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FRAGMENTATION OF THE DEEPLY-BOUND HOLE STATES IN ODD-MASS SPHERICAL NUCLEI

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In recent years a good deal of attention has been paid to the study of the fragmentation of simple nuclear excitations at intermediate and high excitation energies. The effective tool for the experimental investigation of the one-quasiparticle state fragmentation in odd-mass nuclei is the one-nucleon transfer reactions. There are numerous experimental data on the fragmentation of the single-particle states at low excitation energy both in the deformed and the spherical nuclei in the literature. But the data on the fragmentation of single-particle states at intermediate and high excitation energies are rather poor. The attemps have been made to get the information on the neutron strength functions in the deformed nuclei/1/. In odd-mass spherical nuclei side by side with the data on the neutron strength functions, the information on the fragmentation of deeply-bound hole states has emerged. The first experiments on the deeply-bound hole state excitation have been performed in the early seventies/2/. At present time several experimental groups carry out the study of the deeply-bound hole states with the reactions (p,d), (d,t), (^{3}He,d) and (d,^{3}He)/2-12/.

The theoretical investigation of the deep-lying hole states has been performed in refs./13-16/. Ref./14/ is devoted to the calculation of the distribution of the deep-lying hole state strength in light nuclei. In other papers the fragmentation of the neutron deeply-bound hole states has been studied in tin isotopes. However, the theoretical calculations have predicted a stronger concentration of the hole strength than it has been observed in the experiments.According to the results of ref.[15] in the range of $1g_{9/2}$ -peak about 75% of the total $1g_{9/2}$ -strength is exhausted. The calculations performed within the quasiparticle-phonon nuclear model have given the value of 45-49%[16].

The fragmentation of the one-quasiparticle states in odd-mass nuclei is caused by the coupling with a great number of states of more complex structure and mainly with collective states. At the same time the wave functions of excited states used in refs.[14-16] have been rather simple. The authors of refs.[14,15] have directly taken into account the coupling of the hole with the quadrupole and octupole vibrations only. The coupling with noncollective states has been taken into account by spreading the fragments in a semi-statistical way. In ref.[16], in which the interaction of the deep-lying hole state with a large number of one-phonon excitations of a doubly-even core have been taken into account, the model wave function includes one-quasiparticle and "quasiparticle + one phonon" components only.

Recently, in the framework of the quasiparticle-phonon nuclear model[17] the numerical method has been suggested[18,19] for solving the model equations in the case when the model wave function includes a large number of components of the "quasiparticle + phonon" - and "quasiparticle plus two phonons"-type. The phonon basis consists of a large number of phonons with different momenta and parities $\lambda^{\pi} = 1^{\pm}, 2^{\pm}, \dots 7^{\pm}$. Among the phonon excitations there are the states corresponding to the giant resonances. The calculations of ref.[20] have demonstrated an important role of "quasiparticle + two phonons" compo-

nents at high excitation energy and in the nuclei with a strong quasiparticle-phonon coupling.

It the present paper the spreading of deeply bound hole states in ^{57}Ni, $^{115-119}$Sn, ^{123}Te and ^{143}Pm is investigated in the framework of the quasiparticle-phonon model. The model wave function of the excited state of odd-mass spherical nucleus has the following form :

$$\Psi_{\nu}(JM) = C_{J\nu}\Big\{\alpha^{+}_{JM} + \sum_{\lambda j i} D^{\lambda i}_{j}(J\nu)[\alpha^{+}_{jm} Q^{+}_{\lambda\mu i}]_{JM} + \sum F^{\lambda_1 i_1, \lambda_2 i_2}_{jI}(J\nu)[\alpha^{+}_{jm}[Q^{+}_{\lambda_1\mu_1 i_1} Q^{+}_{\lambda_2\mu_2 i_2}]_{IM'}]_{JM}\Big\}\Psi_0 . \qquad (1)$$

In formula (1) α^{+}_{jm} , $Q^{+}_{\lambda\mu i}$ are the quasiparticle and phonon creation operators, respectively; Ψ_0 is the ground state wave function of a doubly-even core. The derivation of equations for the energy $\eta_{J\nu}$ of the state (1) and the coefficients $C_{J\nu}$, $D^{\lambda i}_{j}$ and $F^{\lambda_1 i_1 \lambda_2 i_2}_{jI}$, and the description of the above-mentioned numerical method for solving them have been given in refs.[18-21].

