Results of investigations of isotopes far from the β-stability band (summary of investigations in the Yasnapp program at the Laboratory of Nuclear Problems, Dubna). Part 2

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The results of studies of deformed nuclei with $150 < A < 190$ in the Yasnapp program on the Dubna cyclotron are reviewed.

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INTRODUCTION

In the first part of this review[1] we described the methods used in the Laboratory of Nuclear Problems at our institute to obtain and investigate neutron-deficient radioactive nuclides in order to study the properties of nuclei far from the β-stability band in the Yasnapp program (program of nuclear spectroscopy in a proton beam). The results of the investigations of spherical and transition nuclei were also reviewed. The second part of the review consists of the third chapter, devoted to the results of investigations of deformed nuclei of rare-earth elements. For the convenience of the reader, a brief description of the experimental procedure will be given. A more complete description can be found in Ref. 1.

3. INVESTIGATIONS OF DEFORMED NUCLEI OF RARE-EARTH ELEMENTS

An important task of nuclear physics is to create a theory of the nucleus based on the general laws of interaction of the nucleons in the nucleus and capable of explaining and predicting physical properties of nuclei. This is a very difficult problem since, first, the interaction forces between nucleons in a nucleus are very complicated and inadequately studied and, second, nuclei, apart from the lightest, are systems with many strongly interacting particles. For this reason, the theory of the nucleus is at present based on different models. On the basis of various simplifying assumptions about nuclear forces, attempts are made to explain the experimental data and predict the properties of nuclei. Significant success in understanding the structure of the ground and excited states of nuclei has been achieved on the basis of the shell model, the model of deformed nuclei, the generalized model, the superfluid model, and others. It is well known that from the point of view of these models nuclei are divided into spherical (magic), deformed, and transition nuclei.[2] It is also well known that the structure of deformed nuclei has hitherto been investigated experimentally and theoretically in the most detail. However, even in this region of nuclei there are many problems that require experimental investigation.

For example, new data are needed on the masses of the nuclei. Experimental investigations continue into the parameters of the average one-particle potential of deformed nuclei. Great interest has recently been evinced for the properties of high lying (~2 MeV and higher) states (back bending effect and fragmentation of quasiparticle states).

Valuable information about the properties of neutron-deficient isotopes of rare-earth elements can be obtained in investigations of the radioactive decay of nuclei formed by the irradiation of targets with protons having energies of several hundred MeV. Systematic investigations of this type were first begun at the Laboratory of Nuclear Problems in 1955. In this cycle of investigations, about 80 new isotopes were discovered. The decay schemes of many neutron-deficient deformed nuclei of rare-earth elements were studied. In these studies, nuclei were already investigated with a neutron deficit of up to six or eight units from the β-stability band. These investigations are reviewed in Ref. 3.

A new stage in our investigations of neutron-deficient isotopes of rare-earth elements was begun in 1967, when a start was made on investigating short-lived nuclei (the Yasnapp program). The Yasnapp investigations were carried on, from the methodological point of view, in two directions. The first is the identification and study of the structure of short-lived nuclei far from the β-stability band. The second direction is associated with the continuation of detailed investigations of the properties of ground and excited states relatively close to the β-stability band ($T_{1/2} \approx 1$ h and longer).

Experiments in the first direction were made basically in accordance with the following scheme (see the first part of the review Ref. 1).

The target (tantalum or a complex of rare-earth elements) is irradiated with the extracted proton beam of the Dubna synchrocyclotron. The proton energy is 660 MeV and the current about 0.1 μA. After irradiation, the target is carried by a pneumatic shuttle to the express radiochemical laboratory or to the electromagnetic mass separator. The sample of the rare-earth element removed from the irradiated target is brought to isotope separation. Wide use is also made of a method that eliminates chemical operations; in it, the irradiated tantalum target is brought directly to the ion source of the mass separator to separate the rare-earth elements into isobars.

The radiochemical methods that are used are described in Refs. 1 and 4, and the mass separator, the ion source, and the method of isotope separation in Refs. 1, 5, and 6. Depending on the methods employed, the spectrometric investigations begin 3–20 min after irradiation of the target. The emission accompanying the decay of the short-lived isotopes is investigated by means of gamma, beta, and alpha spectrometers with semiconductor detectors; the spectra of prompt and delayed $\gamma\gamma$ and $\beta\gamma$ coincidences are studied; and an appropriate technique is used to accumulate information and evaluate data by means of computers (Ref. 1).

Isotopes of rare-earth elements with $T_{1/2} \gtrsim 1$ h are investigated by the usual off-line scheme: irradiation of the targets (tantalum) in the internal proton beam of the Dubna synchrocyclotron ($E_p = 660$ MeV, $I_p = 2.3$ μA), chemical separation of the rare-earth elements,[4] and separation of the isotopes of the element in the mass separator.[7] The investigations are begun in this case 1.5–2.0 h after the end of irradiation.

Apart from spectrometers with semiconductor detectors, we have also used beta spectrographs with constant magnetic field, an iron-free toroidal beta spectrometer, a beta spectrometer with twofold double focusing of the beam, and so forth.

Naturally, if the need arises the basic experimental arrangments are modified. For example, the isobars are separated chemically after the mass separation, in some cases the spectra of conversion electrons of the isotopes with $T_{1/2} = 5$–10 min are studied in a toroidal beta spectrometer and beta spectrographs, etc.

Figure 1 shows the scheme of the Yasnapp experiments.

3.1. Experimental results of the investigations of the properties of deformed nuclei in the Yasnapp program

We now consider the main results of the investigations of the radioactive decay of the neutron-deficient isotopes of rare-earth elements in the Yasnapp program. We present the results of our most recent investigations into the decay of nuclei with $150 < A < 190$. The exposition does not pretend to completeness as regards the interpretation of the results of the experimental investigations of the deformed nuclei of rare-earth elements. The results of the investigations of even deformed nuclei are reviewed in the book by Grigor'ev and Solov'ev (Ref. 8). The last review of the properties of odd nuclei was by Bunker and Reich (Ref. 9) in 1971. Results of later investigations can be found in the compilations in Ref. 10.

^{152}Tb, $T_{1/2} = 17.4 \pm 0.2$ h. The results of our investigations into the decay of ^{152}Tb have been presented in Ref. 11. We studied the spectra of γ's, conversion electrons, positrons, and $e\gamma$, $\gamma\gamma$, and $\beta^+\gamma$ coincidences. In the ^{152}Gd nucleus levels are excited of the ground-state rotational band (2^+0, 344.4 keV; 4^+0, 755.6 keV), β-vibrational band (0^+0, 615.5 keV; 2^+0, 931.1 keV), γ-vibrational band (2^+2, 1109.8 keV; 3^+2, 1320.0 keV; 4^+0, 1547.0 keV), band of octupole vibrations (3^-0; 1124 keV; 1^-0, 1314 keV). Besides these states, we observed a number of levels including one with energy 1047.8 keV and $I^\pi K = 0^+0$. The decay energy $Q_\beta(^{152}\text{Tb}) = 3850 \pm 15$ keV was determined in Ref. 12.

^{153}Dy, $T_{1/2} = 6.3$ h. Investigations of the spectra of γ's, conversion electrons, and $\gamma\gamma$ and e^-e^- coincidences made it possible to construct the decay scheme of ^{153}Dy (Ref. 13). For ^{153}Tb, 50 excited states were introduced. It is assumed that the ^{153}Dy nucleus in the ground state is spherical with quantum numbers $f_{7/2}$. The ^{153}Tb nucleus in some states has a spherical shape; in others, it is deformed. The lower levels of ^{153}Tb are states of an odd proton with spherical shape of the nucleus: 0 ($d_{5/2}$), 80.7 ($g_{7/2}$), and 163.2 keV ($h_{11/2}$). At the same time, the properties of the levels at 147.5 ($3/2^+$), 240.4 ($5/2^+$), 389.4 ($7/2^+$), and 572.1 keV ($9/2^+$) are the same as those of the lower levels of the $3/2^+[411]$ rotational band in the strongly deformed nuclei ^{155,157,159}Tb. The levels of 799.8 ($5/2^+$) and 1087.1 keV ($7/2^+$) are possibly members of the rotational band of the state $3/2^+[411]Q_{00}$. The ^{153}Dy nucleus also undergoes α decay. A fine structure of the α spectrum of this nucleus was found in Ref. 14: $E_{\alpha_0} = 3464 \pm 5$ keV ($3.0 \pm 0.3 \cdot 10^{-3}$% per decay of ^{153}Dy) and $E_{\alpha_1} = 3305 \pm 5$ keV ($9 \pm 6 \times 10^{-7}$% per decay).

^{154}Tb, $T_{1/2} = 9.9 \pm 0.1$ h, $I^\pi = 3^-$; ^{154m_1}Tb, $T_{1/2} = 23.1$

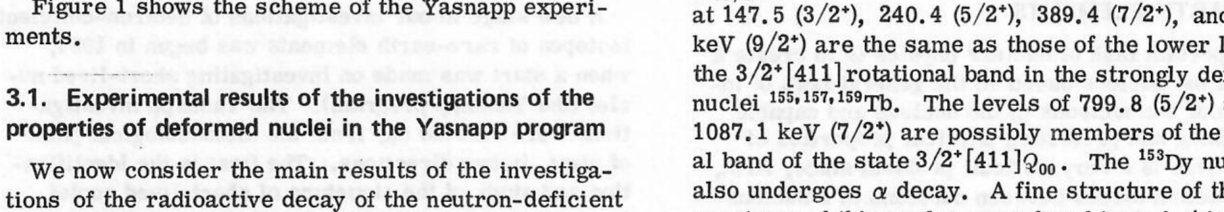

FIG. 1. General arrangement of experiments in the Yasnapp program. The different lines indicate different arrangements of experiments.

±0.9 h, $I^{\pi} \geqslant 6$; ^{154m_2}Tb, $T_{1/2} = 22.0 \pm 1.5$ h, $I^{\pi} = 0^-$. Investigations were made of the spectra of γ's, conversion electrons, and $\gamma\gamma$ coincidences.[15] The level scheme of ^{154}Gd includes a ground-state rotational band: 0 keV, 0^+; 123 keV, 2^+; 371 keV, 4^+, and 718 keV, 6^+; a β-vibrational band: 681 keV, 0^+, 816 keV, 2^+; 1048 keV, 4^+; a γ-vibrational band: 996 keV, 2^+; 1128 keV, 3^+; 1264 keV, 4^+; 1402 keV, 5^+; a band of octupole vibrations with $K^{\pi} = 0^-$: 1241 keV, 1^- and 1252 keV, 3^-, and also a number of other levels.

^{155}Ho, $T_{1/2} = 49 \pm 2$ min. Study of the decay of ^{155}Ho made it possible to determine more accurately the half life of ^{155}Ho, to determine the multipolarity of the transition 39.5 keV ($M1 + 4.4\%E2$) (Ref. 16), and to measure the lifetime of the ^{155}Dy level at 247.9 keV: $T_{1/2} = 63.0 \pm 3.3$ nsec and the level at 39.4 keV: $T_{1/2} \leqslant 3.5$ nsec (Ref. 17).

^{155}Dy, $T_{1/2} = 10.1$ h. Investigations of the decay of ^{155}Dy (ground state of type $3/2^-[521]$, decay energy $Q_{\beta}(^{155}\mathrm{Dy}) = 2100 \pm 10$ keV) led to the establishment of a complicated scheme of excited states of ^{155}Tb (Refs. 18 and 19). We identified rotational bands of the ground-state of ^{155}Tb: $3/2^+[411]$ and of excited states of the type $5/2^-[532]$, $7/2^-[523]$, $5/2^+[413]$, $1/2^-\{[532]\uparrow + Q_{22}\}$, $1/2^+[411]$, $7/2^+[404]$, $3/2^+\{[411]\uparrow + Q_{22}\}$, $3/2^+\{[411]\uparrow + Q_{20}\}$, $1/2^-\{[532]\uparrow + Q_{22}\}$. The level at 1664.7 keV ($5/2^-$) probably contains an appreciable admixture of a three-quasiparticle state of the type $p5/2^-[532]$, $n3/2^-[532]$, $n3/2^-[521]$.

^{155}Tb, $T_{1/2} = 5.6$ days. We studied the spectra of internal conversion electrons, γ's, and $e\gamma$ and $\gamma\gamma$ coincidences. A complicated $^{155}\mathrm{Tb} \to {}^{155}\mathrm{Gd}$ decay scheme was proposed.[20] The scheme includes the rotational band of the ground-state (levels 0, $3/2^-[521]$; 60, $5/2^-$; 146 keV, $7/2^-$), a band based on the state $3/2^+[402]$ (levels 269, $3/2^+$; 326 keV, $5/2^+$), a band based on the state $1/2^+[400]$ (368, $1/2^+$; 427, $3/2^+$; 489 keV, $5/2^+$), a band based on the level $1/2^-[521]$ (560, $1/2^-$; 616 keV, $3/2^-$), and also the states $3/2^-[532]$, 287 keV; $3/2^-$, 451.3 keV, and a number of other states. The level 593 keV, $I^{\pi} = 3/2^-$, has a dominant component $[521]\uparrow + Q_1$ (20).

^{156}Er, $T_{1/2} = 19.5 \pm 1.0$ min. Identified in Ref. 21; the constructed decay scheme includes levels of ^{156}Ho with the energies 52 keV, $I^{\pi} = 2^+$, $T_{1/2} < 2$–3 min; 82 keV, $I^{\pi} = 1^+$, $T_{1/2} = (1.46 \pm 0.15)$ nsec, and 117 keV, $I^{\pi} = 1^-$. The hindrance factor of the 52-keV transition is $F(M3) < 100$. The observed levels can be associated with two-quasiparticle configurations in ^{156}Ho: 0 keV, 5^+—$\{p523\uparrow + n521\uparrow\}$; 52 keV, 2^+—$\{p523\uparrow - n521\uparrow\}$; 82 keV, 1^+—$\{p523\uparrow - n523\downarrow\}$. Note the low value $\lg ft = 5.0$ for the β transition of $^{156}\mathrm{Er}(0^+)$ to the level 117 keV (1^-). The intensity of α decay of ^{156}Er was estimated to be less than $5 \cdot 10^{-7}\%$ per decay.

^{156}Ho, $T_{1/2} = (55 \pm 1)$ min. Investigation of the decay $^{156}\mathrm{Ho} \to {}^{156}\mathrm{Dy}$ (Ref. 22) revealed levels of the rotational band of the ground state (up to 6^+), a β band (up to 6^+), and a γ band (up to 5^+), and also levels of octupole vibrational bands with $K^{\pi} = 2^-$, 0^-, and 1^-. A complicated scheme of the ^{156}Dy levels consisting of 47 levels was constructed. A decay energy $Q_{\beta}(^{156}\mathrm{Ho}) = (4.7 \pm 0.1)$ MeV was determined.

^{157}Tm, $T_{1/2} = (3.6 \pm 0.4)$ min. Discovered in Ref. 23. This decay includes γ transitions with the energies 99.9 keV (38), 110.2 keV (100), 131.1 keV (50), 192.4 keV (66), and 241.4 keV (95). The relative intensities of the γ's are given in the parentheses.

^{157}Er, $T_{1/2} = (22 \pm 2)$ min. Identified in Ref. 24 from the accumulation in the activity of ^{157}Dy. In Ref. 25 studies were made of the spectra of γ's, internal conversion electrons, and positrons. The multipolarities of a number of transitions were determined. The $^{157}\mathrm{Er} - {}^{157}\mathrm{Ho}$ mass difference is (3470 ± 80) keV. The measured lifetime of the 121.8 keV level in ^{157}Ho is $T_{1/2} = (0.75 \pm 0.10)$ nsec.

^{157}Ho, $T_{1/2} = (14 \pm 1)$ min. Discovered in Ref. 24 from the accumulation of the daughter activity of ^{157}Dy. A decay scheme of ^{157}Ho is proposed in Ref. 26. We observed the levels 3/2, 5/2, 7/2, 9/2 of the rotational band of the ground state of ^{157}Dy: $3/2^-[521]$; the levels 5/2, 7/2, and 9/2 of the band $5/2^-[523]$, a level at 187.8 keV of type $5/2^+[642]$, the levels 5/2 and 7/2 of the band $5/2^-[512]$, and a number of other levels. Estimates were made[25] of the lifetimes of the first rotational level at 61 keV of the band $3/2^-[521]$: $T_{1/2} \leqslant 0.4$ sec and the level at 341.1 keV of type $5/2^-[523]$: $T_{1/2} \leqslant 0.3$ nsec. Estimates were made of the internal quadrupole moment and the deformation parameter of the ^{157}Dy ground state: $Q_0 > 3.6$ b and $\beta > 0.20$.

^{157}Dy, $T_{1/2} = 8.06$ h. Careful study was made of the spectra of γ's and internal conversion electrons.[27] In the decay of ^{157}Dy ($3/2^-[521]$) the ^{157}Tb state with energy 326.4 keV ($5/2^-[532]$) is populated most strongly (98.3%; $\lg ft = 5.4$). The level 357.8 keV, $7/2^-$ is the first rotational state of the band. Levels of the ground-state rotational band $3/2^+[411]$ with spins 3/2, 5/2, 7/2 and energies 0, 60.8, and 143.8 keV are excited. Levels with spins 1/2, 3/2, and 5/2 (597.5, 637.0, and 697.0 keV) belong to the level $1/2^+[411]$. The level at 991.6 keV, $I^{\pi} = 3/2^+$, and the rotational level $5/2^+$, 1044.2 keV belonging to it are interpreted as members of a band based on the state ($3/2^+[411] + Q_1$ (20)). The excited state at 1102.5 keV is ascribed the quantum numbers $3/2^-[541]$.

^{158}Yb, $T_{1/2} = (1.1 \pm 0.2)$ min. Reliably identified at Dubna.[28] When ^{158}Yb decays, γ's with energy 74.2 keV are emitted. The intensity of this γ transition is estimated to be approximately 50% on decay of ^{158}Yb and its multipolarity is $E1$. It is possible that the decay of ^{158}Yb to ^{158}Tm takes place principally to the level at 74.2 keV of type 1^+ with $\lg ft \leqslant 5.0$.

^{158}Tm, $T_{1/2} = (4.3 \pm 0.2)$ min. Discovered in 1970 by De Boer *et al.* and Neiman *et al.*[29] At Dubna, studies were made[30] of the spectra of γ's and $\gamma\gamma$ coincidences in the decay of ^{158}Tm. Excitation of levels at 191 keV (2^+) and 526 keV (4^+) of the rotational band of the ground state of ^{158}Er were established.

^{158}Er, $T_{1/2} = (2.25 \pm 0.10)$ h. Discovered at Dubna in 1960. The latest results on the investigation of the de-

TABLE 1.

E, keV	I^{π}	$T_{1/2}$, min	Proposed configuration	lg ft
0	5+	11 (β)	p523↑ − n521↑	—
67	2−	27 (β I.T.)	p523↑ − n651↑	> 8.4
115	2+		p523↑ − n521↑	> 8.4
139	1−	1.85±0.10 nsec (γ)	p411↑ − n521↑	5.5

cay of ^{158}Er were published in Refs. 31 and 32. A decay energy $Q_{\beta}(^{158}\mathrm{Er}) = (2060 \pm 100)$ keV was measured. The multipolarities of the majority of γ transitions were determined. It was shown that when ^{158}Er decays levels of ^{158}Ho (see Table 1) are excited and also a number of higher lying states with $I^{\pi} = 1^-$, 2^-, and 2^+. It was noted that the probability of β decay to the level 139 Kev (1^-) is unusually large for first-forbidden transitions.

^{158g}Ho, $T_{1/2} = 11$ min, ^{158m_1}Ho, $T_{1/2} = 27$ min. Discovered and investigated in detail at Dubna. In our latest investigations[33-35] of the decay of the ground state and the isomeric state (2^-, 67 keV, 27 min) of this nucleus we observed 170 γ transitions and determine the multipolarities for 120 of them. Experiments were made in which we established that the γ transitions belonged to the decay of the isomeric state or the ground state of ^{158}Ho. A decay energy $Q_{\beta}(^{158g}\mathrm{Ho}) = 4220 \pm 30$ keV was measured. A complicated $^{158g,m_1}\mathrm{Ho} \rightarrow {}^{158}\mathrm{Dy}$ decay scheme was proposed (Fig. 2) which contains almost all the observed γ transitions. We identified rotational bands of the ground state (up to 8^+), of γ states (up to 5^+), of β states (up to 4^+), and of octupole vibrations, and also bands based on two-quasiparticle states.

^{158m_2}Ho, $T_{1/2} = (21 \pm 2)$ min. Discovered by Schepers.[36] The data of Ref. 35 confirm Schepers's conclusions about the spin and structure of this level: 9^+ (p523↑ + n505↑). In 90% of the cases, this state undergoes au−β decay to a level at 2528.5 keV with $I^{\pi} = 8^+$ (n523↓ + n505↑).

