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L.A.Malov, V.G.Soloviev

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Малов Л.А., Соловьев В.Г. **E4 - 10330**

Общие закономерности фрагментации одночастичных состояний в деформированных ядрах

В рамках сверхтекучей модели рассчитана фрагментация большого числа квазичастичных состояний в ядрах редкоземельной области. Исследована зависимость фрагментации от положения, квантовых чисел одночастичного состояния и характеристик коллективных возбуждений. Указывается на отклонение формы распределения силы состояния от брейт-вигнеровской формы.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Malov L.A., Soloviev V.G. **E4 - 10330**

General Regularities of the Fragmentation of Single-Particle States in Deformed Nuclei

General regularities of the fragmentation of single-particle states in deformed nuclei are studied in the framework of a model based on the quasiparticle-phonon interaction. The fragmentation is calculated for the hole, ground and particle states in many nuclei from the beginning, middle and the end of the region $150 < A < 190$. It is shown that the shape of the fragmentation of single-particle states differs strongly from the Breit-Wigner distribution. The fragmentation essentially depends on the position, quantum numbers of the single-particle state and on the characteristics of collective excitations.

The investigation has been performed at the Laboratoty of Theoretical Physics, JINR.

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1. The structure of nuclear states at intermediate and high excitation energies is essentially defined by the fragmentation, i.e., the distribution of the strength of one-quasiparticle and many-quasiparticle states over many nuclear levels. Recently the experimental investigation has been started for the fragmentation of one-quasiparticle states in spherical nuclei /1/. The fragmentation of one-quasiparticle states in deformed nuclei with the odd number of neutrons is first analysed in paper /2/. However, the theoretical study of this phenomenon was based on simplified assumptions (see, e.g., ref. /3/), therefore a more rigorous consideration is necessary.

To study the fragmentation we use a model based on the quasiparticle-phonon interaction /4/. In ref. /5/ the model was generalized to the introduction of spin-multiple forces and approximate methods for solving its equations were developed. In ref. /6/ the model was employed to determine the contribution of quasiparticle-plus-two-phonon components to the wave function of low-lying states. Preliminary results of investigations on the signle-particle fragmentation in deformed nuclei were reported in refs /7,8/, while in ref. /9/ some methodical problems concerning the calculation of the fragmentation and neutron strength functions were studied.

In this paper for several deformed nuclei we calculate the fragmentation of a large number of hole and particle states in neutron and proton systems in the interval from (8-10) *MeV* below the energy of the Fermi-surface up to (8-10) *MeV* above it. And, as a result, we deduce some general regularities of the single-particle fragmentation in deformed nuclei.

2. The model and methods for solving its main equations were described in ref. /9/. In this paper we write only the formulae required for the understanding of the obtained results. In refs. /7, 8/ it was shown that the fragmentation of one-quasiparticle states in deformed nuclei may be studied within a simplified model. The wave function of the non-rotational state with the angular moment projection on the nucleus symmetry axis K and parity π of an odd-A deformed nucleus has the form:

$$\Psi_i(K^\pi) = \frac{1}{\sqrt{2}} C^i_{\rho_0} \sum_\sigma \{ a^+_{\rho_0\sigma} + \sum_\rho \tilde{C}^i_\rho a^+_{\rho\sigma} + \sum_g \tilde{D}^i_g (a^+ Q^+)_g \} \Psi_0 , \tag{1}$$

where Ψ_0 is the wave function of the ground state of a doubly even nucleus having one nucleon less than the studied one; i is the number of the state, $g \equiv \nu\lambda\mu j$, j being the number of the root of the secular equation for the one-phonon state of multipolarity $\lambda\mu$. The set of quantum numbers for any single-particle state is denoted by $(\nu\sigma)$ and for states with fixed K^π by $(\rho\sigma)$ with $\sigma = \pm 1$. We are studying the fragmentation of a certain state denoted by ρ_0. In ref. /9/ it was shown that the study of the fragmentation of state ρ_0 requires taking into consideration also other states ρ with the same K^π. Therefore formula (1) contains the terms $\sum_\rho \tilde{C}^i_\rho a^+_{\rho\sigma}$. The secular equation symbolically is written as follows:

$$F_{\rho_0}(\eta_i) = 0 , \tag{2}$$

(cf. formulae (19) and (25) of ref. /9/), where η_i are the energies of non-rotational states with a given K^π.

