum number K decreases and with it the selection rule is relaxed. It can be seen from the dependence given in Table IV that the selection rule with respect to K is stronger than the suppression associated with the change in the deformation of the nucleus.

The nucleus ^{151}Gd evidently already belongs to the spherical nuclei (in it a rotational band based on the ground state is not observed). The quantum number K must play a small role. However, in this nucleus only

TABLE IV. Values of $B(E2)$ for transitions from $11/2^-$ [505] isomeric levels

Nucleus	I^π	β_2^{gr}	E_{is}, keV	$T_{1/2}$, sec	β_2^{is}	$B(E2)$↑ W. u.
$^{151}_{87}$Gd	$7/2^-$	(0.12)	1210	$<5\cdot10^{-8}$	0.29	$>10^{-4}$
$^{151}_{89}$Sm	$5/2^-$ [523]	0.21	261	$1.4\cdot10^{-5}$	0.33	$8\cdot10^{-3}$
$^{153}_{89}$Gd	$3/2^-$ [521]	(0.20)	171	$7.7\cdot10^{-5}$	0.32	$8\cdot10^{-4}$
$^{155}_{89}$Dy	$3/2^-$ [521]	0.19	233	$6\cdot10^{-6}$	0.31	$3\cdot10^{-3}$
$^{157}_{91}$Dy	$3/2^-$ [521]	0.27	199	$2.1\cdot10^{-2}$	0.33	$1.2\cdot10^{-5}$
$^{159}_{93}$Dy	$3/2^-$ [521]	(0.30)	354	$1.1\cdot10^{-4}$	0.34	10^{-5}
$^{161}_{93}$Er	$3/2^-$ [521]	(0.30)	397	$7.5\cdot10^{-6}$	0.33	10^{-4}

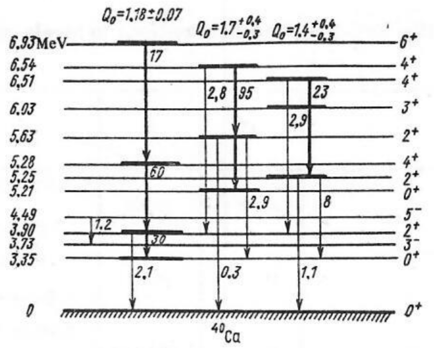

FIG. 8. Scheme of lowest ^{40}Ca levels. The thick lines are levels of the rotational band and transitions between them; the numbers next to the arrows are the $B(E\lambda)$ values in single-particle units.

an upper limit on the lifetime of the $11/2^-$ level is known, so that a conclusion cannot be drawn about a selection rule for $E2$ transition from this level.

2. ROTATIONAL BANDS IN SPHERICAL NUCLEI

It was noted long ago[27] that in numerous spherical nuclei there are systems of levels in which the sequence of spins and the energy intervals correspond to rotational bands. Measurements of the lifetime of the levels in these bands showed that in these states the nucleus has a large quadrupole moment, corresponding to a deformation parameter $\beta_2 = 0.3-0.5$.

Examples of rotational bands in the nuclei ^{40}Ca, ^{44}Sc, ^{115}In are given in Figs. 8–10. In the doubly magic nucleus ^{40}Ca, which is spherical in the ground state, one can distinguish three rotational bands (two of them are based on 0^+ levels and one on a 2^+ level). Measurements of the lifetimes of the levels of the rotational bands showed that the nucleus ^{40}Ca in these states has an intrinsic quadrupole moment of 1.2–1.7 $e \cdot$b and deformation parameter $\beta_2 \approx 0.4-0.5$.

Similar rotational bands are observed in other even-even Ca isotopes, and also in Ar, Ti, Ge, Se, Zr, Mo, Hg isotopes. All these bands are based on an excited state with spin 0^+ and energy 0.5–1.0 MeV. Measurements of the level lifetimes indicate a high deformation of the nucleus in these states, although in some cases the deformation parameter varies with the excitation energy.

Recent investigations of the effect of reorientation accompanying Coulomb excitation have shown that the spectroscopic quadrupole moment of the first 2^+ levels is small (the deformation parameter does not exceed 0.15). The deformation parameter of these nuclei in

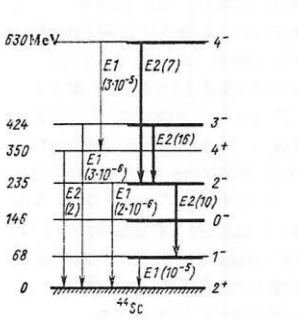

FIG. 9. Scheme of lowest ^{44}Sc levels. The notation is the same as in Fig. 8.