^{159}Yb, $T_{1/2} = (1.8 \pm 0.4)$ min. Discovered at Dubna.[37] When ^{159}Yb decays, γ's with energies 166(100) and 177 keV (48) are emitted.

^{159}Tm, $T_{1/2} = 9.0$ min. The existence of an (11 ± 3) min activity of ^{159}Tm was communicated in 1968 at Dubna.[38] In later investigations in the Yasnapp program a decay scheme was proposed (Fig. 3) which includes 12 excited states of ^{159}Er (Ref. 39). It was shown that the properties of the ground state of ^{159}Tm match a configuration of the type $5/2^+[402]$. In the decay $^{159}\mathrm{Tm} \rightarrow {}^{159}\mathrm{Er}$ identifications were made for the first time of levels of rotational bands of the states $3/2^-[521]$, $5/2^-[523]$, $3/2^+[402] + [651]$, $11/2^-[505]$, and levels with $I^{\pi} = 5/2^+$, $7/2^+$, and $9/2^+$ of a strongly perturbed band were also identified; these were described in the framework of a nonadiabatic model with allowance for residual centrifugal and spin–spin interaction between nucleons. A decay energy $Q_{\beta}(^{159}\mathrm{Tm}) = (3.4 \pm 0.3)$ MeV was determined.

^{159}Er, $T_{1/2} = (37 \pm 2)$ min. The latest results of the investigation of the isotope ^{159}Er discovered at Dubna in 1961 were presented in Ref. 40. A decay energy

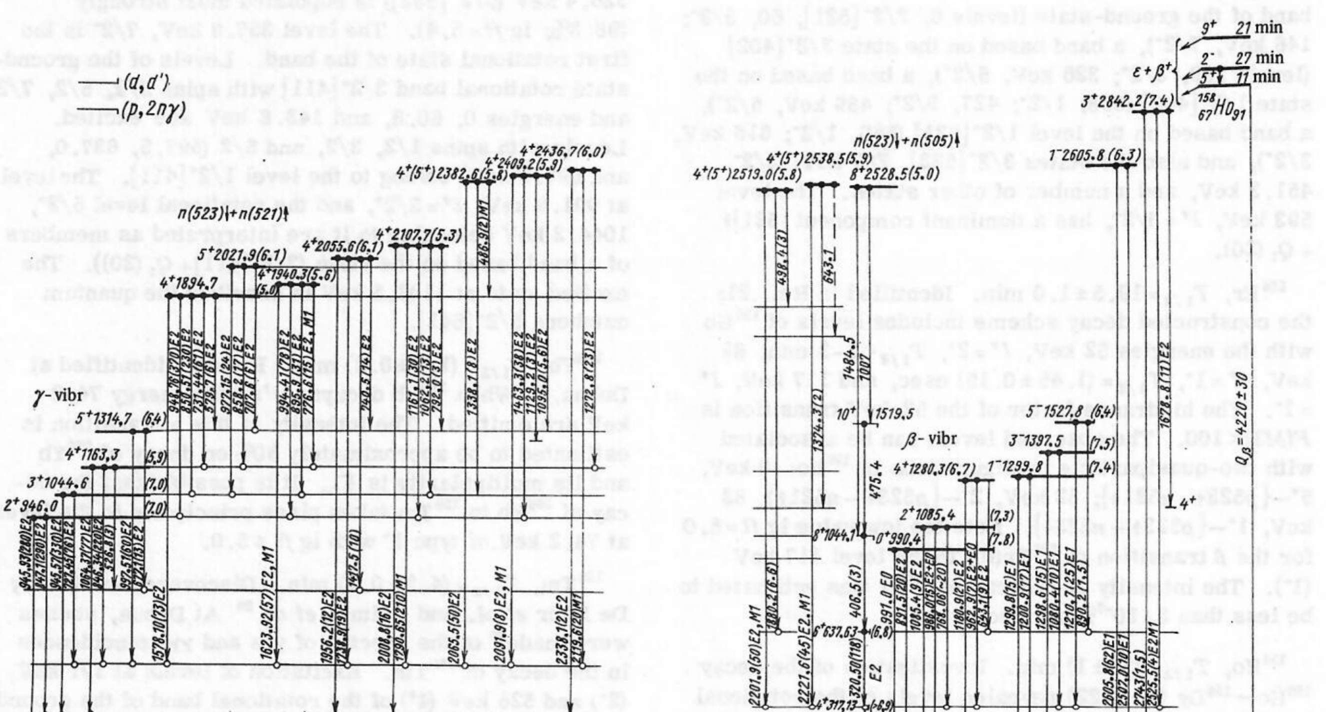

FIG. 2. Decay scheme of ^{158}Ho.

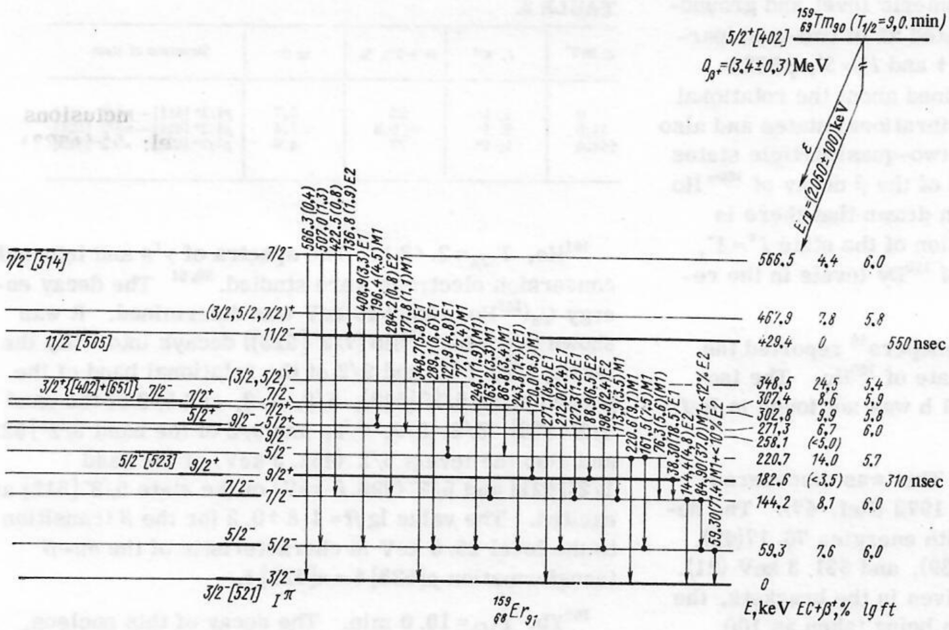

FIG. 3. Decay scheme of ^{159}Tm.

$Q_\beta(^{159}Er) = (2920 \pm 100)$ keV was established.

A scheme of the ^{159}Ho levels that occur as a result of the decay of ^{159}Er was proposed; it includes levels of the rotational band of the ground state 7/2⁻[523], a level at 166 keV with 7/2⁺[404], levels of the band 1/2⁺[411]: 1/2⁺ (205.9 keV), 3/2⁺ (221.2 keV), 5/2⁺ (328.2 keV), and 7/2⁺ (350.2 keV), and the level 1/2⁻ [5411] (431.8 keV); the level 3/2⁺[411] (299.1 keV), and the level 5/2⁻[532] (649.6 keV). When ^{159}Er decays there is strong excitation of a level at 624.5 keV with $I^\pi = 5/2^-$. The level with $I^\pi = 3/2^-$ at 504.8 keV is interpreted as a γ vibrational state of type 7/2⁻[523] + Q_{22}.

^{159}Ho, $T_{1/2} = (33 \pm 1)$ min. Information about the γ's and internal conversion electrons obtained in the Dubna experiments are summarized in Ref. 41. These results are consistent with the later investigations of Torres. In Ref. 41, a $^{159}Ho \rightarrow {}^{159}Dy$ decay scheme was proposed; it includes levels of the rotational band of the ground state 3/2⁻[521] (up to $I = 9/2$), levels of the band 5/2⁺[642] up to $I^\pi = 9/2^+$, and 5/2 and 7/2 levels of the band 5/2⁻[523]. We determine a decay energy $Q_\beta(^{159}Ho) = 1827 \pm 10$ keV and a value lg $ft = 4.84 \pm 0.06$ for the au–β transition of ^{159}Ho (7/2⁻[523]) to the level of ^{159}Dy with energy 309.6 keV (5/2⁻[523]). We measured the lifetime of the level 309.6 keV ($T_{1/2} = 3$ nsec) the level 177.6 keV, 5/2⁺[642] ($T_{1/2} = 9$ nsec), and also of the first rotational level at 57 keV of the ground-state band 3/2⁻[521] ($T_{1/2} = 0.2$ nsec). The quadrupole moment of ^{159}Dy was estimated to be $Q_0 \approx 5.5$ b.

^{160}Yb, $T_{1/2} = (4.8 \pm 0.2)$ min. Recently identified at Dubna.[42] The γ transitions 132.2 (9.9), 140.3 (16.6), 173.8 (77.4), and 215.8 keV (32.0) are ascribed to the decay of ^{160}Yb. The brackets contain the intensities of the γ's, the intensity of the K_α emission of Tm being taken as 100.

^{160}Tm, $T_{1/2} = 9.2$ min. The activity of thulium with $T_{1/2} = 8$ min observed in experiments at Dubna[38] is due to the decay of ^{160}Tm, as became clear from the work of De Boer *et al.*[29] Investigation of the decay of ^{160}Tm (Ref. 43) in the Yasnapp program made it possible to improve the results of Ref. 29 significantly. More than 40 γ transitions have been attributed to the decay of ^{160}Tm and the multipolarities of four of them determined. Experiments with $\gamma\gamma$ coincidences were made. A decay energy $Q_\beta(^{160}Tm) = (4.9 \pm 0.5)$ MeV was determined. The proposed decay scheme of ^{160}Tm contains levels of the rotational band of the ground state of ^{160}Er, levels of a γ-vibrational band, bands with $K^\pi = 0^+$, and some states with energy higher than 1 MeV.

^{160}Er, $T_{1/2} = 28.4$ h. This undergoes only electron capture. Under the assumption that a β transition is allowed, Buttsev *et al.*[44] determined the decay energy $Q_\beta(^{160}Er) = (340^{+190}_{-70})$ keV. It was assumed that the β decay takes place entirely to a hypothetical level of ^{160}Ho with $I^\pi = 1^+$ which lies somewhat higher ($\Delta E \leq 1.5$ keV (Ref. 45)) than the isomeric state of ^{160}Ho with $J^\pi = 2^-$, energy 60 keV, and $T_{1/2} = 5.0$ h. This isomeric state is excited in 100% of the cases of ^{160}Er decay.

^{160m}Ho, $T_{1/2} = 5.0$ h, $I^\pi = 2^-$, $E_{lev} = 60$ keV. This decays by β transitions to ^{160}Dy levels and by an isomeric $E3$ transition to the ground state. The fraction of the isomeric transition is $60 \pm 3\%$ (Ref. 46).

^{160g}Ho, $T_{1/2} = 25$ min, $I^\pi = 5^+$. Prolonged and detailed investigations of the decay of ^{160g,m}Ho are summarized in Ref. 46. Careful studies were made of the spectra of γ's, conversion electrons, and positrons. Studies were made of the spectra of pair-conversion positrons and monoenergetic positrons resulting from the conversion of high energy γ's. The decay energy is $Q_\beta(^{160g}Ho) = 3286 \pm 15$ keV. The energies and intensities of 340 γ transitions were determined, together with the multipolarities of half of them. Decay schemes of ^{160m}Ho and

^{160g}Ho were proposed. The isomeric level and ground-state level of ^{160}Ho are interpreted as of two-quasiparticle type: $I^\pi = 2^-$, $p523\uparrow - n651\uparrow$ and $I^\pi = 5^+$, $p523\uparrow + n521\uparrow$. Information was obtained about the rotational bands of the ground, λ, and β vibrational states and also about the bands of a number of two-quasiparticle states of ^{160}Dy. The strength function of the β decay of ^{160m}Ho was analyzed and the conclusion drawn that there is fragmentation of the wave function of the state $I^\pi = 1^-$, $n523\downarrow - n651\downarrow$ over a number of ^{160}Dy levels in the region 2.6–2.8 MeV.

^{160m_2}Ho, $T_{1/2} \approx 1$ h, $I^\pi = 9^+$. Schepers[18] reported the existence of such a isomeric state of ^{160}Ho. The isomeric state of ^{160}Ho with $T_{1/2} \approx 1$ h was not found in Ref. 46.

^{161}Yb, $T_{1/2} = (4.2 \pm 0.2)$ min. This was discovered during the Yasnapp program in 1973 (Ref. 47). The decay of ^{161}Yb gives rise to γ's with energies 78.17(49), 140.2(3.3), 188.2(4.5), 599.8(39), and 631.3 keV (21). The intensities of the γ's are given in the brackets, the intensity of the K_α x rays of Tm being taken as 100.

^{161}Tm, $T_{1/2} = 37$ min. This was studied at Dubna from 1964. The spectra of conversion electrons, γ's, delayed and instantaneous $\gamma\gamma$ coincidences, and positrons were investigated.[48] The decay energy $Q_\beta(^{161}\text{Tm}) = (3.2 \pm 0.2)$ MeV was determined. A decay scheme of ^{161}Tm was proposed. It was shown that the ground state of ^{161}Tm, in contrast to the other Tm isotopes with odd A, corresponds to the configuration $p7/2^+[404]$. The ground state of ^{161}Er is ascribed the configuration $3/2^-[521]$. In the ^{161}Er nucleus rotational levels associated with states of the type $3/2^-[521]$, $5/2^-[523]$, $3/2^+\{[402]+[651]\}$, $11/2^-[505]$, $3/2^-[532]$, and $5/2^-$ $5/2^-[512]$ were identified. When ^{161}Tm decays, one observes levels of a strongly perturbed rotational band with positive parity and $I = 5/2$, $7/2$, $9/2$, $11/2$, and $13/2$. The small value $\lg ft = 5.0$ for the β decay to the level at 2044.5 keV shows that its principal component is a three-quasiparticle state of the type $9/2^+\{p_1 7/2^-[523],\ p_2 7/2^+[404],\ n5/2^-[523]\}$.

^{161}Er, $T_{1/2} = 3.1$ h. As a result of investigation of the spectra of conversion electrons, γ's, positrons, and $\gamma\gamma$ coincidences a decay scheme of ^{161}Er was proposed in Ref. 49; it includes 37 excited states of ^{161}Ho. The mass difference $Q_\beta(^{161}\text{Er}) = (2.05 \pm 0.04)$ MeV was measured. Identifications were made of levels of rotational bands associated with the states $7/2^-[523]$ (ground state of ^{161}Ho), $1/2^+[411]$, $7/2^+[404]$, $3/2^+[411]$, $1/2^-[541]$, $5/2^+[413]$, and $5/2^-[532]$, and also with a γ-vibrational state of type $3/2^-$: $7/2^-[523] + Q_{22}$. Some of the ^{161}Ho levels with excitation energy higher than 1 MeV are regarded as one-particle states of the type $3/2^-[541]$, $3/2^-[532]$, $1/2^-[530]$, $1/2^-[550]$ or γ vibrations of the type $K-2$ to the state $7/2^+[404]$. The three levels at 1656.8, 1691.5, and 1740.1 keV have $I^\pi = 5/2^-$. It is assumed that these levels have a collective or three-quasiparticle nature. In particular, in Ref. 2 it is assumed that in the range 1.7–1.8 MeV in ^{161}Ho one can expect a multiplet of three-quasiparticle levels of the type $n_1 3/2^-[521]$, $n_2 5/2^-[523]$, $p7/2^-[523]$.

TABLE 2.

E, keV	I, K^π	($\varepsilon + \beta^+$), %	lg ft	Structure of state
0	1; 1^-	22	5,7	$p1/2^+[411] - n3/2^-[521]$
44,6	2; 1^-	<0,3	>7,4	$p1/2^+[411] - n3/2^-[521]$
163,4	1; 1^+	77	4.9	$p7/2^+[523] - n5/2^-[523]$

^{161}Ho, $T_{1/2} = 2.48$ h. The spectra of γ's and internal conversion electrons were studied.[50,51] The decay energy $Q_\beta(^{161}\text{Ho}) = 855 \pm 20$ keV was determined. It was shown that when ^{161}Ho ($7/2^-[523]$) decays into ^{161}Dy the levels 5/2, 7/2, and 9/2 of the rotational band of the ground state $5/2^+[642]$, 5/2, 7/2, and 9/2 of the band $5/2^-[523]$, 3/2, 5/2, 7/2, and 9/2 of the band $3/2^-[521]$, and also the levels $5/2^-$ (451.3 keV) of the band $1/2^-[521]$ and $5/2^-$ (790.6 keV) of the state $5/2^-[512]$ are excited. The value $\lg ft = 4.8 \pm 0.2$ for the β transition to the level 25.6 keV is characteristic of the $au-\beta$ transformation $p[523]\uparrow - n[523]\downarrow$.

^{162}Yb, $T_{1/2} = 19.0$ min. The decay of this nucleus, discovered at Dubna in 1963, was most fully studied in Ref. 43. The limit of the ratio of the intensities of electron capture and positron decay to the level 163.4 keV ($K/\beta^+ > 36$) was used to estimate the decay energy: $Q_\beta(^{162}\text{Yb}) \leq 2.2$ MeV. When ^{162}Yb decays, the levels of ^{162}Tm shown in Table 2 are excited.

In Ref. 52, the lifetime of the level at 44.6 keV was measured: $T_{1/2} = 1.55 \pm 0.20$ nsec, and values were determined for the internal quadrupole moment: $Q_0 = 6.00 \pm 0.49$ b, and the deformation parameter $\beta = 0.27 \pm 0.02$ of the ground state of ^{162}Tm.

^{162}Tm, $T_{1/2} = 21.8$ min. Discovered in 1963 at Dubna. The radiation resulting from the decay of ^{162}Tm was studied in Ref. 43. The mass difference $Q_\beta(^{162}\text{Tm}) = 4.6 \pm 0.3$ MeV was determined. The decay of ^{162}Tm was associated with 140 γ transitions, for ten of which the multipolarities were determined. Only some of the observed γ transitions were included in the decay scheme. The decay of ^{162}Tm is accompanied by the excitation of 0^+, 2^+, 4^+ levels of the rotational band of the ground state, 2^+, 3^+, and 4^+ levels of the γ-vibrational band, 0^+ and 2^+ levels of the β-vibrational band, and also other levels with $K^\pi = 0^+$, 1^-, and 2^-. Altogether, 12 excited states of ^{162}Er were introduced.

^{163}Yb, $T_{1/2} = 11.4$ min. Investigations were made of the spectra of γ's, conversion electrons, delayed and prompt $\gamma\gamma$ coincidences, and $\beta\gamma$ coincidences; these were used to construct for the first time a scheme of the ^{163}Tm levels excited during the decay of ^{163}Yb (Ref. 53). The mass difference $Q_\beta(^{163}\text{Yb}) = (3.37 \pm 0.10)$ MeV was measured.

^{163}Tm, $T_{1/2} = 1.8$ h. The latest data obtained on the decay of ^{163}Tm were presented in Refs. 53–55. In the decay scheme of ^{163}Tm, 23 excited states of ^{163}Er were introduced. They include levels of the rotational bands of the states $5/2^-[523]$, $5/2^+[642]$, $3/2^-[521]$, $1/2^-[521]$, $3/2^+\{[402]+[651]\}$, and $1/2^+\{[400]+[660]\}$. The levels 1538.6 ($3/2^+$) and 1801.5 keV ($1/2^+$) are members of a multiplet of a three-quasiparticle state: $\{p7/2^-[523],$

$p1/2^+[411]$, $n5/2^-[523]\}$. Measurements were made of the lifetimes of the excited states at the energies 69.2, 84.0, and 104.3 keV; they were 7.72, 0.92, and 0.52 nsec, respectively. The decay energy is $Q_\beta(^{163}Tm) = (2.6\pm0.2)$ MeV.

^{163}Er, $T_{1/2}=75$ min. Study of the spectra of γ's and internal conversion electrons solved only some questions[56]; in particular, the multipolarities were determined for the γ transitions at 436 ($M1$) and 440 keV ($E1$).

^{164}Yb, $T_{1/2}=75$ min. Discovered at Dubna in 1960. In the first investigations it was shown that ^{164}Yb decays primarily to the ground state of ^{164}Tm by an allowed unhindered β transition, so that the ground state of ^{164}Tm corresponds to a two-particle configuration: $1^+(p7/2^-[523]-n5/2^-[523]$. In 1971, the Dutch group of De Boer *et al.*[57] made a careful investigation of the γ spectra of the chain $^{164}Yb\to{}^{164}Tm\to{}^{164}Er$, and some of the transitions were attributed to the decay $^{164}Tb\to{}^{164}Tm$. Our investigations of the spectrum of conversion electrons[58] greatly extend the number of transitions that could be attributed to the decay of this nucleus. It is assumed that when ^{164}Yb decays, levels are excited in the nucleus ^{164}Tm at 37.5(2^+), 78.3(1^-), 97.2, 172.3, 261.7, 543.4, and 588.6 keV.