We describe the one-quasiparticle strength distribution in terms of the strength function[22]. The definition of the strength function is the following:

$$C^2(\eta) = \frac{\Delta}{2\pi}\sum_{\nu}\frac{C^2_{J\nu}}{(\eta-\eta_{J\nu})^2+\Delta^2/4} . \qquad (2)$$

The function $C^2(\eta)$ describes the change of the one-quasiparticle components squared which is averaged over the energy interval $\simeq\Delta$ as a function of excitation energy η . The value of Δ is equal to 0.2 MeV in ^{57}Ni and 0.5 MeV in all other nuclei. The justification of the choice and the physical sense of the parameter Δ have been discussed in refs./15,16,19/. The other model parameters have been given in refs./19,23/.

Much information is gained on the excitations of the deeply-bound hole states in spherical nuclei in the one-nucleon transfer reactions. The data concern mainly the integral characteristics of the peaks observed in the reaction cross sections, however there are numerous disagreements between different results. This is partly due to the uncertainties which arise in the DWBA analysis of the data at the excitation energies $E_x \simeq 5 \div 10$ MeV. As it is shown in ref./9/ the contribution of multistep processes is not very large at maximum of distribution of the single-particle component, but may cause the 50-100% errors in the spectroscopic factor in the high-energy tail of distribution. Therefore, the comparison of integral characteristics of the experimental and theoretical strength distributions of the hole states will be qualitative one.

In what follows we use the integral characteristics of strength distributions of the hole states, which are very often cited in the experimental papers. These are the centroid of distribution $\bar{E}_x$ in the interval $E_1 \le E_x \le E_2$ and the spreading width $\Gamma^{\downarrow}$. Their definitions are

$$\bar{E}_x = \frac{1}{N}\int_{E_1}^{E_2} C^2(\eta)\,\eta\,d\eta \ \text{MeV} \ ; \quad (\Gamma^{\downarrow})^2 = \frac{1}{N}\int_{E_1}^{E_2} C^2(\eta)(\eta-\bar{E}_x)^2\,d\eta \ \text{MeV}^2 ,$$

$$N = \int_{E_1}^{E_2} C^2(\eta)\,d\eta \ .$$

Besides we use the integral spectroscopic factor $S_j = (2j+1)v_j^2 N$, which is calculated in the excitation energy interval $E_1 \le E_x \le E_2$.

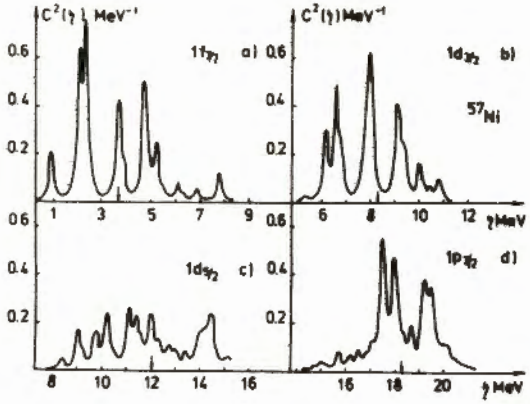

Fig. 1. Fragmentation of the neutron hole states in ^{57}Ni.
a) The $1f_{7/2}$ -state strength functions;
b) the $1d_{3/2}$ -state strength function;
c) the $1d_{5/2}$ -state strength function;
d) the $1p_{3/2}$ -state strength function.
The arrows show the positions of the corresponding one-quasiparticle levels.

The strength distribution of the neutron hole states is thoroughly studied in ^{57}Ni in refs.8,12). A detailed information on the fragmentation of the $1f_{7/2}$ and $1d_{3/2}$ neutron hole states in ^{57}Ni has been obtained by the (^{3}He, α) reaction in ref.12). 14 states with $J^{\pi}=7/2^-$ and 18 states with $J^{\pi}=3/2^+$ are detected at the excitation energy up to 8 MeV. The strength functions of the $1f_{7/2}$ and $1d_{3/2}$ states are shown in fig. 1a,b. The excitation spectrum in ^{57}Ni has been divided into the zones, and for each zone the theoretical and experimental values of $\bar{E}_x$, $\Gamma^{\downarrow}$ and S_j have been calculated. The results are shown in table 1. The comparison of the experimental and

