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TWO-QUASIPARTICLE STRENGTH DISTRIBUTIONS IN ^{62}Ni AND ^{206}Pb

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1. INTRODUCTION

Experimental investigations [1-7] of the one- and two-nucleon transfer reactions for many nuclei provide information on few-quasiparticle strength distributions. The most important information has been obtained on the fragmentation of deep-hole states [4].

In recent years a good deal of attention has been paid to the calculation of the few-quasiparticle state strength distribution [7,8] within the quasiparticle-phonon nuclear model [9] (QPM). Values of the neutron and radiative strength functions [10,11], the giant resonance widths [11,12] are determined by the few-quasiparticle state fragmentation (distribution of strength).

Spectroscopic factors of high-lying states have been measured recently in the reactions $^{61}Ni(\vec{d},p)^{62}Ni$ and $^{207}Pb(^{3}He,\alpha)^{206}Pb$ in refs. [13,3], respectively. Most of theoretical calculations [14-17] are devoted to the energies and spectroscopic factors of the low-lying states only. Our calculations [8] and the comparison with experimental data for some Sn, Te and Cd isotopes show that within the QPM one can correctly describe the two-quasiparticle strength distribution.

The aim of this paper is to calculate the two-quasiparticle strength distribution in ^{62}Ni and ^{206}Pb for a wide energy region and to compare with experimental data.

2. BASIC FORMULAE AND NUMERICAL DETAILS

The QPM Hamiltonian includes the average field as the Saxon-Woods potential for protons and neutrons, the pairing interaction and the effective residual multipole and spin-multipole forces. The model Hamiltonian in terms of the creation and annihilation operators of quasiparticles and phonons is given in refs. [9,12].

The excited state wave functions of doubly even spherical nuclei are

$$\Psi_{\nu}(JM)=\{\sum_{i} R_{i}(J\nu)Q^{+}_{JMi}+\sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu)[Q^{+}_{\lambda_1\mu_1 i_1}Q^{+}_{\lambda_2\mu_2 i_2}]_{JM}\}\Psi_0 , \qquad (1)$$

where Ψ_0 is the phonon vacuum wave function, $Q^{+}_{\lambda\mu i}$ is the phonon creation operator. The secular equation for the eigenvalues of energies η_{ν} and equations for coefficients R and P are given in refs. [8,9,12].

The two-quasiparticle component $\{j_1 j_2\}$ in the state $Q^+_{\lambda\mu i}\Psi_0$ with spin $J=\lambda$, in the RPA is determined by $\frac{1}{2}|\psi^{Ji}_{j_1 j_2}|^2$. Here $\psi^{Ji}_{j_1 j_2}$ is phonon amplitude [9], j_1, j_2 are quantum numbers of single-particle states. The one-phonon states are fragmented provided the quasiparticle-phonon interaction is taken into account. The two-quasiparticle component $\{j_1 j_2\}$ with spin J of the state ν, described by the wave function (1) is [8]:

$$\Phi_{j_1 j_2}(J;\eta_\nu) = \frac{1}{2}\Big|\sum_i R_i(J\nu)\psi^{Ji}_{j_1 j_2}\Big|^2. \qquad (2)$$

Now we get the spectroscopic factors of one-nucleon transfer reactions on odd-A target nuclei. The wave function of an odd-A target nucleus is taken in the form

$$\Psi_{\nu_0}(j_0 m_0) = C_{j_0\nu_0}\alpha^+_{j_0 m_0}\Psi_0 \qquad (3)$$

neglecting the quasiparticle plus one- and two-phonon terms. The wave function of final states with spin J_f is taken in the form of (7). The spectroscopic factors of the nucleon transfer on a subshell j have the following form:

for the reaction of type (dp)

$$S_j(j_0 J_f;\eta_\nu) = C^2_{j_0\nu_0}u^2_j\Phi_{jj_0}(J_f;\eta_\nu), \qquad (4)$$

for the reaction of type (dt)

$$S_j(j_0 J_f;\eta_\nu) = C^2_{j_0\nu_0}v^2_j\Phi_{jj_0}(J_f;\eta_\nu), \qquad (5)$$

where u_j, v_j are the Bogolubov transformation coefficients.