To determine the single-particle fragmentation in deformed nuclei, we use the direct calculational method of averaged characteristics without a detailed calculation of each state. Following refs. /8,9/, we construct the strength function of the energy distribution of one-quasiparticle state ρ_0 in the form

$$\Phi_{\rho_0}(\eta) = \sum_i (C^i_{\rho_0})^2 \rho(\eta_i - \eta) \tag{3}$$

averaged with the weight

$$\rho(\eta_i - \eta) = \frac{1}{2\pi} \frac{\Delta}{(\eta_i - \eta)^2 + (\Delta/2)^2} . \tag{4}$$

The energy interval of averaging Δ specifies the type of calculational results. For Δ very small we obtain the envelopes of quantities $(C^i_{\rho_0})^2$ for each state i , while for Δ large enough the averaged values of those quantities. The choice of Δ is discussed in ref. /9/ , here we take $\Delta = 0.4$ *MeV*. As a result of transformations performed in /9/, we have

$$\Phi_{\rho_0}(\eta) = \frac{1}{\pi} \mathrm{Im} \left(\frac{1}{F_{\rho_0}(\eta + i\frac{\Delta}{2})} \right) . \tag{5}$$

If wave function (1) does not include terms $\sum_\rho \tilde{C}^i_\rho a^+_{\rho\sigma}$ the function $\Phi_{\rho_0}(\eta)$ is simplified to

$$\Phi_{\rho_0}(\eta) = \frac{\Delta}{2\pi} \frac{\Gamma(\eta)}{(\epsilon(\rho_0) - \gamma(\eta) - \eta)^2 + (\Delta/2)^2 \Gamma^2(\eta)} , \tag{6}$$

where $\epsilon(\rho_0)$ is the energy of one-quasiparticle state ρ_0 and

$$\Gamma(\eta) = 1 + \sum_g \frac{\Gamma^2_{\rho_0 g}}{(p(g) - \eta)^2 + (\Lambda/2)^2}, \tag{7}$$

$$\gamma(\eta) = \sum_g \frac{\Gamma^2_{\rho_0 g}(p(g) - \eta)}{(p(g) - \eta)^2 + (\Lambda/2)^2}. \tag{8}$$

Here $p(g) = \epsilon(\nu) + \omega_j^{\lambda\mu}$ is the energy of the quasiparticle-plus-phonon state, $\Gamma_{\rho_0 g}$ defines the interaction of states ρ_0 and ν through phonon $\lambda\mu j$. It is important that functions $\Gamma(\eta)$ and $\gamma(\eta)$ depend strongly on η. Therefore the form of eq. (6) differs noticeably from the Breit-Wigner one. In refs. /8,9/ it is shown that the function $\Phi_{\rho_0}(\eta)$ follows the histogram obtained by summing of $(C^i_\rho)^2$ over the energy intervals Λ. Therefore the single-particle fragmentation in deformed nuclei can be calculated by formula (5).

3. In numerical calculations we use the single-particle energies and wave functions of the axial-symmetric Saxon-Woods potential. The potential parameters, pairing and miltipole-multipole interaction constants, and phonon number are taken from ref. /9/. In ref. /9/ it was shown that a large number of weakly collectivized phonons strongly influences the fragmentation of single-particle states and neutron strength functions. Therefore the phonon space cannot be greatly restricted in the calculations.

To clarify the general regularities the fragmentation of one-quasiparticle states in deformed nuclei, one should perform systematic calculations of the fragmentation of a great number of one-quasiparticle states in many nuclei. A part of the calculational

results is given in *Figs. 1* to *6*. Figure 1 shows the fragmentation of states 400↑, 521↑, 624↑, 512↓, 642↓, 640↑ in ^{179}Hf. The general regularities of the fragmentation are illustrated in *Figs. 2-4* by functions $\Phi_{\rho_0}(\eta)$ for states 642↑, 633↑, 624↑, 400↑, 615↑, 642↓, 521↑, 521↓, 512↓ in ^{153}Sm, ^{165}Dy, ^{175}Yb, ^{185}W and in *Figs. 5,6* for states 420↑, 411↓,