Table 1. Experimental[12] and theoretical characteristics of strength distribution of the neutron hole states $1f_{7/2}$ and $1d_{3/2}$ in ^{57}Ni

$(n\ell_j)^{-1}$	ΔE_x MeV	Number of states observed in ref.[12]	$\bar{E}_x$ MeV exp.	$\bar{E}_x$ MeV theor.	S_j exp.	S_j theor.	$\Gamma^{\downarrow}$ MeV exp.	$\Gamma^{\downarrow}$ MeV theor.
	0.0–3.0	1	-	-	3.1	3.5	-	-
$1f_{7/2}$	3.0–4.2	5	3.34	3.7	0.92	1.2	0.18	0.22
	4.2–5.8	8	4.88	4.9	1.11	2.0	0.56	0.30
	5.6–7.2	5	6.13	6.5	1	1.1	0.25	0.33
$1d_{3/2}$	7.2–8.5	13	7.76	7.9	1.51	1.1	0.31	0.23
	8.5–9.7	-	-	9.2	-	0.86	-	0.24

theoretical values of $\bar{E}_x$, $\Gamma^{\downarrow}$ and S_j shows that the model gives a correct description of the integral characteristics of the $1f_{7/2}$ and $1d_{3/2}$ strength distribution. It has been shown in ref.[12] that the full $1f_{7/2}$ and $1d_{3/2}$ strength is exhausted up to the excitation energy $E_x \simeq 13$ MeV. This is in agreement with our results. In ref./12/ spin 5/2 has been attributed to all the states with the energy $E_x > 8{,}3$ MeV, corresponding to the transferred momentum $\ell = 2$. However, our results indicate that more than 20% of the $1d_{3/2}$-strength is concentrated in the interval $8.5 < E_x < 9.7$ MeV.

There are no detailed data for the fragmentation of the $1d_{5/2}$ and $1p_{3/2}$ hole states in ^{57}Ni. Figs. 1c,d show the strength functions of the $1d_{5/2}$ and $1p_{3/2}$ states. The energy of the $1p_{3/2}$ state is larger than that of the $1d_{5/2}$ state, and the density of states with $J^{\pi}=3/2^-$ at the energy $E_x \simeq 18$ MeV exceeds the density of states with $J^{\pi}=5/2^+$ at $E_x > 12$ MeV. However, the $1d_{5/2}$ state is fragmented much stronger than the $1p_{3/2}$ - state. The region of location of the main part of the $1d_{5/2}$- strength is 6–7 MeV, whereas of the $1p_{3/2}$- strength 4 MeV. The reason is that the $1d_{5/2}$ -quasiparticle interacts much stronger with the phonons than the $1p_{3/2}$ -quasiparticle. Up to the excitation energy E_x=13 MeV, 60% of the $1d_{5/2}$-strength is experimentally detected versus 63% given by calculations. According to ref./12/, the $1p_{3/2}$ -strength is not detected below the energy E_x=15 MeV, and this is in agreement with our calculations. The fragmentation of the $1p_{3/2}$- state may change strongly allowing for the influence of the single-particle continuum, which is significant in the nuclei with $A < 60$ at $E_x \simeq 20$ MeV. In all other cases which we investigate in present paper the influence of the single-particle continuum on the strength function can be neglected /24/.

Most of the experimental papers are devoted to the study of the fragmentation of hole states in the odd mass tin isotopes/2-9/. A peak with the width ~ 1 MeV is observed in the $^{111-121}Sn$ isotopes in the reactions (p,d), (d,t) and ($^3He,\alpha$) at the excitation energies E_x=5÷6 MeV. This peak is interpreted as a result of excitation of the $1g_{9/2}$- neutron hole state. According to refs./2,5,7/ 10% of the total strength of the $2p_{1/2}$ and $2p_{3/2}$ neutron hole states is concentrated in the region of the $1g_{9/2}$-peak. The $1g_{9/2}$ -peak is clearly seen in the light Sn isotopes; with increasing A it spreads and its amplitude diminishes. The maximal value of the $1g_{9/2}$ -strength (62)% has been obtained/9/ in the ($^3He,\alpha$) reaction in the ^{111}Sn isotope. In this reaction from 46% to 49% of the state strength has been found in the $^{113-119}Sn$ isotopes/4/. A lesser part of the $1g_{9/2}$ -