The following expressions are often used:

$$S'_j(j_0 J_f;\eta_\nu) = \frac{2J_f+1}{2j_0+1}S_j(j_0 J_f;\eta_\nu), \qquad (6)$$

$$G_j = \sum_{J_f\nu} S'_j(j_0 J_f;\eta_\nu). \qquad (7)$$

It is more practical and convenient to use the strength functions for (4)-(7) at high excitation energies. Following ref. [9] we introduce the strength function

$$\Phi_{j_1 j_2}(J;\eta) = \sum_\nu \Phi_{j_1 j_2}(J;\eta_\nu)\rho(\eta-\eta_\nu), \qquad (8)$$

where

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

Using the R-coefficient analytical properties one can obtain an expression for $\Phi_{j_1 j_2}(J;\eta)$ (see refs. [8,9]). The energy

interval Δ determines the way of presentation of results of the calculation. In the limit $\Delta\to 0$ ρ is transformed to the δ-function, so the calculation results are represented for individual states. In the calculations for low-lying states in ^{62}Ni and ^{206}Pb the parameter Δ is small (Δ=0.05-0.1 MeV). To calculate the $1h_{11/2}$ subshell fragmentation we use Δ= =0.5 MeV.

For the numerical calculations we use the same parameters of the QPM and resudial interaction constants as in refs. [8,18,19]. So we have no free parameters in present calculations.

3. RESULTS OF CALCULATION

The fragmentation of two-quasiparticle states is caused, first, by the interaction between quasiparticles, which leads to the formation of one-phonon states, and second, by the quasiparticle-phonon interaction, which couples the one- and two-phonon states. The influence of each of these factors on the fragmentation of two-quasiparticle states is demonstrated in fig.1. Figure 1 shows the spectroscopic factors $S'_j(j_0 J_f;\eta_\nu)$ for two-quasiparticle states $\{2p_{3/2}1g_{9/2}\}$ in ^{62}Ni with $J^\pi=3^-$, calculated in RPA and using the wave function (1). The main part of the two-quasiparticle strength is distributed over three RPA roots in the energy interval from 6 to 8 MeV. It is seen from fig.1 that the quasiparticle-phonon interaction enchances the fragmentation of the state $\{2p_{3/2}1g_{9/2}\}$. The strength of this state is redistributed in the energy interval from 4 to 9.5 MeV. Our investigations show that the quasiparticle-phonon interaction influences greatly the fragmentation of two-quasiparticle states in ^{62}Ni. The RPA calculation with the wave function (1) gives similar results for low-lying states of ^{206}Pb. For the excitations with energies higher than 4 MeV in ^{206}Pb the quasiparticle-phonon interaction is important.

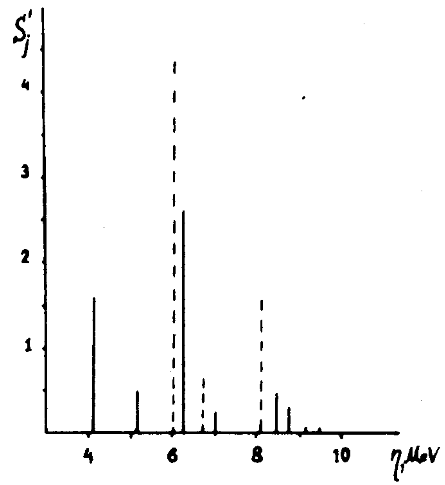

Fig.1. Spectroscopic factors $S'_j(j_0 J_f;\eta_\nu)$ for the $\{2p_{3/2}1g_{9/2}\}$ configuration with J^π_f = =3^- in ^{62}Ni; the dashed line is the RPA calculation; the solid line is the calculation with the wave function (1).