^{164}Tm, $T_{1/2}=2.0$ min. A decay scheme of this nucleus, which was discovered at Dubna, was proposed in Ref. 59. The decay energy is $Q_\beta(^{164}Tm)=3.96\pm0.02$ MeV. Levels of the rotational bands of the ground state and of a γ-vibrational state, and a number of other levels, were identified. An interesting result was the discovery of several 0^+ levels in the ^{164}Er nucleus. Subsequently, the decay of ^{164}Tm was studied in detail by the Dutch group.[57] Investigations of the conversion electron spectrum continue.[60]

^{165}Lu, $T_{1/2}=11.3$ min. For the first time, γ's and conversion electrons from the decay of ^{165}Lu were observed. The half life is $T_{1/2}=(11.3\pm0.3)$ min (Ref. 61). In Ref. 62 a fragment of the decay scheme of ^{165}Lu is proposed.

^{165}Yb, $T_{1/2}=10.5$ min. A decay scheme of this nucleus was proposed on the basis of the spectra of γ's and $\gamma\gamma$ coincidences obtained by Rasmussen *et al.*[63] Our group is making investigations of the spectra of conversion electrons from the decay of ^{165}Yb. Preliminary results were published in Ref. 64.

^{165}Tm, $T_{1/2}=30.1$ h. The decay of ^{165}Tm has been the subject of several studies of the Dubna group[65–67,55] and other investigations.[68,69] It has been established that when ^{165}Tm decays 28 levels of ^{165}Er are populated. The spins and parities of 21 of them have been established. Identifications have been made of the ground and rotational levels of the following one-quasiparticle states: $5/2^-[523]$; $5/2^+[642]$; $3/2^-[521]$; $1/2^-[521]$; $5/2^-[512]$; $1/2^+\{[400]+[660]\}$, $3/2^+\{[402]+[651]\}$, $3/2^-[532]$ and a three-quasiparticle state of the type $3/2^+\{p7/2^-[523], p1/2^+[411], n5/2^-[523]\}$. The method of $e\gamma$ delayed coincidences was used to measure the lifetimes of nine excited states of ^{165}Er, and the probabilities of the γ transitions were determined.[55]

^{165}Er, $T_{1/2}=10.39\pm0.07$ h. The transformation of ^{165}Er($5/2^-[523]$) is entirely to the ground state of ^{165}Ho ($7/2^-[523]$). The decay energy $Q_\beta(^{165}Er)=371\pm6$ keV (Ref. 70) was deduced from the internal bremsstrahlung spectrum.

^{166}Hf, $T_{1/2}=6.0\pm0.5$ min. The half life of the new ^{166}Hf isotope was determined from the decrease in the intensity of the γ's from ^{166}Tm in preparations of Lu separated successively from the Hf fraction.[71]

^{166}Lu, $T_{1/2}=3.3\pm0.2$ min. The new isotope ^{166}Lu was discovered in the Yasnapp program in 1969 (Ref. 71). Gammas at energies 102, 228, 338, and 428 keV were observed.

^{166}Yb, $T_{1/2}=56.7$ h. The latest and most accurate data on the decay of this nucleus were obtained by the Dutch group of De Boer *et al.*[72] Electron capture in the nucleus ^{166}Yb ($Q_\beta(^{166}Yb)=215^{+33}_{-18}$ keV, $\lg ft=4.5\pm0.1$) leads to excitation of a level at 82.3 keV of ^{166}Tm of type $1^+\{p[523]\uparrow-n[523]\downarrow\}$. The F-forbidden γ transition from this level to the ground state of type $2^+\{p[411]\downarrow-n[642]\uparrow\}$ has a low hindrance factor $F_W<400$.

^{166}Tm, $T_{1/2}=7.7$ h. The decay scheme of ^{166}Tm is very complicated. The most complete of the previously published investigations of this isotope[73,74] were made by the Dubna group. The investigations of the decay of ^{166}Tm have now been completed and preliminary results communicated in Ref. 75. The electron capture and β^+ decay in ^{166}Tm is accompanied by about 300 γ transitions with the excitation of levels in ^{166}Er with energy up to 2.8 MeV. Identifications have been made of levels of rotational bands of the ground state of ^{166}Er up to $I^\pi=6^+$, of a γ-vibrational state up to $I^\pi=5^+$, and of an octupole state up to $IK^\pi=42^-$. The series of levels at 1918, 2002, 2021, 2216, and 2160 keV and others are regarded as two-quasiparticle excitations. On the basis of the low value of $\lg ft=5.5$ and 6.1 it is concluded in Ref. 73 that the levels at 2133 and 2160 keV contain an appreciable admixture of the four-quasiparticle state $3^+\{n[642]\uparrow, n[523]\downarrow, p[411]\downarrow, p[523]\uparrow\}$. The decay energy is $Q^\pi(^{166}Tm)=3030\pm5$ keV.

^{167}Ta, $T_{1/2}=(2.9\pm1.5)$ min. This was discovered by the method of successive separation of the daughter activities from an Hf preparation.[76]

^{167}Hf, $T_{1/2}=(1.9\pm0.2)$ min. This was discovered by the radiochemical method.[71] A fragment of the decay scheme has been proposed: ^{167}Hf from a ground state of type $5/2^-[523]$ by allowed unhindered β decay goes over into an excited state of ^{167}Lu with energy 316 keV of type $7/2^-[523]$.

^{167}Lu, $T_{1/2}=55$ min. The results of investigations of the decay of ^{167}Lu are summarized in Ref. 78. The proposed decay scheme includes 21 excited levels of ^{167}Yb. Of these, 19 are identified as members of rotational bands of the states $5/2^-[523]$, $5/2^+[642]$, $7/2^+[633]$, $3/2^-[521]$, $1/2^-[521]$, $5/2^-[512]$, $7/2^-[514]$. The $^{167}Lu-{}^{167}Yb$ mass difference is $Q_\beta(^{167}Lu)=3.1\pm0.1$ MeV.

^{167}Yb, $T_{1/2}=18$ min. The most complete investigation of the radiation accompanying the decay of ^{167}Yb was made in Ref. 79. Of the 25 established excited levels of ^{167}Tm, 20 were identified as members of rotational bands of the states $1/2^+[411]$, $1/2^-[541]$, $7/2^+[404]$, $7/2^-[523]$, $3/2^+[411]$, $5/2^+[413]$ and $5/2^-[532]$. The state at energy 1216.5 keV is associated with an octupole vibration based on the state $7/2^-[404]$ with a certain admixture of the configuration $7/2^-[523]$. The decay energy is $Q_\beta(^{167}\text{Yb}) = 1970 \pm 30$ keV.

^{167}Tm, $T_{1/2} = 9.6$ days. The relatively simple decay scheme of this isotope was analyzed in Refs. 80–82.

^{168}Ta, $T_{1/2} = 2.5 \pm 1.2$ min. This was first identified in Ref. 76 by the radiochemical method.

^{168}Lu, $T_{1/2} = 7.1$ min. The first detailed investigation of the decay of the seven-minute ^{168}Lu was Ref. 83. When this nucleus decays, 16 levels of ^{168}Yb are excited. Identifications have been made of the levels of a rotational band of the ground state up to $I^\pi = 6^+$ and of a γ-vibrational state up to $J^\pi = 5^+$. It is assumed that a four-quasiparticle state makes an important contribution to the wave functions of the excited levels at 2205 and 2405 keV. The identification of the structure of this state is determined by the structure of the two-quasiparticle ground state of ^{168}Lu, which is unknown. The decay energy is $Q_\beta(^{168}\text{Lu}) = 4.8 \pm 0.4$ MeV.

^{168}Tm, $T_{1/2} = 85$ days. Some refinements to the detailed decay scheme of ^{168}Tm were published in Ref. 84.

^{169}Ta, $T_{1/2} = 5.0 \pm 0.5$ min. This was discovered in an analysis of the γ spectra of Hf preparations separated successively from the Ta fraction of the reaction products of deep spallation.[76]

^{169}Hf, $T_{1/2} = 3.2 \pm 0.1$ min. Identified by Arl't *et al.*[71] When ^{169}Hf decays, γ transitions are observed with energies (intensities in parentheses) at 123(7), 369(13), and 493 keV (100). A fragment of the decay scheme has been proposed: When ^{169}Hf($5/2^-[523]$) decays by an au–β transition, the level at 493 keV ($7/2^-[523]$) is mainly populated, and this level decays to the ground state ($7/2^+[404]$) and its rotational level with $I^\pi = 9/2^+$. These results were recently confirmed in Ref. 77.

^{169}Lu, $T_{1/2} = 36$ h. Several of our studies, the last of which were Refs. 85 and 86, were devoted to the decay scheme of ^{169}Lu. We established the excitation of 41 energy levels of ^{169}Yb. We identified levels of rotational bands of the following states $7/2^+[633]$; $7/2^+[642]$; $3/2^+[651] + 7/2^+[633]Q_{22}$; $1/2^-[521]$; $5/2^-[512]$; $5/2^-[523]$; $3/2^-[521] + 1/2^-[521]Q_{22}$; $7/2^-[514]$; $9/2^+[624]$; $7/2^+[633]Q_{22}$; $7/2^-[503]$ and $7/2^-[514]$. The value $Q_\beta(^{169}\text{Lu}) = 2820 \pm 50$ keV was determined.

^{170}Ta, $T_{1/2} = 7.0 \pm 0.5$ min. This was identified in Ref. 76. When ^{170}Ta decays, there are γ transitions with energies 101, 221, and 986 keV. The first two transitions take place between 4^+, 2^+, and 0^+ rotational levels and the ^{170}Hf ground state. These results were confirmed in Ref. 87.

^{170}Lu, $T_{1/2} = 48.2 \pm 0.5$ h. A detailed analysis of the results of investigations into the decay of ^{170}Lu, and other nuclei with $A = 170$, can be found in the book (Ref. 88) of Dzhelepov and Shestopalova. On decay of ^{170}Lu, which has $I^\pi = 0^+$ in the ground state, more than 40 levels of ^{170}Yb with low spins $I^\pi = 0^+$, 1^+, 2^+, 0^-, and 1^- are excited. Finally, $Q_\beta(^{170}\text{Lu}) = 3467 \pm 20$ keV.

^{171}Ta, $T_{1/2} = 25 \pm 2$ min. This was first identified by the radiochemical method.[76]

^{171}Lu, $T_{1/2} = 8.23$ days. In our latest investigations, Refs. 89–92, of the decay of ^{171}Lu the data on the emission accompanying this decay were made much more precise. It was shown that when ^{171}Lu decays 26 levels of ^{171}Yb are excited, and these are interpreted as members of rotational bands of the states $1/2^-[521]$; $5/2^-[512]$; $7/2^+[633]$; $7/2^-[514]$; $7/2^-[523]$; $9/2^+[624]$; $5/2^+[642]$; $3/2^-[521] + 1/2^-[512]Q_{22}$; $3/2^-[521]$, and $3/2^-[521] + 7/2^-[514]Q_{22}$. We estimated the ^{171}Lu–^{171}Yb mass difference: $Q_\beta(^{171}\text{Lu}) = 1.7 \pm 0.2$ MeV.

^{172}W, $T_{1/2} = 6 \pm 2$ min. This was obtained in the reaction Re(p, xp, yn)W by the irradiation of the oxide of Re by protons in the Dubna synchrocyclotron.[93] The identification was by the radiochemical method.

^{172}Lu, $T_{1/2} = 6.7$ days. The results obtained in the first stage in the investigations of the complicated decay scheme of ^{172}Lu were presented in Refs. 94 and 95. Very complete information about the decay of ^{172}Lu and the structure of the ^{172}Yb levels was then published in the paper Ref. 96 of the American physicists Sen and Zganjar. In our papers published in 1971–1975 we obtained more accurate and additional information about the spectrum of internal conversion electrons[92,97–99] and the γ spectrum[100] associated with the decay of ^{172}Lu.

^{173}Ta, $T_{1/2} = 3.7$ h. Investigation of the decay ^{173}Ta $\to$ ^{173}Hf led to the identification of levels of rotational bands of the states $1/2^-[521]$, $5/2^-[512]$, and $7/2^+[633]$, and some highly energetic states. We measured the lifetimes of the levels at 107.2 keV ($5/2$ $5/2^-[512]$: 180 nsec, and 197.3 keV ($7/2$ $7/2^+[633]$): 170 nsec (Ref. 101).

^{174}W, $T_{1/2} = 31 \pm 2$ min. Discovered by Demeter *et al.* at the Laboratory of Nuclear Problems at Dubna.[102]

^{175}Re, $T_{1/2} = 5 \pm 1$ min. Discovered by Dubna.[103]

^{175}Ta, $T_{1/2} = 10.5$ h. Investigations of the decay of ^{175}Ta in Ref. 104 led to the introduction of 23 new levels of ^{175}Hf. Identifications were made of levels of the rotational bands of the one-quasiparticle states $5/2^-[512]$, $1/2^-[521]$, $7/2^+[633]$, $7/2^-[514]$, $9/2^+[624]$, and $5/2^+[642]$ and the β-vibrational states $7/2^+[633]Q_{20}$, $5/2^-[512]Q_{20}$, $7/2^-[514]Q_{20}$ and $9/2^+[624]Q_{20}$.

^{176}Os, $T_{1/2} = 3.0 \pm 0.7$ min. Discovered by Arl't *et al.*[105]

^{176}Re, $T_{1/2} = 5 \pm 1$ min. The discovery of this isotope was communicated in Ref. 103.

^{176}Ta, $T_{1/2} = 8.0$ h. A decay scheme of this nucleus was proposed in Ref. 106. Information was obtained about levels of the rotational bands of quadrupole ($K^\pi = 0^+$ and 2^+) and octupole ($K^\pi = 0^-$, 1^-, and 2^-) vibrational states and some two-quasiparticle states. The low value of lg ft for the β decay to the levels at 2911, 2920, and 2943 keV suggests that the wave functions of these ^{176}Hf levels contain an appreciable admixture of a four-quasiparticle state of the type $\{p7/2^+[404], p9/2^-[514], n5/2^-[512], n7/2^-[514]\}$.

^{177}Os, $T_{1/2}=3.5\pm0.8$ min. Discovered in Ref. 105. Information was obtained about the γ's accompanying the β decay of this isotope.

^{178}Ir, $T_{1/2}=0.5\pm0.3$ min. Discovered in Ref. 107. It was established that the decay of ^{178}Ir is accompanied by the excitation of levels of the rotational band of the ground state of ^{178}Os up to $I^\pi=6^+$.

^{179}Re, $T_{1/2}=20$ min. Results of investigations of the ^{179}Re decay were communicated in Refs. 105 and 108. A decay scheme was constructed. It was established that the ground state of ^{179}W is of type $5/2^+[402]$. One-quasiparticle states were identified: $7/2^-[514]$, $1/2^-[521]$, $9/2^+[624]$, $5/2^-[512]$, $7/2^+[633]$, and $1/2^-[510]$. The levels with energy (I^π) 720.5 ($3/2^+$) and 1680.1 keV ($7/2^+$) are members of a three-quasiparticle multiplet: $\{p9/2^-[514], p5/2^+[402], n7/2^-[514]\}$.

^{180}Ir, $T_{1/2}=1.5\pm0.1$ min (Ref. 107). When ^{180}Ir decays, levels with $I^\pi=2^+$ and 4^+ of the rotational band of the ground state of ^{180}Os are excited.

^{181}Ir, $T_{1/2}=5.0\pm0.3$ min (Ref. 107). Twenty-one γ transitions with energy up to 2 MeV have been ascribed to the decay of this nucleus.

^{181m}Os, $T_{1/2}=105$ min. The decay of the 105-min isomeric state of ^{181}Os was studied.[109] The ^{181}Os $\to$ ^{181}Re decay energy was measured: $Q_\beta(^{181m}\text{Os})=3.04\pm0.20$ MeV. It was found that the isomeric state of ^{181}Os must be ascribed the configuration $1/2^-[521]$. In ^{181}Re, rotational levels of the following states are excited: $5/2^+[402]$, $9/2^-[514]$, $1/2^-[514]$, $3/2^+[402]$, $3/2^-[532]$, $1/2^+[411]$, $3/2^+[411]$ and $1/2^-[510]$. The lowest level of the rotational band of the state $1/2^-[541]$ has $I^\pi=5/2^-$. The lifetime of this level ($E_{1ev}=356.7$ keV) is 96 ± 4 nsec.

^{182}Ir, $T_{1/2}=15\pm1$ min. Study of the decay of ^{182}Ir led to the identification of rotational levels of the ground state of ^{182}Os with $I^\pi=2^+$, 4^+, and 6^+ and rotational levels of a γ-vibrational state with $I^\pi=2^+$, 3^+, 4^+, and 5^+ (Ref. 107).

^{182}Os, $T_{1/2}=22$ h. In Ref. 110 a decay scheme is proposed for ^{182}Os, containing 11 excited levels of ^{182}Re. The spins and parities of all 11 lines were determined. Measurements were made of the lifetimes of the levels with energies 235.7 ($T_{1/2}=0.35\pm0.04$ nsec) and 263.3 keV ($T_{1/2}=5.27\pm0.16$ nsec). The structure of the excited states of ^{182}Re was discussed.

^{182}Re, $T_{1/2}=64$ h. The decay scheme of ^{182}Re (Ref. 111) was made more precise and augmented. The quantum numbers of the ground state of ^{182}Re were determined: $7^+\{p5/2^+[402]+n9/2^+[624]\}$. Four new levels were introduced in the ^{182}W nucleus. The following two-particle states were identified: $2^-\{p5/2^+[402]-n9/2^-[514]\}$; $4^-\{n9/2^+[624]-n1/2^-[510]\}$; $5^-\{n9/2^+[624]+n1/2^-[510]\}$; $7^-\{p5/2^+[402]+p9/2^-[514]\}$; $3^-\{n9/2^+[624]-n3/2^-[512]\}$; $6^-\{n9/2^+[612]+n3/2^-[512]\}$ and $2^-\{n9/2^+[624]-n5/2^-[512]\}$.

^{182m}Re, $T_{1/2}=13$ h. In Ref. 112 the decay scheme of the isomeric state of ^{182}Re with $T_{1/2}=13$ h was made more precise and augmented. The structure of this state of ^{182}Re was determined: $2^+\{p5/2^+[402]-n9/2^+[624]\}$. A new level was introduced: 1538 keV with $I^\pi K=2^+0$. The levels at energy 1057 (1^+) and 2116 keV (2^+) are regarded as rotational levels of a state of the type $1^+\{p5/2^+[402]-n7/2^+[404]\}$.

^{183m}Os, $T_{1/2}=10$ h; ^{183}Os, $T_{1/2}=12$ h. In the investigation of the decay of the ^{183}Os isomers[113] an estimate was made of the ^{183}Os $\to$ ^{183}Re decay energy: $Q_\beta(^{183}\text{Os})<2110$ keV. Rotational levels of one-quasiparticle states were identified: $5/2^+[423]$; $9/2^-[514]$; $7/2^+[404]$; $1/2^-[541]$; $3/2^+[402]$; $1/2^+[411]$; $3/2^-[532]$ and $3/2^+[411]$. The level at 2030 keV in ^{183}Re was identified as a three-quasiparticle state of the type $11/2^+\{p9/2^-[514], n9/2^+[624], n7/2^-[514]\}$.

^{184}Ir, $T_{1/2}=3.2$ h. The method of delayed $\gamma\gamma$ coincidences was used to determine the lifetime of the 2^+ level of the rotational band of the ground state at energy 119.8 keV: $T_{1/2}=1.18\pm0.05$ nsec (Ref. 114).

^{186}Ir, $T_{1/2}=15$ h; ^{186m}Ir, $T_{1/2}=1.7$ h. The ^{186}Os levels were studied through the decay of the ^{186}Ir isomers.[114–116] The results of investigations of the decay of ^{186m}Ir were used in Ref. 115 to construct a scheme of ^{186}Os levels including ten levels. Their spins and parities were determined. In Ref. 116 a level was introduced at energy 2377 keV ($I^\pi=5^+$ or 6^+). In Ref. 114 the lifetime of the 2^+ state (137.2 keV) of the rotational band of the ground state of ^{186}Os was determined: $T_{1/2}=(0.84\pm0.05)$ nsec.

^{188}Ir, $T_{1/2}=41$ h. The lifetime of the rotational level 1550 keV((2^+) in ^{188}Os was found to be $T_{1/2}=(0.71\pm0.03)$ nsec (Ref. 114).

3.2 Discussion of the results of experimental investigations of deformed nuclei of rare-earth elements

We now consider some general conclusions that follow from the experimental investigations of the structure of deformed nuclei of rare-earth elements and, in particular, from the Yasnapp results. Some of the questions in this area were discussed in the reviews Refs. 8, 9, 117–121.