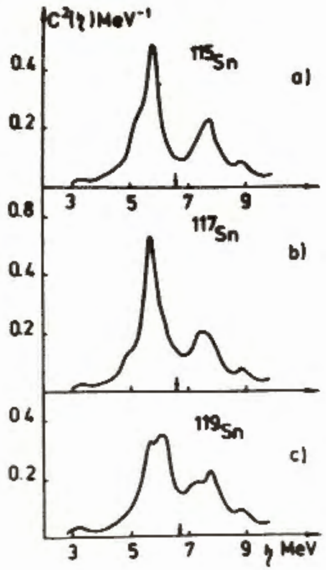

Fig.2. Fragmentation of the $1g_{9/2}$-neutron hole state in the tin isotopes; a) ^{115}Sn; b) ^{117}Sn; c) ^{119}Sn. The arrows show the position of the one-quasiparticle states $1g_{9/2}$.

strength (15%/7/, 25%/3,5/) has been extracted in the (p,d) and (d,t) reactions. This is due to the mechanism of the ($^3He,\alpha$) reaction in which the transitions with a low transfer momentum are suppressed and the transitions with ℓ =4 are more clearly seen. In ref./4/ the energy spectrum of α -particles from the reaction $^ASn(^3He,\alpha)^{A-1}Sn$ has been fitted by two Gaussians in the energy region $E_x \leq 11$ MeV. The first Gaussian coincides with the peak observed in all experiments, and the second describes another peak having the centroid 1.5 MeV higher than the first one and a considerably larger width (FWHM ≈ 2÷3 MeV). The second peak exhausts 20-30% of the total $1g_{9/2}$ -strength.

We have calculated the strength function of the $1g_{9/2}$ neutron hole state with the wave function (1) in three tin isotopes $^{115,117,119}Sn$ (see figs. 2a,b,c). Let us discuss, at first, the general characterictics of the strength function. The function $C^2(\eta)$ has two pronounced maxima in all three isotopes. The first maximum is at the energy $\eta \simeq 5.5$ MeV and its energy slowly increases with increasing A. This peak has been observed in many experimental papers. The second peak is sufficiently smaller than the first one and has a higher energy by 1.5-2 MeV. It should be noted that two peaks in the $1g_{9/2}$ -strength distribution have been obtained in the previous calculations/15,16/. It the present calculations the second maximum of the function $C^2(\eta)$ is much pronounced than in ref./16/ and exhausts the larger part of the single-hole strength. This is due to the influence of the components of "quasiparticle + two phonons"- type and to the difference in the values of the parameters of the effective separable

Table 2. Experimental[9]) and theoretical characteristics of strength distribution of the $1g_{9/2}$ neutron hole state of the Sn isotopes

Isotopes	ΔE_x MeV	$\bar{E}_x$ MeV exp.	$\bar{E}_x$ MeV theor.	S_j exp.	S_j theor.	$\Gamma^{\downarrow}$ MeV exp.	$\Gamma^{\downarrow}$ MeV theor.
^{115}Sn	4.8-5.8	5.47	5.5	2.5	2.7	0.25	0.27
	3.6-6.5	5.19	5.5	4.66	4.8	0.73	0.59
	6.7-8.6	-	7.6	-	2.6	-	0.44
^{117}Sn	3.7-6.5	-	5.6	-	4.9	-	0.56
	6.7-8.2	-	7.5	-	2.4	-	0.39
^{119}Sn	4.3-6.5	5.61	5.8	2.5	4.3	0.45	0.49
	3.8-6.5	5.36	5.7	2.85	4.5	0.62	0.58
	6.5-8.6	-	7.5	-	3.4	-	0.54

quadrupole and octupole forces. The first peak in $^{115,117}Sn$ is rather narrow whereas in ^{119}Sn it considerably broadens and the maximum value of the function $C^2(\eta)$ decreases. As it has been shown in ref./20/ this is mainly due to the coupling of the hole state with the low-lying octupole resonance of the even-mass core.