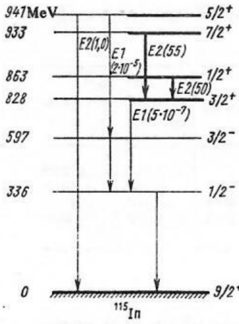

FIG. 10. Scheme of lowest ^{115}In levels.

the ground state is evidently the same, which is appreciably less than for the levels of a rotational band. At the same time, a number of irregularities in the energies and level lifetimes indicates that these bands have a more complicated structure. It is possible that the deformation of the nucleus deduced from the measured lifetimes is dynamical (associated with a large amplitude of vibrations) and not static, as in the well known regions of deformed nuclei.

In recent years, rotational bands have also been investigated in odd nuclei. In some of them (^{44}Sc, ^{115}In, ^{117}In), the method of perturbed angular correlations was used to measure the spectroscopic quadrupole moments of one of the levels of the rotational band.[28] It was found that these quadrupole moments agree well with the ones obtained from measurements of the level lifetimes of the rotational band (Table V). This agreement between the values of the quadrupole moments and, therefore, between the deformation parameters determined in different ways, indicates a static nature of the nuclear deformation in the states of the rotational band.

Thus, in the above nuclei there are two systems of levels with very different quadrupole deformation parameters. At least in some of these nuclei (see Table V) there is the same difference for the static deformations. Radiative transitions between the levels of different systems will be accompanied by an appreciable change in the deformation of the nucleus. From Fig. 8 one can see the values of the reduced probabilities of $E2$ transitions between different levels in the nucleus ^{40}Ca. The $B(E2)$ values for transitions within a band are a few tens of single-particle units. At the same time, for transitions between different bands (the deformation parameter changing little) and for transitions between levels with spin 2$^+$ of the rotational bands and the ground state (in this case, $\Delta\beta_2 \approx 0.3-0.4$) the values of $B(E2)$ are of the order of single-particle units Such a ratio of the $B(E2)$ values indicates that the change in the deformation of the nucleus has slight influence on the probability of the radiative transition.

TABLE V. Quadrupole moments of excited states measured in different ways

Nucleus	Q_0^{gr}, $e \cdot b$	E_{ex}, keV	I^π	Q_0^{ex}, $e \cdot b$	
				τ	ϑ
^{44}Sc	0.34±0.03 [2]	68	1$^-$	0.8±0.1 [52]	1.05±0.10 [28]
^{115}In	1.3±0.1 [2]	829	3/2$^+$	2.6±0.3 [53]	3.0±0.4 [28]
^{117}In	—	659	3/2$^+$	3.2±0.2 [54]	2.9±0.4 [28]

Note. τ is from measurement of the lifetimes of the levels of the rotational band; ϑ is from measurement of the perturbed angular correlations.

TABLE VI. Values of $B(E2)$ for transitions from levels of the rotational band to the first 2$^+$ level in even–even nuclei of the $f_{7/2}$ shell

Nucleus	$\beta_2(2^+)$	$E(0^+)$, MeV	$\bar{\beta}_2$ (rot)	$I_i \to I_f$ def→sph	$B(E2)$, W. u	Literature
^{38}Ar	0.16	3.38	0.36	0$^+$ → 2$^+$ 2$^+$ → 2$^+$ 4$^+$ → 2$^+$	1.5 3.6 1.0	Ref. 55
^{42}Ca	0.22	1.84	0.40	0$^+$ → 2$^+$ 2$^+$ → 2$^+$ 4$^+$ → 2$^+$	10 12 2.3	Ref. 56
^{44}Ti	0.20	1.90	0.32	0$^+$ → 2$^+$ 2$^+$ → 2$^+$ 4$^+$ → 2$^+$	3 7 2.5	Ref. 57

It can be seen from Fig. 10 that in the odd nucleus ^{115}In too the reduced probability of $E2$ transition is close to a single-particle unit. In this nucleus, the spectroscopic quadrupole moments of the ground state and the 3/2$^+$ (829 keV) level, on which the rotational band is based, have been measured and the change in β_2 accompanying the transition between these states is 0.10.

In the nucleus ^{44}Sc (see Fig. 9) there are $E1$ transitions between levels of a rotational band and the ground state. For these transitions, the values of $B(E1)$ are 10^{-5} of the single-particle estimate, and the change in the deformation parameter is 0.15. Such changes in $B(E1)$ are typical of transitions in this region of nuclei.

The rotational bands in nuclei (both even and odd) of the $f_{7/2}$ shell are the ones that have been best studied. In even-even nuclei, spectroscopic quadrupole moments of the first 2$^+$ levels are known (from measurements of the reorientation effect accompanying Coulomb excitation[5]). The reduced probabilities of $E2$ transitions to these levels from levels with spins 0$^+$, 2$^+$, and 4$^+$ of the rotational band for a number of nuclei are shown in Table VI. The values of β_2 for the 2$^+$ levels, and also for states of the rotational band, averaged over all states for which the lifetimes have been measured, make it possible to estimate the change in the deformation of the nucleus accompanying such transitions. It can be seen that the $B(E2)$ values lie in the range 1–10 single-particle units.

