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ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

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ENERGIES OF THE EXCITED STATES OF SOME EVEN STRONGLY DEFORMED NUCLEI IN THE RANGE $164 \leq A < 190$

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Энергии возбужденных состояний некоторых чётных сильно деформированных ядер в области $164 \leq A < 190$.

На основе сверхтекучей модели ядра рассчитаны двухквазичастичные возбужденные состояния для деформированных ядер Dy^{164}, Er^{164}, Yb^{168}, Yb^{174}, Yb^{176}, Hf^{176}, W^{184}, O^{186}. Приведены энергии квадрупольных и октупольных коллективных состояний. Даны анализ ряда схем бета-распада и оценка энергий расщепления ряда двухквазичастичных состояний.

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Energies of the Excited States of Some Even Strongly Deformed Nuclei in the Range $164 \leq A < 190$.

The two-quasi-particle excitations for the deformed nuclei Dy^{164}, Er^{164}, Yb^{168}, Yb^{174}, Yb^{176}, Hf^{176}, W^{184}, Os^{186} have been calculated using the nuclear superfluid model. The energies of the quadrupole and octupole collective states are given. Several beta decay schemes are analysed. The splitting energies of some two-quasi-particle states are estimated.

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E - 1621

ENERGIES OF THE EXCITED STATES OF SOME EVEN STRONGLY DEFORMED NUCLEI IN THE RANGE $164 \leq A < 190$

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The nuclear superfluid model has been considerable success in recent years in accounting for the energies of the non-rotational excited states of even nuclei and various regularities in nuclear properties.

The basic assumptions of the superfluid nuclear model and the methods for calculation of the characteristics of strongly deformed nuclei are presented in ref.[1]. The energies of the two-quasi-particle excited states of strongly deformed even nuclei were first calculated in ref.[2]. A detailed investigation of the excited states of even nuclei in the range $150 < A < 188$ is given in ref.[3]. In that paper the experimental data are analysed, the energies of the two-quasi-particle states of most nuclei in the range $160 \leq A \leq 182$ and the relative probabilities of the corresponding beta transitions are calculated. The experimental data on the excited states of odd-A nuclei appeared after publication of paper[3] allowed one to find the position of the average field levels for nuclei with $A < 160$. Then it became possible to calculate the energies of the two-quasi-particle excited states and the relative probabilities of beta transitions for some isotopes of Sm, Gd, Dy[4]. The energies of the beta and gamma vibrational and the octupole states of strongly deformed even nuclei have recently been calculated and a microscopic structure of these states has been cleared up[5]. Using the later results and the calculations of two-quasi-particle states we can analyse all non-rotational levels of even deformed nuclei. After publication of paper[3] there have appeared new experimental data on the levels of even nuclei for which there are no theoretical calculations in[3,4]. Thus, now it is necessary to calculate the energies of the excited states for some nuclei in the range $164 \leq A < 190$, investigate the structure of these states and compare the results of calculations with the corresponding experimental data. This is just the subject of the present paper.

1. Single-Particle Levels of the Average Field and Pairing Energies

In calculations we use the wave functions and the single-particle levels of the Nilsson scheme[8]. Some modifications have been made in the position of the average field levels according to the experimental data on the single-particle levels of odd-A nuclei. Therefore our scheme of the average field single-particle levels is somewhat different from that given in ref. [8], but it is rather close to the scheme with parameters given in ref. [9]. The energies of the average field single-particle levels $E(s)$, the correlation functions C and the chemical potentials λ for the ground states of systems with even and odd number of nucleons are written in Tables 1 and 2. The quantum numbers describing the single particle levels are denoted by $Nn_z\Lambda\uparrow$, provided $K = \Lambda + 1/2$, and $Nn_z\Lambda\downarrow$, provided $K = \Lambda - 1/2$, where N represents the total number of oscillator quanta, n_z is the number of oscillator quanta along the symmetry axis, Λ is the component of the orbital angular momentum along this axis, $\pm 1/2$ is the projection of the nucleon spin. All quantities in Table 1 and 2 are given in units $\hbar\omega_0^0 = 41\, A^{-1/3}$ MeV. It is taken into account in ref. [4] that there are some intersections of single-particle levels in neutron system at $N<96$. The energies of these levels given in Table 1 differ therefore from those in ref. [4]. In the proton single-particle levels scheme the state 404↓ is the ground state for the isotopes of Lu and Ta, the levels 404↓ and 514↑ intersect. The sequence of the levels 404↓ and 514↑ changes therefore, the values of $E(s)$ being unaffected.

The pairing energies are given as

$$P_N = (1/4)\{3\mathcal{E}(Z,N-1) + \mathcal{E}(Z,N+1) - 3\mathcal{E}(Z,N) - \mathcal{E}(Z,N-2)\} \quad (1)$$

where $\mathcal{E}(Z,N)$ is the energy of the ground state of a nucleus consisting of Z protons and N neutrons. The results of calculations are given in Figs. 1 and 2. The open circles denote the pairing energies determined through mass differences given in [10]. The pairing energies denoted by the dark circles or the straight lines are calculated for the following values of the pairing interaction constants

$$G_N = \frac{26}{A}\ MeV$$

$$G_Z = \frac{28}{A}\ MeV \quad (2)$$

which, as is seen from [1], are the same as those used earlier in both regions of strongly deformed nuclei. From Figs. 1 and 2 it is seen that the calculated pairing energies with constants (2) are in good agreement with the corresponding experimental data. Notice that the pairing energies of all nuclei are calculated for the same deformation with the single-particle level schemes presented in Tables 1 and 2.

