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PROPERTIES OF THE GROUND-AND EXCITED STATES OF STRONGLY DEFORMED NUCLEI

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Abstract

The calculations of the even-even nuclei energies and the probabilities of the β -transitions in even and odd nuclei carried out on the basis of the superfluid nuclear model in the regions $154 \leq A \leq 188$ and $225 \leq A \leq 255$ have been summed up. The properties of the ground- and excited states of strongly deformed nuclei have been investigated which follow from the superfluid model of the nucleus. Experiments have been suggested with the indication of the most favourable cases of finding three - or four-quasi-particle states being populated for appropriate β- decays. An attention has been paid to the neoessity of the experimental finding of all levels of the even-even nuclei given by the model. It is shown that the experimental determination of the degree of the F-forbiddenness of the β - decays will poipt out how the residual forces which are not taken into account in the superfluid model affect the properties of the ground- and excited states. All the even strongly deformed nuclei have been analysed and the cases have been pointed out which are the most favourable from the point of view of the determination of the degree of the F-forbiddenness for the β - transitions.

Аннотация

Подведены итоги расчетов энергий четно-четных ядер и вероятностей β -переходов в четных и нечетных ядрах в областях $154 \leq A \leq 188$ и $225 \leq A \leq 255$, проведенных на основе сверхтекучей модели ядра. Рассмотрены свойства основных и возбужденных состояний сильнодеформированных ядер, которые следуют из сверхтекучей модели. Предложены опыты с указанием наиболее благоприятных случаев по нахождению трех и четырехквазичастичных состояний, заселяющих при соответствующих β -распадах. Обращено внимание на необходимость опытной прверки всей совокупности уровней четно-четных ядер, даваемых моделью. Показано, что экспериментальное определение степени F запрещенности β -распадов укажет на то влияние, которое оказывают неучтенные в сверхтекучей модели остаточные силы на свойства основных и возбужденных состояний. Проанализированы все четные сильнодеформированные ядра и указаны случаи наиболее благоприятные с точки зрения определения степени F запрета для β -переходов.

I. Introduction

The investigations [2] of the properties of the ground - and some excited states of strongly deformed nuclei carries out on the basis of the superfluid nuclear model [1] are rather fruitful. This model based on the model of independent particles takes into account the short range part of the residual nucleon-nucleon forces in a nucleus. In the framework of the model we have calculated the energies of the two-quasi-particle levels of even-even nuclei and the values of $\log(ft)_z$ for the beta-transitions in the even and odd nuclei in the region $154 \leq A \leq 188$ [3,4,5] and $225 \leq A \leq 255$ [6]. All the parameters used in the calculations are determined from the experimental data on the single-particle levels of the odd nuclei and the pairing energies which are found from the differences of the nuclear masses. We note that in calculating the characteristics of the even-even nuclei no use is made of any new parameter since all parameters have been determined in investigating odd nuclei. Therefore, an investigation of the even-even nuclei is especially valuable from the point of view of the check of the correctness of the basis foundations of the superfluid nuclear model.

We count the number of parameters used in calculating nuclear properties in the region $154 \leq A \leq 188$ and $225 \leq A \leq 255$. As single-particle levels of the average field we take the corrected levels of the Nilsson's scheme [7]. For determination of those single-particle levels twenty parameters have been used which characterize both the Nilsson's scheme and the alterations in this scheme. From the comparison of the calculated values of the pairing energies with the experimental data it has been found [6,8] that the pairing interaction constants of the neutron G_N and the proton G_z systems change as $1/A$ and their values are in both regions of strongly deformed nuclei

$$G_N = \frac{26}{A}\ Mev ,$$

$$G_z = \frac{29}{A}\ Mev . \qquad (1)$$

The twenty-two parameters are used in all calculations which have been found on the basis of 58 values of the pairing energies and of 205 data on the ground - and excited states of the odd nuclei. Thus, the twenty-two free parameters are fixed so as to discribe roughly 263 experimental data on the single-particle levels of odd nuclei and on the pairing energies.

The values of the pairing interaction constants (1) are got in summing over 36 levels of the average field in the basic equations of the model. The investigations [6,8] have shown that the superfluid properties of the system are independent of a cutoff if it is made at energies higher than (3-5) MeV both higher and lower than the K-state. In restricting the summation there is no necessity at all to introduce a cutoff constant into basic equations of the model since the pairing interaction constant G seems as though it would be renormalized with account of this cutoff.

The difference of the energies of the two-quasi-particle excited- and ground states is calculated with an error of the order of 10%. In most unfavourable cases the error does not exceed 20%. The error is first due to the uncertainties in the details of the average field and to the fluctuation in these single-particle levels in passing from one nucleus to another, and, secondly, it is due to an inaccuracy of the mathematical method used. The use of the experimental data on the single-particle levels of the odd - A nuclei has led one to smaller error related to the behaviour of the average field levels. However, purposely, (in order to clear up the correctness of the basic foundations of the superfluid model of the nucleus without introducing a large number of parameters) the fluctuations of the single-particle levels of the average field were not taken into account in passing from one nucleus to another. The accuracy of the calculations can therefore be somewhat improved if to each even-even nucleus there will correspond an approximate set of the single-particle levels. The single-particle levels of the neighbouring odd nuclei calculated according to these sets will describe well corresponding experimental data. The comparison of the results of calculation with experiment shows that their accuracy is to a greater extent restricted by the fluctuation of the average field.