In odd nuclei of the $f_{7/2}$ shell, the levels of the rotational band are coupled to the ground state by $E1$ transitions. The $B(E1)$ values for these transitions are given in Table VII. It can be seen that when the deformation parameter changes by 0.1–0.3 the values of

TABLE VII. Values of $B(E1)$ for γ transitions from levels of the rotational band to the ground state in odd nuclei of the $f_{7/2}$ shell[58]

Nucleus	β_2^{gr}	$E(3/2^+)$, keV	$\bar{\beta}_2$ (rot)	$I_i \to I_f$ def→sph	$B(E1)$, W. u
^{43}Sc	0.16	151	0.25	5/2$^+$ → 7/2$^-$	$1.1\cdot10^{-4}$
^{45}Sc	0.14	12	0.26	5/2$^+$ → 7/2$^-$	$0.9\cdot10^{-4}$
^{47}Sc	0.14	767	0.29	5/2$^+$ → 7/2$^-$	$1.5\cdot10^{-4}$
^{45}Ti	~0.01	329	0.33	7/2$^+$ → 7/2$^-$	$0.8\cdot10^{-5}$
^{47}V	—	260	0.34	3/2$^+$ → 3/2$^-$ 5/2$^+$ → 3/2$^-$	$3.6\cdot10^{-4}$ $2.6\cdot10^{-4}$
^{49}V	—	748	0.28	5/2$^+$ → 7/2$^-$	$1.0\cdot10^{-4}$

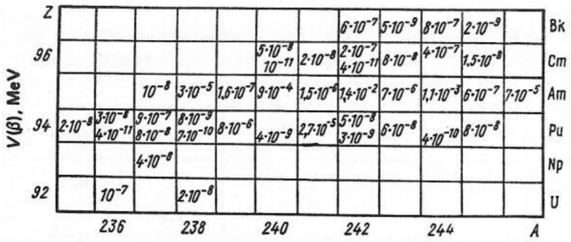

FIG. 11. Abundances of spontaneously fissile isomers and their lifetimes.

$B(E1)$ are $10^{-4}-10^{-5}$ single-particle units.

For heavier nuclei, the data are not so complete. However, in all cases the known values of $B(E2)$ for transitions from levels of a rotational band to the ground state or first excited (2^+) state are a few single-particle units. All these examples show that there is virtually no suppression for radiative transitions from levels of rotational bands to states with appreciably smaller deformation.

3. SPONTANEOUSLY FISSILE ISOMERS

In heavy nuclei ($Z \geqslant 92$) one observes isomeric states whose main decay mode is spontaneous fission (spontaneously fissile isomers, discovered at Dubna by Flerov, Polikanov, and their collaborators[29]). Figure 11 shows the abundances of these isomers and their half-lives. Investigation of the production reactions for spontaneously fissile isomers indicated that they have unusual properties—comparatively high energy (2.5–3.0 MeV), low spin ($\leqslant 4$), high excitation energy needed to populate the isomeric state ($\geqslant 5.5$ MeV). Such properties may characterize a new type of isomeric state.

Calculations of the potential surface made by means of the shell-correction method proposed by Strutinskiĭ[30] showed that it has a complicated shape. At a deformation twice the equilibrium deformation there may be a second minimum. In numerous nuclei this minimum is fairly deep, containing an entire system of levels, the lowest of which is the isomeric level (Fig. 12). The reason for the isomerism is the large difference between the deformations and the high potential barrier separating the ground state and the isomeric state (this leads to a very weak overlapping of the wave functions). Recent measurements of the quadrupole moments of spontaneously fissile isomers in the nuclei ^{236}Pu ($Q_0^{is}=37^{+14}_{-8}\,b$) (Ref. 31) and ^{239}Pu ($Q_0^{is}=34-39\,b$) (Ref. 32) showed that these values are 3 times larger than for the ground states (for example, for ^{239}Pu, $Q_0^{gr}=11.0\,b$; Ref. 21). This corresponds to a deformation parameter of the nucleus in the isomeric state of ~0.7 (the semi-axis ratio of the ellipsoid is 1:2) compared with $\beta_2=0.27$ for the ground state.

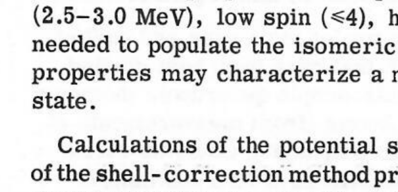

FIG. 12. Shape of the fission barrier of heavy nuclei and decay modes of the spontaneously fissile isomers.