2. Excited States of Even-Even Nuclei

The energies of two-quasi-particle excited states are calculated on the basis of the nuclear superfluid model, taking into account the blocking effect. The energies of collective quadrupole and octupole states as well as the structure of these states are taken from /5-7/. The energies of the non-rotational excited states for all nuclei are calculated for the same system of the average field levels, i.e. for the same deformation.

The results of calculations of the energies of two-quasi-particle and collective states are tabulated (Table 3-10). The tables differ from one another in the form because some of them contain an analysis of beta transitions to the levels of the considered nucleus. At the top of these tables are given the energies of neutron and proton two-quasi-particle states and below are presented the energies of a number of collective states. The first column of Tables 3-10 contains the configurations of two-quasi-particle states, K denotes the last filled orbital of the average field in the independent-particle model, $K+1$ is the first unfilled level and so on. The quantum characteristics of the states K, $K+1$, $K+2$ and other are written at the foot of the corresponding part of the table. In the second column one gives the total angular momentum projection on the nuclear symmetry axis K and the parity π, first, for the states with $\Sigma = 0$ which, according to the Gallagher's rule, have lower energy, and below for the states with $\Sigma = 1$. We note that whenever for one of the states of the doublet $K\pi = 0-$ as is shown in /11/, the Gallagher's rule may be violated and the state with $K \neq 0$ has always lower energy. Further we present the energies of all two-quasi-particle states as high as 2 - 2.5 MeV.

According to the superfluid nuclear model the collective non-rotational states are superpositions of two-quasi-particle states of various kind. A state is considered as two-quasi-particle one if admixtures of other states do not exceed 5%. States which are not displayed as two-quasi-particle ones but take part in the formation of the corresponding collective states are marked in the tables by "coll".

In the lower parts of Tables 3-10 are presented the calculated and experimental energies of collective states and for gamma vibrational and octupole states are given three two-quasi-particle states which yield the largest contribution to the given collective state. This contribution is determined from the normalization condition of the wave function of each collective state. We denote by nn the neutron and pp the proton two-quasi-particle states.

The particularities of some nuclei will be discussed further and may be considered as additions to [3].

$A = 164.$

The energies of the non-rotational excited states of Dy^{164} and Er^{164} are given in Tables 3 and 4. The energies of gamma vibrational states are found in [12], a number of levels is observed in the reactions (d , p) and (p , p') [13]. The levels of Er^{164} from beta decay have been investigated in [14]. The state with $K\pi = 6-$ in Dy^{164}, by analogy with Er^{166} may have the configuration nn 523 ↓ + 633 ↑ but its interpretation as pp 413 ↓ + 523 ↑ cannot be excluded now. Note that in Dy^{164} and Er^{164} the state with $K\pi = 2^+$ and the configuration pp 404 ↓ − 411 ↑ is two-quasi-particle one, it does not take part in the formation of a collective state. The value of $\log ft$ for the decay of Tm^{164} to the beta vibrational state of Er^{164} must be somewhat larger than that of $\log ft$ corresponding to the decay to the ground state.

$A = 168.$

As to Er^{168} we note the following. In [3] it is assumed that in Er^{168} there are two levels with $K\pi = 3-$: a neutron level nn 633↑ − 521↓ at 1,095 MeV and a proton level pp 523↑ − 411↓ at 1,543 MeV. This interpretation contains the following disagreement with experiment: the calculated value $\log ft = 6{,}2$ in the decay of Tm^{168} to the 1.095 MeV level strongly differs from the measured one $\log ft = 7.7$. Further, two levels with $K\pi = 4-$ of the two doublets may lie lower in energy than the 3− states; the beta decay of Tm^{168} to these levels being Λ -forbidden. Yet there is no rigorous experimental evidence for existence of such states. At last, if both states with $K\pi = 3-$ contain no admixtures to two-quasi-particle states, then the gamma transition between them is theoretically forbidden, while the intensive 448 KeV(M1)-transition is observed experimentally. These disagreements are eliminated if basing on ref. [15], where the 1,095 MeV level is believed to have spin 2,3 or 4 and on Pokrovsky's data we assume that this level has $K\pi = 4-$. Then one can consider the 1.095 MeV and 1.543 MeV states as the proton doublet pp 523↑ ± 411↓ with $K\pi$ equal to 4− and 3− respectively. Hence the beta decay from Tm^{168} to the 4− state is Λ -forbidden, the value of $\log ft$ increases by 1.5 what is quite reasonable. The neutron 3− state nn 521↓ − 633↑ may lie higher in energy than 1.543 MeV. It is known that the half-life of the 1.543 MeV level $T_{1/2} \leq 8.10^{-10}$ sec., we obtain therefore the hindrance factor $F_N \leq 10^4$ in the Nilsson model for the value $g_R = Z/A$. This is a rather large hindrance for single-particle MI transition. However, by small decrease of the value of the gyromagnetic ratio g_R this disagreement may be eliminated. Note that according to [7] admixtures to the 3– state of the configuration *pp* 523↑ - 411↓ do not exceed 0,5% because of the octupole-octupole interactions.