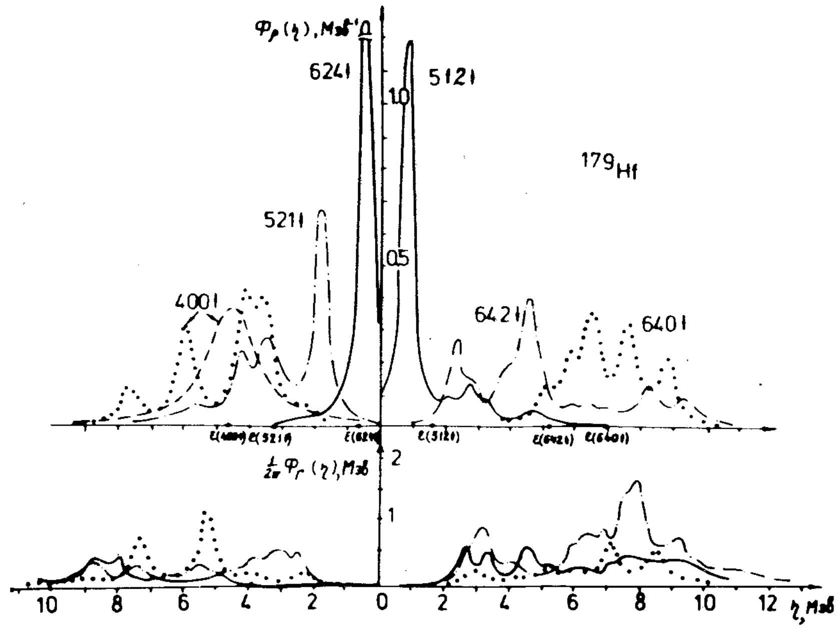

Fig. 1. The fragmentation of one-quasiparticle states 400↑, 521↑, 624↑, 512↓, 642↓, 640↑ in ^{179}Hf The excitation energy η in MeV is plotted on an abscissa in both directions from zero. On the left is the fragmentation of the hole states, on the right, of the particle states. The top figure represents the functions $\Phi_{\rho_0}(\eta)$ in MeV^{-1}. The quantities $\epsilon(\rho_0)$ are given. The bottom figure represents the functions $\frac{1}{2\pi}\Phi_\Gamma(\eta)$ for the values of ρ_0 given in the top figure. For comparison the top figure represents the strength distribution of the state 400↑ by the Breit-Wigner law (dashed curve) with the constant width $\Gamma_0 = 1.7$ MeV.

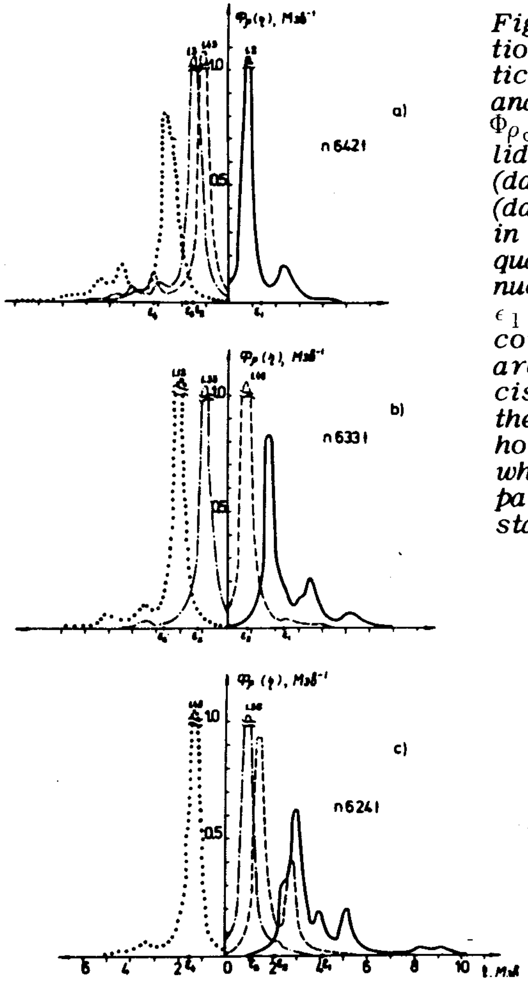

Fig.2. The fragmentation of the one-quasiparticle states 642↑, 633↑ and 624↑ : the functions $\Phi_{\rho_0}(\eta)$ in ^{153}Sm (solid line), in ^{165}Dy (dashed line), in ^{175}Yb (dash-dotted line) and in ^{185}W (dots). The quantities $\epsilon(\rho_0)$ for each nucleus are denoted by ϵ_1, ϵ_2, ϵ_3 and ϵ_4, correspondingly, and are shown on the abscissa. In the left part the fragmentation of the hole states is given, whereas in the right part, of the particle states.