TABLE VIII. Reduced widths for α decay of spontaneously fissile isomers

Isomer	$T_{1/2}$, sec	E_α, MeV	$\frac{W_\alpha}{W_\gamma+W_f}$	$T_{1/2}(\alpha)$, sec	δ_α^2, MeV	
					$\beta_2=0,3$	$\beta_2=0,7$
^{242}Am	$1,4\cdot10^{-2}$	8,5	$<1,5\cdot10^{-2}$	>1	$<2\cdot10^{-3}$	$<2\cdot10^{-6}$
^{240}Am	$9\cdot10^{-4}$	8,8	$<2\cdot10^{-2}$	$>5\cdot10^{-2}$	$<10^{-2}$	$<10^{-5}$
^{241}Pu	$2,7\cdot10^{-5}$	7.8	$<4\cdot10^{-3}$	$>7\cdot10^{-3}$	$<10^{3}$	<1
^{236}U	$1.1\cdot10^{-7}$	7.0	$<3\cdot10^{-4}$	$>3\cdot10^{-3}$	$<3\cdot10^{4}$	$<3\cdot10^{1}$

The spontaneously fissile isomers can undergo the same decays as heavy nuclei (α, β, and γ decay, spontaneous fission) and be populated by transitions associated with the emission of these forms of radiation. Measurement of the probabilities of these transitions makes it possible to obtain information about selection rules for transitions associated with a change in the deformation that is appreciably larger (~0.5) than in the cases already considered (transitional nuclei and rotational bands in spherical nuclei).

α Decay. Searches for α emission accompanying the decay of spontaneously fissile isomers were made in Refs. 33 and 34. The appreciably higher (by 2.5–3.0 MeV) energy of the α particles compared with transitions from the ground state permitted a high sensitivity of the measurements. However, in all cases the results of the searches were negative. Upper limits for the intensities of α emission from isomeric levels and limits corresponding to them for the reduced α widths are given in Table VIII, from which one can see that for the even-even nucleus ^{236}U the limit found on $\delta_\alpha^{(2)}$ is too high to draw a conclusion about the hindrance factor. For the odd nuclei ^{240}Am and ^{242}Am, the δ_α^2 limits are much lower, but in such nuclei, as a rule, there is a selection rule associated with a change of the spin or parity of the nucleus accompanying an α transition. As can be seen from Table V, the typical values of δ_α^2 for odd nuclei are of the same order as the bounds obtained for α transitions from the isomeric states of ^{240}Am and ^{242}Am. This prevents our drawing a conclusion about the suppression factor associated with a change in the deformation of the nucleus in odd nuclei.

However, there is a feature of the α decay of spontaneously fissile isomers that facilitates the emission of α particles. The appreciably greater deformation of the nucleus in the isomeric state has the consequence that for the emission of α particles from the poles of the nucleus the Coulomb barrier is appreciably lower. According to Ref. 35, the increase in the probability of α-particle emission with increasing deformation parameter (under the assumption that the wave function is constant on the surface of the nucleus) is given by

$$\lambda_\beta/\lambda_0=\Big[\int_0^1 \exp\{8.5\beta_2 P_2(\cos\vartheta)\,d\vartheta\}\Big]^2. \quad (6)$$

According to (6), the mean penetrability of the Coulomb barrier increases by 1000 when the deformation parameter increases from 0.25 (ground state) to 0.7

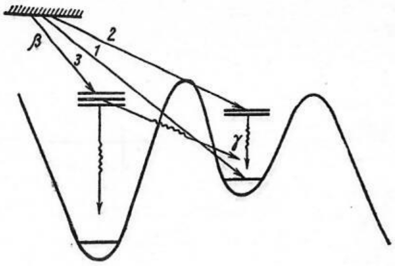

FIG. 13. Population of spontaneously fissile isomers in the case of β decay.

(the isomeric state). With allowance for this, the bound for the α width for the isomeric states of ^{240}Am and ^{242}Am reaches 10^{-5} MeV, as can be seen from Table VIII, and this will already mean that α transitions from the isomeric level are strongly forbidden.

β Decay. If the energy of a β transition is greater than the energy of the isomeric state, then it is energetically possible for a nucleus to be formed in the isomeric state after β decay. The isomeric level can be populated in different ways (Fig. 13):

1) β transition directly to the isomeric state;

2) β transitions to levels of the second minimum with subsequent γ transitions to the isomeric state;

3) β transitions to the levels of the first minimum with subsequent γ transitions to the levels (including the isomeric level) of the second minimum.