It is very difficult to appreciate strictly the accuracy of the approximate method. Rough estimations show that the errors should not exceed 10%. An accuracy of the method has been investigated in [9] on the basis of the model in which the superconductive-type interaction of six particles situated on five single-particle levels has been considered. The comparison of the exact solution of the model with the approximate ones shows that in accordance with the superfluid nuclear model the calculations yield just the same sequence of the energy levels as the exact solution. These calculations, on the whole, agree better with the exact solution than the calculations based on a original formulation of the pairing correlations [10,11]. Since the calculations made yield a correct sequence of the energy levels and are based on the experimental data on the pairing energies then the accuracy of the method is believed to be effectively improved. The investigation of the above- mentioned model proves this fact. Thus, in the approximate method (compared to the exact one) the errors in the energy differences decreases by a factor of two if the calculations carried out for one and the same value of the pairing energy in comparison with the errors in the calculations carried out for one and the same value of the pairing interaction constant G .

The investigations carried out in [3-5,8] have shown that the superfluid nuclear model describes correctly the properties of the ground- and some excited states of strongly deformed nuclei and can be a good basis for further investigations.

In the present paper besides the investigations summed up above we consider what consequences follow from the superfluid nuclear model which concern the properties of the ground- and exited states of strongly deformed nuclei and what experiments are to be made to check them. Experiments are suggested which allow one to appreciate the influence upon the properties of the ground- and excited states of those residual forces which are not taken into account in the superfluid model of the nucleus.

In the present paper we shall not deal with interactions which lead to collective effects, especially important for the states 2+, 0+, 0- and we shall not takes into account the connection with rotational states. Although these effects are essential in some cases however they do not change noticeably the strongly-deformed nuclear properties under consideration. Furthermore, our investigations may give additional information, namely, in what cases the account of these effects is necessary.

2. The nature of the ground- and excited states of the odd nuclei

The superfluid nuclear model yields a single-quasi-particle aspect of the ground- and some excited states and a three- quasi-particle aspect for a number of higher excited states. The analysis of the experimental data on the levels of the odd strongly-deformed nuclei carried out by Mottelson and Nilsson [12] has shown that the spins and the parities of these states are unambiguously comparable with the corresponding characteristics of the Nilsson's scheme and the values of $\log ft_e$ for β - transitions are classified according to the selection rules based on the asymptotic quantum numbers. From this analysis follows the single-quasi-particle aspect of the ground- and low-excited states of the odd nuclei.

As mentioned in [3] the pairing correlations of a superconductive type affect essentially the probabilities of the β decays and lead one to a necessary systematization of the values of $\log[ftR_2]$ (R is the superfluid correction,

η is the statistical factor) instead of $\log ft_e$, as in [12]. This systematization is of the form:

$$\begin{aligned} 4,0 < \log[ft_e R\eta] &< 4,7 \qquad au \\ 5,5 < \log[ft_e R\eta] &< 6,5 \qquad ah \\ 5,5 < \log[ft_e R\eta] &< 6.5 \qquad 1u\,. \end{aligned} \tag{2}$$

The distribution of the values of $\log[ft_e R\eta]$ for the whole experimental data on β - decays of odd nuclei given in Figs. 1a) and 2b), shows that the systematization (2) is executable. From Fig. 1a) it is seen that there are two groups of allowed transitions au and ah . The clear separation between them testifies the fact that the selection rules based on the asymptotic quantum numbers are executable Figs. 2a) and 2b) give histograms for the first forbidden unhindered β - transitions. From these hystograms it can be seen that in passing form the $\log ft_e$ to the $\log[ft_e R\eta]$ classification the regions of the values of the latter become narrower compared to the first ones and move on the side of smaller values. Comparing these hystograms we see what an important role play the superfluid corrections to the β - transition probabilities. Note all the three values of $\log[ft_e R\eta] \approx 7.2$ (Fig.2b) are referred to the transitions between states* $402\uparrow$ and $512\downarrow$[8] and a number of β - transitions in the transuranic region with $\log[ft_e R\eta] \leq 5,6$ is badly determined experimentally. The dispersion of values of $\log[ft_e R\eta]$ are due both to the fluctuation in the average field levels and the inaccuracy of experimental data. The probabilities of the hindered β - transitions (ah and 1h) are more sensitive to the fluctuations in the average field compared to unhindered ones.