Nonrotational states of odd deformed nuclei ($150<A<190$). Let us consider the nonrotational, nearly one-quasiparticle states of odd deformed nuclei and the influence of the interaction of the quasiparticles with phonons on their energy and structure; we shall systematize the existing experimental data on one-quasiparticle states of odd nuclei and compare them with theoretical calculations in the framework of current models.[2,117] The experimental data on this question were considered in Ref. 9 in 1971. In the four years that have since elapsed, the amount of experimental information has increased considerably.

One-quasiparticle excited states. The simplest representation of the structure of odd deformed nuclei is

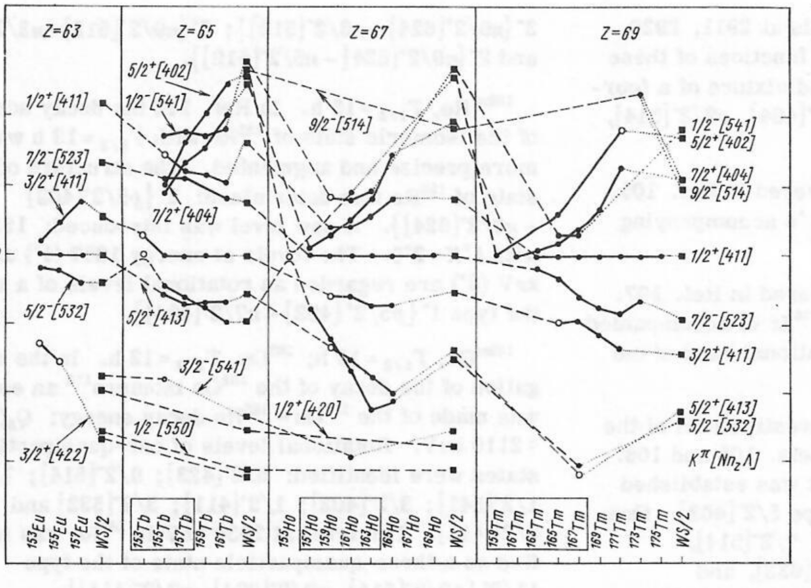

FIG. 4. Energies of one-quasiparticle levels in nuclei with odd A ($Z=63-69$). The black circles are reliably established states; the open circles, assumed states; the open squares, calculated one-particle energies of the average field described by the deformed Woods–Saxon potential.

given by the model of independent quasiparticles.[2] In this model, the interaction between nucleons of the nucleus is divided into two parts: an average nuclear potential (the average field) created by all the nucleons of the nucleus, and a residual interaction leading to pairing correlations of superconducting type. In the model of independent quasiparticles, the ground state and a large number of excited states have a one-quasiparticle structure; the higher states have a three-quasiparticle structure, etc. The behavior of the one-quasiparticle states—their energy and sequence—is determined basically by the average field of the nucleus. To describe the average field of deformed nuclei one uses the potentials of Nilsson[2,122] or Woods and Saxon.[2,117,123] The one-quasiparticle states are characterized by the quantum numbers $K^\pi[Nn_z\Lambda]$ of the state of the average field in which the quasiparticle is situated.

The experimental data on the energies of the one-quasiparticle states in odd deformed nuclei with $150<A<190$ are shown in Figs. 4–7. The nuclei are divided into groups with the same odd Z (Figs. 4 and 5) and N (Figs. 6 and 7) numbers. The experimental data are taken from our studies, the reviews Refs. 9 and 120, and the large number of investigations published up to the middle of 1974. For comparison, we use the one-particle energies of the deformed Woods–Saxon potential calculated by Gareev *et al.*[123] for four bands with the values $A=155$, 165, 173, and 181. The calculations were made for hexadecapole deformation parameters $\beta_{40}=0.06$, 0.02, -0.02, and -0.06 for each band, respectively. The energies were taken for the values $\beta_{20}=0.28$, 0.26, and 0.24 for the quadrupole deformation parameter, respectively. The groups of nuclei with the same odd number of protons Z or neutrons N were distributed over these zones as follows: $A=155$: $Z=63$, 65, and $N=91$, 93; $A=165$: $Z=67$, 69, and $N=95$, 97, 99; $A=173$: $Z=71$ and $N=101$, 103, 105; $A=181$: $Z=73$, 75, and $N=107$, 109, 111, 113. The average value of the mass number A in each group was

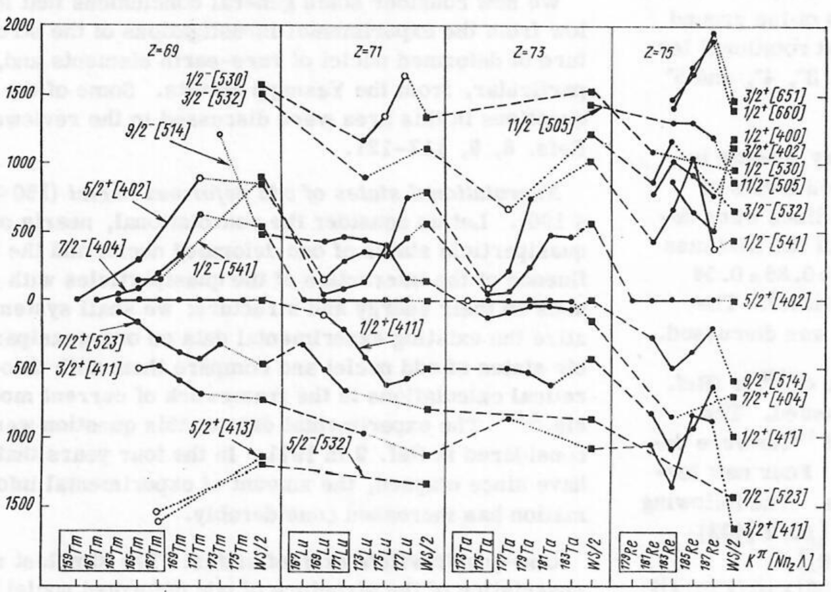

FIG. 5. Energies of one-quasiparticle levels in nuclei with odd A ($Z=69-75$). The notation is the same as in Fig. 4.

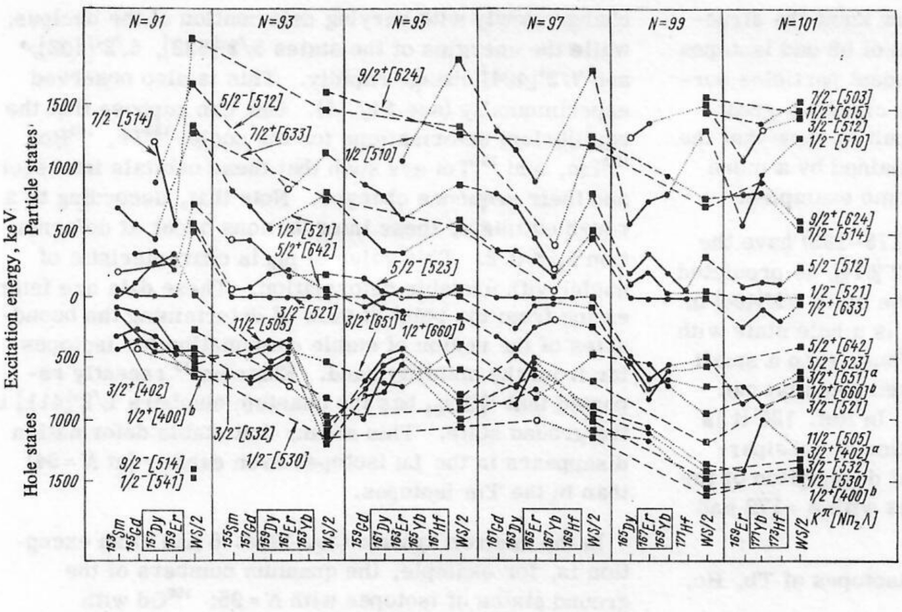

FIG. 6. Energies of the one-quasiparticle levels in nuclei with odd A (Z = 91–101). The notation is the same as in Fig. 4.

near the A value of the selected band. It is known that pairing correlations of superconducting type increase the density of one-quasiparticle states.[2] Therefore, in Figs. 4–7 we have plotted the one-particle energies calculated in Ref. 123 but divided by two.

One can object to the use for comparison with experimental data of the one-particle energies of the Woods–Saxon potential on the ground, that, as was already known more than ten years ago,[124,125] the low-lying nonrotational states of odd nuclei frequently exhibit collective properties, i.e., their wave functions contain an appreciable admixture of vibrational states. In Ref. 123 it was shown that the interaction of quasiparticles with phonons changes the properties of the quasiparticle levels and, in particular, reduces their energy. In Figs. 4–7 we show in compact form the experimental data hitherto obtained on the nonrotational levels in odd nuclei. Comparison of these data with the energies of the one-particle states in the Woods–Saxon potential enables one to draw some helpful conclusions.

As can be seen in Figs. 4–7, the model of independent quasiparticles gives a satisfactory qualitative description of the excited states in odd deformed nuclei. The experimentally observed density of states corresponds to the calculated density when the reduction coefficient of 2 mentioned above is introduced. One can clearly see that each chosen proton or neutron state is manifested first as a particle state whose energy decreases with increasing number of protons or neutrons; at a definite odd number of protons or neutrons, this state becomes the ground state, and it then appears as a hole state. It is remarkable that, as a rule, the quantum numbers of the ground states are described by the model. Thus, the 65th proton in the ground state must be in the state $3/2^+[411]$; it is established experimentally that the four isotopes of Tb (A = 155–161) have these quantum numbers in the ground state. The 67th proton must be in the state $7/2^-[523]$—and the seven isotopes of Ho (A = 157–169) have these quantum numbers. The seven isotopes of Tu (A = 163–175) have the quantum numbers $1/2^+[411]$ in the ground state, and so

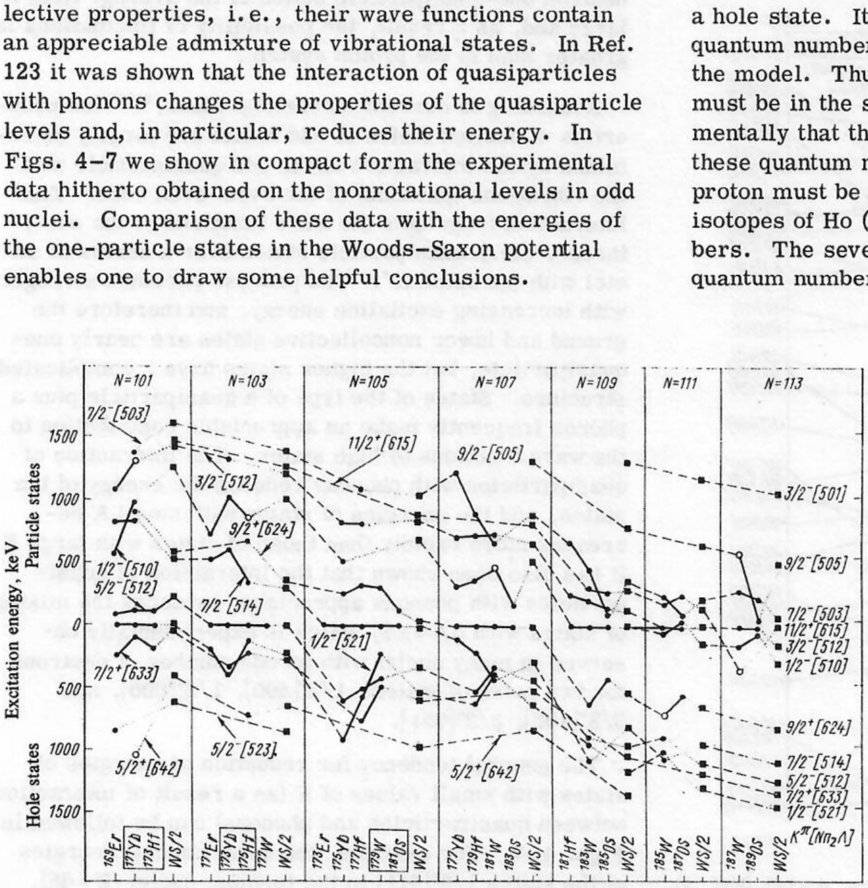

FIG. 7. Energies of the one-quasiparticle levels in nuclei with odd A (N = 101–113). The notation is the same as in Fig. 4.

forth. From the experiments, we now know the structure of the ground states of the nuclei of 98 odd isotopes of this region. The model of independent particles correctly describes 70 of them. This is clearly a great success of the model. It is not difficult to show that the majority of the deviations can be explained by a more detailed examination. Let us give some examples.

All the six odd isotopes of Ta ($A=175-183$) have the quantum numbers $7/2^+[404]$ and not $9/2^-[514]$, as predicted by the model, in the ground state. The state $7/2^+[404]$ in the Woods–Saxon potential for $Z=73$ is a hole state with low excitation energy (~ 100 keV). Thus, even a small change in the parameters of the chosen potential can change the sequence of these levels. In Ref. 123 it is shown that allowance for the interaction of quasiparticles with phonons leads to a correct description of the ground states of the tantalum isotopes with $A=179$ and 181 (but not 177).

Exceptions are also found for the isotopes of Tb, Ho, and Tm:

$^{153}_{65}Tb_{88}$ has $5/2^-$ [532]; $^{155}_{67}Ho_{88}$ has $5/2^+$ [402] or $5/2^-$ [532];

$^{159}_{69}Tm_{90}$ has $5/2^+$ [402]; $^{161}_{69}Tm_{92}$ has $7/2^+$ [404].

The most probable explanation of this is that the deformation of the nuclei decreases with decreasing number of neutron pairs in them. As can be seen from Fig. 8, the energies of the one-particle states $3/2^+[411]$, $7/2^-[523]$, and $1/2^+[411]$ in the Woods–Saxon potential

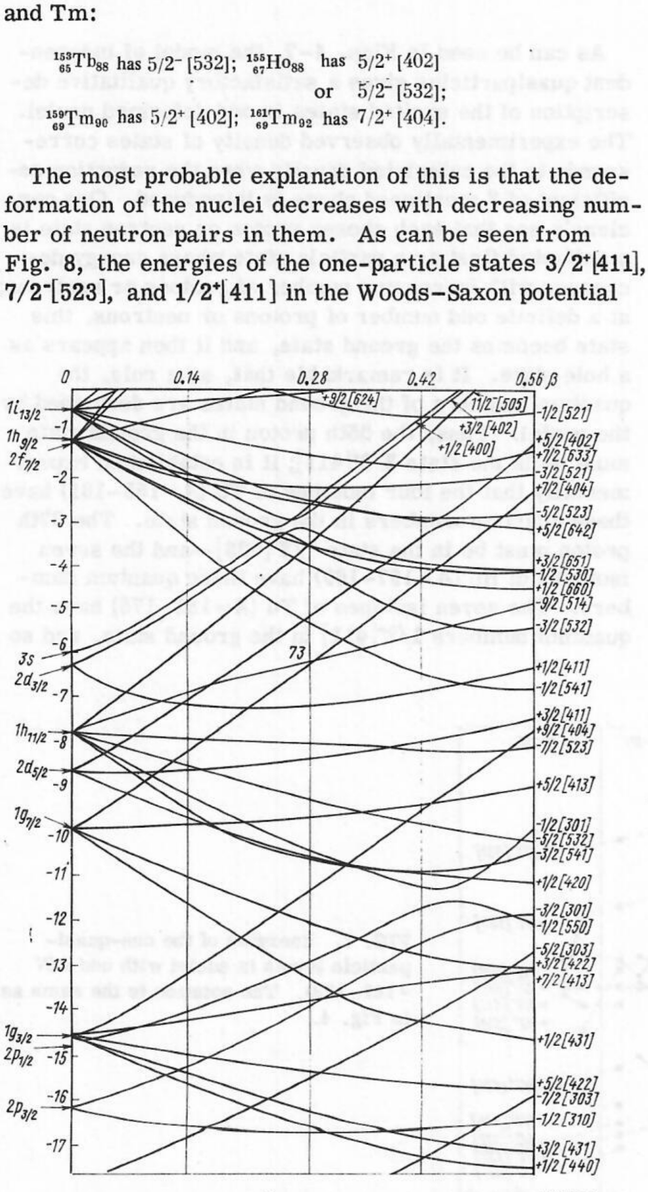

FIG. 8. Scheme of proton one-particle states, $A=181$ (Ref. 2).

change slowly with varying deformation of the nucleus, while the energies of the states $5/2^-[532]$, $5/2^+[402]$, and $7/2^+[404]$ change rapidly. This is also observed experimentally (see Fig. 4). One can suppose that the equilibrium deformations for the nuclei ^{153}Tb, ^{155}Ho, ^{159}Tm, and ^{161}Tm are such that these orbitals intersect and their sequence changes. Note that, according to a rough estimate, these intersections occur at deformation $\beta_{20} \lesssim 0.2$. This value of β_{20} is characteristic of nuclei with unstable deformation. These data are interesting from the point of view of determining the boundaries of the region of stable deformation for isotopes far from the stability band. Ekström[126] recently reported that $^{165}_{71}Lu_{94}$ has the quantum numbers $1/2^+[411]$ in the ground state. This means that stable deformation disappears in the Lu isotopes even earlier (at $N=94$) than in the Tm isotopes.

In the neutron system (see Figs. 6 and 7) an exception is, for example, the quantum numbers of the ground states of isotopes with $N=95$: ^{159}Gd with $3/2^-[521]$, ^{161}Dy with $5/2^+[642]$, ^{163}Er with $5/2^-[523]$, ^{165}Yb with $5/2^-[523]$, and ^{167}Hf with $5/2^-[523]$. Only in the case of ^{161}Dy are the quantum numbers predicted by the model observed. The position for isotopes with $N=95$ can be explained by pointing out that all these states are very near the Fermi surface and small fluctuations of the average field due, for example, to a change in the number of proton pairs can alter the sequence of levels. It can be seen from Figs. 4–7 that the neutron system of one-particle states is much more complicated than the proton system. The number of neutron one-quasiparticle states of the average field is large and, as a result, the possibility of fluctuations is greater than in the proton system.

According to current theoretical ideas,[2,117] the properties of excited states of odd nuclei are largely determined by the interaction of the odd quasiparticle with the vibrations (phonons) of the even–even core. This interaction fragments the wave functions of the one-, three-, etc., quasiparticle states over a series of nuclei with the same K^π. The process becomes stronger with increasing excitation energy, and therefore the ground and lower noncollective states are nearly one-quasiparticle, but the higher states have a complicated structure. States of the type of a quasiparticle plus a phonon frequently make an appreciable contribution to the wave functions of high states. The interaction of quasiparticles with phonons reduces the energy of the states, and the energies of states with small K decreases more rapidly than those of states with large K. It has also been shown that the interaction of quasiparticles with phonons appreciably enhances the mixing of states with $\Delta N=\pm 2$, which is experimentally observed in many nuclei with an odd number of neutrons for two pairs of states: $1/2^+[400]$, $1/2^+[600]$, and $3/2^+[402]$, $3/2^+[651]$.

The general tendency for reduction of energies of states with small values of K (as a result of interaction between quasiparticles and phonons) can be followed in Figs. 4–7. For example, the experimental energies of the states $1/2^+[411]$ in the terbium nuclei ($Z=65$),

TABLE 3. Energies and structure of nonrotational states in the nucleus ^{167}Tm.

K^π	Energy, keV experiment	Energy, keV theory	Structure
1/2+	0	0	411↓97 %,
7/2−	292.8	360	523↑96 %, 411↑ + Q_1 (32) 2 %
9/2−	—	560	514↑96 %, 402↑ + Q_1 (32) 2 %
7/2+	179.5	370	404↓97 %, 651↑ + Q_1 (22) 2 %
3/2+	470.7	670	411↑82 %, 411↓ + Q_1 (22) 11 %, 523↑ + Q_1 (32) 4 %
5/2+	—	820	402↑12 %, 413↓3 % 411↓ + Q_1 (22) 84 %
3/2−	—	900	541↑ 3 %, 523↑ + Q_1 (22) 97 %
11/2−	—	940	523↑ + Q_1 (22) 100 %
3/2+	—	990	411↑10 %, 411↓ + Q_1 (22) 89 %
5/2+	—	1000	402↑74 %, 411↓ + Q_1 (22) 13 %, 660↑ + Q_1 (22) 4 %
7/2+	—	1140	413↑1 %, 411↑ + Q_1 (22) 98 %
1/2+	—	1200	411↑ + Q_1 (22) 100 %
1/2−	171.7	950	541↑96 %, 411↓ + Q_1 (30) 3 %
5/2−	1527.4	1510	532↑81 %, 514↑ + Q_1 (22) 6 %, 411↓ + Q_1 (32) 5 %
5/2+	1580.8	1620	413↑94 %, 411↓ + Q_1 (22) 3 %
19/2+	—	2110	p523↑n523↓n633↑100 %

Note: The theoretical energies and the structure of the states are taken from Ref. 117; the experimental energies of the levels, from Ref. 78.