The first and second ways involve a change in nuclear deformation accompanying the β decay; the third, accompanying the γ transitions. This mode of populating the isomeric level does not differ from all the others when the excitation of the levels of the first minimum occurs as a result of nuclear reactions. Since each of the ways of populating the isomeric state is associated with a change in the deformation of the nucleus, the ratio of the probabilities for the different routes will be determined by the energy of the β decay and the spins of the initial state and the isomeric state. If the energy of the β decay slightly exceeds that of the isomeric level, and the spins of the initial and final states are nearly equal, then the first mode is the most probable. With increasing energy of the β decay, population through the excited states of the first and second minima becomes more probable.

Fission after β decay can be deduced from a yield of fission fragments whose intensity varies with the time in accordance with the half-life of the initial nucleus. This phenomenon (delayed fission) was observed for the first time in the isotopes ^{232}Am, ^{234}Am, and ^{228}Np in Refs. 36 and 37. However, in all these cases the isomeric shifts in the daughter nuclei are unknown. The situation is different for the delayed fission of the neutron-rich Pa isotopes. In these cases, spontaneously fissile isomers are known (see Fig. 11) in the daughter nuclei (^{238}U, ^{236}U). It should be noted that, besides fission from the isomeric state, there may also be prompt fission from levels of the first minimum populated during β decay. However, it was shown in Refs. 38 and 39 that at excitation energies below 4.5 MeV fission through the isomeric state is predominant.

TABLE IX. Comparative half-lives for β transitions to levels of the first and the second minimum

β transition and $T_{1/2}$, min	$I_i \to I_f$	β_2	E_β, MeV	I_β	lg $f\tau$
^{238}Pa → ^{238}U	$3^- \to 2^+$	0.3	2.9	$5\cdot10^{-2}$	7.3
2.3		0.7	0.5	10^{-8}	10.3
^{236}Pa → ^{236}U	$1^- \to 0^+$	0.3	3.1	10^{-1}	7.5
9.1		0.7	0.6	10^{-9}	12.0

The properties of the investigated Pa isotopes (spin and parity, half-life, total β-decay energy, and the fraction of β transitions accompanied by fission[40]), and also the values of log$f\tau$ for transitions to levels of the first and the second minimum, are given in Table IX. It was assumed that the structure of the excited states is similar in the two minima, and therefore levels with the same quantum numbers as in the first minimum are populated in the second (see Fig. 13). It can be seen from Table IX that the values of $f\tau$ for transitions to the levels of the second minimum are $5\cdot10^4$ (^{236}Pa) and $6\cdot10^3$ (^{238}Pa) times smaller than for transitions to the same levels of the first minimum. These values determine the hindrance factor for the β transitions associated with the change in the deformation of the nucleus. Since, as we have already noted above, the isomeric state can be populated in other ways as well, these values must be regarded as lower limits for the factor.

γ Decay. The high energy of the isomeric states opens up considerable possibilities for investigating various kinds of γ transitions associated with a change in the nuclear deformation. However, the investigation of γ rays emitted during the spontaneous fission of isomers presents considerable difficulties. The cross section for the production of spontaneously fissile isomers is much smaller than the cross sections of other reactions (in particular, the fission reaction), and therefore the γ lines associated with decay of the isomeric state are hard to distinguish on the background of the intense γ's of the fission fragments. In fission of nuclei, isotopes and isomers are produced with all possible half-lives, including some close to those of the investigated spontaneously fissile isomers, and this complicates the identification of the γ lines even more. Because of these difficulties, most searches for a branch of γ radiation accompanying the decay of spontaneously fissile isomers have been unsuccessful. It was only in Ref. 41 that two lines with energies 2514 and 1879 keV and intensities 15 and 7 gammas per fission event, respectively, were observed and ascribed to the decay of the spontaneously fissile isomer of ^{238}U. This result was confirmed in Ref. 42, in which measurements were made of the spectra of conversion electrons emitted during the decay of spontaneously fissile isomers of U, Pu, and Am. This method makes it possible to achieve a high sensitivity since the yield of conversion electrons from the fission fragments (the main source of the background) is several times smaller than the yield of γ's. In addition, the distances between conversion lines from different shells or subshells (K, L_I, L_{II}, L_{III}, M) are a function of the atomic number of the emitter and permit a more reliable identification of radiative transitions from an isomeric level. Therefore, fairly low bounds were obtained on the intensities of

TABLE X. Intensities of γ transitions accompanying the decay of spontaneously fissile isomers.