The energies of the levels of Yb^{168} are listed in Table 5, the classification of beta transitions from Lu^{168} with $K\pi = 1+$ is presented there. The energy of gamma vibrational state is found in [13]. Note that the calculations made in [5] give some higher energy for beta and gamma vibrational states than that observed, however, they describe rather well the position of these levels.

A = 174

The energies of the levels of Yb^{174} are given in Table 6. In contrast to [3] the state with $K\pi = 2-$ is considered as collective, although the contribution of the nearest two-quasi-particle state *nn* 624↑ -512↑ is 91%. The energy of the 2- state decreases by 0.3 MeV due to the octupole-octupole interaction and the calculated value 1,4 MeV well agrees with the observed energy of 1,321 MeV. Notice that the states with $K\pi = 2+$ and configurations *nn* 512↑ -521↓, *pp* 402↑ - 411↓ and *pp* 404↓ - 411↑ can be observed experimentally as two-quasi-particle, they do not take part in the formation of a collective state.

A = 176 .

A gamma vibrational 2 + level [12] and an isomeric state [16] of Yb^{176} have recently been established. The isomeric state may be assigned as the 8- neutron configuration *nn* 514↓ + 624↑ , just as in Hf^{178} and W^{180} . From Table 7 it is seen that the available experimental data on Yb^{176} agree with the presented calculations.

The energies of the excited non-rotational states of Hf^{176} and a classification of beta transitions from 1- 404↓ -512↑ Ta^{176} to the two-quasi-particle levels of Hf^{176} are given in Table 8. The assignement for Ta^{176} is supported by the results obtained in [17]. Note that the change of the calculated neutron two-quasi-particle energies (in comparing with [3]) is connected with the change of the position of some single-particle levels.

A = 184 .

The energies of the two-quasi-particle states of W^{184} and the analysis of beta transitions to these states from Ta^{184} and Re^{184} are given in Table 9 which is constructed in the same form as in [3]. The decay scheme of Ta^{184} with $K\pi = 3-$ and a possible configuration 404↓ -510↑ has recently been studied [18]. A number of papers [19-21] is devoted to the establishment of the decay scheme of Re^{184} with $K\pi = 3-$ and a possible configuration 402↑ + 510↑ .

Nevertheless the level scheme of W^{184} remains very ambiguous.

$A = 186$.

As is known, in the region of osmium isotopes a successive transition takes place from strongly deformed nuclei to spherical. The nuclei W^{186}, Os^{186}, Os^{188} and others have an essentially smaller equilibrium deformation than nuclei with $A < 180$. The calculations of the energies of two-quasi-particle states are performed for the same system of the average field levels, i.e. for the same equilibrium deformation for all nuclei. Therefore, the accuracy of these calculations for nuclei with $A \geq 186$ is considerable worse than for other nuclei. The energies of the two-quasi-particle states in Os^{186} are listed in Table 10. These calculations should be considered as tentative.

Some interesting experimental data are available concerning the levels of Os^{186}, Os^{188} and Os^{190}. So, there are two levels with $K\pi = 2+$ and two levels with $K\pi = 0+$ in Os^{188}, an isomeric state with $K\pi = 10-$ in Os^{190} and others[22,23]. However, the calculation of the energies of the non-rotational excited states of these nuclei and the probabilities of the corresponding beta transitions should be tested separately taking into account the specific features of these nuclei.

3. Remarks

As is known, the energies of the two-quasi-particle states calculated on the basis of the superfluid nuclear model are identical for all nuclei with definite N or definite Z. Data presented in Tables 3-10 and in papers[3,4] allow one to find the energies of the two-quasi-particle states for all even-even nuclei in the region $90 \leq N \leq 110$ and $62 \leq Z \leq 76$. So, the energies of the two-quasi-particle levels of Er^{166} are given in Table III 8b[3] and the recalculated energies are given: neutron in Table 5 and proton in Table 4 of the present paper.

In[4] a more accurate method, as compared with[1], is suggested to calculate the energies and properties of the two-quasi-particle states. In[5] using this method one has calculated the energies of the two-quasi-particle states for some nuclei in the region $150 < A < 190$. In these calculations use has been made of the average field level schemes given in Tables 1 and 2 and pairing energies close to the values shown in Figs. 1 and 2. From a comparision of the two-quasi-particle state energies calculated in[5] with data presented in Tables 3-10 it follows that the accuracy of our calculations is good enough. Note that the correlation functions of some two-quasi-particle states found in/5/ strongly differ from those obtained in/3/. Yet in the method/24/ the correlation functions of the excited states have a somewhat different sense as compared to the method presented in/1/.