The experimental and theoretical values of $\bar{E}_x$, $\Gamma^{\downarrow}$ and S_j for the $1g_{9/2}$-strength distribution in different intervals ΔE_x are given in table 2. The experimental data are from ref./9/, where a detailed investigation of the distribution of $1g_{9/2}$ -strength in $^{111,115,119}Sn$ has been performed in the region of the first peak. On the whole, our results are in good agreement with the date of this paper, especially in ^{115}Sn. However, in ^{119}Sn we obtain a considerably higher concetration of the $1g_{9/2}$-strength in the region of the first maximum. The data on the second peak are available only in ref./4/. But they are difficult to compare with, since only the Gaussian parameters of the α -particle spectrum are known. In our calculations the distance between the peaks is larger than in the experiment. The distance between the Gaussian maxima in ref./4/ is 1.3-1.6 MeV whereas its theoretical value is 1.5-2.0 MeV. The value of the spectroscopic factors S_j for the second peak is close to the experimental one (S_j=2÷3 in different isotopes). However, while in ref./4/ the S_j-value for the second peak decreases with increasing A, in our calculations it increases.

The fragmentation of the $1g_{9/2}$-state becomes stronger owing to the interaction with the configurations "quasipar-

Table 3. Experimental[11,10] and theoretical characteristics of strength distribution of the $1g$ hole states in ^{123}Te and ^{143}Pm

Nucleus	$(nl_j)^{-1}$		ΔE_x MeV	$\bar{E}_x$ MeV	S_j	$\Gamma^{\downarrow}$ MeV
^{123}Te	$1g_{9/2}$	theor.	4.2–6.0	5.3	3.3	0.42
			6.0–8.4	7.0	4.3	0.56
			4.2–8.4	6.3	7.6	1.0
		exp.	-	6.1	-	1.6
^{143}Pm	$1g_{9/2}$	theor.	3.9–5.9	4.8	6.3	0.45
		exp.	-	5	7.7	-
	$1g_{7/2}$	theor.	-	0.20	5.2	-
		exp.	-	0.27	8.0±1.9	-

ticle plus two phonons". The ratio of the spectroscopic factors $S^{(2)}$ ans $S^{(1)}$, calculated with the wave function (1) and the wave function without $\alpha^+ Q^+ Q^+$ components respectively, for the interval ΔE_x=2.5 MeV including the first peak of the $1g_{9/2}$ -strength distribution is equal to 0.90 in ^{115}Sn, 0.88 in ^{117}Sn and 0.82 in ^{119}Sn.

The first data on the excitation of the $1g_{9/2}$ neutron hole state in the tellurium isotopes have been obtained in ref.[11]. A broad (FWHM ≃ 3.8 MeV) asymmetric peak has been observed in the $(^3He,\alpha)$ reaction on ^{124}Te at the energy $E_x \simeq$ 6.1 MeV; the width of the same peak in ^{129}Te is larger (FWHM ≃ 4.5 MeV). The broadening of the peak in comparison with the tin isotopes is due to a higher excitation energy of the one-quasiparticle neutron state $1g_{9/2}$ and a stronger quasiparticle-phonon interaction. The main qualitative features of the experimental $1g_{9/2}$ -strength distribution in ^{123}Te are reproduced in our calculations (fig. 3). The strength function $C^2_J(\eta)$ has two approximately equal peaks. These two peaks in ^{123}Te can be compared with two peaks in the tin isotopes,but in ^{123}Te the second peak exhausts a larger part of the $1g_{9/2}$ -strength than the first one. The values of $\bar{E}_x$ and $\Gamma^{\downarrow}$ for both the peaks are given in table 3. About 77% of the $1g_{9/2}$ -strength is concentrated in the energy interval $\Delta E_x \simeq$ 4 MeV. As has been demonstrated in ref.[19], the role of the components $\alpha^+ Q^+ Q^+$ in tellurium isotopes is larger than in tin. The ratio $S^{(2)}/S^{(1)}$ calculated for the interval ΔE_x=2 MeV including the first peak of the strength function is equal to 0.72.

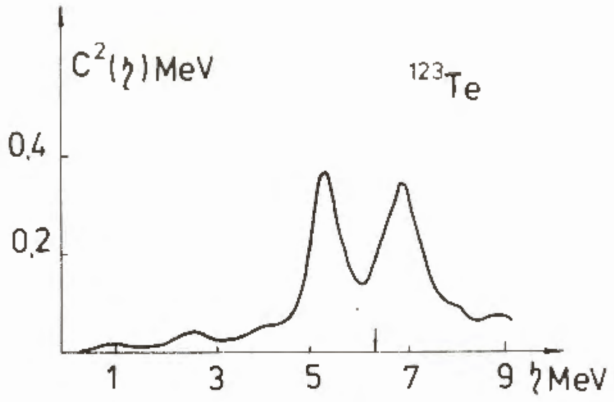

Fig. 3. The strength function of the neutron hole $1g_{9/2}$ - state in ^{123}Te. The arrow shows the position of the one-quasiparticle level $1g_{9/2}$.