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* To determine the average field states we have used notations based on the asymptotic quantum numbers: N, the total number of nodes in the wave function n_z the number of nodal planes perpendicular to the symmetry axis, Λ the component of the particles orbital angular momentum along the symmetry axis and Σ is the projection of the nucleon spin on this axis, $K = \Lambda \pm \Sigma$, π is the parity; the state is characterized as $K\pi\,[Nn_z\Lambda]$ or $Nn_z\Lambda\uparrow$ provided $K = \Lambda + \Sigma$ and $Nn_z\Lambda\downarrow$ provided $K = \Lambda - \Sigma$;

$\hbar\mathring{\omega}_0 = 41 A^{-1/2}$ Mev.

As far as the basic assumptions of the superfluid nuclear model are true there should appear the three- quasi-particle levels in the odd nuclei. The three-quasi-particle states must be of the two types: the first type (3n) and (3p), when all the three quasi-particles are either neutron or proton ones, the second type (p, 2n) and (n, 2p) when one quasi- particle is proton and two quasi-particles are neutron ones or, on the contrary, two quasi-particles are proton and one quasi-particle is neutron one.

The three quasi-particle states such as (3n) and (3p) must be at energies 2 MeV and higher, only in Dy^{161} the states such as (3n) may be at energies of the order of 1 MeV. The β - transitions from the ground states of the even system of a parent nucleus to the states (3n) and (3p) are F-forbidden and it is rather difficult to detect them in the β - transitions. Experimentally such states can be found either by the Coulomb excitation method or by studying γ - spectra in the transitions from high excited states, as in [15]. A detection of the states of such a type and a determination of the degree of the F-forbiddenness for β - transitions imposed upon them is of very great interest from the point of view of the considered model.

The three-quasi-particle states of the type (p,2n) and (n,2p) must be well filled in the β - decays. Once we digress from the interaction of three quasi-particles between them then the probabilities of β - transitions to these states are the same as for transitions to the excited states of even-even nuclei. Let us look in what nuclei it is earsiest to detect experimentally the levels of such a type. Since the lowest states (2n,p) and (2p,n) are in the region (1-2) MeV then it is necessary that the energy Q released in the β - transitions to the ground state would be sufficiently high and the β - transitions themselves to these states would be not strongly hindered i.e. of the kind au, ah and lu so as they could be found at a low decay energy. Table 1 gives the β - transitions to the states (2n,p) and (2p,n) which satisfy these requirements. In the second column of the table we give the configuration of the state of a parent nucleus, in the fourth one the configuration of the three-quasi-particle states of a daughter nucleus. Here n,p denote the neutron and proton quasi-particles, K - is the last filled single particle level of the average field at G = 0 , K+1 is the first particle state, K-1 is the first hole level and so on. The values of e energies of the states (2n,p) and (2p,n) given in the fifth column are roughly calculated without the account of the interaction between quasi-particles. In the seventh column is given the classification of the corresponding β - transition and in the eighth column is given the energy Q for β - transitions to the ground states.

The β - decay $Er^{161} \longrightarrow Ho^{161}$ where the au transition with $\log(ft)_2 = 4,8$ is possible according to our calculations is very favourable for finding levels of the type (2n,p). It is quite possible that the states in Ho^{161} with the energies 1,700 MeV and 1,830 MeV discovered in [13] should be three-quasi-particle states with $K\pi\ 5/2-,\ 1/2-$.

The analysis of the data given in Table 1 shows that the three-quasi-particle states lead in a number of cases to other interpretation of the levels 7/2 - and 9/2- in the region (1 - 1.5) MeV which have been detected in several nuclei [14]. In W^{181}, Hf^{177} and Hf^{175} the assignment of the levels 7/2- and 9/2- as the single-quasi- particle states 7/2- [503] and 9/2- [505] does not give rise to doubt while in Yb^{169} such a treatment seems to be unlikely. In Yb^{169} must be observed the three-quasi-particle states 9/2- and 7/2- with the energy of the order of (1.5-1.6) MeV and with the lu β - transitions from Lu^{169}. Therefore, it is more correctly to treat the states 7/2 with the energy 1.465 MeV and 9/2- with the energy 1.452 in Yb^{169} as three-quasi-particle ones, since for the treatment them as 7/2-[503] and 9/2-[505] the energy values found experimentally are very low.

From Table 1 it is seen that there is a number of favourable possibilities for the experimental detection of the three-quasi-particle states of the type (2n,p) and (2p,n) One of the most suitable criteria of finding these levels may be allowed unhindered (au) β - transitions to these levels in those cases when there are no such transitions to single-quasi-particle levels. In Table I we give, as an example, a number of β - decays to the levels (2p,n) and (2n,p) in order to draw the experimenter's attention to these decays. The existence of the levels (2p,n) and (2n,p) follows immediatly from the superfluid nuclear model and their absence would at least be strange.

An investigation of very high excited states of odd nuclei is of great interest from the point of view of the clearing up: up to what excitation energies the single- three-, five - and so on quasi-particle aspect of the odd-nuclei excited states is conserved.