As is known, the two-quasi-particle states are twice generated with $K = K_1 + K_2$ and $K = |K_1 - K_2|$. The interaction between quasi-particles eliminates this degeneration and the spacing of the two-quasi-particle states is therefore observed experimentally. In/11/ the spin splitting energies have been calculated in the first order of perturbation theory. The calculated energies are given in Table 11. Necessary parameters are found from the spin splitting of state pp 413↓ ± 411↑ in Gd^{156}. In Table II are given the configurations of two-quasi-particle states, the values of $K\pi$, the energies of these states measured experimentally and their difference as well as a theoretical estimate of the spin splitting energy. Changes in the energies due to quadrupole-quadrupole and octupole-octupole interactions are not taken into account since for states given in Table II these changes are small enough. It should be noted that the theoretical estimates of the spin splitting energies are rough and may serve only as tentative ones.

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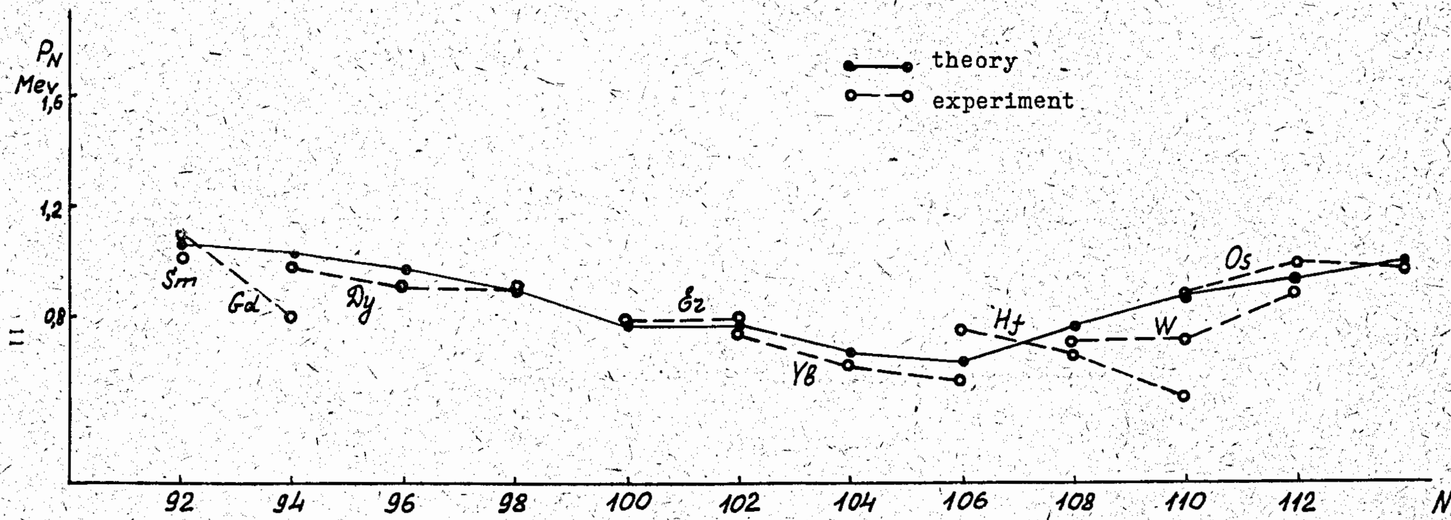

Fig. I.

$$P_N = 1/4 \left[3\mathcal{E}(z, N-1) + \mathcal{E}(z, N+1) - 3\mathcal{E}(z, N) - \mathcal{E}(z, N-2) \right]$$

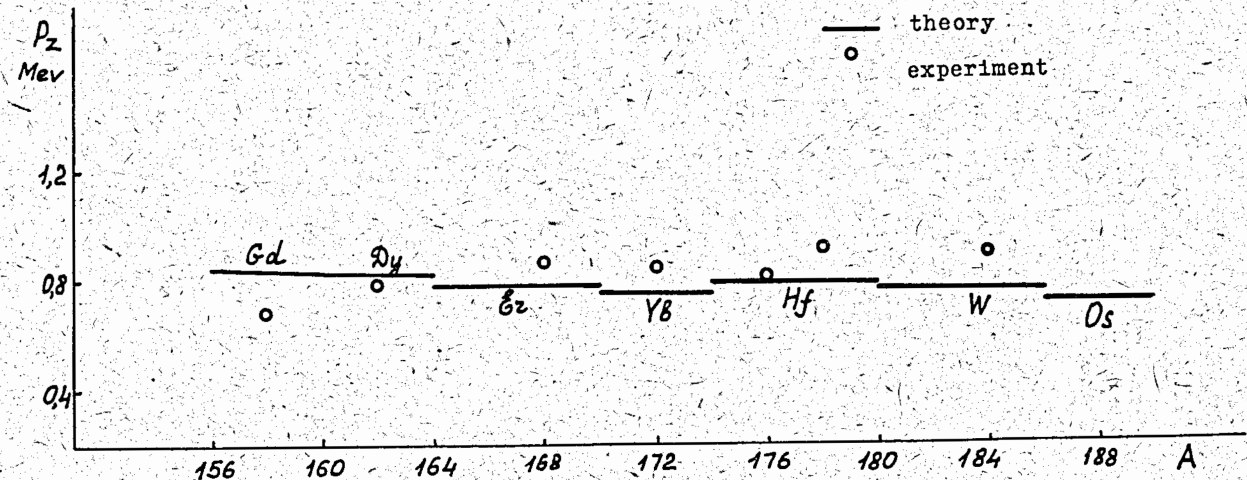

Fig. 2.