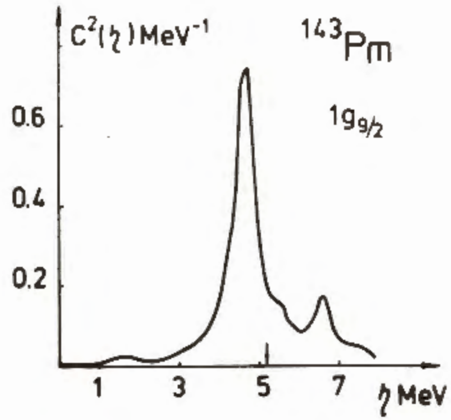

Fig. 4. The strength function of the proton hole $1g_{9/2}$ -state in ^{143}Pm. The arrow shows the position of the one-quasiparticle level $1g_{9/2}$.

The excitation of the deep-lying proton hole states in heavy spherical nuclei has been studied in ref./10/. In the reaction (d, ^{3}He) on ^{144}Sm the $1g_{9/2}$ - proton hole state of ^{143}Pm has been excited. The excitation energy is about 5 MeV. The coupling of the $1g_{9/2}$ -hole with the phonons of the semi-magic nucleus ^{144}Sm (which is the core in this case) is weak. Due to these reasons the fragmentation of the $1g_{9/2}$ -proton state should be weak. Fig. 4 shows the calculated $1g_{9/2}$ - strength distribution. Table 3 gives the theoretical and experimental values of $\bar{E}_x$, $\Gamma^{\downarrow}$ and S_j. Though the energy interval ΔE_x in which the $1g_{9/2}$ -strength is exhausted, is not presented in ref./10/ there is an agreement between the theoretical and experimental results. A weak fragmentation of the $1g_{9/2}$ - state is shown both by experiment and theory. The fragmentation of the $1g_{7/2}$ proton state has also been investigated in ref./10/ and the authors have assumed that a part of the $1g_{7/2}$ -strength is in the region of the $1g_{9/2}$ -peak. Though our results show a stronger fragmentation of the state than experiment, its full strength is exhausted at the excitation energy below 4 MeV, and this state should not contribute to the cross section at the energy $E_x > 5$ MeV. It should be noted, that in ref./10/ the value of the spectroscopic factor of the $1g_{7/2}$ -state is overestimated. It coincides with the value of S_j=8 following from the shell model for j=7/2. However, the S_j-value should be less owing to the effect of the pairing correlations and quasiparticle-phonon interaction. For instance, assuming that the $1g_{7/2}$ -state is purely one-quasiparticle $S_j=(2_j+1)v_j^2$. The value of v_j^2

is equal to 0.77 at our parameters of the superconducting pairing forces, and consequently $S_j \lesssim 6.2$ which is closer to our result $S_j=5.2$.

In this paper we have presented the results of the study of the fragmentation of hole states in the spherical odd-mass nuclei within the quasiparticle-phonon nuclear model. We have taken into account the interaction of the hole states with many states of the type "quasiparticle plus phonon" and "quasiparticle plus two phonons". The calculations have shown that the interaction with the "quasparticle plus two phonons" states is important for the description of the hole streugth distribution.

The comparison of the theoretical and experimental data has shown that the quasiparticle-phonon model describes correctly the centroids, spreading widths and spectroscopic factors of the hole strength distribution in the spherical nuclei. However, for the accurate description of the low-lying excitations of odd-mass spherical nuclei one should carefully take into account the influence of the Pauli principle and other high order effects.

The use of the wave function (1) for the calculation of the structure of odd-mass nuclei at the excitation energy $E_x \simeq 5 \div 10$ MeV rises new possibilities. In particular, we can calculate the fragmentation of the "quasiparticle plus phonon" states, since this fragmentation is mainly determined by the interaction with the one-quasiparticle and "quasiparticle plus two phonons" states. This allows one to approach the problems of microscopic calculation of the radiative streugth functions

in odd-mass nuclei and the probabilities of excitation of three-quasiparticle components in the many-nucleon transfer reactions.

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