3/2⁺[411] in the thulium nuclei ($Z=69$), and 3/2⁺[402] and 1/2⁺[400] in the rhenium nuclei ($Z=75$) in the proton system and of the states 1/2⁻[521] in the nuclei with $N=91$–97, 1/2⁻[501] in the nuclei with $N=95$–103, and 3/2⁻[521] in nuclei with $N=99$–105 are appreciably lower than the corresponding energies in the Woods–Saxon potential. These numbers of protons Z and neutrons N are appreciably different from the ones for which these states are ground states. The energies of states with small K change little if one has a state which is the ground state in a nucleus with Z or N differing by unity. An example are the states 1/2⁺[411] and 3/2⁺[411] in the Ho nuclei ($Z=67$). This is because the phonon admixtures to the low-lying states are small. There are also other experimental indications, apart from the energies, of an appreciable interaction between the quasiparticle states and phonons: the probabilities of $E2$ and $E1$ γ transitions, the reaction cross sections, and so forth. The interaction is particularly strong in nuclei for which the neighboring even–even nucleus has low vibrational levels[121]

Gareev *et al.*[117] calculated the energies of nonrotational states for 57 deformed nuclei with odd A. In the calculations they used the Woods–Saxon potential and took into account the interaction between quasiparticles and phonons. The Coriolis interaction was not taken into account. The results of the calculations are shown in Table 3. The experimental energies of the levels in

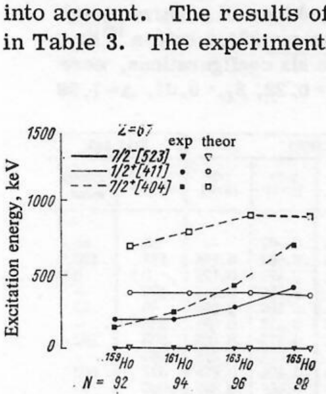

FIG. 9. Comparison of the energies of experimentally established levels in Ho isotopes ($Z=67$) with the energies calculated in the superfluid model.

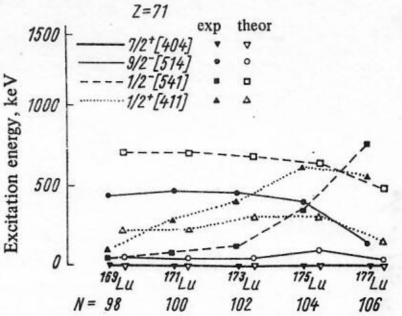

FIG. 10. Comparison of the energies of experimentally established levels in Tm isotopes ($Z=71$) with the energies calculated in the superfluid model.

Table 3 were given in Ref. 78. It can be seen that, in accordance with the calculations, the contribution of the one-particle components to the low-lying states is large (97–94%). The high states have a complicated structure. The calculation of Ref. 117 is compared more clearly with the experiments in Figs. 9–12. The accuracy of the calculations in Ref. 117 is estimated to be about 300 keV. It can be seen that to within this accuracy the agreement is fair. It is interesting to note that the theory also gives a reasonable explanation of the tendency for the energy of states to change on the transition from nucleus to nucleus. An exception is the state 1/2⁻[541] in Lu nuclei: The experiment gives a large reduction of the energy of this state ($\Delta E \approx 750$ keV) on the transition from ^{177}Lu to ^{169}Lu; according to the calculation, it changes by not more than 200 keV. The reason for this large discrepancy is not clear. It does not appear possible to explain it by a change in the deformation of the nucleus, which was ignored in the calculations, since the energy of the state 1/2⁻[541] increases with decreasing deformation (see Fig. 8). Other, smaller discrepancies in the change of the energy of states on the transition from nucleus to nucleus can apparently be attributed to changes in the deformation of the nucleus and, especially in the neutron system, fluctuations of the Woods–Saxon potential and the Coriolis interaction.

The Coriolis interaction, or the interaction of an unpaired nucleon with the rotating even–even core, has been considered in reviews by Winter *et al.*[119] and Baznat *et al.*[118] The experimental and theoretical in-

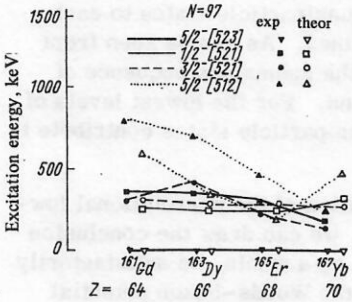

FIG. 11. Comparison of the energies of experimentally established levels in the isobars $N=97$ with the energies calculated in the superfluid model.

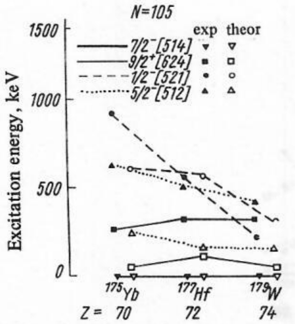

FIG. 12. Comparison of the energies of experimentally established levels in the isobars $N=105$ with the energies calculated in the superfluid model.

vestigations showed that the Coriolis interaction is manifested in the majority of odd nuclei through strong deviations of the energies of rotational states from a dependence of the type $I(I+1)$. The Coriolis interaction can have its strongest influence on states coupled to $i_{13/2}$ spherical subshells in the neutron system and $h_{11/2}$ subshells in the proton system. As was shown by Pyatov *et al.* (see Ref. 118), the interaction of the rotational bands in these cases can lead to their being so strongly distorted that it becomes necessary to describe them as a mixture of many states.

Rotational bands of such states have been identified, for example, in the nuclei of ^{161}Er and ^{159}Er in the studies, Refs. 39 and 48, made in the Yasnapp program and also in Refs. 127–129. In an investigation of the radioactive decay of ^{159}Tm and ^{161}Tm in Refs. 39 and 48, some lower rotational levels of these states were established. In Refs. 127–129, in a study of the prompt γ spectra in nuclear reactions, levels of a rotational band with I^{π} from $9/2^+$ to $25/2^+$ were observed. To analyze rotational bands of this type, Baznat *et al.*[118] used a modified description in the framework of the nonadiabatic model, taking into account the centrifugal and spin–spin interaction between nucleons. To calculate the wave functions and energies of the rotational levels they used two free parameters: the moment of inertia J and the gap parameter. The results obtained for the nucleus ^{161}Er when the experimental data are analyzed in this manner were presented in Ref. 48. In Table 4, we give the results of such an analysis for the nucleus ^{159}Er. It is possible to achieve good agreement between the experimental and calculated energies for levels with given I^{π}. At the same time, the contribution of the different one-quasiparticle states to each rotational level is determined. As can be seen from Table 4, one can explain the anomalous sequence of rotational levels in the band. For the lowest levels of the band, several one-quasiparticle states contribute to the wave function.

Concluding our examination of the nonrotational low-lying states in odd nuclei, we can draw the conclusion that their properties can, as a whole, be satisfactorily described on the basis of the Woods–Saxon potential with allowance for pairing correlations and interaction between quasiparticles and phonons. For states coupled to spherical subshells with large internal angular momentum j it is necessary to take into account the Goriolis interaction. It would be very interesting to obtain new experimental data on the one-quasiparticle states in odd nuclei and particularly in nuclei far from the β-stability band. The accumulation of such data for nuclei far from the stable nuclei is important for determination of the parameters of the average field in these nuclei.

Probabilities of β transitions between one-quasiparticle states. The experimental data on the probabilities of β transitions between one-quasiparticle states of deformed nuclei in the region of the rare–earth elements have been analyzed on several occasions.[125,130,131] It would, however, be interesting to repeat this analysis now in view of the great increase in the volume of available experimental data. The values of $\lg ft$ known up to Fall 1974 for allowed and first-forbidden β transitions between one-quasiparticle states of deformed nuclei in the region of rare-earth elements are presented in the Appendix. All the available data are classified in accordance with the spin and parity selection rules for β decay and in accordance with the asymptotic quantum numbers, i.e., *au* for allowed unhindered β transitions, *ah* for allowed hindered ($\Delta N=0$ and 2); 1*u* first-forbidden unhindered; 1*h* first-forbidden hindered; 1**h* first-forbidden unique hindered transitions (see Ref. 2). In the Appendix we give the proton and neutron configurations between which the β transition takes place, and the experimental values of $\lg ft$. The data are analyzed in the same way as in Ref. 2. Therefore, we indicate the additional classification of β transitions in the superfluid model and the pairing correlation correction factors $R=R_N\cdot R_Z$ calculated in Ref. 2. The statistical factor η is taken into account.

In the last column, we give the values of $\lg ft_e R\eta$, in which the influence of superfluid corrections and the statistical factor has been eliminated. The analysis was made without allowance for the experimental errors in the determination of $\lg ft$. For the majority of au–β transitions they are less than 0.1, while for β transitions of other types they are as a rule less than 0.3. It can be seen that these errors cannot significantly affect the conclusions which can be drawn. It should be noted

TABLE 4. Energies and amplitudes of wave functions for states of a strongly perturbed band of positive parity based on the $5/2^+$ level at the energy 271.3 keV in ^{159}Er. The calculations, which include six configurations, were made using the parameters $\beta_{20}=0.32$, $\beta_{40}=0.04$, $\Delta=1.06$ MeV, and $h^2/2I=15.6$ keV.

I^{π}	Amplitude of wave functions						$E(1)$, keV	
	1/2+ [400]	1/2+ [660]	3/2+ [402]	3/2+ [651]	5/2+ [642]	7/2+ [633]	theory	experiment
5/2+	0.170	0.516	—0.093	0.663	0.507	—	85	88.7
7/2+	0.073	0.213	—0.093	0.658	0.697	0.148	124	120.2
9/2+	0.192	0.559	—0.094	0.631	0.477	0.123	0*	0*
11/2+	0.078	0.220	—0.094	0.641	0.685	0.235	176	—
13/2+	0.204	0.584	—0.094	0.615	0.456	0.150	49	43
15/2+	0.079	0.222	—0.094	0.628	0.677	0.282	288	—
17/2+	0.211	0.598	—0.093	0.605	0.443	0.165	225	252
19/2+	0.080	0.222	—0.093	0.617	0.672	0.315	664	—
21/2+	0.216	0.606	—0.092	0.598	0.434	0.175	527	602
23/2+	0.080	0.220	—0.093	0.607	0.667	0.340	1095	—
25/2+	0.219	0.612	—0.092	0.592	0.428	0.183	953	1068

*Normalized value

that the values of the superfluid corrections R_N and R_Z were calculated for the sequence of states in Nilsson's scheme with $\beta = 0.28$ for $150 < A < 180$ and with $\beta = 0.23$ for $18 < A < 190$. The experimentally established sequence for one-quasiparticle levels does not always coincide with the one adopted in the calculations of R_N and R_Z. The resulting errors may be particularly large for states near the Fermi surface. The values of R in which inaccuracies of this kind (a factor 2–5) are possible are indicated by an asterisk. It is clear from the Appendix that the corrections for pairing correlations are important for β transitions of group II of the superfluid model.

It is of interest to determine the limits of the $\lg ft$ values in the adopted classification of β transitions. To this end, in Figs. 13 and 14 we have represented the distributions of the $\lg ft_e$ and $\lg ft_e R\eta$ values for allowed and first-forbidden β transitions. All the $\lg ft$ values are shown in the figures by equally large squares, i.e., each $\lg ft$ was taken into account with the same weight. In Table 5 we give the resulting intervals of $\lg ft_e$ and $\lg ftR\eta$ values for variously forbidden β transitions. The resulting intervals are compared with the results of analysis in Refs. 125 and 130.

Examining the experimental values of $\lg ft_e$ for the transitions, we pose the following problems:

1) explanation of the hindrance of the β decay of the nuclei as compared with the β decay of the free neutron;

2) establishment of the limits of the $\lg ft_e$ values for variously forbidden β transitions and study of the factors that increase the intervals of $\lg ft_e$. This problem is very important for analysis of new experimental data (decay schemes).

The first problem for au–β transitions between one-particle states in deformed nuclei was considered in Refs. 132 and 2. It was shown that the probabilities of au–β transitions between the states $7/2^-[523] \rightleftarrows 5/2^-[523]$ and $9/2^-[514] \rightleftarrows 7/2^-[514]$ ($\lg ft_e = 4.4$–4.9) are hindered

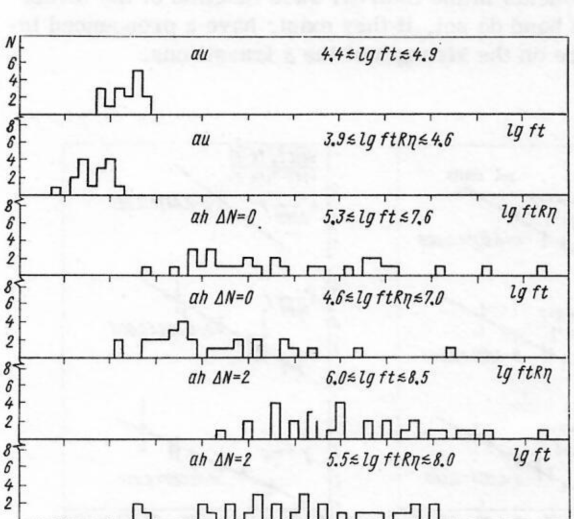

FIG. 13. Histogram of values of $\lg ft$ for allowed β transitions between one-quasiparticle states of rare-earth nuclei.

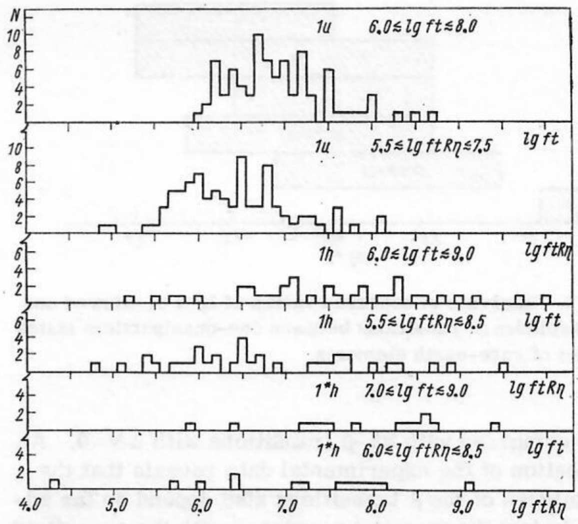

FIG. 14. Histogram of values of $\lg ft$ for first-forbidden β transitions between one-quasiparticle states of rare-earth nuclei.

relative to the values calculated with the wave functions in Nilsson's potential ($\lg ft_N \approx 3.4$–3.6) by about a factor of 10. The discrepancy is partly removed if one takes into account the superfluid corrections $R = R_N \cdot R_Z$ considered above and the statistical factor.[2] On the average, $\lg ft_e R\eta - \lg ft_N = 0.8$. As is shown Ref. 132, the remaining discrepancy can be removed by taking into account the spin polarization of the nucleus by the odd particle.

With regard to the second problem, we can make the following remarks. Although more experimental $\lg ft_e$ values were used (and their accuracy was higher) than in Refs. 125 and 130, the limits of the $\lg ft_e$ values are almost unchanged. Introduction of the corrections $R\eta$ does not reduce the intervals. At the same time, one can clearly follow the dependence of the probability of the β transition on its class: au, $ah\,(\Delta N = 0)$, $ah\,(\Delta N = 2)$, etc. This systematization shows the importance of the selection rules with respect to the asymptotic quantum numbers. For example, the N-forbidden ah–β transitions are on the average hindered by a fac-

TABLE 5. Limits of values of $\lg ft_e$.

Type of β transition	Mottelson (Ref. 130), 1959	Gromov (Ref. 125), 1065	Present work, 1974
au	4.5–5.0	4.6–4.8	4.4–4.9
$ah\,(\Delta N=0)$	} 6.0–7.5	5.5–8.0	5.3–7.6
$ah\,(\Delta N=2)$			6.0–8.5
$1u$	5.5–7.5	6.2–7.9	6.0–8.0
$1h$	7.5–8.5'	—	6.0–9.0
$1{}^*h$	—	—	7.0–9.0

Limits of values of $\lg ft_e R\eta$.

Type of β transition	Gromov (Ref. 125), 1965	Present work, 1974
au	4.2–4.5	3.9–4.6
$ah\,(\Delta N=0)$	} 4.9–7.6	4.6–7.0
$ah\,(\Delta N=2)$		5.5–8.0
$1u$	5.5–7.4	5.5–7.5
$1h$	—	5.5–8.5
$1{}^*h$	—	6.0–8.5

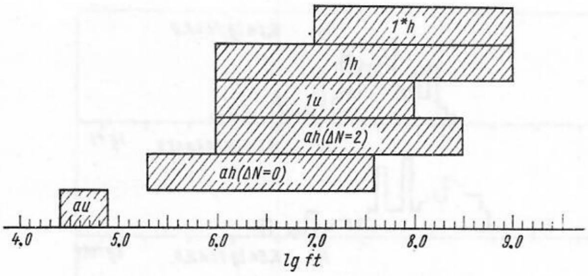

FIG. 15. Intervals of observed values of lg ft of allowed and first-forbidden β transitions between one-quasiparticle states of nuclei of rare-earth elements.

tor 10 compared with ah–β transitions with $\Delta N=0$. An examination of the experimental data reveals that the probabilities of the β transitions also depend on the additional classification in accordance with the superfluid model. For example, ah–β transitions of type II (see Ref. 2) are on the average 20 times faster than transitions of the type I–II and II–I.

In principle, the considerable volume of experimental data on the probabilities of β transitions enables one to attack the problem in more detail. Beta transitions between individual pairs of one-quasiparticle states were considered. For some pairs, up to ten $\lg ft_e$ values are known (see the Appendix). One can expect a narrowing of the interval between the extreme values of $\lg ft_e$ for each chosen pair of states. Apparently, this really is observed. However, the interval remains fairly large ($\Delta \lg ft_e$ up to 1). One can also expect the $\lg ft_e$ values to depend on the purity of the one-particle states under consideration. In this case, one would observe a difference in the values of $\lg ft_e$ for β transitions to ground and excited states. Analysis of the data (see the Appendix) does not reveal such a situation. At the same time, one observes an appreciable spread in the $\lg ft_e$ values, even for β transitions between ground states of nuclei in each chosen pair of one-quasiparticle states.

Thus, at the present time it is hard to explain the large spread in the probabilities (of about two orders of magnitude) for allowed, hindered, and first-forbidden β transitions. To analyze the decay schemes of radioactive nuclei, one can recommend the use of the limits of the $\lg ft_e$ values for variously forbidden β transitions given in Fig. 15. It can be seen that β transitions of au type can be reliably established from the value of $\lg ft_e$ (less than 5.0). Note that in the region of nuclei under consideration this unambiguously indicates β transitions between the states $p7/2^-[523] \rightleftarrows n5/2^-[533]$ and $p9/2^-[514] \rightleftarrows n7/2^-[514]$. Unfortunately, there is no such certainty for β transitions of other types. In these cases, it is helpful to consider the values of $\lg ft_e$ for β transitions between definite pairs of one-quasiparticle states. However, in this case too it is impossible to draw a reliable conclusion about the nature of the one-quasiparticle states between which the β transition takes place.

Properties of even–even deformed nuclei of rare-earth elements. The considerable successes of the modern theory of the nucleus are associated above all with the description of the properties of even–even deformed nuclei. Let us consider here some conclusions that can be drawn from our investigations of even–even nuclei and comparison of the results with the predictions of models. In radioactive decay, states of daughter nuclei with small angular momentum are excited. We know only a few isomers with fairly high spin (for example, ^{158m_2}Ho, $I^\pi = 9^+$) whose β decay results in the excitation of rotational bands and individual two-quasiparticle states up to $I^\pi = 10^+$. Therefore, the very interesting back bending effect remains outside the scope of this review. The properties of even–even deformed nuclei (energies, electric quadrupole moments, moments of inertia, gyromagnetic ratios for rotational bands of the ground, β-, and γ-vibrational states) have been systematically analyzed in the lectures of Dzhelepov.[133] The properties of even–even deformed nuclei of rare-earth elements are reviewed in the book Ref. 8 by Grigor'ev and Solov'ev. We shall therefore dwell here only on some special questions.

The existing experimental data on the lowest states of even–even nuclei indicate that they are fairly pure states. Figure 16 illustrates the determination of the mixing parameters of some rotational bands of ^{158,160}Dy. The mixing parameter of rotational bands with $\Delta K = 2$ in Mikhaĭlov's expression (Ref. 134) $B(E2, I2 - I'0) = \langle M\rangle^2 \langle I2;\, 2{-}2 \mid I'0\rangle^2 \{1 + a[I'(I'+1) - I(I+1)]\}$ is determined from the ratios of the reduced probabilities of γ transitions from levels from one band to the levels of another band. In the coordinates of Fig. 16, the experimental points must lie on a straight line if the ideas about mixing of the wave functions of bands are correct.