$$P_z = 1/4\,[3\mathcal{E}(z-1,N) + \mathcal{E}(z+1,N) - 3\mathcal{E}(z,N) - \mathcal{E}(z-2,N)]$$

Table 1

Single-particle energy levels and the ground state parameters for neutron system

N	$E(s)/\hbar\mathring{\omega}_0$	$Nn_z\Lambda\Sigma$	$C/\hbar\mathring{\omega}_0$	$\lambda/\hbar\mathring{\omega}_0$
85 86	0,85	505 ↑	— —	— —
87 88	0,91	402↓	0.116 0,I48	0,891 0,917
89 90	0,95	660↑	0,123 0,152	0,943 0,968
91 92	1,00	651↑	0,125 0,152	0,991 1,018
93 94	1,04	521↑	0,122 0,147	1,044 1,070
95 96	1,08	642↑	0.111 0,I37	1,098 1,127
97 98	1,11	523↓	0,085 0,124	1,173 1,197
99 100	1,26	633↑	0,073 0,123	1,220 1,272
101 102	1,30	521↓	0,082 0,122	1,310 1,342
103 104	1,36	512↑	0,050 0,110	1,389 1,418
105 106	1,48	514↓	0,037 0,111	1,452 1,497
107 108	1,55	624↑	0,078 0,124	1,530 1,559
109 110	1,62	510↑	0,099 0,135	1,585 1,613
111 112	1,66	512↓	0,113 0,142	1,637 1,660
113 114	1,71	503↑	0,122 0,146	1,679 1,703
115 116	1,74	505↓	0,125 0,145	1,720 1,743
117 118	1,75	501↑	— —	— —
119	1,78	651↓	—	—

Table 2

Single-particle energy levels and the ground state parameters for proton system

Z	$E(s)/\hbar\mathring{\omega}_0$	$Nn_z\Lambda\Sigma$	$C/\hbar\mathring{\omega}_0$	$\lambda/\hbar\mathring{\omega}_0$
59	1,20	422↓	0,075	1,218
60			0,124	1,252
61	1,31	532↑	0,079	1,280
62			0,127	1,325
63	1,36	513↓	0,090	1,359
64			0,129	1,391
65	1,42	411↑	0,089	1,424
66			0,127	1,458
67	1,48	523↑	0,081	1,495
68			0,123	1,528
69	1,56	411↓	0,071	1,566
70			0,121	1,601
71	1,66	404↓	0,081	1,627
72			0,123	1,671
73	1,69	514↑	0,085	1,709
74			0,121	1,737
75	1,76	402↑	0,073	1,776
76			0,118	1,808
77	1,86	402↓	0,075	1,834
78			0,118	1,877
79	1,90	400↑	—	—
80			—	—
81	1,97	505↑	—	—
82			—	—

Table 3

$^{98\ -\ 164}_{66}Dy$

Neutron two-quasi particle states				Proton two-quasi-particle states			
Configuration	Kπ	Energy (MeV) Calc.	Experiment.	Configuration	Kπ	Energy (MeV) Calc.	Experim.
K,K+1	6− 1−	1,7	(1,68o)	K,K+1	2− coll 5−	1,4	
K,K+2	2+ coll. 3+	1,9	(1,987)	K−1,K+1	6− 1−	1,8	(1,68o)
K−1,K+1	1+ 6+	1,9		K,K+2	2+ coll 1+	1,9	(1,987)
K−1,K+2	3− 2−	2,2		K−1,K	4+ 1+	2,1	
K−2,K+1	2− coll. 5−	2,2		K−2,K+1	1+ 6+	2,1	
K,K+3	5+ 0+ coll.	2,4		K+1,K+2	4− 3−	2,1	
K+1,K+2	4− 3−	2,4		K−1,K+2	2+ coll 3+	2,2	
K−1,K	5− 0−	2,6		K−2,K	1− 4−	2,4	
K+1,K+3	1− 6−	2,8		K,K+3	5+ 2+	2,6	
K−2,K	4+ 1+	2,9		K−2,K−1	5− 0−	2,8	
K−2=521↑; K−1=642↑; K=523↓; K+1=633↑; K+2=521↓; K+3=512↑.				K−2=532↑; K−1=413↓; K=411↑; K+1=523↑; K+2=411↓; K+3 =4o4↓;			

Collective states

Kπ	Energy (MeV) Calc.	Experim.	Structure of states
2+	0,8	0,770	pp411↑+411↓ 36%; pp413↓−411↓ 19%; nn523↓−−521↓ 16%
0+	1,5	—	
0−	1,6	—	nn642↑−523↓ 29%; nn642↑−512↑ 15%, nn660↑−−770↑ 14%
2−	1,2	—	pp411↑−523↑ 75%; nn633↑−521↑ 20%; nn642↑−−521↓ 0,6%.