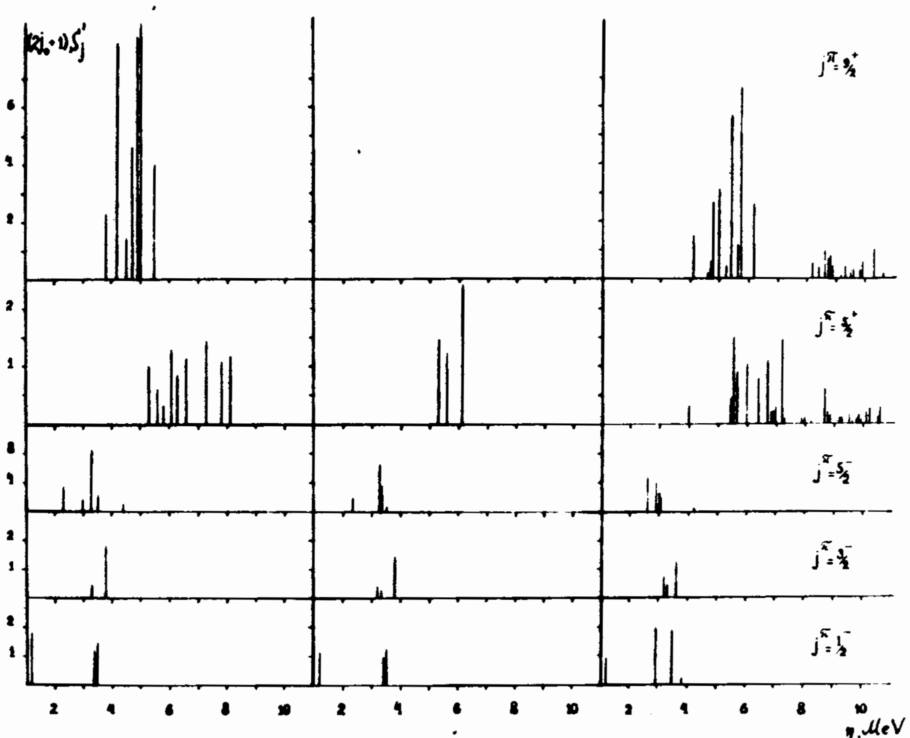

Fig.2. Spectroscopic factors of the neutron transfer on the subshells with $j^\pi = 1/2^-$, $3/2^-$, $5/2^-$, $5/2^+$, $9/2^+$ in ^{62}Ni : a) experimental data from ref./13/, b) experimental data from ref./20/, c) the QPM calculations.

Let us discuss the two-quasiparticle strength distribution in ^{62}Ni. Experimental data /13,20/ for the spectroscopic factors S'_j of the neutron transfer on different subshells j in ^{62}Ni and our calculations are drawn in fig.2. Spins of final states J_f have not been determined in ref./3/ and the spectroscopic factors S'_j are presented for all possible spins J_f of each quasiparticle state. New data on the $1g_{9/2}$ and $2d_{5/2}$ strength distribution for excitations below 8.5 MeV have been obtained in ref./13/. It is seen from fig.2 that the values of spectroscopic factors obtained in ref./13/ and ref./20/ differ considerably. The absolute spectroscopic factors can be extracted from experiment to only about 25-30% in the best cases. On the whole the experimental data and our calculations provide a similar picture of the fragmentation of two-quasiparticle states in ^{62}Ni. The QPM describes correctly the enhancement of the fragmentation with increasing energy excitation. Our calculations predict two groups of the $1g_{9/2}$ states. The first group of

Table 1

Integral characteristics of two-quasiparticle states in ^{62}Ni

nlj	$\bar{E}_j$, MeV		G_j	
	Exp.	Calc.	Exp.	Calc.
$2p_{1/2}$	2.52	2.7	1.14	1.32
$1f_{5/2}$	3.14	2.8	4.44	3.3
$1g_{9/2}$	4.73	5.2(6.3)	9.7	6.1(8.2)
$2d_{5/2}$	6.72	6.2(7.2)	2.26	2.3(3.2)

strong $1g_{9/2}$ states has excitation energies equal to (4-6) MeV. The second group of weak levels is located at excitation energies of (8-10) MeV. There is a similar picture for the $2d_{5/2}$ strength distribution.