The single particle levels of the odd nuclei give information on the average -field energy levels which are necessary for calculating energies of the even-even nuclei, for analysing the probabilities of β transitions etc. Experiments on finding these levels are therefore of especially great interest. So, for example, an analysis of the two-quasi-particle levels in Gd^{154}, Gd^{156}, Gd^{158}, Dy^{158} and in others is very difficult because of unknown positions of the levels in the neutron system with N=89-95.

Therefore, it would be very useful to determine $K\pi$ for the ground states of $Gd^{153,159}$ $Dy^{155,157,159}$ and also the spins and parities of higher excited states of $Gd^{155,157}$ $Dy^{161,163,165}$ and $Er^{163,165}$ which are interesting also from the point of view of determination of the difference of energies between the single-particle levels $523\downarrow$ and $633\uparrow$. In the transuranum region it would be very important to prove, basing on data on single-particle levels of odd N nuclei, the existence of a subshell for N=152; the information about this subshell has been getted from the spontaneous fission and the α - decay.

3. Two-quasi-particle aspeot of the excited states of the even-even nuclei

From the superfluid nuclear model it follows naturally a two-quasi-particle aspect of a number of levels of the even-even nuclei, the validity of which is proved by means of comparison with experimental data given in [5]. The superfluid nuclear model is the model of independent quasi-particles. However, in this model one takes into account the influence of non-paired particles on the superfluid properties of the system which is called a blooking effect. The agreement of the theory with the experiment as far as the depression of the (K,K+1) state energy below the gap is concerned gives evidence [3,4,8] for the importance of the blocking effect.

The two-quasi-particle aspect of a number of excited states of even-even nuclei is proved by the analysis of experimental data on the β - transition probabilities (see hystograms in Figs.I and 2). From these hystograms it follows that the regions of the values of $\log[ft_e R_2]$ for β - transitions in even nuclei are approximately the same as in odd nuclei. A larger dispersion of the values of $\log[ft_e R_2]$ is related both to the interactions of quasi-particles and the fluctuations in the average field levels which we have not taken into account and to an insufficient accuracy and reliability of the experimental data available.

The comparison of the calculated energy of even-even nuclei with experimental data shows that the overwhelming majority of the calculated lowest two-quasi-particle levels is discovered experimentally which are to be populated rapidly for appropriate β - transitions. The task is to find experimentally all levels obtained from the calculations (or, to prove that some levels are absent). Thus, we should go over from the oheck of the validity of the main foundations of the model to an investigation of the total essembly of the levels of even-even nuclei and find deviations from the simple picture given by the superfluid nuclear model. If the assumed scheme of the single- particle levels of the average field is true then the following levels rapidly populated in β - decays must be observed: the proton level 1+ with $E > 1.4$ MeV in W^{182}, which must be populated in the ah β - decay of the 13 hours Re^{182} with $\log(ft)_2 = 6.5$; the proton level 1- with $E \sim 1.3$ MeV in Hf^{178} from lu β - transition of the 9.3 minutes Ta^{178}; the neutron level 4 - with $E \sim 1.7$ MeV in Yb^{172} which must be populated in the ah β - transition of Lu^{172} and the proton level 5- with $E > 1.4$ MeV in Dy^{160} which must be populated in the lu β - decay of Ho^{160}.

In [5] a spin splitting has been found for some states whose energies (according to the Gallagher's rules in the states with antyparallel spins ($\Sigma = 0$) are somewhat lower than those in the states with parallel spins ($\Sigma = 1$). The spin splitting follows from the quasi-particle interaction. It points out that it is necessary to introduce in the Hamiltonian additional terms. However, the available experimental data on the spin splitting are very poor and it wound be desirable to increase the amount of experimental material. For example, two levels 4- should be observed in Er^{168} : the neutron level with the energy lower than 1.1 MeV and the proton one with the energy lower than 1.5 MeV. The β - decay to these levels from the state 3+ of Tm^{168} is Λ - forbidden and classified as 1Λ (lu).

It is very interesting to find those states of even-even nuclei the β -decay to which is F-forbidden. These levels can be observed in the γ- transitions from higher excited states.

Only a part of the residual forces acting between nucleons in a nucleus is taken into account (and besides, approximately) in the superfluid nuclear model. Therefore it is interesting to investigate how strongly the residual interactions not taken into account affect the properties of the ground- and excited states of strongly deformed nuclei. The investigation of the influence of pairing correlations on the β - transition probabilities has shown [3,4] that the β - transitions belonging to the third group (and named in [5] as F-forbidden) are strictly forbidden in the superfluid nuclear model. An experimental determination of the degree of F-forbiddenness of the β -transitions is quite important from the point of view of the clearing up of the role of the residual forces not taken into account as well as from the point of view of clearing up as far as the formulation of the properties of the ground and excited states of strongly deformed nuclei following from the superfluid nuclear model is true and exact.

The analysis of experimental data made in [5] has shown that there does not exist any strictly fixed F-forbidden β - transition. Table 2 gives a number of transitions which are most convenient to determine the degree of the F-forbiddenness.