411↑, 402↓, 523↓, 512↑ in ^{155}Eu, ^{165}Ho, ^{175}Lu and ^{185}Re. The fragmentation is calculated for the hole, ground and particle states in nuclei from the beginning, middle, and end of the region $150<A<190$ The fragmentation is not shown here for the one-quasiparticle states with the energy by 10 *MeV* further than that of the Fermi surface, since in these cases the basis of single-particle states

should be extended and the effect of the continuous spectrum should be considered.

The results at the bottom of *Fig. 1* allow one to understand some peculiarities of the fragmentation of quasiparticle states, the reason for noticeable deviations of the distribution form from the Breit-

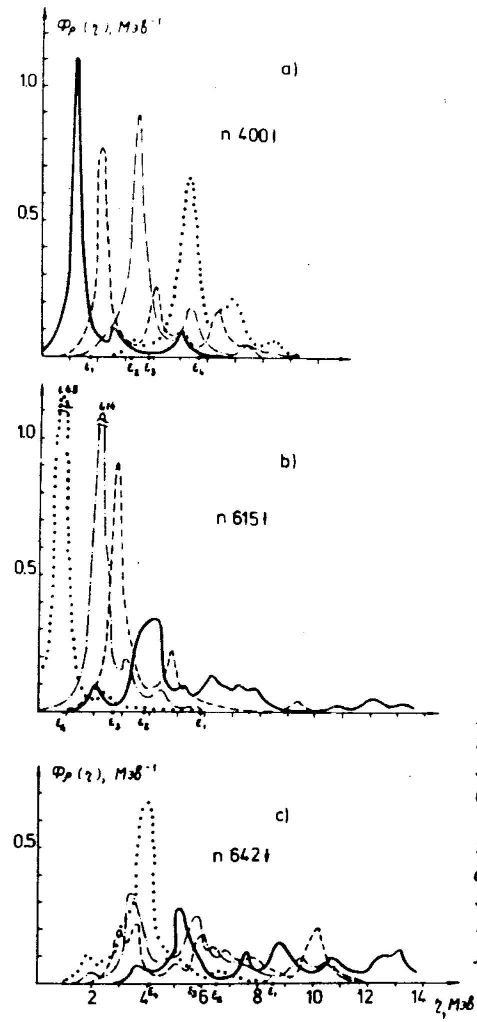

Fig. 3. The fragmentation of one-quasiparticle states 400↑, 615↑, and 642↑ in ^{153}Sm, ^{165}Dy, ^{175}Yb and ^{185}W; the notation for the particle and hole states is the same. The other notation is the same as in fig. 2.

Wigner one. At the bottom we give the strength functions

$$\Phi_{\Gamma}(\eta) = \Lambda \sum_{g} \frac{\Gamma^{2}_{\rho_0 g}}{(p(g)-\eta)^{2} + (\Lambda/2)^{2}}, \qquad (9)$$

which characterize the energy distribution of $\Gamma^{2}_{\rho_0 g}$. It is clear that $\Gamma_{\rho_0} = \int_0^{\infty} \frac{1}{2\pi} \Phi_{\Gamma}(\eta) d\eta \simeq \sum_g \Gamma^{2}_{\rho_0 g}$ may specify the strength of interaction of the quasiparticle state ρ_0 with all quasiparticle-plus-phonon states g. This interaction certainly defines the degree of the fragmentation of state ρ_0. Note that $\Phi_{\Gamma}(\eta)$ coincides with the width Γ introduced in /3/ and is simply related to the quantity $\Gamma(\eta)$ given by (7) for one ρ_0. From *Fig.1* it is seen that $\Phi_{\Gamma}(\eta)$ is not constant therefore the distribution of the strength of quasiparticle states essentially differs in form from the Breit-Wigner one. Maxima of the function $\Phi_{\Gamma}(\eta)$ are due to large matrix elements or to strongly collectivized phonons (sometimes, with both the factors), corresponding to poles $p(g)$ in a given energy interval.