Table 4

$_{68}^{98}Er^{164}$

Configuration	Kπ	Energy (MeV)	β-decay of Tm^{164} 1+ 523↑ - 523↓		Energy (MeV)	Kπ	Configuration
Neutron two-quasi-particle states				Proton two-quasi-particle states			
K,K+1	5–	1,6	–		1,3	4–	K,K+1
	0–coll	–	1h	1* h	–	3–	
K–1,K+1	1–	1,9	1F	aF	1,7	2+coll	K–1,K+1
	4–	–	–	aF	–	1+	
K–2,K+1	1+	2,1	1F	–	2,0	7–	K,K+2
	4+	–	–	1h	–	0–coll	
K–1,K	4+	2,1	–	1h	2,2	2–	K–1,K
	1+	–	a(2)	–	–	5–	
K,K+2	6–	2,3	–	aF	2,2	2+coll	K–2,K+1
	1–	–	1u	–	–	3+	
K+1,K+2	1+	2,3	aF	a(2)	2,2	1+	K,K+3
	6+	–	–	–	–	8+	
K–2,K	4–	2,3	–	–	2,3	3+	K+1,K+2
	1–	–	1*h	–	–	4+	
K–1,K+2	2–	2,4	1F	–	2,3	5+	K–1,K+2
	5–	–	–	aF	–	2+	
K,K+3	2+coll	2,6	a(3)	–	2,5	5–	K+1,K+3
	3+	–	–	–	–	4–	

Neutrons: K–2=651↑; K–1 =521↑; K=523↓
K+1= 642↑; K+2 =633↑; K+3 =521↓.

Protons: K–2=413↓; K–1 =411↑; K=523↑;
K+1=411↓; K+2 =404↓; K+3 = 514↑.

Collective states

Kπ	Energy (MeV) Calc.	Energy (MeV) Experim.	Structure of states
2+	0,9	0,811	pp411↑+411↓ 48%; pp413↓–411↓ 16%, nn521↑+521↓ 12%.
0+	1,5	—	
0–	1,3	—	nn642↑–523↓ 49%; nn651↑–521↑ 14% nn660↑–770↑ 9%

Table 5

$^{168}_{70}Yb_{98}$

Configuration	$K\pi$	Energy (MeV)	β-decay of Lu^{168} 1+ 404↓ − 642↑		Energy (MeV)	$K\pi$	Configuration
Neutron two-quasi-particle states				**Proton two-quasi-particle states**			
K,K+1	6−	1,7	—	a(2)	1,4	3+	K,K+1
	1−	—	1F	—	—	4+	
K,K+2	2+coll.	1,9	aF	—	1,6	5−	K,K+2
	3+	—	—	—	—	4−	
K−1,K+1	1+	1,9	ah	—	1,9	7−	K−1,K+1
	6+	—	—	1h	—	0− coll	
K−1,K+2	3−	2,2	—	—	2,1	8−	K+1,K+2
	2−	—	1(3)	1*h	—	1−	
K−2,K+1	2−	2,2	1F	—	2,1	3+	K,K+3
	5−	—	—	aF	—	2+	
K,K+3	5+	2,4	—	aF	2,1	1+	K−1,K+2
	0+coll.	—	aF	—	—	8+	
K+1,K+2	4−	2,4	—	—	2,2	4−	K−1,K
	3−	—	1* F	1*F	—	3−	
K−1,K	5−	2,6	—	—	2,3	5+	K−2,K+1
	0−coll.	—	1h	ah	—	2+	
K+1,K+3	1−	2,8	1F	—	2,6	6+	K+1,K+3
	6−	—	—	ah	—	1+	

K−2=521↑; K−1=642↑; K=523↓; K+1 =633↑; K+2 =521↓; K+3 =512↑ .	K−2= 411↑; K−1 =523↑; K=411↓ K+1 =404↓; K+2 =514↑; K+3=402↑

Collective states

$K\pi$	Energy (MeV) Calc.	Energy (MeV) Experim.	Structure of states
2+	1,3	0,944	nn523↓−521↓ 39%; nn521↑+521↓ 23%; pp411↑ +411↓ 12%
0+	1,5	1,191	