For example, the β - decay of Ta^{182} 3- with the configuration p 404 ↓ -n510 ↑ to the proton state 2- of W^{182} with the configuration 514 ↑ - 402 ↑ is F-forbidden. The energy of this state which is well populated in the β - decay of 13 hours Re^{182} equal to I.289 MeV is in a good agreement with the calculated one E=1.3 MeV. According to the data available $\log ft_e$ = 8.2 for this aF β - transition. However, the values of the spin of 112 days Ta^{182} 16 the configuration of this state and the values of $\log ft_e$ = 8.2 are not quite reliable. If we assume that the treatment is correct then the F-forbiddenness will lead to the β - decay rate being hindered by about a factor of 100. It is difficult to agree such a small hindering with all the available experimental data. As a second good example we take the 1F β -transition from the 2+ state of a 7.7 hours Tm^{166} with the configuration p 411 ↓ - n 642 ↑ to the neutron state 1- of Er^{166} with the configuration 523 ↓ - 633 ↑ and the energy E = 1.828 MeV which are determined from the β - decay of a 27 hours Ho^{166}. Besides the transitions given in Table 2 a large number of the F-forbidden β - transitions is given in [5,8] too.

Among the comparatively high excited states of even-even nuclei there must be also observed the four- quasi-particle states besides the two-quasi-particle ones. There are two types of such states: the first type (4n) and (4p) when all the four quasi-particles are proton or neutron ones, the second type (2n,2p) when two quasi-particles are proton ones and two others are neutron ones. The β - transitions to four- quasi-particle states such as (4n) and (4p) are F-forbidden and such states should be filled in γ - transitions from high excited states. Apparently the degree of the F-forbiddenness will in this case be greater than in the β - transitions to the two-quasi-particle states. The pairing correlations of a superconductive type will be absent in the majority of these states. The states (K-1,K,K+1,K+2) have the lowest energy. We evaluate this energy without taking into account the interaction between quasi-particles. For example, in W^{182} such a state (4n) has an energy about 3 MeV, spins 10, 9, 7, 6, 3, 2, 1, 0 and a negative parity, and the state (4p) has an energy higher than 3 MeV, spins 11, 10, 6, 6, 4, 3, 2, 1 and a negative parity. In Yb^{172} the (4n) state (K-1, K, K+1, K+2) has an energy about 2.5 MeV, spins 10, 9, 5, 4, 3, 2 and a negative parity, and the (4p) state has $E \approx 2.8$ MeV, spins 12, 11, 5, 4, 3, 2 and a positive parity. In Er^{168} the neutron levels of this type must have energy about 2.5 MeV, spins 9, 8, 4, 3, 2, I and a negative parity and the proton levels must have $E > 3$ MeV, spins 10, 9, 7, 6, 3, 2, I 0 and a positive parity. The energies of a number of these states can be somewhat depressed because of the interaction between quasi- particles. The four-quasi-particle states with other distributions of quasi-

-particles over the average field levels are somewhat higher. At excitation energies higher than 3 MeV the density of the even-even nuclear levels increase strongly owing to the four-quasi-particle states.

The superfluid properties of the four-quasi-particle states (2n, 2ρ) are close to those of the corresponding two-quasi-particle states. These states should be well filled in the β - decays. As an example, we give in Table 3 a number of possible beta transitions to the states. (2n,2p). The estimations of the energies of these states are given without account of the quasi-particle interaction which can lead to the lowering of some levels. From Table 3 it can be seen that in a number of cases (especially, if this lowering will be large) such states can be found experimentally in the appropriate β - transition. The four- quasi-particle levels of both types must be observable in all even-even strongly-deformed nuclei.

Among higher excited states of even-even nuclei there must be six-and more-quasi-particle states although it is not clear up to what energies such a treatment of the excited states will be remained true in its general features. It is possible that the neutron-spectroscopic experiments can answer this question. Thus, an observation of the γ - spectra of various shapes or various forbiddennesses in transitions to low-laying states from high excited states with identical spins and very close energies would testify a different internal structure of these strongly excited states.

In conclusion we note that the most important experiments dealing with the clearing up of the properties of the ground- and excited states of strongly deformed nuclei are, first, the experiments on the determination of the degree of the F-forbiddenness in the β - decays and, secondly, the discovering of the three- and four- quasiparticle excited states.