These are confirmed by the fulfillment of Alaga's rules for β transitions to the rotational band of a number of nuclei. Thus, the experimental ratios of the reduced probabilities of β transitions of ^{160}Ho ($I^\pi = 5^+$) to the levels 4^+, 5^+, 6^+ of the band 4^+, $n[523]\downarrow + n[521]\uparrow$ ($100 : 18 \pm 2 : 1.3 \pm 0.5$) agree with the calculated values $100 : 20.4 : 1.95$. This indicates that the admixture components in the internal wave function of the levels of the band do not, if they exist, have a pronounced influence on the strength of the β transitions.

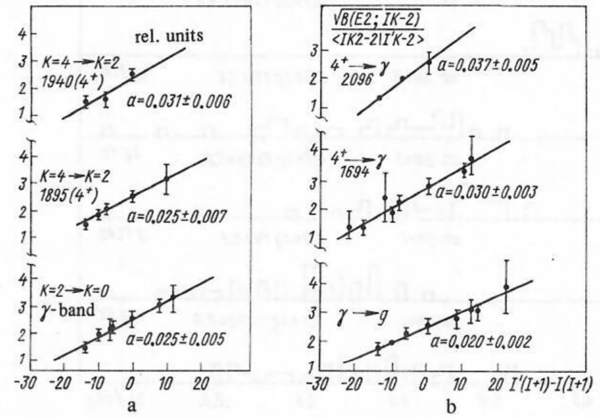

FIG. 16. Determination of the mixing parameter of some rotational bands in ^{158}Dy (a) and ^{160}Dy (b).

TABLE 6. Comparison of experimentally established properties of collective states of ^{158,166}Dy and ^{164,166}Er with calculations in the superfluid model.

Quantum numbers	^{158}Dy	^{160}Dy	^{164}Er	^{166}Er
$K^\pi = 2^+$				
E, MeV:				
experiment	0.946	0.966	0.858	0.786
theory	0.97	0.94	0.80	0.78
$B(E2,\ 0^+0 \to 2^+2)$:				
experiment	6.3	4.2	7.1	5.7
theory	4.7	4.9	4.1	3.3
$K^\pi = 0^+$				
E, MeV:				
experiment	0.990	1.280	1.25	1.46
theory	0.99	1.26	1.25	1.46
$B(E2)$:				
experiment	0.3	—	>0.05	—
theory	0.60	1.35	0.98	0.66
$\rho(E0)$:				
experiment	0.06	—	>0.01	—
theory	0.08	0.13	0.14	0.09
$X = B(E0)/B(E2)$:				
experiment	0.08	0.26	0.15	0.07
theory	0.08	0.09	0.11	0.09
$\sigma(p, t)/\sigma_0$				
experiment	0.09	0.16	0.15	0.06
$S(p, t)/s_0$				
theory	0.13	0.15	0.07	0.01
$K^\pi = 0^-$				
E, MeV:				
experiment	1.283	—	1.386	1.663
theory	1.20	1.24	1.37	1.64
$B(E3,\ 0^+0 \to 3^-0)$:				
experiment	1.5	11	8.1	6.1
theory	7.7	6.8	6.4	7.7
$K^\pi = 1^-$				
E, MeV;				
experiment	—	1.286	—	1.824
theory	1.50	1.57	1.85	1.59
$B(E3,\ 0^+0 \to 3^-1)$:				
experiment	—	—	3.6	3.0
theory	5.2	2.9	1.6	(2.1)
$K^\pi = 2^-$				
E, MeV;				
experiment	—	1.265	—	1.460
theory	1.25	1.15	1.48	1.47
$B(E3,\ 0^+0 \to 3^-2)$:				
experiment	—	—	1.1	2.2
theory	6.5	6.6	3.3	2.4

Note. The values of $B(E2)$ and $B(E3)$ are given in "single particle" units (s.p.u.). For the nucleus ^{164}Er in Ref. 59 it was established that there exist four excited 0^+ states with energies 1.25, 1.70, 1.77, and 2.17 MeV and Rasmussen parameters $X = 0.15$, 0.39, 0.78, 1.76, respectively. The theory predicts states with energies 1.25, 1.64, 2.0, and 2.11 MeV and $X = 0.11$, 0.22, 0.23, and 0.37.

In almost all even–even nuclei collective β- and γ-vibrational states have been identified, and in some nuclei octupole vibrational states. The existing models of nuclei (and above all the microscopic approach) successfully describe the properties of these states. In the phenomenological description of the properties of nuclei one introduces collective coordinates, and the excitations of a nucleus are associated with the rotation of the nucleus as a whole and with vibrations of the nuclear surface. In the semimicroscopic approaches the nucleus is regarded as a system of quasiparticles moving in a self-consistent field and interacting with one another through residual interactions. One of the main semimicroscopic models is the superfluid model. In it, one takes into account residual interactions leading to pairing correlations of superconducting type, and multipole–multipole interactions, which enable one to describe collective states of nuclei.

The calculations made in the framework of the superfluid model using the one-particle energies and wave functions of the Woods–Saxon potential made it possible to explain the structure of a number of deformed nuclei of rare-earth elements.[135] The experimental and calculated energies of collective states and the reduced probabilities of transitions to these states in some of the investigated nuclei are compared in Table 6. Note the fair agreement between theory and experiment. The 0^+ states present the greatest difficulty for theoretical description since, theoretically, there exist several different types of nucleon–nucleon residual interactions that could generate 0^+ levels. For example, collective 0^+ states with energy in the region 1.5–2 MeV ($E \gtrsim 2c$) could be pairing vibrations. The 0^+ states can be generated by spin–quadrupole forces and two-particle spin–orbit forces. In addition, two-phonon 0^+ levels can sink.

The available experimental data on 0^+ states (the parameter X, the value of ρ, the $B(E2)$ values in Coulomb excitation and in the dd' reaction, and the cross sections to two-nucleon transfer reactions) suggest that the low-lying 0^+ states are not pure. The model with spin–quadrupole interaction[136] only qualitatively explains the experimental data.

The energies and structures of two-quasiparticle states of even–even nuclei calculated in the superfluid model give the experimenters an approach to explaining the nature of the experimentally observed nuclear levels. To illustrate the possibilities of the model description of even–even nuclei, we compare in Table 7 the experimentally known energies of two-quasiparticle and one-phonon states of ^{160}Dy with the calculated energies.[137,8]

Analysis of the probabilities of β decay of ^{158}Ho, ^{160}Ho, and ^{166}Tm to levels of ^{158}Dy, ^{160}Dy, and ^{166}Er, respectively, enables one to draw conclusions about the fragmentation of a definite wave function over a number of energy states. Histograms representing the dependence on the excitation energy of the strength of β decay, $\Sigma(ft)^{-1}$, to the levels of ^{160}Dy with $I^\pi = 1^-$, 2^-, and 3^- in 100-keV intervals are shown in Fig. 17,

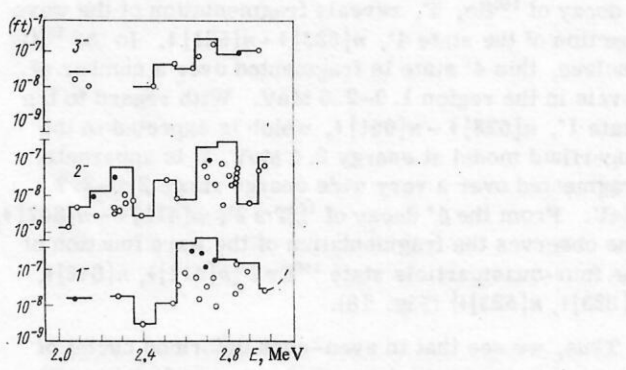

FIG. 17. Strength function of the β decay of ^{160}Ho as a function of the excitation energy of 1^-, 2^-, and 3^- levels in ^{160}Dy.

TABLE 7. Two-quasiparticle and one-phonon states of ^{160}Dy.

Two-quasiparticle proton states

Configuration	K^π	Energy, MeV: experiment	Energy, MeV: calculation
F F+1	2^- c	—	1.6
411↑ 523↑	5^-		
F−1 F+1	6^-	—	2.2
413↓ 523↑	1^- c		
F F+2	2^+ c	—	2.5
411↑ 411↓	1^+		
F−2 F+1	1^+	—	2.6
532↑ 523↓	6^+		
F−1 F	4^+	—	2.7
413↓ 411↑	1^+		
F−1 F+2	2^+ c	—	2.8
413↓ 411↓	3^+		
F+1 F+2	4^-	—	3.0
523↑ 411↓	3^-		
F−2 F+2	3^-	—	3.2
532↑ 411↓	2^- c		

Two-quasiparticle neutron states

Configuration	K^π	Energy, MeV: experiment	Energy, MeV: calculation
F F+1	1^- c	—	1.6
521↑ 642↑	4^-		
F F+2	4^+	1.694	1.7
521↑ 523↓	1^+		
F+1 F+2	5^-	—	1.8
642↑ 523↓	0^- c		
F−1 F+1	1^+	—	2.1
651↑ 642↑	4^+		
F−1 F	3^-	—	2.2
651↑ 521↑	0^- c		
F−1 F+2	4^-	—	2.2
651↑ 523↓	1^- c		
F−2 F+1	3^-	—	2.5
505↑ 642↑	8^-		
F−3 F+1	4^+	—	2.5
402↓ 642↑	1^+		
F−2 F+2	8^+	2.555	2.6
505↑ 523↓			

One-phonon states

K^π	Energy, MeV: experiment	Energy, MeV: calculation	$B(E\lambda)$, s. p. u.: experiment	$B(E\lambda)$, s. p. u.: calculation	Structure, %
2^+	0.966	0.9	5.7	6.0	nn521↑ 521↓ 20.8 pp411↑ 411↓ 15.9 nn642↑ 660↑ 12.9
					nn523↓ 521↓ 8.8 pp413↓ 411↓ 8.4 nn633↑ 651↑ 5.9
2^-	1.265	1.1	11	5.2	pp523↑ 411↑ 65.8 nn633↑ 521↑ 13.8 nn642↑ 530↑ 2.9
					nn512↑ 400↑ 2.2 nn651↑ 521↓ 1.2 nn660↑ 521↑ 1.1
1^-	1.285	1.2	5.8	3.0	nn642↑ 521↑ 76.1 nn523↓ 651↓ 4.8 pp532↑ 411↑ 2.1
0^+	1.263	1.4	—	1.3	nn642↑ 642↑ 64.7 nn521↑ 521↑ 11.7 nn505↑ 505↑ 4.4
					nn523↓ 523↓ 4.4 nn402↓ 402↓ 3.4 pp532↑ 532↑ 1.4
0^-		1.5	—	2.1	nn642↑ 523↓ 65.4 nn651↑ 521↑ 14.1 nn615↑ 505↑ 1.6
					pp550↑ 400↑ 1.5 nn400↑ 510↑ 1.3 pp541↑ 402↓ 1.3
0^+	1.953	1.9	—	0.2	nn521↑ 521↑ 66.9 nn523↓ 523↓ 26.0 nn505↑ 505↑ 3.2
1^-		2.0	—	0.6	nn523↓ 651↑ 84.7 nn642↑ 521↑ 5.5 pp532↑ 411↑ 1.2
0^-		2.1	—	0.5	nn651↑ 521↑ 73.4 nn642↑ 523↑ 21.1
2^-		2.3	—	0.7	nn633↑ 521↑ 48.8 pp522↑ 411↑ 30.9 nn660↑ 521↑ 4.7
					nn642↑ 530↑ 2.9 nn642↑ 521↓ 2.0 nn523↓ 660↑ 1.8
2^+		2.4	—	0.2	pp411↑ 411↓ 62.8 nn521↑ 521↓ 17.2 nn642↑ 660↑ 14.7
					nn523↓ 521↓ 2.5

Note. F is the Fermi level; c means that there are no two-quasiparticle states with the given K^π values. The energies in the table are, respectively, the first, second, etc., poles of the corresponding secular equation of the theory.

from which it can be seen that: a) 1^- levels are populated with greatest intensity; b) the strength function has a clear maximum in the region of 2.6–2.8 MeV; c) for 2^- and 3^- levels the maximum is shifted to higher energies; d) if the strength of all the β transitions in the region of the peak at 2.6–2.8 MeV to 1^- levels is attributed to a transition to one level, then lg *ft* of this β transition is 5.6, i.e., it would be an *(au)* β transition.

To explain these facts, we make the assumption that the isomer ^{160m}Ho, 2^-, $p[523]\uparrow - n[651]\uparrow$ undergoes an *au*–β transition $p[523]\uparrow - n[523]\downarrow$ to the level ^{160}Dy, 1^-, $n[523]\downarrow - n[651]\uparrow$. In accordance with the calculations in the superfluid model, its energy is 2.0–2.2 MeV, although a level with this structure is not observed. It is concluded that the corresponding wave function enters as a component into the wave functions of a number of 1^- states in the region of 2.6–2.8 MeV, i.e., the wave function is fragmented with a distribution width of about 200 keV. Each of the 1^- states has 2^- and 3^- rotational levels, which are also populated by fast β transitions. The center of gravity of the peak of the strength function will be shifted to higher energies, as is observed qualitatively. A similar analysis of the β decay of ^{160}Ho, 5^+, reveals fragmentation of the wave function of the state 4^+, $n[523]\downarrow + n[521]\uparrow$. In the ^{158}Dy nucleus, this 4^+ state is fragmented over a number of levels in the region 1.9–2.5 MeV. With regard to the state 1^-, $n[523]\downarrow - n[651]\uparrow$, which is expected in the superfluid model at energy 2.4 MeV, it is apparently fragmented over a very wide energy range 2.0–2.7 MeV. From the β^+ decay of $^{166}_{69}$Tm 2^+, $p[411]\downarrow - n[642]\uparrow$, one observes the fragmentation of the wave function of the four-quasiparticle state ^{166}Er $3^+\{p[411]\downarrow, n[642]\uparrow, p[523]\uparrow, n[523]\downarrow\}$ (Fig. 18).

Thus, we see that in even–even deformed nuclei of rare-earth elements the wave functions of states with spins $I^\pi \leqslant 4^+$ are fragmented over a number of energy states already in the region 2–3 MeV. Such a phenomenon was expected on the basis of the superfluid model.

In contrast to the results of Hansen and Karnaukhov, who studied delayed proton emitters and discovered the phenomenon of fragmentation of highly excited (5–6 MeV) nuclear states, it follows from our experiments that the observed fragmented states in the region 2–3 MeV still retain a certain individuality and are manifested as a series of concrete energy levels.

The β decay of ^{158}Ho, $I^\pi = 5^+$, to the level 4_g^+ of ^{158}Dy is characterized by lg *ft* = 8.65. The value of lg *ft* is too low for a strongly *K*-forbidden β transition ($\Delta K = 5$, $\nu = 4$). In addition, there are *K*-forbidden γ transitions ($\Delta K = 4$, $\nu = \Delta K - L = 2$) from $I^\pi K = 4^+4$ levels to the rotational band of the ground state. These facts indicate that there is a weakening of the *K* selection rules in the case of ^{158}Dy.

Properties of odd–odd deformed nuclei. The lowest states of odd–odd nuclei are multiplets of two-quasiparticle states whose spins and parities are determined by the Gallagher–Moshkowski rules. As an example, in Fig. 19 we give the scheme of two-quasiparticle states of $^{166}_{67}$Ho$_{99}$. For the majority of these two-quasiparticle levels it is known that there are developed ro-

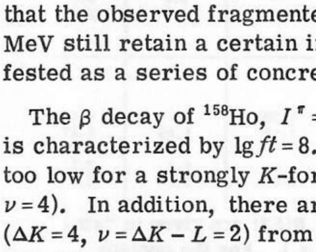

FIG. 18. Strength function of the β decay of ^{166}Tm as a function of the excitation energy of 3^+ levels in ^{166}Er.

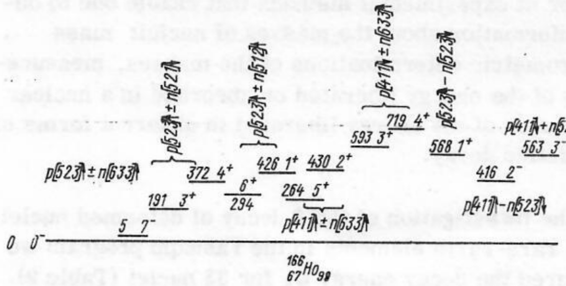

FIG. 19. Energies of levels of the two-quasiparticle multiplets of ^{166}Ho.

tational bands. The nucleus ^{166}Ho is interesting in that the Gallagher–Moshkowski rules are broken in it: The level 7^-, $p[523]\uparrow + n[633]\uparrow$ is above (by 5 keV) the ground state 0^-, $p[533]\uparrow - n[633]\uparrow$. A Gallagher–Moshkowski rule is broken when one of the states of the doublet has $K^\pi = 0^-$. The energy of splitting of the doublet is usually small.

In a number of odd–odd nuclei of Ho ($A = 156$, 162) and Tm ($A = 162$, 164, 166) a two-quasiparticle 1^+ level of type $p[523]\uparrow - n[523]\downarrow$ is revealed by allowed unhindered β decay; its excitation is associated with the transformation $p[523]\uparrow - n[523]\downarrow$.

$$^{156}\text{Er}\,(0^+) \to {}^{156}\text{Ho}\,(1^+),\ \lg ft \leqslant 4.8;$$
$$^{162}\text{Yb}\,(0^+) \to {}^{162}\text{Tm}\,(1^+),\ \lg ft \leqslant 4.9;$$
$$^{164}\text{Tm}\,(1^+) \to {}^{164}\text{Er}\,(0^+),\ \lg ft = 4.5;$$
$$^{166}\text{Yb}\,(0^+) \to {}^{166}\text{Tm}\,(1^+),\ \lg ft = 4.5 \pm 0.1;$$
$$^{162}\text{Ho}\,(1^+) \to {}^{162}\text{Dy}\,(0^+),\ \lg ft = 4.7.$$

However, in the nuclei between ^{156}Ho and ^{162}Ho, i.e., ^{158,160}Ho, levels of the type 1^+, $p[523]\uparrow - n[523]\downarrow$ have not yet been identified. True, in the case of ^{160}Ho it is assumed that the level lies near the state 2^-, $p[523]\uparrow - n[651]\uparrow$. At the same time, $\Delta E_{1^+ \to 2^-} < 1.5$ keV, which leads to very great experimental difficulties in discovering the 1^+ level. In some odd–odd nuclei of Ho ($A = 156$, 158) one observes "unusual" levels with $I^\pi = 1^-$. The 1^- level excited at 117 keV in the β decay of ^{156}Er (Fig. 20) into ^{156}Ho cannot be associated with the configuration 1^-, $p[411]\downarrow - n[521]\uparrow$, known in the neighboring odd–odd nuclei. For this configuration, the observed transition at 35 keV would be associated with a change in the states of two nucleons, whereas a one-particle transition at 65 keV, $1^- \to 2^+$, is not observed. The 1^- state at 139 keV in ^{158}Ho is another of these anomalous levels.

One can assume that configuration mixing due to the residual and Coriolis interactions is responsible for the weakening of the Ω and F selection rules. The F selection rule ($pn \nrightarrow p'n'$) is more fundamental than the Ω selection rule (a change of the Ω projection in the transition). The known hindrance factors (according to Weisskopf) for several F-forbidden γ transitions are

$$^{162}\text{Tm}\,[p523\uparrow - n523\downarrow] \to [p411\downarrow - n521\uparrow]: E_\gamma = 163\text{ keV};\quad F_W(E1) < 8\cdot 10^5;$$

$$^{166}\text{Tm}\,[p523\uparrow - n523\downarrow] \to [p411\downarrow - n642\uparrow]: E_\gamma = 82\text{ keV},\quad F_W(M1) < 380;$$

$$^{172}\text{Tm}\,[p523\uparrow - n512\uparrow] \to [p411\downarrow + n521\downarrow]: E_\gamma = 203\text{ keV},\quad F_W(E1) < 10^6;$$

$$^{172}\text{Lu}\,[p411\downarrow + n512\downarrow] \to [p404\downarrow - n633\downarrow]: E_\gamma = 67\text{ keV},\quad F_W(E1) \approx 10^9;$$

$$^{182}\text{Re}\,[p514\uparrow - n514\downarrow] \to [p402\uparrow - n624\uparrow]: E_\gamma = 510\text{ keV},\quad F_W(M1) < 3\cdot 10^2.$$

Comparison with Löbner's systematization[138] for $E1$ ($\Delta K = 0$, 1) and $M1$ ($\Delta K = 1$) transitions in A-odd nuclei shows that only the $E1$ transition with energy 67 keV in ^{172}Lu exhibits a very appreciable hindrance. It follows from the systematization of the Ω-forbidden transitions in odd–odd nuclei that the Ω selection rule remains in force only in the case of ^{182}Re for the level at 236 keV.