At low and intermediate excitation energies (~ 1-3 *MeV*) $\Phi_{\Gamma}(\eta)$ is small. It increases with excitation energy and thus determines the strengthening of the fragmentation of states ρ_0 with increasing quasiparticle energy $\epsilon(\rho_0)$. This strengthening is illustrated in *Figs.2-6* for many states. For instance, *Fig. 2a* shows the fragmentation of the state 642↑ . In ^{153}Sm and ^{165}Dy state 642↑ lies near the Fermi surface and is fragmented weakly. In ^{175}Yb there appears a tendency of growing fragmentation. In ^{185}W the state 642 ↑ is fragmented essentially stronger. A still more striking example of strengthening the fragmentation with increasing excitation energy is the strong fragmentation of state 521↑ in ^{175}Yb and ^{185}W as compared to the weak fragmentation of this state in ^{153}Sm and ^{165}Dy (*Fig. 4a*). In *Fig. 3b* the fragmentation of state 615↑ is shown. This level is the particle one in all the nuclei we consider here. However, with increasing atomic number the energy of the Fermi surface approaches the level 615↑ , the value of ϵ(615↑) diminishes, and the fragmentation of state 615↑ is weakened in ^{185}W and ^{175}Yb as compared to the strong fragmentation in ^{153}Sm.

In certain cases the energy dependence of $\Phi_{\Gamma}(\eta)$ may be considered to be proportional to the state density or approximately to η^2 (for $\eta \lesssim$ 3*MeV*) as is assumed in /2/. It should be noted that for higher energies the assumption of the smooth dependence of $\Phi_{\Gamma}(\eta)$ on energy does not hold, though there is a tendency of the increase of $\Phi_{\Gamma}(\eta)$ with energy that accounts for the strengthening fragmentation with increasing energy observed from *Figs. 1-6*.

From *Fig. 1* it is seen that at energy ~ (1-2) *MeV* $\Phi_{\Gamma}(\eta)$ is small in magnitude therefore the states with small $\epsilon(\rho_0)$ are weakly fragmented. Around (80-90)% of the strength of such states is concentrated on a single level (e.g., states 512↓, 624↑ in ^{179}Hf in *Fig.1*, all states in *Fig. 2*, state 400↑ for ^{153}Sm in *Fig. 3*, etc).

The Figures show that the remaining (10-20)% of the strength of states are fragmented over a large energy interval. From *Fig. 2* it is seen that additional peaks in the distribution of quasiparticle component C^2_{ρ} are defined by the fluctuation of $\Phi_{\Gamma}(\eta)$ In some cases the state with large $\epsilon(\rho_{\sigma})$ (e.g., 400↑ for ^{185}W in *Fig. 3*) appears to be fragmented relatively weakly if the value of $\Phi_{\Gamma}(\eta)$ is small in the energy interval near $\epsilon(\rho_0)$.

As has been shown earlier /10/ and is confirmed by the present calculations for the single-particle states lying near the energy of the Fermi surface, the distribution maximum is shifted from 0.5 to 1.5 *MeV* towards low energies with respect to $\epsilon(\rho_0)$. This shift is a result of the quasiparticle-phonon