Table 6

$^{174}_{70}Yb_{104}$

Configuration	Kπ	Energy (MeV)	Configuration	Kπ	Energy (MeV)
Neutron two-quasi-particle states			**Proton two-quasi-particle states**		
K,K+1	6+	1,2	K,K+1	3+	1,4
	1+	—		4+	—
K-1,K+1	3+	1,6	K,K+2	5-	1,6
	4+	—		4-	—
K,K+2	2- coll.	1,7	K-1,K+1	7-	1,9
	7-	—		0- coll.	—
K-2,K+1	7-	1,9	K+1,K+2	8-	2,1
	0- coll.	—		1-	—
K-1,K+2	5-	2,1	K,K+3	3+	2,1
	4-	—		2+	—
K,K+3	2+ coll.	2,2	K-1,K+2	1+	2,1
	3+	—		8+	—
K-1,K	3+	2,3	K-1,K	4-	2,2
	2+	—		3-	—
K+1,K+2	8-	2,3	K-2,K+1	5+	2,3
	1-	—		2+	—
K-2,K	1-	2,5	K+1,K+3	6+	2,6
	6-	—		1+	—
K+1,K+3	4+	2,8	K-2,K	2+ coll.	2,6
	3+	—		1+	—
K-2=633↑; K-1=521↓; K=512↑; K+1=514↓; K+2=624↑; K+3=510↑.			K-2=411↑; K-1=523↑; K=411↓; K+1=404↓; K+2=514↑; K+3=402↑.		

Collective states

Kπ	Energy (MeV) Calc.	Energy (MeV) Experim.	Structure of states
2+	1,7	—	nn512↑-510↑50%, pp411↑+411↓18%, pp413↓-411↓9%
0+	1,5	—	
2-	1,4	1,321	nn624↑-512↑91%, pp402↑-514↑5%, pp411↑-523↑ 2%

106 $^{176}_{70}$YB

Table 7

Neutron two-quasi particle states			Proton two-quasi-particle states		
Configuration	Kπ	Energy (MeV)	Configuration	Kπ	Energy (MeV)
K,K+1	8– 1–	1,1 —	K,K+1	3+ 4+	1,4 —
K,K+2	4+ 3+	1,6 —	K,K+2	5– 4–	1,6 —
K–1,K+1	2– coll. 7–	2,0 —	K–1,K+1	7– 0– coll.	1,9 —
K,K+3	2+ coll. 5+	2,0 —	K+1,K+2	8– 1–	2,1 —
K+1,K+2	4– 5–	2,1 —	K,K+3	3+ 2+	2,1 —
K–1,K	6+ 1+	2,2 —	K–1,K+2	1+ 8+	2,1 —
K–1,K+2	2+ coll. 3+	2,3 —	K–1,K	4– 3–	2,2 —
K–2,K+1	5– 4–	2,4 —	K–2,K+1	5+ 2+	2,3 —
K+1,K+3	6– 3–	2,4 —	K+1,K+3	6+ 1+	2,6 —
K–2,K	3+ 4+	2,6 —	K–2,K	2+ coll. 1+	2,6 —
K–2= 521↓; K–1 =512↑; K= 514↓; K+1 = 624↑; K+2 = 510↑; K+3 =512↓.			K–2= 411↑; K–1 =523↑; K= 411↓; K+1 = 404↓; K+2 = 514↑; K+3 = 402↑		

Collective states

Kπ	Energy (MeV) Calc.	Energy (MeV) Experiment.	Structure of states
2+	1,4	1,270	nn514↓– 512↓50%;nn512↑–510↑16%;pp411↑+411↓10% .
0+	1,5	—	

Table 8

$^{104}_{72}Hf^{176}$

Configuration	Kπ	Energy (MeV)	β - decay of ^{176}Ta 1− 404↓ − 512↑		Energy (MeV)	Kπ	Configuration
Neutron two-quasi particle states				**Proton two-quasi-particle states**			
K,K+1	6+ 1+	1,2 —	— 1u	— a(2)	1,2 —	8− 1−	K,K+1
K−1,K+1	3+ 4+	1,6 —	1*F —	— 1u	1,7 —	6+ 1+	K,K+2
K,K+2	2− 7−	1,7 —	ah —	— —	1,8 —	5− 4−	K−1,K+1
K−2,K+1	7− 0− coll.	1,9 —	— aF	aF —	1,8 —	2− 7−	K+1,K+2
K−1,K+2	5− 4−	2,1 —	— —	1*u —	1,9 —	3+ 4+	K−1,K
K,K+3	2+ coll. 3+	2,2 —	1(3) 1*Λ(3)	— 1F	2,1 —	3+ 2+	K−1,K+2
K−1,K	3+ 2+	2,3 —	1*Λ(3) 1(3)	1u —	2,4 —	2+ coll. 5+	K,K+3
K+1,K+2	8− 1−	2,3 —	— aF	1F —	2,4 —	1+ 8+	K−2,K+1
K−2,K	1− 6−	2,5 —	ah —	— —	2,5 —	6− 3−	K+1,K+3
K+1,K+3	4+ 3+	2,8 —	— 1*F	— ah	2,5 —	7− 0− coll.	K−2,K
K−2=633↑; K−1 =521↓; K= 512↑ K+1 =514↓; K+2 =624↑; K+3 =510↑.				K−2 =523↑; K−1 =411↓; K=404↓; K+1 =514↑; K+2 =402↑; K+3=402↓.			