The integral characteristics of the two-quasiparticle strength distributions in ^{62}Ni are shown in table 1. These are the centroid energies

$$\bar{E}_j = \sum_{\nu\in\Delta E} \eta_\nu S'_j(j_0 J_f;\eta_\nu) / \sum_{\nu\in\Delta E} S'_j(j_0 J_f;\eta_\nu)$$

and the sum of spectroscopic factors G_j in the energy interval ΔE. These characteristics are given for the experimentally /13/ investigated energy interval ΔE =(0-8.2) MeV. Being calculated for the excitation energies up to the neutron binding energy of ^{62}Ni B_n=10.6 MeV, values of $\bar{E}_j$ and G_j for $1g_{9/2}$ and $2d_{5/2}$ subshells are shown in the brackets in table 1. The experimental data and our calculations show that about (50-60)% of the $2d_{5/2}$ strength is pushed to the continuum. On the whole the QPM describes correctly the integral characteristics of the two-quasiparticle strength distributions in ^{62}Ni.

The experimental data for spectroscopic factors of the ^{207}Pb(^{3}He, α)^{206}Pb reaction in a wide energy interval have been obtained in ref./3/. The DWBA analysis /3/ of cross sections allows one to identify quantum numbers of the neutron hole subshells. This identification is not unique. So the experimental two-quasiparticle strength distribution for excitation energies higher than 4.3 MeV in ^{206}Pb is now known qualitatively.

Table 2

Energies and spectroscopic factors $S'_j(j_0 J_f; \eta_\nu)$ for low-lying states in ^{206}Pb

nlj	J_f^π	η_ν, MeV Exp.	η_ν, MeV Calc.	$S'_j(j_0 J_f; \eta_\nu)$ ref.3 ($^3He,\alpha$)	ref.21 ($\vec{d}$,t)	ref.22 (p,d)	Calc.
$2f_{7/2}$	4^+	1.684	1.9	0.22	-	0.17	0.16
	4^+	1.998	2.2	0.2	-	0.14	0.23
	4^+	2.928	2.9	3.02	3.45	3.97	2.9
	3^+	3.122	3.0	2.60	2.69	3.37	2.6
	4^+	3.519	3.9	0.23	-	0.21	0.16
$1i_{13/2}$	7^-	2.200	1.8	4.25	5.5	7.05	6.4
	6^-	2.384	2.1	3.60	5.0	6.47	5.4
	7^-	2.865	3.0	0.2	-	0.32	0.24
$1h_{9/2}$	4^+	4.008	3.9	1.85	-	4.3	3.7
	5^+	4.116	4.0	2.55	-	5.00	4.8

The low-lying states in ^{206}Pb are investigated in detail. The experimental values of energies and spectroscopic factors obtained in the ($^3He,\alpha$) /3/ , ($\vec{d}$,t) /21/, and (p,d) /22/ reactions are given in table 2. The results of our ealculation with the wave function (1) are shown in table 2 also. As can be seen from this table the absolute values of spectroscopic factors obtained in these experimental papers differ considerably. The calculated energies for the low-lying states in ^{206}Pb are in good agreement with experimental data. Our calculations describe correctly changes of spectroscopic factors in magnitude for different levels. For the levels having large values of spectroscopic factors S'_j our results are similar to other theoretical calculations /15,16/. Our results and experimental data for the values of $G_j/(2j+1)$ which characterize the exhaustion of the sum rule limit, are shown in table 3. As can be seen, to a few per cent accuracy the total sum rule strength for $2f_{7/2}$, $1i_{13/2}$, $1h_{9/2}$ states with excitation energies below 4.2 MeV has been observed in the $^{207}Pb(p,d)^{206}Pb$