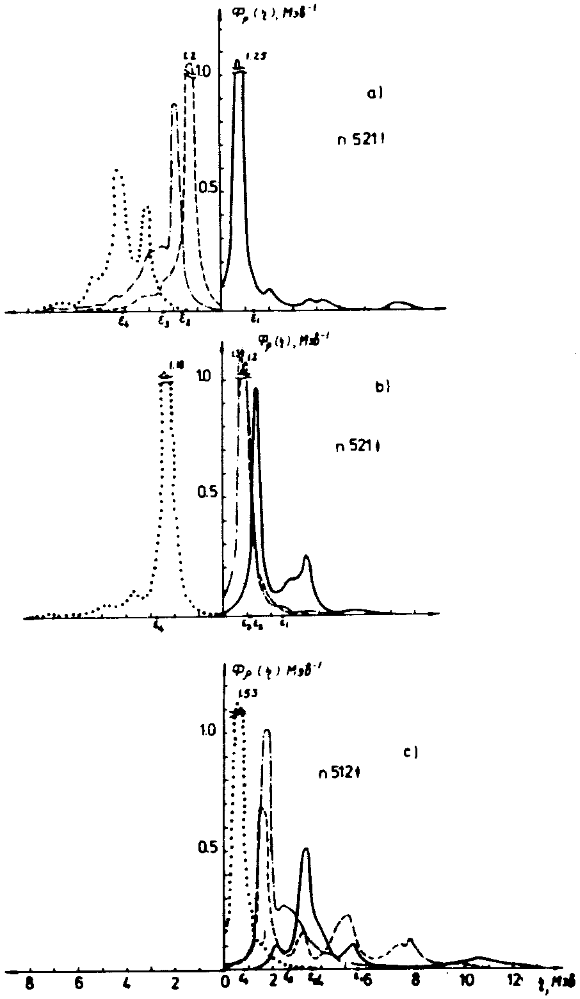

Fig. 4. The fragmentation of the one-quasiparticle states 521 ↑, *521*↓, *and 512*↓ *in* ^{153}Sm, ^{165}Dy, ^{175}Yb *and* ^{185}W *The notation is the same as in fig. 2.*

interaction. If the energy of a single-particle state is by 2 *MeV* higher than that of the Fermi level, the distribution maximum fluctuates near $\epsilon(\rho_0)$. For instance, from *Fig. 6b* it is seen that the main maximum of the strength distribution of the state

523↓ in ^{155}Eu is somewhat shifted with respect to $\epsilon(\rho_0)$ towards large excitation energies. The same holds also for the main maximum of the strength distribution of state 521↑ in ^{185}W (*Fig. 4a*). State 642↓ in ^{185}W (*Fig. 3c*) is fragmented almost symmetrically with a center close to the quasiparticle energy ϵ (642↓).

Specific features of the fragmentation are a long tail and, as a rule, the presence of several peaks, in addition to the main distribution maximum. These peculiarities may turn out to be essential in calculating the spectroscopic factors in nuclear transfer reactions and neutron strength functions.

The fragmentation of a quasiparticle state depends on the projection of its angular momentum onto the symmetry axis. As a rule, with increasing K the fragmentation decreases. This is explained by decreasing number of matrix elements, especially, those which define the coupling with the most collectivized phonons with $\lambda = 2$ and 3. Calculations do not display the dependence of the fragmentation on the state parity.

In most cases there is a center of the strength distribution with a maximum close to energy $\epsilon(\rho_0)$. However, there are cases of a very strong fragmentation when the state strength is distributed more or less homogeneously over a very wide energy interval. Usually those states are so strongly fragmented which have the single particle energy far from the Fermi level (by order (5-10) *MeV*) (see the fragmnetation of state 642↓ in ^{153}Sm, ^{165}Dy and ^{175}Yb in *Fig. 3*). In some cases $\Phi_{\rho_0}(\eta)$ splits into several large peaks, and at energy $\epsilon(\rho_0)$ a minimum of the strength function may appear (e.g., state 400↑ in ^{179}Hf, *Fig. 1*, 624↑ in ^{153}Sm, , *Fig. 3c*), 512↓ - in ^{165}Dy, *Fig. 4c*), 402↓ in ^{155}Eu, *Fig. 6a*)).

The fragmentation has been calculated also for odd-Z nuclei. The general regularities of their fragmentation are the same as for odd-N nuclei, however, the fragmentation is weaker. The reason