In the β decay of the ground states of odd–odd nuclei of Re ($A = 174$, 176, 178) and ^{174}Ta, $I^\pi = 3^+$, there are β transitions to the levels 2^+ and 4^+ of the ground-state rotational band of the daughter nuclei, and $\lg ft = 6$–7. Such low values of $\lg ft$ force one to suggest[139] that with spin $I = 3$ of the parent nuclei the quantum number K is not three but unity (or zero). As a result of the Coriolis interaction of the levels with $K = 1$ (or 0) the $I = 3$ rotational state may sink below the states with spins 2 and 1.

In recent years in reactions induced by heavy ions it has become possible to excite developed rotational bands in odd–odd nuclei. For example, in ^{160}Ho it has been possible to excite the band of the 5^+ ground state (up to spin 9) and the band of the 6^- state (up to spin 15). The same bands are known in ^{162}Ho. While the energy positions of a band with positive parity are satisfactorily described by the Bohr–Mottelson formula, this formula is quite unsuitable for describing bands with negative parity. The best agreement with experiment (Table 8) is observed in the phenomenological approach to the description of rotational and quasirotational bands that uses the method of projecting the angular momentum and fits the parameters to the energies of the lowest states.[140]

The moments of inertia of the odd–odd nuclei can be described qualitatively in a representation according to

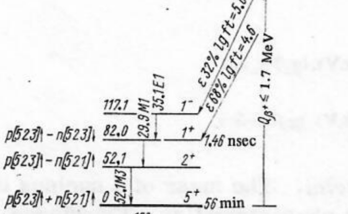

FIG. 20. Scheme of levels in ^{156}Ho excited by the decay of ^{156}Er.

TABLE 8. Comparison of energies of rotational bands with $K^{\pi} = 5^{+}$ and 6^{-} in ^{160}Ho established experimentally and calculated by the Bohr–Mottelson method and by the model in Ref. 140.

$K^{\pi} = 5^{+}$			$K^{\pi} = 6^{-}$				
					E_{calc}, keV		
I	E_{exp}, keV	E_{calc}, keV*	I	E_{exp}, keV	with one-term formula	with two-term formula	with model of Ref. 140
5	0	0	6	169.2	≡ 169.2	≡ 169.2	168.8
6	107	≡ 107.0	7	241.8	≡ 241.8	≡ 241.8	241.6
7	232	231.8	8	335.0	324.8	≡ 335.0	334.9
8	374	374.8	9	450.0	418.1	452.9	450.0
9	533	535.0	10	584.5	490.7	600.0	587.4
—	—	—	11	744.0	635.9	781.6	747.1
—	—	—	12	921.7	760.4	1003.3	928.7
—	—	—	13	1124.7	—	—	1131.2
—	—	—	14	1349.3	—	—	1353.9
—	—	—	15	1590.9	—	—	1595.4

*Calculations with the one-term Bohr–Mottelson formula.

which

$$J_{oo} = J_{ee} + \delta J_p + \delta J_n,$$

where J_{ee} is the moment of inertia of the even–even core; δJ_p is the correction introduced by the unpaired proton; and δJ_n is the correction introduced by the unpaired neutron. These corrections are determined from the moments of inertia of the neighboring isotopes and isotones. The equation gives the moment of inertia of odd–odd nuclei fairly accurately. For example, in the rotational band in ^{158}Ho of the level 1^-, $p411\downarrow - n521\uparrow$, the 2^- state has energy 43.5 keV, while the equation predicts 46.4 keV.

The electric quadrupole moments of odd–odd nuclei deduced from measurements of the lifetime of the first rotational state of the ground-state band do not differ greatly from those of the neighboring even–even nuclei. For example, the nucleus ^{162}Tm has $Q_0 = 6.0 \pm 0.5$ b and a deformation parameter $\beta_0 = 0.27 \pm 0.02$, whereas ^{162}Er has $Q_0 = 7.02 \pm 0.18$ b and $\beta_0 = 0.304 \pm 0.07$.

The β decay of the weakly deformed nucleus ^{156}Er(0^+) to the state 1^+, $p523\uparrow - n523\downarrow$, of the strongly deformed nucleus ^{156}Ho occurs at the same rate as between states of strongly deformed nuclei. Thus, the additional selection rule on the probability of β and γ transitions due to the change in the shape of the nucleus is in all probability not observed (see the review Ref. 133).

There are anomalously fast first-forbidden β transitions to "unusual" 1^- states in ^{156,158}Ho:

$$^{156}\mathrm{Er}\,(0^+) \to {}^{156}\mathrm{Ho}\,(1^-,\ 117\ \mathrm{keV}),\ \lg ft \leqslant 5.0$$

$$^{158}\mathrm{Er}\,(0^+) \to {}^{158}\mathrm{Ho}\,(1^-,\ 139\ \mathrm{keV}),\ \lg ft = 5.4.$$

Mass differences of nuclei. The mass of a nucleus is one of its most important characteristics. Knowledge of the masses of nuclei is sufficient to determine the mode and energy of the decay of unknown isotopes, to estimate their half lives, and so forth. There are a number of experimental methods that enable one to obtain information about the masses of nuclei: mass spectrometric determinations of the masses, measurements of the energy liberated or absorbed in a nuclear reaction or of the energy liberated in different forms of radioactive decay.

In the investigation of the β decay of deformed nuclei of the rare-earth elements in the Yasnapp program we measured the decay energy Q_β for 33 nuclei (Table 9). The energy liberated in the β decay was determined by measuring the end-point energies of the positron spectra by means of magnetic beta spectrometers, and also by measuring the ratios of the intensities of K and L electron capture, of electron capture and positron decay, and in other ways. In all cases, we obtained information about the decay schemes of the nuclei, which made it possible to determine reliably the energy of the level to which the β decays occurs, and thus obtain precise data on the mass differences of the nuclei.

In Table 9, the mass differences are compared with the data of different semiempirical mass tables. In the first column we give the nuclide for which the energy of β decay is measured. In the second, the measured energies of β decay: the energy differences between the ground states of the nucleus in the first column and the daughter nucleus in the β decay. In the third column we give the values of Q_β obtained by interpolation and extrapolation of the experimental data on the decay energies E_β and E_α and the two-neutron and two-proton stripping energies E_{2n} and E_{2p} in the tables of Viola et al.[141] With the errors, we give in this column the in-

TABLE 9. Comparison of experimental mass differences of nuclei in the region $150 < A < 190$ obtained in the Yasnapp program and values of the tables of nuclear masses (Refs. 141–148).

Nuclide	Q_β, keV	Viola (Ref. 141)	Cameron (Ref. 142)	Hillman (Ref. 143)	Myers (Ref. 144)	Seager (Ref. 145)	Wing (Ref. 146)	Garvey (Ref. 147)	Zeldes (Ref. 148)
^{152}Tb	3850±15	3820±30	3278	4544	3854	3618	3566	3730	3738
^{153}Tb	1600±20	1667	1491	1550	1586	1718	1353	1420	1488
^{155}Dy	2099±10	2099±6	1758	2625	1954	2118	1732	2020	1877
^{156}Ho	4700±100	5235	4526	4734	4563	4718	4332	5040	5170
^{158}Ho	4220±30	3977±5	3800	3747	3569	3918	3508	4130	4228
^{159}Ho	1827±10	2063	1376	1873	1330	1618	1258	1810	1513
^{160}Ho	3286±15	2920±30	2888	2535	2584	2918	2657	3140	3240
^{161}Ho	855±20	820±40	335	879	363	918	415	920	702
^{156}Er	⩽1700	1274	2451	3030	2369	2318	1782	1850	2252
^{157}Er	3470±80	3159	3676	4497	3641	3718	3244	3840	4266
^{158}Er	2060±100	1276	1589	1887	1399	1618	1012	1360	1431
^{159}Er	2930±100	2649	2948	3308	2658	3118	2431	2960	3342
^{160}Er	340^{+190}_{-70}	762	521	1065	429	818	194	600	652
^{161}Er	2050±40	2050±40	2033	2308	1682	1918	1593	1940	2371
^{165}Er	371±6	371±4	−59	117	−222	218	−97	−80	251
^{159}Tm	3400±300	4559	4359	4744	3980	3818	3596	4170	3900
^{160}Tm	4900±500	5965	5717	5399	5228	5318	5004	5740	5802
^{161}Tm	3200±200	3520±100	3290	3737	2999	3318	2766	3420	3139
^{162}Tm	4600±300	4700±100	4799	5012	4240	4418	4154	4740	4849
^{163}Tm	2600±200	2417±20	2244	2856	2029	2318	1923	2520	2363
^{164}Tm	3962±20	3962±20	3785	4110	3267	3518	3298	3830	3836
^{166}Tm	3030±5	3035±12	2703	2374	2312	2618	2442	2730	2766
^{167}Tm	612±2	747±26	41	411	138	418	235	790	641
^{162}Yb	⩽2200	1864	2279	2842	2092	2118	1708	2560	2280
^{163}Yb	3370±100	3426	2787	4279	3334	3618	3096	3890	3981
^{167}Yb	1970±30	1956±20	1687	1822	1423	1818	1406	1879	1934
^{167}Lu	3100±100	3070±70	3064	3233	2706	3218	2576	3460	3212
^{168}Lu	4800±400	4360±80	4633	4626	3931	4618	3930	4500	4427
^{169}Lu	2820±50	2270±30	1968	2470	1766	2218	1733	2610	2353
^{170}Lu	3470±20	3440±20	3558	3362	2990	3618	3079	3500	3357
^{171}Lu	1700±200	1361	884	1309	843	1718	894	1520	1435
^{181}Os	3040±200	2796	2901	3011	2526	2818	2478	3000	2545
^{183}Os	<2116	1359	1865	1777	1657	2018	1663	2010	1620

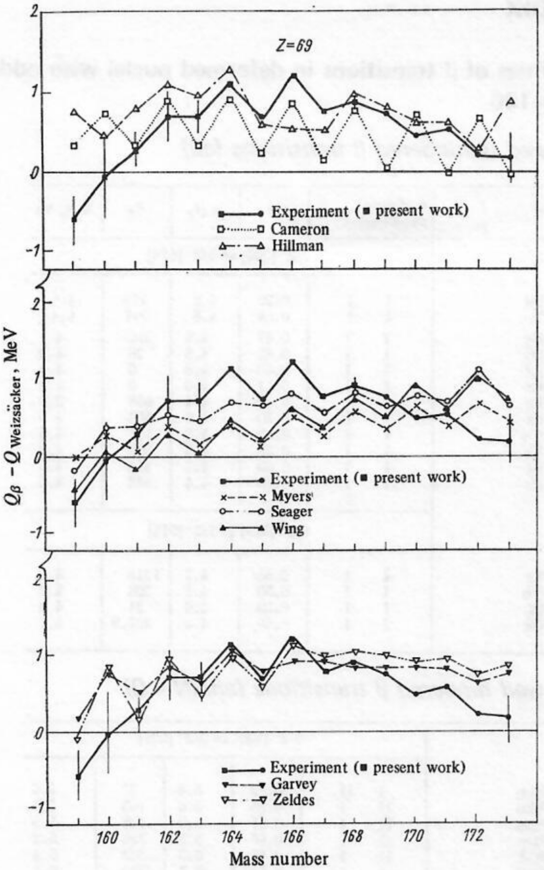

FIG. 21. Comparison of experimentally established values of Q_β of Tm nuclides ($Z=69$) with values of Q_β calculated by different expressions for the masses of nuclei.

put experimental data according to Wapstra *et al.*[149]; without errors, the results of extrapolation (Ref. 141). The mass differences from the tables of Refs. 142–148 calculated in accordance with different expressions for the masses of nuclei are shown in the fourth to the tenth columns.

The known experimental mass differences Q_β for the nuclides Tm, $Z=69$, and Er, $Z=68$, are compared in Figs. 21 and 22. As the ordinates in these figures we have plotted the differences $Q_\beta - Q_{\text{L.D.}}$ where Q_β is the experimental or calculated energy and $Q_{\text{L.D.}}$ is the decay energy calculated for the liquid-drop model by Weizsäcker's formula with parameters taken from Ref. 150.

It can be seen from Table 9 and Figs. 21–22 that in a number of cases the experimental values differ from the tabulated values of Refs. 141–149 by more than 500 keV. At the same time, it is hard to choose tables with which the agreement is best. Some preference can be given to the tables of Wapstra and Gove,[149,141] Garvey *et al.*,[147] and Zeldes *et al.*[148] It can also be seen from Figs. 21 and 22 that the discrepancies between the experimental and tabulated values are especially large for nuclei far from the β-stability band. The reasons for this are obvious: All the calculations and extrapolations are based mainly on the mass differences of nuclei near the stability band. Thus, it is important to accumulate information about the masses of nuclei far from the stability band.

CONCLUSION

In this review, in the first part (Ref. 1) and the second part, we have considered the main results of investigations of nuclides far from the β-stability band in the Yasnapp program at the Joint Institute for Nuclear Research at Dubna during 1967–1974.

During these investigations, 52 new short-lived isotopes were discovered; 48 of them are listed in Table 1 in the first part of the review; communications about the four other new isotopes were published in 1974–1975 (see Refs. 23, 28, 37, and 42). The decay of more than 150 radioactive nuclei has been investigated. For a large number of isotopes decay schemes have been proposed for the first time and in the remaining cases the decay schemes have been significantly augmented. A large amount of new information has been obtained about the properties of the ground and excited states of the nuclei.

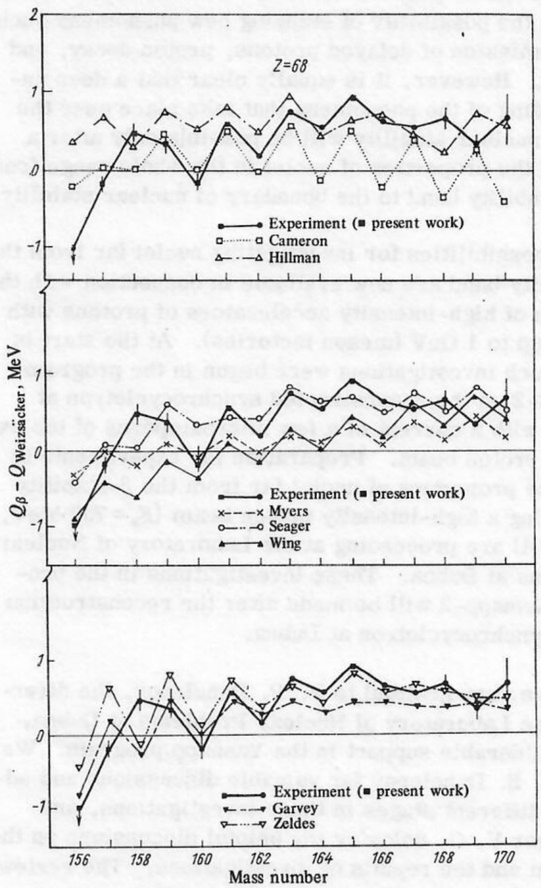

FIG. 22. Comparison of experimentally established values of Q_β for Er nuclides ($Z=68$) with values of Q_β calculated by different expressions for the masses of the nuclei.

The results obtained in the Yasnapp program demonstrate the great efficiency of using proton accelerators with $E_p \approx 600-700$ MeV to obtain and investigate properties of neutron-deficient nuclei far from the β-stability band. For example, in this way we obtain Yb nuclides with neutron deficit up to 15 units and Tl nuclides with a neutron deficit of 16 units. We should here also emphasize the importance of developing fast methods of separating the radioactive nuclei from the irradiated targets: radiochemistry and electromagnetic separation of isotopes. An important element in experiments of this type is the modern methods of obtaining and evaluating spectrometric information.

Nuclei far from the β-stability band have been investigated in recent years in several scientific centers (see Ref. 151). These investigations have been carried on most intensively on the CERN synchrocyclotron at Geneva in the ISOLDE program and at Dubna in the Yasnapp program. On account of the particular features of the experimental methods, a certain division of labor between these two programs has been established. Whereas in the ISOLDE program the main attention is devoted to studying nuclei as far as possible from the β-stability band, with half lives of a few seconds or tenths of a second, the investigations in the Yasnapp program have been concerned with nuclei with $T_{1/2} \approx 1$ min and longer. It is undoubtedly very important to investigate exotic nuclei as far as possible from the stability band. Here there is the possibility of studying new phenomena such as the emission of delayed protons, proton decay, and so forth. However, it is equally clear that a deep understanding of the phenomena that take place near the edge of nuclear stability will be possible only after a study of the properties of nuclei in the whole range from the β-stability band to the boundary of nuclear stability.

New possibilities for investigating nuclei far from the β-stability band are now available in connection with the creation of high-intensity accelerators of protons with energy up to 1 GeV (meson factories). At the start of 1975, such investigations were begun in the program ISOLDE-2 on the reconstructed synchrocyclotron at Geneva with a current of a few microamperes of the extracted proton beam. Preparation for experiments to study the properties of nuclei far from the β-stability band using a high-intensity proton beam ($E_p \approx 700$ MeV, $I_p \approx 15$ μA) are proceeding at the Laboratory of Nuclear Problems at Dubna. These investigations in the program Yasnapp-2 will be made after the reconstruction of the synchrocyclotron at Dubna.

We are very grateful to V. P. Dzhelepov, the director of the Laboratory of Nuclear Problems at Dubna, for considerable support in the Yasnapp program. We thank B. S. Dzhelepov for valuable discussions and advice at different stages in these investigations, and Professor V. G. Solov'ev for helpful discussions on the program and the results of investigations. The review was based on original work done in the Yasnapp program during 1967–1974. We also thank the large international teams that carried out and published this work.

APPENDIX

Probabilities of β transitions in deformed nuclei with odd $A = 150$-190

a. *Allowed unhindered β transitions (au)*

Beta transition	Additional classification	R	$\lg ft_e$	E_f	$\lg ft_e R\eta$
	7/2⁻ [523] ⇄ 5/2⁻ [523]				
^{161}Tb ← ^{161}Gd	I I	0.29	4.9	418	4.4
^{157}Ho → ^{157}Dy	I I	0.54	4.8	341	4.4
^{159}Ho → ^{159}Dy	I I	0.47	4.6	310	4.1
^{161}Ho → ^{161}Dy	I I	0.42	4.8	26	4.3
^{163}Ho ← ^{163}Er	I I	0.40	4.8	0	4.4
^{165}Ho ← ^{165}Er	I I	0.41	4.6	0	4.2
^{167}Ho → ^{167}Er	I I	0.46	4.4	668	3.9
^{169}Ho → ^{169}Er	I I	0.50	4.9	853	4.5
^{165}Tm ← ^{165}Yb	I I	0.55	4.8	161	4.5
^{167}Tm ← ^{167}Yb	I I	0.55	4.5	293	4.2
^{167}Lu ← ^{167}Hf	I I	0.60	4.7	315	4.5
^{169}Lu ← ^{169}Hf	I I	0.60	4.4	493	4.2
	9/2⁻ [514] ⇄ 7/2⁻ [514]				
^{173}Tm ← ^{173}Er	I I	0.65	4.7	1213	4.5
^{175}Lu ← ^{175}Yb	I I	0.59	4.8	396	4.6
^{179}Ta ← ^{179}W	I I	0.39	4.6	31	4.2
^{181}Re ← ^{181}Os	I I	0.48	4.4	262.9	4.1

b. *Allowed hindered β transitions (ah$\Delta N = 0$)*

	5/2⁻ [532] ⇄ 3/2⁻ [521]				
^{153}Pm → ^{153}Sm	I II	0.22	5.4	37	4.6
^{155}Eu ← ^{155}Sm	II I	0.26	5.6	105	5.0
^{157}Eu ← ^{157}Sm	II I	0.21	6.0	198	5.3
^{157}Tb ← ^{157}Dy	I I	0.46	5.5	326	5.2
^{159}Tb ← ^{159}Gd	II I	0.12	6.3	363	5.4
^{159}Tb ← ^{159}Dy	I I	0.50	6.7	363	6.4
^{159}Ho ← ^{159}Er	I I	0.50	$\geqslant$5.6	624	$\geqslant$5.3
^{161}Ho ← ^{161}Er	I I	0.54	5.4	827	5.1
	5/2⁻ [532] ⇄ 3/2⁻ [532]				
^{153}Pm → ^{153}Sm	I I	0.42	5.6	127	5.0
	3/2⁺ [411] ⇄ 1/2⁺ [400]				
^{155}Tb → ^{155}Gd	I II	0.10	7.4	368	6.1
	3/2⁺ [411] ⇄ 3/2⁺ [402]				
^{155}Tb → ^{155}Gd	I II	0.13	7.6	287	6.7
	7/2⁻ [523] ⇄ 5/2⁻ [512]				
^{157}Ho → ^{157}Dy	I I	0.63	5.2	897	4.9
^{159}Ho → ^{159}Dy	I I	0.60	4.9	1016	4.6
^{167}Ho → ^{167}Er	I II	0.15	5.8	347	4.9
^{169}Ho → ^{169}Er	I II	0.24	6.0	92	5.3
^{171}Tm ← ^{171}Er	II I	0.21	6.3	425	5.6
	1/2⁻ [541] ⇄ 3/2⁻ [521]				
^{161}Ho ← ^{161}Er	II I	0.05	7.3	424	5.9
	5/2⁻ [532] ⇄ 5/2⁻ [523]				
^{163}Ho ← ^{163}Er	I I	0.67	5.9	1527	5.7
^{167}Tm ← ^{167}Yb	I I	0.64	6.1	1114	5.9
	7/2⁻ [523] ⇄ 7/2⁻ [514]				
^{157}Ho → ^{157}Dy	I I	0.64	5.4	1211	5.2
^{173}Tm ← ^{173}Er	II I	0.26	5.7	318	5.1
	1/2⁻ [541] ⇄ 1/2⁻ [521]				
^{173}Lu ← ^{173}Hf	II I	0.17	>7.3	128	>6.5
^{179}Ta ← ^{179m}W	II I	0.07	6.4	750	5.2
	3/2⁻ [532] ⇄ 5/2⁻ [512]				
^{177}Ta ← ^{177}W	II I	0.08*	7.4	690	6.1