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Table 1

Three-quasi-particle states (2n,p) and (2p,n)

Parent nucleus	State	Daughter nucleus	Three-quasi-particle state	$\mathcal{E}$ Mev	$K\pi$	Class. β -decay	Q Mev
${}^{93}_{68}\mathrm{Er}^{161}$	n 521 ↑	${}^{94}_{67}\mathrm{Ho}^{161}$	n521↓K, n523↑K+2, p523↑K	1.6–1.7	15/2–		>2.0
					9/2–	2Λ (au)	
					5/2–	au 4.8	
					1/2–	au 4.8	
			n521↑K, n642↓K+1, p523↓K	~1.5	15/2+9/2+		
					5/2 +	lh	
					1/2+	lh	
			n521↓K, n521↑K, p411↑K+1	~1.8–2.0	1/2+	lu	
			n521 K, n642 K+1, p411 K+1	~1.8–2.0	9/2–	2 Λ (ah)	
					1/2–	2 Λ (ah)	
					3/2–	a Λ (ah)	
					1/2–	ah	
${}^{96}_{69}\mathrm{Tm}^{165}$	p 411 ↓	${}^{97}_{68}\mathrm{Er}^{165}$	p411↓K+1, p523↑K, n523↓K	~1.3	13/2+11/2		
					3/2+	au	
					1/2+	au	
${}^{96}_{69}\mathrm{Tm}^{163}$	p 411 ↓	${}^{95}_{68}\mathrm{Er}^{163}$	p411↓K+1, p523↑K, n523↓K+1	~1.3	13/2+11/2		
					3/2+	au	
					1/2+	au	
	p 523 ↑		p523↑K+1, p411↓K, n523↓K	~1.3	13/2+	Λ	
					11/2+	2	

					3/2+	2	
					1/2+	Λ	
$^{98}_{71}\mathrm{Lu}^{169}$	p 404↓	$^{99}_{70}\mathrm{Yb}^{169}$	p404↓K+1, p523↑K−1, n633↑K	~ 2	7/2−	lu	1.970
					21/2−		
			p404↓K+1, p411↓K, n521↓K+1	~1.5–1.7	9/2−	lu	
					7/2−	lu	
					5/2−	lu	
	p 514↑		p514↑K+1, p411↓K, n521↓K+1	~1.5–1.7	11/2+	lu	
					9/2+	lu	
					7/2+	lu	
$^{100}_{73}\mathrm{Ta}^{173}$	p 404↓	$^{101}_{72}\mathrm{Hf}^{173}$	p404↓K+1, p411↓K, n521↓K	~ 1.7	9/2−	lu	2.800
					7/2−	lu	
					5/2−	lu	
			p404↓K+1, p514↑K, n514↓K+2	1.5–2.2	23/2+		
					9/2+	au	
					5/2+	aΛ (au)	
$^{102}_{73}\mathrm{Ta}^{175}$	p 404↓	$^{103}_{72}\mathrm{Hf}^{175}$	p404↓K+1, p402↑K+2, n512↑K	~1.9	17/2−		1.830
					7/2−	lu	
					3/2−	1*Λ (1u)	
			p404↓K+1, p514↑K, n514↓K+1	1.4–1.8	23/2+		
					9/2+	au	
					5/2+	au	
$^{104}_{73}\mathrm{Ta}^{177}$	p 404↓	$^{105}_{72}\mathrm{Hf}^{177}$	p404↓K+1, p514↑K, n514↓K	1.0–1.2	23/2+		1.160
					9/2+	au	
					5/2+	au	
$^{104}_{75}\mathrm{Re}^{179}$	p 402↑	$^{105}_{74}\mathrm{W}^{179}$	p 402↑K+1, p514↑K, n514↓K	~1.3	21/2+11/3		2.615
					7/2+	au	
					3/2+	aΛ (au)	
			p 402↑K+1, p404↓K−1, n514↓K	1.4–1.7	21/2−		
					9/2−	1*Λ (1u)	
					5/2−		
$^{106}_{75}\mathrm{Re}^{181}$	p 402↑	$^{107}_{74}\mathrm{W}^{181}$	p 402↑K+1, p514↑K, n 624↑K	~ 1.3	23/2–12/2		1.670
					5/2−	lu	
			p 402↑K+1, p404↓k−1, n624↑K	~1.4	7/2+	ah	
					3/2+	ah	
					21/2–11/2	ah	
$^{146}_{91}\mathrm{Pa}^{237}$	3/2 p530↑	$^{145}_{92}\mathrm{U}^{237}$	p530↑K, p523↑K+2, n631↓K	~1.7	7/2+		2.3
					5/2+	1* u	
					3/2+	1 (1* u)	
			p530↑K, p642↑K+1, n622↓K+1	1.8–2.1	11/2–9/2−		
					1/2−	ah	
			p530↑K, p523↑K+2, n622↓K+1	1.9–2.2	11/2+9/2+		
					1/2+	lu	
$^{101}_{72}\mathrm{Hf}^{173}$	n521	$^{102}_{71}\mathrm{Lu}^{173}$	n521 K, n512 K+1, p514 K+1	1.3	15/2− 13/2		
					5/2−	2	
					3/2−	ah	
			n521 K, n514 K+2, p514 K+1	1.8	17/2−,15/2		
					3/2−	au	
					1/2−	au	