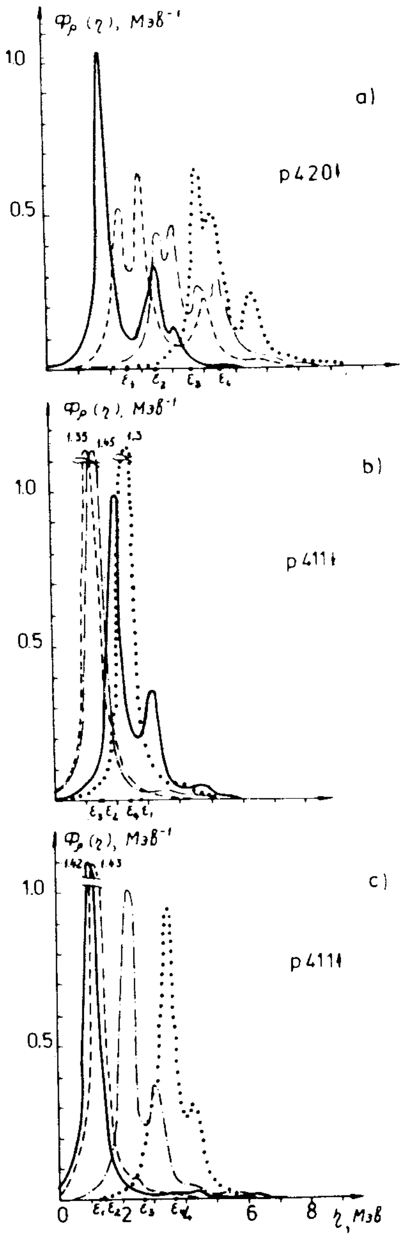

Fig. 5. The fragmentation of the one-quasiparticle states 420↓, 411↑ and 411↓ in ^{155}Eu (solid line); in ^{165}Ho (dashed line) in ^{175}Lu (dash-dotted line) and in ^{185}Re (dotts), the values of $\epsilon(\rho_0)$ for each nucleus are given by ϵ_1, ϵ_2, ϵ_3 and ϵ_4, correspondingly. The other notation is the same as in fig. 3.

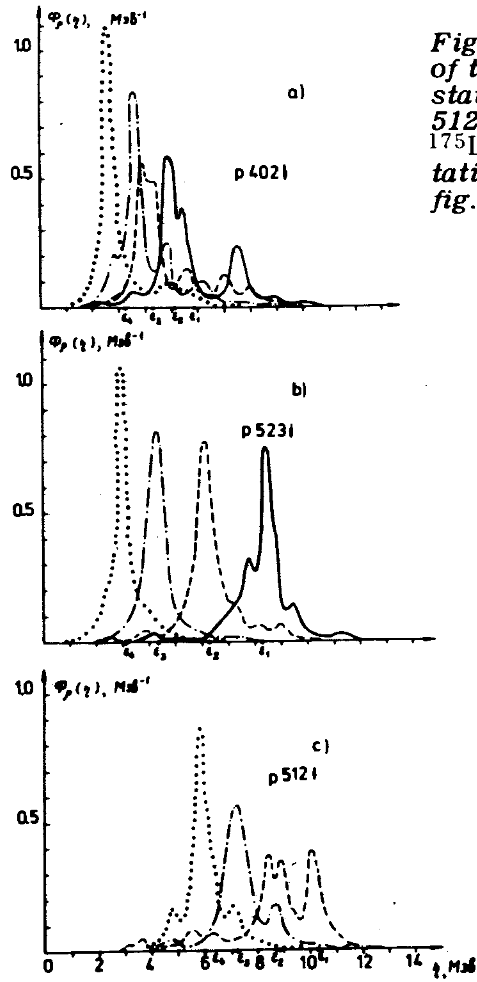

Fig. 6. The fragmentation of the one-quasiparticle states 402↓, 523↓ and 512↑ in ^{155}Eu, ^{165}Ho, ^{175}Lu and ^{185}Re. The notation is the same as in fig. 5.

is a smaller state density and decrease in matrix elements. The quantities Γ_{ρ_0} for proton levels, on the average, are by a factor of 2-3 smaller than those for neutron levels. Thus, e.g. the fragmentation of state 523↓ (*Fig. 6b*) in all considered odd-Z nuclei is weaker in contrast with that of the state 642↓ (*Fig.3c*) in odd-N nuclei though the quasiparticle energies of these states are close in magnitude.

4. It is generally accepted and widely used that the strength distribution of the single-particle state at intermediate and high excitation energies has approximately the Breit-Wigner form with the center which coincides with the single-particle or quasiparticle energy of a given state. The width of this distribution is considered to be either the constant or smooth function of the excitation energy. In ref. /2/ it is postulated that this width is proportional to the energy squared. The fragmentation of a given state is usually assumed to be independent of its quantum characteristics whether it is particle or hole state. It is also assumed that the structure peculiarities of a certain nucleus slightly influence the fragmentation. In ref. /3/ it is shown that for the equidistant spectrum with constant matrix elements the fragmentation of the single-particle state has the Breit-Wigner form. However, the result strongly changes if the spectrum differs from the equidistant one and the matrix elements are not constant. Our calculations have shown that the fragmentation of the state strength is highly complicated. The fragmentation essentially depends on the position and quantum numbers of one-quasiparticle states and on the collective characteristics of nuclear excitations. The form of the distribution in many cases differs from the Breit-Wigner one.