Continuation

Beta transition	Additional classification		R	$\lg ft_e$	E_f	$\lg ft_e R\eta$
	1/2⁻ [530] ⇌ 1/2⁻ [510]					
^{181}Re ← ^{181m}Os	II	I	0.02	7.1	1180	5.4
	1/2⁻ [541] ⇌ 1/2⁻ [510]					
^{183}Re ← ^{183m}Os	II	I	0.04	⩾8.6	665	⩾7.2
^{181}Re ← ^{181m}Os	II	I	0.03	⩾6.8	432	⩾5.3
	3/2⁻ [532] ⇌ 1/2⁻ [510]					
^{183}Re ← ^{183m}Os	II	I	0.02	8.1	1108	6.4
^{181}Re ← ^{181m}Os	II	I	0.02	⩾7.5	867	⩾5.8
	1/2⁻ [541] ⇌ 3/2⁻ [512]					
^{189}Ir ← ^{189}Pt	II	I	0.18	9.2	540	8.2

c. Allowed hindered β transitions (ahΔN = 2)

	3/2⁺ [411] ⇌ 3/2⁺ [651]					
^{151}Pm ← ^{151}Nd	I	I	0.47	6.9	256	6.6
^{153}Eu ← ^{153}Sm	I	I	0.40	6.7	103	6.3
^{153}Eu ← ^{153}Gd	II	I	0.40	6.5	103	6.1
^{161}Tb → ^{161}Dy	I	I	0.62	6.0	551	5.8
	5/2⁺ [413] ⇌ 5/2⁺ [642]					
^{157}Eu → ^{157}Gd	I	II	0.32	7.3	64	6.8
^{159}Eu → ^{159}Gd	I	II	0.42	~7.0	68	~6.6
	3/2⁺ [422] ⇌ 3/2⁺ [651]					
^{153}Eu ← ^{153}Sm	II	I	0.04	7.5	637	6.1
	5/2⁺ [413] ⇌ 3/2⁺ [651]					
^{153}Eu ← ^{153}Sm	I	I	0.32	7.3	0	6.8
^{153}Eu ← ^{153}Gd	I	I	0.32	7.8	0	7.3
^{157}Eu → ^{157}Gd	I	I	0.51	7.0	477	6.5
	3/2⁺ [411] ⇌ 5/2⁺ [642]					
^{161}Tb → ^{161}Dy	I	I	0.49	7.7	0	7.4
	5/2⁺ [413] ⇌ 7/2⁺ [633]					
^{159}Eu → ^{159}Gd	I	II	0.13*	7.0	733	6.1
^{165}Ho ← ^{165}Dy	II	I	0.12	5.7	995	4.8
	7/2⁺ [402] ⇌ 7/2⁺ [633]					
^{165}Ho ← ^{165}Dy	I	I	0.61	7.8	715	7.6
^{169}Tm ← ^{169}Yb	II	I	0.16	8.6	316	7.8
^{173}Ta → ^{173}Hf	I	II	0.24	>8.3	198	>7.7
^{175}Ta → ^{175}Hf	I	II	0.12	6.7	207	5.8
^{177}Ta → ^{177}Hf	I	II	0.08	8.1	746	7.0
	1/2⁺ [411] ⇌ 1/2⁺ [651]					
^{175}Tm → ^{175}Yb	I	II	0.03	6.3	1469	4.8
	7/2⁺ [404] ⇌ 5/2⁺ [642]					
^{167}Lu → ^{167}Yb	I	II	0.19	>6.3	30	>5.5
^{169}Lu → ^{169}Yb	I	II	0.11	9.2	591	8.0
	7/2⁺ [404] ⇌ 9/2⁺ [624]					
^{171}Lu → ^{171}Yb	I	I	0.63	8.0	935	7.8
^{177}Lu → ^{177}Hf	I	II	0.22	6.3	321	5.6
^{177}Lu ← ^{177}Yb	I	I	0.39	6.5	0	6.0
^{179}Lu → ^{179}Hf	I	I	0.37	7.0	0	6.6
^{177}Ta → ^{177}Hf	I	I	0.41	8.4	321	8.0
^{179}Ta → ^{179}Hf	I	I	0.30	6.0	0	5.5
^{181}Ta ← ^{181}W	I	I	0.49	6.7	0	6.3
^{183}Re ← ^{183}Os	I	I	0.59	7.5	851	7.2
	5/2⁺ [402] ⇌ 7/2⁺ [633]					
^{179}Re → ^{179}W	I	II	0.05	6.3	477	4.9

d. First-forbidden unhindered β transitions (1u)

Beta transition	Additional classification		R	$\lg ft_e$	E_f	$\lg ft_e R\eta$
	3/2⁻ [541] ⇌ 3/2⁺ [651]					
^{151}Pm ← ^{151}Nd	II	I	0.16	7.0	540	6.2
	3/2⁺ [411] ⇌ 3/2⁻ [521]					
^{155}Eu ← ^{155}Sm	I	I	0.39	6.7	246	6.3
^{157}Eu ← ^{157}Sm	I	I	0.32	6.2	394	5.8
^{157}Tb ← ^{157}Dy	I	I	0.37	8.0	0	7.6
^{157}Tb → ^{157}Gd	I	I	0.28	8.0	0	7.4
^{155}Tb → ^{155}Gd	I	I	0.29	7.1	0	6.6
^{159}Tb ← ^{159}Dy	I	I	0.40	7.2	0	6.8
^{159}Tb ← ^{159}Gd	I	I	0.24	6.6	0	6.0
^{161}Tb → ^{161}Dy	I	I	0.51	6.8	75	6.5
^{163}Tb → ^{163}Dy	I	I	0.57	6.3	422	6.1
^{161}Ho ← ^{161}Er	I	I	0.49	7.1	299	6.8
	5/2⁺ [413] ⇌ 5/2⁻ [512]					
^{159}Eu → ^{159}Gd	I	II	0.07	7.0	733	5.8
	5/2⁺ [413] ⇌ 3/2⁻ [512]					
^{159}Eu → ^{159}Gd	I	II	0.02	6.8	1520	4.9
	1/2⁺ [411] ⇌ 3/2⁻ [521]					
^{159}Ho ← ^{159}Er	II	I	0.17*	⩾6.0	206	⩾5.0
^{161}Ho ← ^{161}Er	II	I	0.17	~6.7	211	~5.7
^{163}Tm → ^{163}Er	I	II	0.27	6.4	104	5.7
^{165}Tm → ^{165}Er	I	II	0.27	6.9	243	6.1
	1/2⁺ [411] ⇌ 1/2⁻ [521]					
^{165}Ho ← ^{165m}Dy	I	I	0.61	6.5	429	6.3
^{163}Tm → ^{163}Er	I	I	0.55	6.8	346	6.5
^{165}Tm → ^{165}Er	I	I	0.58	6.7	297	6.5
^{167}Tm → ^{167}Er	I	I	0.50	~6.1	208	~5.8
^{169}Tm → ^{169}Er	I	I	0.37	6.4	0	6.0
^{171}Tm → ^{171}Yb	I	I	0.35	6.2	0	5.7
^{173}Tm → ^{173}Yb	I	I	0.45	6.4	399	6.1
^{175}Tm → ^{175}Yb	I	I	0.48	6.2	920	5.9
^{173}Lu ← ^{173}Hf	I	I	0.48	6.7	425	6.4
^{179}Ta → ^{179m}W	I	I	0.79	~6.8	520	~6.7
	3/2⁺ [411] ⇌ 1/2⁻ [521]					
^{155}Tb → ^{155}Gd	I	I	0.48	8.7	560	8.1
^{161}Tb → ^{161}Dy	I	II	0.12	8.5	368	7.2
^{165}Ho → ^{165m}Dy	II	I	0.22	>6.1	362	>5.4
^{173}Lu ← ^{173}Hf	I	I	0.62	8.0	975	7.8
	5/2⁻ [532] ⇌ 7/2⁺ [633]					
^{165}Ho ← ^{165}Dy	II	I	0.09	7.0	1056	5.8
	7/2⁻ [523] ⇌ 7/2⁺ [633]					
^{165}Ho ← ^{165}Dy	I	I	0.44	6.2	0	5.8
^{167}Ho ← ^{167}Er	I	I	0.30	6.5	0	6.0
^{169}Tm ← ^{169}Yb	I	I	0.41	7.2	379	6.8
^{171}Lu ← ^{171}Hf	I	I	0.45	7.2	662	6.8
	1/2⁺ [411] ⇌ 3/2⁻ [512]					
^{175}Tm → ^{175}Yb	I	II	0.04	7.0	811	5.6
^{187}Re ← ^{187}W	II	I	0.10	7.6	625	6.3
	5/2⁺ [413] ⇌ 5/2⁻ [523]					
^{157}Eu → ^{157}Gd	I	II	0.21	7.2	437	6.5
^{159}Eu → ^{159}Gd	I	II	0.30*	6.7	146	6.2
^{163}Ho ← ^{163}Er	I	I	0.62	7.0	876	6.8
^{167}Tm ← ^{167}Yb	I	I	0.66	6.2	1581	6.0
	1/2⁺ [411] ⇌ 1/2⁻ [510]					
^{181}Re ← ^{181m}Os	I	I	0.09	6.6	827	5.6
^{165}Tm → ^{165}Er	I	II	0.68	7.1	921	6.9
^{175}Tm → ^{175}Yb	I	II	0.06	~6.4	515	~5.2
^{181}Ta ← ^{181}Hf	II	I	0.19	7.2	615	6.5
^{183}Re ← ^{183m}Os	I	I	0.18	6.2	1102	5.5
^{185}Re ← ^{185}Os	I	I	0.44	7.3	880	6.9
	7/2⁺ [404] ⇌ 7/2⁻ [514]					
^{167}Lu → ^{167}Yb	I	I	0.64	6.9	411	6.7
^{169}Lu → ^{169}Yb	I	I	0.64	7.2	960	7.0
^{174}Lu → ^{174}Yb	I	I	0.60	7.0	835	6.8
^{175}Lu ← ^{175}Yb	I	I	0.46	6.3	0	5.9

Continuation

Beta transition	Additional classification		R	$\lg ft_e$	E_f	$\lg ft_e R\eta$
^{177}Lu → ^{177}Hf	I	I	0.31	6.6	0	6.4
^{179}Lu → ^{179}Hf	I	I	0.41	7.5	214	7.1
^{175}Ta → ^{175}Hf	I	I	0.44	6.4	348	6.0
^{177}Ta → ^{177}Hf	I	I	0.35	6.7	0	6.2
			9/2⁻ [514] ⇄ 9/2⁺ [624]			
^{177}Lu ← ^{177}Yb	I	I	0.50	6.8	150	6.5
^{181}Ta ← ^{181}W	I	I	0.38	6.9	6	6.5
^{183}Re ← ^{183}Os	I	I	0.54	6.5	496	6.2
			7/2⁺ [404] ⇄ 9/2⁻ [505]			
^{175}Ta → ^{165}Hf	I	I	0.53	6.4	1227	6.1
			7/2⁺ [404] ⇄ 7/2⁻ [503]			
^{171}Lu → ^{171}Yb	I	I	0.67	8.3	1377	8.1
^{175}Ta → ^{175}Hf	I	I	0.50	6.2	1046	5.9
^{177}Ta → ^{177}Hf	I	I	0.50	6.5	1058	6.2
^{183}Ta → ^{183}W	I	II	0.36*	6.7	453	6.3
^{185}Ta → ^{185}W	I	II	0.47*	6.3	244	6.0
			5/2⁺ [402] ⇄ 5/2⁻ [512]			
^{175}Lu ← ^{175}Hf	II	I	0.14	6.7	343	5.9
^{177}Ta ← ^{177}W	II	I	0.36	>6.9	71	>6.5
^{179}Re → ^{179}W	I	II	0.14	6.8	430	5.9
^{181}Re → ^{181}W	I	II	0.07*	6.7	366	5.6
			5/2⁺ [402] ⇄ 3/2⁻ [512]			
^{183}Ta ← ^{183}Hf	I	I	0.38	6.8	459	6.4
^{181}Re ← ^{181}W	I	I	0.43	7.0	726	6.5
^{183}Re ← ^{183}W	I	I	0.42	7.3	209	6.7
^{185}Re ← ^{185}W	I	I	0.23	7.5	0	6.9
^{187}Re ← ^{187}W	I	I	0.23	7.9	0	7.6
^{189}Re → ^{189}Os	I	I	0.37	7.2	0	6.6
			3/2⁺ [411] ⇄ 5/2⁻ [512]			
^{177}Ta ← ^{177}W	I	I	0.67	~7.7	865	~7.3
			3/2⁺ [411] ⇄ 1/2⁻ [510]			
^{183}Re ← ^{183m}Os	I	I	0.19	7.5	1354	6.8
			1/2⁺ [400] ⇄ 1/2⁻ [510]			
^{185}Re ← ^{185}Os	II	I	0.03*	7.2	646	5.7
			3/2⁺ [402] ⇄ 3/2⁻ [512]			
^{185}Ir → ^{185}Os	I	I	0.74	~7.8	128	~7.6
^{189}Ir → ^{189}Os	I	I	0.56	7.5	0	7.2
^{189}Ir ← ^{189}Pt	I	I	0.11	6.9	0	5.9
			3/2⁺ [402] ⇄ 5/2⁻ [503]			
^{187}Ir → ^{187}Os	I	I	0.80	6.7	711	6.6
			5/2⁺ [402] ⇄ 7/2⁻ [503]			
^{181}Re → ^{181}W	I	I	0.42	7.5	662	7.1
^{183}Re → ^{183}W	I	I	0.33	7.3	453	6.8
^{189}Re → ^{189}Os	I	I	0.68*	7.5	217	7.3

e. First-forbidden hindered β transitions (1h)

			5/2⁻ [532] ⇄ 3/2⁺ [651]			
^{151}Pm ← ^{151}Nd	I	I	0.40	>7.3	117	>6.9
^{153}Eu ← ^{153}Sm	II	I	0.27	8.6	98	8.0
^{153}Eu ← ^{153}Gd	I	I	0.26	6.6	98	6.0
			5/2⁺ [413] ⇄ 7/2⁻ [514]			
^{159}Eu → ^{159}Gd	I	II	0.05	7.0	1163	5.7
			3/2⁺ [411] ⇄ 3/2⁻ [532]			
^{155}Tb → ^{155}Gd	I	II	0.10	8.3	287	7.3

Continuation

Beta transition	Additional classification		R	$\lg ft_e$	E_f	$\lg ft_e R\eta$
			3/2⁺ [413] ⇄ 3/2⁻ [521]			
^{155}Eu → ^{155}Gd	I	I	0.27	8.8	0	8.2
^{157}Eu → ^{157}Gd	I	I	0.37	8.3	0	7.7
^{159}Tb ← ^{159}Gd	II	I	0.16	8.3	348	7.5
^{159}Ho ← ^{159}Er	I	I	0.49	≥5.8	650	≥5.5
^{161}Ho ← ^{161}Er	I	I	0.52	7.9	760	7.6
			7/2⁻ [523] ⇄ 5/2⁺ [642]			
^{161}Ho → ^{161}Dy	I	I	0.28	<6.7	0	<6.0
			7/2⁺ [404] ⇄ 5/2⁻ [523]			
^{161}Tm → ^{161}Er	I	I	0.51	6.6	172	6.2
^{167}Lu ← ^{167}Hf	I	I	0.36	>5.2	0	>4.8
^{169}Lu ← ^{169}Hf	I	I	0.36	>5.5	0	>5.1
^{169}Lu → ^{169}Yb	I	II	0.19	8.5	570	7.6
			7/2⁺ [404] ⇄ 5/2⁻ [512]			
^{161}Tm → ^{161}Er	I	I	0.65	6.9	843	6.5
^{171}Tm ← ^{171}Er	I	I	0.48	9.2	636	8.9
^{167}Lu → ^{167}Yb	I	I	0.62	7.1	213	6.7
^{169}Lu → ^{169}Yb	I	I	0.57	8.1	191	7.7
^{173}Ta → ^{173}Hf	I	I	0.39	7.0	107	6.4
^{177}Ta → ^{177}Hf	I	II	0.16	9.7	508	8.7
^{177}Ta ← ^{177}W	I	I	0.48	~6.8	0	~6.5
			3/2⁺ [411] ⇄ 5/2⁻ [523]			
^{165}Tm ← ^{165}Yb	I	I	0.34	7.0	491	6.6
^{167}Tm ← ^{167}Yb	I	I	0.65	7.8	471	7.4
			1/2⁺ [411] ⇄ 1/2⁻ [530]			
^{165}Tm → ^{165}Er	I	II	0.02*	8.2	991	6.5
			5/2⁺ [402] ⇄ 5/2⁻ [523]			
^{159}Tm → ^{159}Er	I	I	0.51	5.7	221	5.4
^{165}Tm ← ^{165}Yb	II	I	0.07	>7.1	316	>5.9
			5/2⁺ [402] ⇄ 7/2⁻ [514]			
^{159}Tm → ^{159}Er	I	I	0.59	6.0	566	5.8
^{181}Re → ^{181}W	I	II	0.19*	7.5	409	6.7
			9/2⁻ [514] ⇄ 7/2⁺ [633]			
^{171}Lu ← ^{171}Hf	II	I	0.14	7.2	470	6.5
			3/2⁺ [402] ⇄ 1/2⁻ [510]			
^{181}Re ← ^{181m}Os	II	I	0.02	7.1	788	5.4
^{183}Re ← ^{183m}Os	II	I	0.03	7.6	1035	6.1
^{185}Ir → ^{185}Os	I	I	0.70	~6.5	0	~6.0
^{189}Ir → ^{189}Os	I	II	0.40	>9.0	36	>8.3
			1/2⁺ [400] ⇄ 3/2⁻ [512]			
^{187}Re ← ^{187}W	I	I	0.65	>10	512	>9.5
^{187}Ir ← ^{187}Pt	II	I	0.04*	7.9	94	6.2

f. First-forbidden (unique) hindered β transitions (1*h)

			7/2⁺ [404] ⇄ 3/2⁻ [532]			
^{161}Tm → ^{161}Er	I	II	0.10	7.3	729	6.0
			1/2⁺ [411] ⇄ 5/2⁻ [512]			
^{165}Tm → ^{165}Er	I	I	0.63	8.7	478	8.0
^{167}Tm → ^{167}Er	I	I	0.60	9.4	347	9.1
^{171}Tm ← ^{171}Er	I	I	0.38	8.6	0	7.7
^{173}Tm → ^{173}Yb	I	I	0.36	8.5	0	8.1
^{177}Ta ← ^{177}W	I	I	0.60	>6.4	488	>5.7
			7/2⁺ [404] ⇄ 3/2⁻ [521]			
^{167}Lu → ^{167}Yb	I	II	0.16	<7.5	180	<6.4

Continuation

Beta transition	Additional classification		R	$\lg ft_e$	E_f	$\lg ft_eR\eta$
	$5/2^+$ [402] $\rightleftarrows$ $1/2^-$ [521]					
^{173}Lu $\leftarrow$ ^{173}Hf	II	I	0.16	8.6	357	7.8
^{179}Ta $\leftarrow$ ^{179m}W	II	I	0.48	7.4	239	7.1
^{179}Re $\rightarrow$ ^{179}W	I	II	0.07	>5.9	222	>4.3
	$5/2^+$ [402] $\rightleftarrows$ $1/2^-$ [510]					
^{181}Ta $\leftarrow$ ^{181}Hf	I	I	0.39	8.3	482	7.9
^{179}Re $\rightarrow$ ^{179}W	I	I	0.42	7.2	705	6.4
^{189}Re $\rightarrow$ ^{189}Os	I	I	0.50	8.4	36	7.6
	$5/2^+$ [402] $\rightleftarrows$ $9/2^-$ [505]					
^{189}Re $\rightarrow$ ^{189}Os	I	II	0.25	7.8	31	7.2

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