Table 2

Beta-transitions of the type F

Odd-odd nuclei	Even-even nuclei			Energy in MeV	Klass. of β - transition	Remarks
$_{63}^{91}Eu^{156}$ 1 - p 413↓ -n 521↓	$_{64}^{92}Gd^{156}$	p	1- 532↑ -411↑	~1.7	aF	The same level must be in Gd^{158}
$_{71}^{101}Lu^{172}$ 4 - p 404↓ +n 521↓	$_{70}^{102}Yb^{172}$	p	3+ 411↓ +402↑	~1.7	1F	$\Sigma=0$ 1Λ (1u) } — Tm^{172} 2-
			2+ 411↓ -402↑		1^* F	$\Sigma=1$ 1u
		p	5- 411↓ +514↑	~1.8	aF	$\Sigma=0$
			4- 411↓ -514↑		aF	$\Sigma=1$
$_{73}^{109}Ta^{182}$ 3- p 404↓ -n510↑	$_{74}^{108}W^{182}$	p	2- 514↑ -402↑	1.3	aF	
$_{93}^{147}Np^{240}$ 1+ p 642↑ -n 624↓	$_{94}^{146}Pu^{240}$	n	2+ 631↓ -622↑	~1	aF	$\Sigma=1$
		n	1- 743↑ -622↑	~1.3	1F	
$_{69}^{97}Tm^{166}$ 2+ p411 - n642	$_{68}^{98}Er^{166}$	n	1- 523 -633	1.828	1F	
		n	2+ 523 -521	1.7	aF	
			3+ 523 +521		af	

Table 3

Four-quasi-particle states (2n,2p)

Parent nucleus	State	Daughter nucleus	Four-quasi-particle state	ℰ Mev	Kπ	Class. log ft	Q Mev
$_{75}^{107}Re^{182}$	p 402↑, n624↑	$_{74}^{108}W^{182}$	p 402↑K+1, p514↑K, n624↑K, n514↓K-1	3,3	15+,10+		
					8+	au	~2,3
					6+	au	
					3+	au	~2,5
					1+	au	
			p402↑K+1, p514↑K, n624↑K, n624↑K	2,9	16-		
					7-	lu	
					2-	lu	
$_{69}^{97}Tm^{166}$	p411↓, n 642↑	$_{68}^{98}Er^{166}$	p523↑K, p402↑K+1; n642↑K-1, n523↓K	3.7	9+,8-		
					4+		2,7
					3+	au	
					2+		
					1+		
			p523↑K, p402↑K+1; n624↑K-1, n633↑K+1	3.1	11-,10-		
					6-,5-,4-		
					2-	F	
					1-	lu	
					3-	lu	
	p411↓, n523↓		p523↑K; p402↑K+1; n523↓K, n633↑K+1	2.9	10+,4+,3+	F	
					9+,5+	Λ	
					2+	lu	
$_{67}^{93}Ho^{160}$	p523↑, n 521↑ 5+	$_{66}^{94}Dy^{160}$	p411↓K, p523↑K+1, n521↑K, n642↑K+1	2,9	6+,2+	F	3.28
					3+,1+		
					9+,1+		
					6+	ah	
					4+	ah	
			p413↓K-1. p523↑K+1, n521↑K. n523↓K+2	3.3	10-,0-		
					7-.3-	F	
					2-		
					5-	lu	