For comparison see *Fig. 1* which shows the strength function of the distribution of the quasiparticle state $400\uparrow$ as the Breit-Wigner curve with the values $\langle \Lambda \cdot \Gamma(\eta) \rangle = \Gamma_0 = 1.7$ *MeV* and $\langle \gamma(\eta) \rangle = \gamma_0 = 0.11$ *MeV*, the values of $\Lambda \cdot \Gamma(\eta)$ and $\gamma(\eta)$ being averaged over the interval (0-10) *MeV*. It is seen from the figure that the calculated strength distribution of the state $400\uparrow$ differs from the Breit-Wigner distribution. The deviation from the energy of the fragmentation maximum of the state $400\uparrow$ is considerably larger than γ_0.

The performed calculations indicate to the decisive influence of the low-lying most collective phonons on the fragmentation of quasiparticle states. The contribution of many other phonons results in smoothing of sharp peaks and broadening of the distribution.

5. Based on the performed calculations, let us formulate general regularities of the fragmentation of signle-particle states in deformed nuclei. They, mainly, confirm our preliminary conclusions on the fragmentation /7,8/ obtained from the study of the fragmentation of several states in some nuclei. They are the following:

1). The form of the distribution strongly differs from the Breit-Wigner one. As a rule, in addition to the main maximum, there appear several additional maxima.

2). The shape of the distribution function is mainly defined by the position of the signle-particle state with respect to the Fermi level. If the signle-particle state is near the energy of the Fermi level, then 80-90% of the state strength is concentrated on the lower level with the given K^{π}. With increasing quasiparticle energy the fragmentation is increasing, the distribution function becomes wider the main maximum is decreasing and the additional maxima are increasing. At $\epsilon(\rho_0) \simeq$ $\simeq$ (5-8) *MeV* the state strength is fragmented in a wide energy interval.

3). The distribution function is nonsymmetric with respect to its largest value due to a slower decrease towards high excitation energies. Even for the single-particle states lying near the Fermi level, the distribution tail extends farther than the nucleus binding energy. In many cases the distribution maximum is near $\epsilon(\rho_0)$. For the states with small $\epsilon(\rho_0)$ the distribution maximum is displaces towards lower excitation energies.

4). The fragmentation depends strongly on K. With increasing K the fragmentation, as a rule, decreases. The fragmentation depends weakly on the state parity.

5). The values of additional maxima are mainly determined by asymptotic quantum numbers of single-particle states and by the collectiveness of low-lying vibrational states of a given nucleus.

6). The fragmentation of single-particle states in odd-Z nuclei is somewhat weaker than in odd-N ones.

The deviations from the above pointed regularities of the fragmentation are observed in some cases of large values of $\epsilon(\rho_0)$. They are the following:

i) strong fragmentation without clearly observed maximum,

ii) instead of the maximum near $\epsilon(\rho_0)$ there appears a minimum, and the state strength is divided into two or three fragments;

iii) the weak fragmentation of individual states even with sufficiently large values of $\epsilon(\rho_0)$ corresponding to these states.

Note, that the presence of large single-particle components $C^2_{\rho_0}$ in some high-lying states, as a rule does not lead to large local maxima in the neutron strength functions and cross-sections of direct reactions. This is due to the fact that these quantities are defined by the total influence of many one-quasiparticle states ρ and by the expansion coefficients of the one-particle wave function over the spherical basis (see (33)-(36) in ref. /9/). Therefore, the fluctuations are essentially weakened.

It should be noted that the influence of the quasiparticle-plus-two-phonon components on the fragmentation of single-particle states is evaluated only inaccurately. This will, obviously, result in some smoothing of the highest maxima and deep minima. There are reasons to suppose that the general regularities of the fragmentation formulated above will not be changed. One should further investigate the role of the wave function components containing the quasiparticle-plus-two- and more phonons in the fragmentation of single-particle states.

In conclusion we should like to emphasize that the concrete form of the fragmentation of single-particle states is the basis for calculating the neutron strength functions and the strength functions of one-nucleon transfer reactions of the type (d,p), (d,t), (d,n), (d, ^{3}He). In ref. /11/ it is shown that the consideration of the fragmentation appears to be very important for the investigation of the reaction (n,α) on deformed nuclei.

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