Isomers	$T_{1/2}$, sec	E_{is}, MeV	W_γ/W_f
^{238}U	$2\cdot10^{-7}$	2,5	10 40* [41]
^{239}Pu	$8.5\cdot10^{-6}$	2.4	<3
^{241}Pu	$2.7\cdot10^{-5}$	2.5	<1
^{240}Am	$9\cdot10^{-4}$	2.7	<1
^{241}Am	$1.5\cdot10^{-6}$	2.2	<3
^{242}Am	$1.4\cdot10^{-2}$	2.4	<5
^{243}Am	$6.5\cdot10^{-6}$	2.2	<10

radiative transitions and these make it possible to estimate which de-excitation method (γ emission or spontaneous fission) is the main one for a series of isomeric states. The results of these measurements are given in Table X. It can be seen that for the ^{238}U isomer the main method is γ emission, while for the ^{241}Pu and ^{240}Am isomers it is spontaneous fission.

Another (indirect) source of information about the intensity of the branch of γ emission from the isomeric level is obtained by comparing the measured and calculated reaction cross sections for the production of spontaneously fissile isomers. If the shape of the fission barrier is known (it can be determined from an investigation of the reactions of fission and production of spontaneously fissile isomers[43,44]), then one can calculate the cross section for the production of the nucleus in the isomeric state. Since the yield associated with only one de-excitation channel—spontaneous fission—is determined experimentally, a difference between the measured and calculated cross sections may be due to the fact that the main decay mode of the isomer is γ emission that was not detected in the measurements. The applicability of such a method was tested on the above isomers, for which the relationship between the γ emission and spontaneous fission for the de-excitation of the isomeric state was obtained directly from the experiment. It was shown that in two further spontaneously fissile isomers (^{236}U and ^{237}Np) γ emission is the main decay mode (for all the remaining isomers, spontaneous fission is predominant).

To estimate the hindrance for the γ transitions from the isomeric level, it is necessary to know the multipolarities of these transitions. Since they are unknown [except for the γ transitions mentioned above in ^{238}U, i.e., 2514 keV ($E2$) and 1879 keV ($E1$) (Fig. 14)], it was assumed that γ transitions with multipolarities $E1$, $M1$, and $E2$ from the isomeric level are possible.

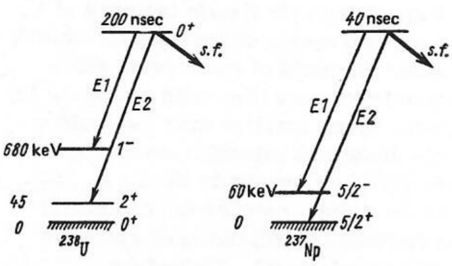

FIG. 14. Schemes of γ transitions from ^{238}U and ^{237}Np isomeric levels.

TABLE XI. Reduced probabilities of γ transitions accompanying decay of spontaneously fissile isomers.

Isomer	$T_{1/2}$, sec	E_{is}, MeV	$B(E1)$, W. u	$B(E2)$, W. u
^{236}U	$1,1\cdot10^{-7}$	2.5	$5\cdot10^{-10}$	$5\cdot10^{-5}$
^{238}U	$2\cdot10^{-7}$	2,5	10^{-11}	10^{-6}
^{237}Np	$4\cdot10^{-8}$	2.4	10^{-10}	10^{-5}
^{241}Pu	$2.7\cdot10^{-5}$	2.5	$<10^{-13}$	$<10^{-8}$
^{240}Am	$9\cdot10^{-4}$	2.7	$<10^{-15}$	$<10^{-10}$

Indeed, in odd nuclei near the ground state there are levels with both signs of the parity, on which rotational bands are based. The energy of these levels does not exceed 0.5 MeV, and therefore transitions of the above multipolarities are possible from the isomeric state (see Fig. 14). In Table XI we give the reduced probabilities of the transitions (or their upper bounds) obtained from the known lifetimes of the spontaneously fissile isomers and the intensities of the γ-emission branches. It can be seen from Table XI that the values of $B(E2)$ and $B(E1)$ are much less than single-particle units, which indicates that γ transitions from the isomeric levels are strongly forbidden.

It is of considerable interest to follow the influence on the value of the hindrance factor of the nature of the levels, the excitation energy, and the height and width of the potential barrier separating the first and second minima. However, data on the intensities of γ transitions from the isomeric state to different levels of the first minima are almost nonexistent because of the experimental difficulties mentioned above. A different way is more promising—to investigate radiative transitions from different excited states to the isomer or another level of the second potential well. This opens up great possibilities since here the initial state is given (by the energy of the bombarding particle or the particle emitted in the reaction), and one can deduce the existence of radiative transitions to the isomeric level from its decay, i.e., from the spontaneous fission. The detection of fission fragments appreciably raises the sensitivity of the measurements. Such an approach enables one, without observing the radiative transitions themselves, to estimate the extent to which they are forbidden. However, one can only speak of an average hindrance for all the γ transitions between the initial state and the isomeric state.