Table 3

Sum-rule limit exhaustion for low-lying states in ^{206}Pb

nlj	$G_j/(2j+1)$ ($^3He,\alpha$)	($\vec{d}$,t)	(p,d)	Calc.
$2f_{7/2}$	0.78	0.77	0.99	0.76
$1i_{13/2}$	0.58	0.75	0.98	0.86
$1h_{9/2}$	0.44	-	0.93	0.85

Table 4

Two-quasiparticle strength distributions in ^{206}Pb

nlj	ΔE, MeV	$\sum_{\Delta E} S'_j$ Exp.	Calc.
$2f_{7/2}$	0-4.33	6.27	6.2
	4.33-7.4	0.55	1.3
		6.82(85%)	7.5(94%)
$1i_{13/2}$	0-4.33	8.05	12.5
	4.33-7.4	2.8	0.7
		10.85(78%)	13.2(94%)
$1h_{9/2}$	0-4.33	4.4	8.5
	4.33-7.4	1.8	1.2
		6.2(62%)	9.7(97%)
$1h_{11/2}$	7.4-7.9	0.69	0.83
	7.9-8.68	1.1	4.56
	8.68-9.29	0.9	2.02
	9.29-10.59	1.35	0.96
		4.04(34%)	8.37(70%)

reaction. The (^{3}He, α) data show a much lower sum-rule limit exhaustion than the (p,d) one. Our results are similar to the ($\vec{d}$,t) data.

The two quasiparticle strength distributions for high-lying states are known from the (^{3}He,α) reaction, only. The results of our calculations and experimental data /3/ are given in table 4. The sum-rule exhaustion for states from the energy interval ΔE is shown in brackets. The results of our calculations are in a qualitative agreement with experimental data of ref./3/.

Let us discuss the $\{3p_{1/2}\,1h_{11/2}\}$ state strength distribution in ^{206}Pb. The calculated strength functions for spectroscopic factors $S_j(j_0J_f;\eta)$ for states with $J_f^\pi = 5^+, 6^+$ are shown in fig.3. The summed strength function is shown in fig.3,