Collective states

Kπ	Energy (MeV) Calc.	Experiment	Structure of states
2+	1,7	—	nn512↑−510↑37%; pp404↓−402↓33%; pp402↑−400↑ 8%
0+	1,5	—	
0−	1,9	—	nn633↑−514↓48%; nn660↑−770↑14%, nn651↓−521↓ 9%

$^{110}_{74}W^{184}$

Table 9

Configuration	Kπ	Energy (MeV) Calc.	Exper.	β-decay of Ta^{184} 3- 404↓ - 510↑	β-decay of Re^{184} 3- 402↑ + 510↑
Neutron two-quasi-particle states					
K,K+1	2+ coll.	1,6		1∧(1*h)	1u
	1+	—		1*h	—
K-1,K	4-	1,8		ah	a(2)
	5-	—		—	—
K-1,K+1	6-	1,8		—	—
	3-	—		aF	aF
K,K+2	3+	1,9		1u	1∧(1u)
	4+	—		1∧(1u)	1u
K,K+3	5+	2,0		1∧(1u)	1*h
	4+	—		1u	1∧(1*h)
K+1,K+2	5+	2,0		—	—
	2+	—		1F	1F
K-1,K+2	1-	2,0		—	—
	8-	—		—	—
K-2,K	4+	2,2		1∧(1u)	1h
	3+	—		1u	1∧(1h)
K+1,K+3	3+	2,2		1F	1F
	6+	—		—	—
K-2=514↓; K-1 = 624↑; K= 510↑; K+1 =512↓; K+2 =503↑;K+3=505↓.					
Proton two-quasi-particle states					
K,K+1	2-	1,3	(1,15)	aF	a(4)
	7-	—	—	—	—
K-1,K+1	6+	1,5		—	—
	1+	—		1*u	—
K-1,K	8-	1,9		—	—
	1-	—		—	—
K,K+2	6-	1,9		—	—
	3-	—		aF	aF
K-1,K+2	2+	2,0		1h	1F
	5+	—		1∧(1h)	1*F
K+1,K+2	4+	2,1		1F	1h
	1+	—		—	1∧(1h)
K-2,K+1	3+	2,2		1F	1u
	2+ coll.	—		1F	1∧(1u)
K,K+3	4-	2,2		aF	aF
	5-	—		—	—
K-2=411↓; K-1 = 404↓; K= 514↑; K+1 = 402↑; K+2 = 402↓; K+3 = 400↑.					

Table 10

$^{110-186}_{76}Os$

Neutron two-quasi-particle states			Proton two-quasi-particle states		
Configuration	Kπ	Energy (MeV)	Configuration	Kπ	Energy (MeV)
K,K+1	2+ coll. 1+	1,6	K,K+1	4+ 1+	1,3
K-1,K	4- 5-	1,8	K,K+2	2+ coll. 3+	1,6
K-1,K+1	6- 3-	1,8	K-1,K+1	6- 3-	1,8
K,K+2	3+ 4+	1,9	K-2,K+1	2+ coll. 5+	2,0
K,K+3	5+ 4+	2,0	K-1,K+2	4- 5-	2,0
K+1,K+2	5+ 2+	2,0	K+1,K+2	2+ coll. 1+	2,0
K-1,K+2	1- 8-	2,0	K,K+3	3- 8-	2,1
K-2,K	4+ 3+	2,2	K-1,K	2- 7-	2,1
K-2,K+1	2+ coll. 5+	2,2	K-2,K	6+ 1+	2,3
K+1,K+3	3+ 6+	2,2	K+1,K+3	7- 4-	2,5
K+1,K+4	3+ 0+ coll.	2,3	K-2,K-1	8- 1-	2,7

K-2 =514↓; K-1 =624↑; K=510↑; K+1=512↓; K+2=503↑; K+3 =505↓; K+4=501↑.

K-2=404↓; K-1=514↑; K=402↑; K+1=402↓; K+2=400↑; K+3=505↑.

Table 11

Splitting energy of two-quasi-particle states

Nucleus	Configuration	$K\pi$	Energy (MeV)	$\Delta E_{exp.}$ (MeV)	$\Delta E_{theor.}$ (MeV)
GD^{156}	pp413↓± 411↑ nn521↑± 523↓	4+ 1+ 4+ 1+	1,511 2,026 — 1,966	0,515 —	0,51 0,4
Dy^{158}	nn521↑± 523↓	4+ 1+	1,672 —	—	0,4
Dy^{160}	nn521↑± 523↓	4+ 1+	1,694 —	—	0,4
Er^{166}	nn633↑± 523↓	6– 1–	1,785 1,826	0,041	0,6
Er^{168}	pp523↑± 411↓	4– 3–	(1,095) 1,543	(0,448)	0,4
Yb^{172}	nn512↑± 52I ↓	3+ 2+	1,174 1,468	0,294	0,4
Yb^{172}	nn 514↓∓ 521↓	3+ 4+	1,702 2,075	0,373	0,2
Hf^{178}	pp514↑± 404↓ nn624↑± 514↓	8– 1– 8– 1–	1,148 — 1,480 —	— —	1,1 0,8
Hf^{180}	pp514↑± 404↓	8– 1–	1,142 —	—	1,1
W^{182}	pp 514↑∓ 402↑ nn 624↑∓ 510↑	2– 7– 4– 5–	1,290 1,961 1,554 —	0,671 —	0,7 0,1