In this case, the process of population of the isomeric state is treated statistically, and the probability for the production of the isomer is determined by the expression

$$P_{is}=\int_{E_{is}}^{E_0}(E_0-E)^3\,\rho(E-E_{is})\,dE\Big/\int_0^{E_0}(E_0-E)^3\,\rho(E)\,dE, \qquad (7)$$

where E_{is} and E_0 are the energies of the isomeric state and the initial state; $\rho(E)$ and $\rho(E-E_{is})$ are the densities of levels at the excitation energy E, measured respectively from the ground state and the isomeric state. The expression (7) is based on the fact that only dipole γ transitions take place from the initial state and population of any of the levels of the second minimum leads to formation of the isomer.

In such a treatment, the hindrance factor is defined as the ratio of the probabilities of isomer production measured experimentally and calculated by means of the expression (7), since no other selection rules were taken into account in the calculation. For the actual calculations of P_{is}, the experimentally known values of the level density at the neutron binding energy[45] and the energy dependence $\rho(E)$ from the constant-temperature model were used. Of course, the hindrance factors obtained in this way will depend on the chosen model and the parameters adopted in the calculation. Therefore, in this case we should speak, not of the value of the hindrance factor, but of its dependence on these nuclear properties. The nature of this dependence is not significantly changed if one goes over to a different dependence of the level density on the excitation energy (for example, that from the Fermi-gas model), to other parameters, or to the assumption that there are quadrupole rather than dipole transitions from the initial state.

A fairly large volume of experimental data has now been accumulated on the probabilities of population of spontaneously fissile isomers from excited states in the energy range 3–7 MeV. These excited states were obtained in different nuclear reactions: (n, γ) (Refs. 46 and 47), (γ, γ') (Refs. 38 and 48), (d, p) (Ref. 49), Coulomb excitation,[50] and β decay.[40]

It must be noted that the production of spontaneously fissile isomers in the above reactions occurs not only through levels of the first minimum, but also through direct population of levels of the second minimum. In this case, there will be a selection rule for population of these levels in the investigated reaction, but then transitions from such levels to the isomeric state will no longer be associated with the selection rule. The relationship between these routes was considered in Ref. 51 for the example of the (γ, γ') reaction leading to formation of a spontaneously fissile isomer. It was shown that the first routes (through the levels of the first minimum) is more probable at high excitation energies (as in the case of β decay), when the total width of the levels in the second minimum becomes larger (because of the greater fission width) than in the first minimum.

Figures 15 and 16 show the probabilities of isomer production and the hindrance factors for transitions between the levels of the different minima in the case of the nuclei ^{236}U, ^{238}U, and ^{242}Am as functions of the excitation energy. The hindrance factors were determined in the manner described above. It can be seen that the rapid change of the hindrance factors at low

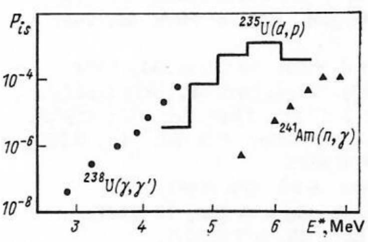

FIG. 15. Probability for production of spontaneously fissile isomers as a function of the excitation energy in the reactions.

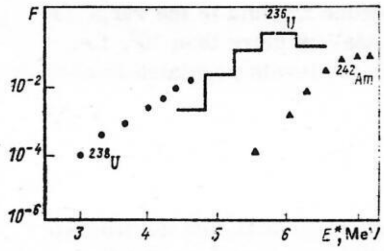

FIG. 16. Hindrance factor F for the production of spontaneously fissile isomers as a function of the excitation energy (the reactions and their designations are the same as in Fig. 15).

excitation energies slows down appreciably when the energy 5.5 MeV is reached for the nucleus ^{236}U and 6.5 MeV for ^{242}Am. These energies correspond[43,44] to the heights of the potential barriers separating the first and the second minima in the nuclei ^{236}U and ^{242}Am.

The energy of the β decay of ^{238}Pa appreciably exceeds the energy of the isomeric state in the daughter nucleus ^{238}U (by 1.5 MeV). Therefore, in this case the population of the isomeric state, and also of the other levels of the second minimum, may take place by means of γ transitions from levels of the first minimum excited during β decay (see Fig. 13). This can apparently explain the higher probability of delayed fission of ^{238}Pa (10^{-8}) compared with ^{236}Pa (10^{-9}). On the basis of the well known ideas about the population of excited states during β decay,[52] one can calculate the probability of delayed fission. It will correspond to the measured value (10^{-8}) at the same values of the hindrance factors for transitions between levels of the first and second minima in the range of energies 3–4 MeV, which are obtained in the reaction ^{238}U$(\gamma, \gamma')^{238m}$U (see Fig. 16), although in the two cases different levels are excited (with spin 1^- and 2^+ for the (γ, γ') reaction and spins $2^-, 3^-, 4^-$ for β decay).