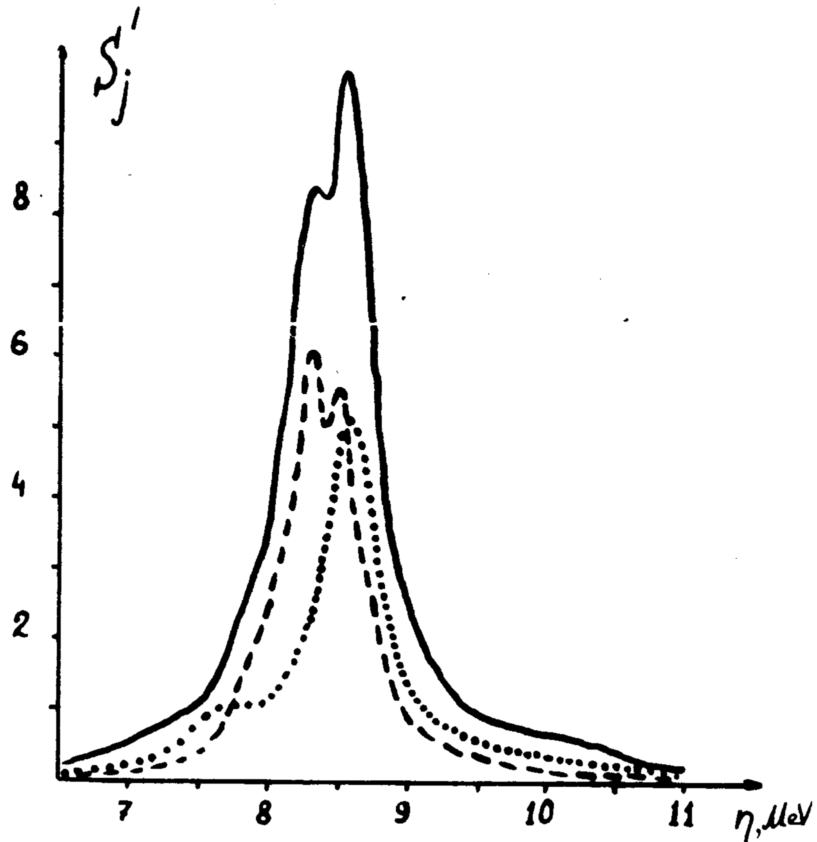

Fig.3. Strength functions for spectroscopic factors $S'_j(j_0J_f;\eta)$ for the $\{3p_{1/2}1h_{11/2}\}$ configuration; the dashed curve is $S'_j(j_0J_f;\eta)$ for $J_f^\pi=6^+$, the dotted curve is $S'_j(j_0J_f;\eta)$ for $J_f^\pi=5^+$, the solid curve is $S_f(\eta) = \sum_{J_f} S'_j(j_0J_f;\eta)$.

too. The residual excitation energy spectrum from the ^{207}Pb(^{3}He, α)^{206}Pb reaction in the energy interval (7.4-10.6) MeV exhibits an asymmetric bump with clear additional fine structure /3/. This bump is due to the fragmentation of the $\{3p_{1/2}\,1h_{11/2}\}$ configuration including the deeply-bound hole state $1h_{11/2}$. The spectroscopic factors shown in table 4 were obtained for the fine structure states. The observed fine structure strength is about 35% of the total $1h_{11/2}$ strength. The calculated integral $1h_{11/2}$ strength is twice that from the experimental one. Practically, the measured experimentally $1h_{11/2}$ strength is a lower bound for the total strength. A similar situation takes place for the $1h_{11/2}$ strength distribution in ^{207}Pb. About 45% of the sum-rule limit is exhausted by the fine structure levels /3/. However, the analysis /5/ of the spectroscopic strength localized in the whole bump gives the value 71%. This is in good agreement with our results /19/ and those of paper /23,24/.

The calculated value of the energy centroid for the $1h_{11/2}$ shell in ^{206}Pb is equal to 8.6 MeV. The experimental one equals 8.9 MeV. The width Γ_j of the $1h_{11/2}$ bump is difficult to define as the ordinary Breit-Winger spreading width. An estimate of the FWHM is $\Gamma_j \sim 4$ MeV in ^{206}Pb (see refs. /3,4/). Our calculation gives the value $\Gamma_j = 2$ MeV. At present the fragmentation of deep hole states in the ^{208}Pb(α, ^{6}He)^{206}Pb is being investigated at Orsay /5/. Our calculations can be used for the experimental investigation of this fragmentation.

4. CONCLUSION

The calculations and comparison with experimental data show that within the QPM one can correctly describe the fragmentation of two-quasiparticle states in doubly even spherical nuclei. The quasiparticle-phonon interaction influences greatly the fragmentation of two-quasiparticle states at intermediate and high excitation energies.

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Воронов В.В., Журавлев И.П. E4-82-512

Распределение силы двухквазичастичных состояний в ^{62}Ni и ^{206}Pb

В рамках квазичастично-фононной модели ядра рассчитана фрагментация двухквазичастичных состояний в ^{62}Ni и ^{206}Pb в широкой области энергий возбуждения. Проведено сравнение результатов расчетов с экспериментальными данными для спектроскопических факторов реакций однонуклонных передач.

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Two-Quasiparticle Strength Distributions in ^{62}Ni and ^{206}Pb

The fragmentation of two-quasiparticle states in ^{62}Ni and ^{206}Pb is calculated within the quasiparticle-phonon nuclear model. Experimental data for the one-nucleon transfer reaction spectroscopic factors and theoretical results are compared.

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

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