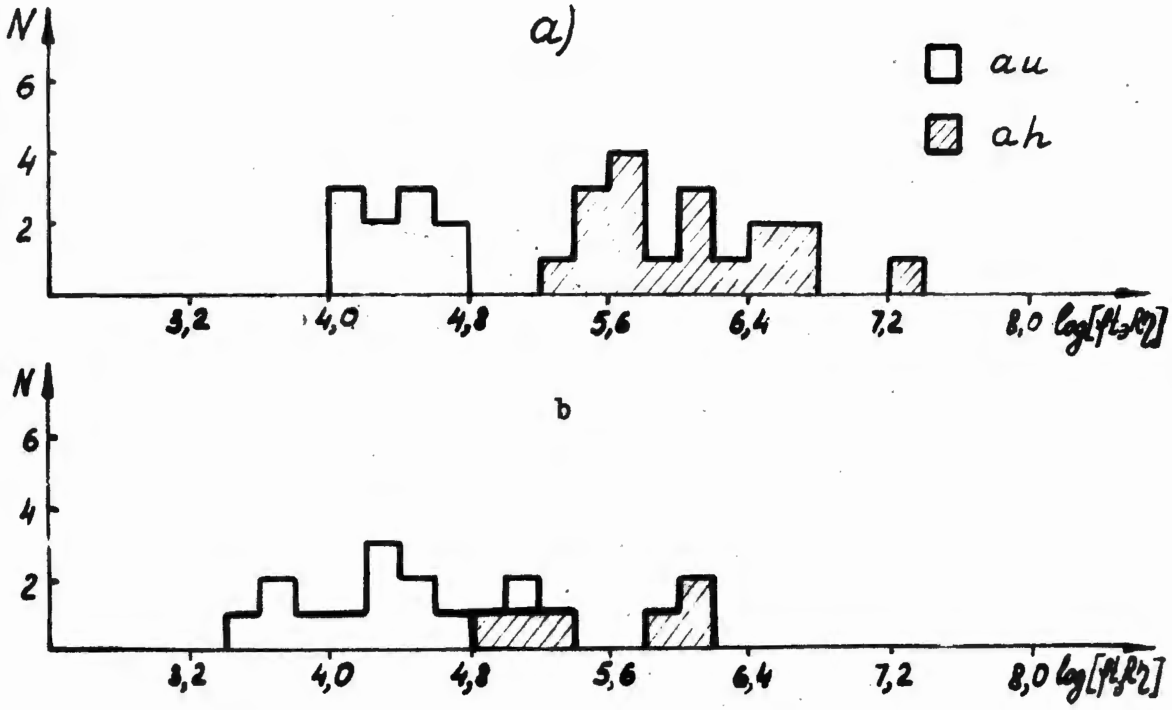

Fig. I

Allowed beta transitions

a) are the odd nuclei, b) are the even nuclei

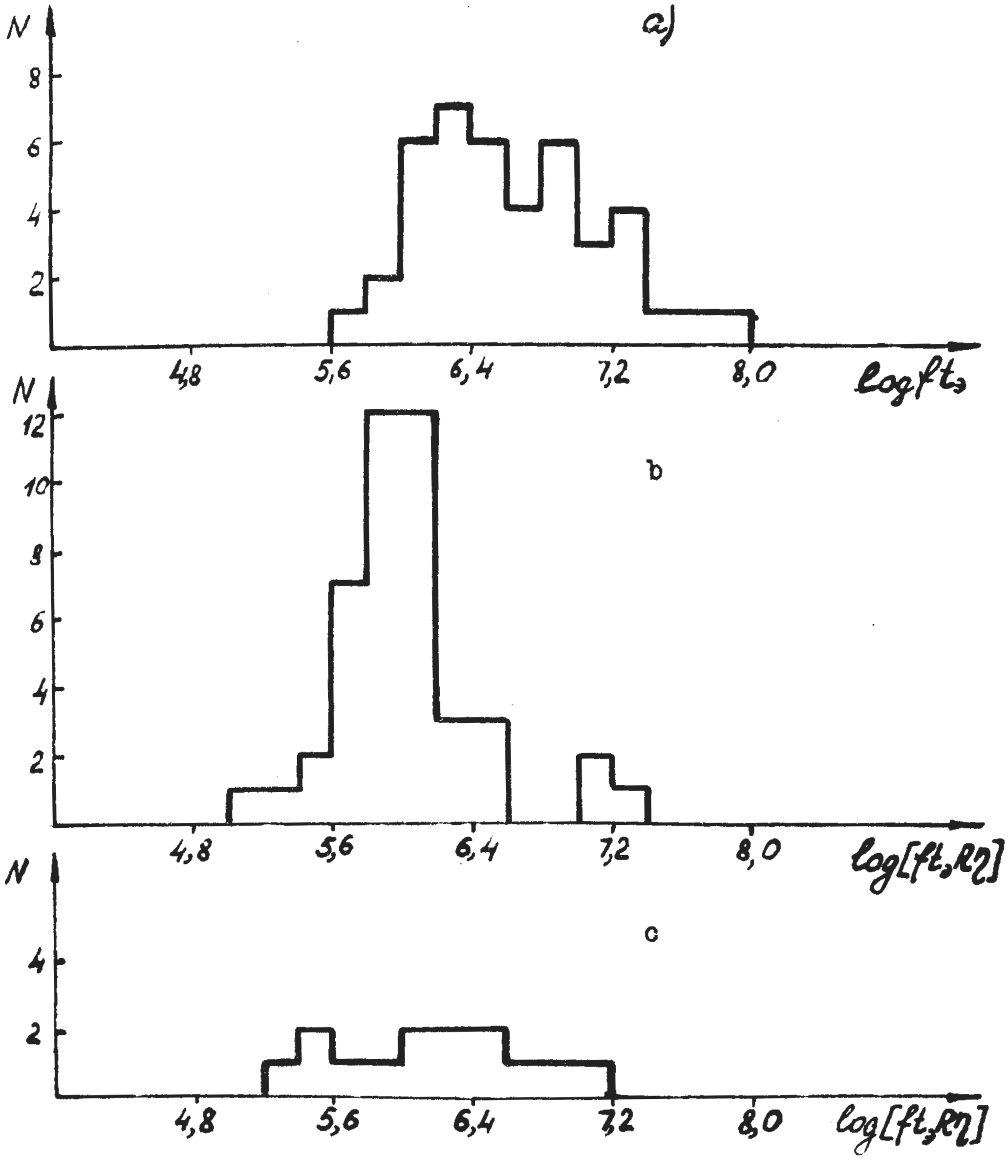

Fig. 2

Iu beta transitions

a), b) are the odd nuclei, c) are the even nuclei