The method of population of the spontaneously fissile isomers during Coulomb excitation depends on the charge of the bombarding ion. For comparatively light ions ($Z \leq 10$) levels with spins 1^- and 2^+ (dipole and quadrupole excitation) are excited in the energy range 5–6 MeV with subsequent γ transitions to levels of the second minimum. When heavier ions (Kr, Xe) are used, the mechanism of multiple Coulomb excitation, in which vibrational or rotational levels of the second minimum are excited as a result of a cascade of $E2$ transitions, becomes predominant. In this case, there may be a selection rule for only the last stage of the excitation, and for the de-excitation of the levels and population of the isomeric state there will no longer be a selection rule.

Experiments on the Coulomb excitation of the spontaneously fissile isomers of ^{238}U and ^{235}Pu made it possible to obtain only upper limits on the cross sections (10^{-33} cm^2 for ^{12}C ions[50] and ^{20}Ne ions[52] and 10^{-31} cm^2 for ^{136}Xe ions[50]). These bounds for the ions ^{12}C and ^{20}Ne agree with the hindrance factors for γ transitions to the levels of the second minimum that were obtained in the reactions mentioned above. For ^{136}Xe ions, the absence of the effect indicates that the hindrance factor for $E2$ transitions between collective levels of the first and second minima in the range of excitation energies 3–4 MeV is more than 10^3, i.e., virtually the same as for the levels populated in nuclear reactions and β decay.

CONCLUSIONS

The large number of experimental data considered above enable us to establish the main features for transitions associated with a change of the nuclear shape. The data as a whole can be divided into two groups: In the first, we have transitional nuclei and rotational bands in spherical nuclei in which the transitions are not associated with a large hindrance factor; in the second, we have spontaneously fissile isomers, for whose decay there is a large hindrance factor.

The reduced probabilities of the transitions (or the reduced widths, or comparative half-lives) depend, as we have already said, on numerous factors that are determined by the structure of the initial and final states. It is of interest to separate the actual value of the hindrance factor associated with the change in the nuclear shape. However, this is not a simple problem. Comparison of the probabilities of transitions for different changes of the deformation parameter is not always justified since it refers to different nuclei and, therefore, may be due to the different structure of the initial or the final states. One can identify only a number of cases when the structure of the initial and final states is preserved under different changes of the deformation parameter:

1) α transitions between the ground states of even-even nuclei. It can be seen from Figs. 5 and 6 that the values of δ_α^2 change by not more than 20 times for a change in β_2 right up to 0.2–0.25. Further, a possible change in the sign of the deformation (for the isotopes ^{190}Pb and ^{188}Pt) accompanying an α transition has virtually no influence on the reduced α width;

2) β decay of odd-odd nuclei to levels of the ground-state rotational band of two neighboring even-even nuclei. It can be seen from Table II that in this case too for transitions in which β_2 changes by up to 0.12 the values of $f\tau$ change by not more than ten times.

In none of the other cases is it possible to separate clearly the change in the deformation from other factors. However, the values of the transition probabilities (or hindrance factors) can be explained (at least qualitatively) by known causes associated with changes in the orbital angular momentum, the spin projection onto the symmetry axis of the nucleus, the number and position of unpaired quasiparticles, etc. This may mean that a change in the deformation of the nucleus has less influence on the probabilities of α, β, and γ transitions than the mentioned factors. This weak influence is apparently due to the fact that, despite the different deformation of the initial and final states, there is still a strong overlapping of the wave functions of the two states because of the zero-point vibrations of the nucleus.

A completely different situation is observed for decay or population of spontaneously fissile isomers. The reduced probabilities of $E2$ and $E1$ transitions from an isomeric state to the ground state are many orders of magnitude (up to 10^{10} and more) lower than single-particle units, and the comparative half-lives for β transitions to the isomeric state are at least 10^4 times longer than for transitions to the ground state. Such a large hindrance factor cannot be explained by the known causes listed above (change in the orbital angular momentum, the number of unpaired quasiparticles, etc). These causes are operative for only certain transitions, and the hindrance factor associated with them usually does not exceed 10^2. For spontaneously fissile isomers similar (and appreciably larger) values of the hindrance factors are observed for transitions between completely different states in even and odd nuclei. Obviously, this has a common origin—the large difference between the deformations of the initial and final states, and also the presence of the high potential barrier separating these states. The barrier leads to a strong damping of the wave functions of the states of the first and the second minima, and therefore to a very weak overlapping of the wave functions.

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