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FRAGMENTATION OF FEW-QUASIPARTICLE COMPONENTS OF HIGHLY EXCITED STATES IN ^{207,208}Pb

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1. INTRODUCTION

In recent years many investigations have been performed within the quasiparticle-phonon nuclear model [1] to study the fragmentation of a few quasiparticle wave function components in a wide region of excitation energies. The neutron strength functions are defined by the fragmentation of one-quasiparticle components in odd-A nuclei and two-quasiparticle components of the wave functions in doubly even nuclei [2-5] in the neutron-binding energy B_n region. Integral characteristics of the giant multipole resonances depend on the one-phonon strength distribution [6-8].

New data have been obtained on the neutron strength functions [10] of $^{207,208}Pb$ and giant resonances [11-15] of ^{208}Pb. A review of experimental and theoretical works on the giant resonance problem is given in ref. [16].

The aim of this paper is to calculate the neutron strength functions of $^{207,208}Pb$ and the giant quadrupole and octupole resonance characteristics of ^{208}Pb.

2. THE MODEL AND NUMERICAL DETAILS

The Hamiltonian of the quasiparticle-phonon nuclear model includes the average field as the Saxon-Woods potential, the pairing interaction and the effective residual and spin-multipole forces. The radial dependence of these forces is chosen in the form of $R(r) = r^\lambda$ (λ is a multipole phonon momentum) or $R(r) = \partial V/\partial r$, which is a derivative of the average field potential V(r). The model Hamiltonian in terms of the creation and annihilation operators of quasiparticles and phonons is given in ref. [1,6].

We make calculations taking into account the quasiparticle-phonon interaction. The excited state wave functions of doubly even spherical nuclei are

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

where Ψ_0 is the phonon vacuum wave function. For odd-A spherical nuclei the wave functions are

$$\Psi_\nu(JM) = C_{J\nu}\{\alpha^+_{JM} + \sum_{\lambda i j} D^{\lambda i}_j (J\nu)[\alpha^+_{jm} Q^+_{\lambda\mu i}]_{JM} +$$

$$+ \sum_{\lambda_1 i_1 \lambda_2 i_2 jI} F^{\lambda_1 i_1 \lambda_2 i_2}_{jI}(J\nu)[\alpha^+_{jm}[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{IM'}]_{JM}\}\Psi_0 . \tag{2}$$

Here α^+_{jm} and $Q^+_{\lambda\mu i}$ are the quasiparticle and phonon creation operators. The wave functions (1) and (2) satisfy the normalization condition

$$\langle\Psi^*_\nu(JM)\Psi_\nu(JM)\rangle = 1 .$$

Using the variational principle we find the secular equation for the energies η_ν

$$F(\eta_\eta) = 0$$

and the equations for the coefficients of the wave functions (1) and (2). Their explicit form is given in refs. [1,17]. To find the energies and coefficients of the wave functions (1) and (2), one should solve very complicated systems of nonlinear equations with large dimension. For the investigation of highly excited states, it is reasonable to calculate the corresponding strength functions [1,6,17]. Let $\Phi_{J\nu}$ be the amplitude of excitation of the state $\Psi_\nu(JM)$ in the nuclear reaction. Then, instead of the values of $|\Phi_{J\nu}|^2$ for each state with energy η_ν we calculate the strength function

$$b(\Phi,\eta) = \sum_\nu \rho(\eta-\eta_\nu)|\Phi_{J\nu}|^2 , \quad \rho(\eta-\eta_\nu) = \frac{1}{2\pi}\,\frac{\Delta}{(\eta-\eta_\nu)^2 + \frac{1}{4}\Delta^2} . \tag{3}$$

The energy interval Δ defines the way of presentation of the results of calculation. If excitation of the state $\Psi_\nu(JM)$ of doubly even nuclei proceeds mainly through the one-phonon components of the wave function (1), then [5,6]

$$\Phi_{J\nu} = \sum_i R_i(J\nu)\Phi_{Ji} ,$$

$$b(\Phi,\eta) = \frac{1}{\pi}\mathrm{Im}\left\{\frac{\sum_{ii'} M_{ii'}(\eta + i\frac{1}{2}\Delta)\Phi_{Ji}\Phi_{Ji'}}{F(\eta + i\frac{1}{2}\Delta)}\right\} , \tag{4}$$

where $F(\eta + i\frac{1}{2}\Delta)$ is the determinant at complex energies, and $M_{ii'}$ are the minors of this determinant. For instance, for the $E\lambda$ transitions from the ground to the excited states described by the wave function (1)

$$\Phi_{Ji} = \langle\Psi_0 \,||\, M(EJ)Q^+_{JMi} \,||\, \Psi_0\rangle , \tag{5}$$

where $M(EJ)$ is the electromagnetic transition operator. The strength functions for the one-quasiparticle components of the wave function (3) are (see refs. [17])

$$C^2_J(\eta) = \sum_\nu \rho(\eta-\eta_\nu)C^2_{J\nu} = \frac{1}{\pi}\mathrm{Im}\frac{1}{F(\eta + i\frac{1}{2}\Delta)} . \tag{6}$$

For numerical calculations we use the following parameters of the quasiparticle-phonon nuclear model. The parameters of the Saxon-Woods potential are given in ref. [9]. The single-particle energy levels, lying near the Fermi surface, obtained with this potential are close to the experimental values. The constants of the multipole and spin-multipole forces have been determined from the experimental data on the energies and electromagnetic transition probabilities as in refs. [9,18]. The ratio of the isoscalar and isovector constants in calculations with the radial dependence $R(r) = \partial V/\partial r$ has been fixed so as to describe the experimental energies of the 2^+_1 level and isovector quadrupole resonance. We have used the value $\Delta = 0.2$ MeV.

3. NEUTRON STRENGTH FUNCTIONS

If a neutron with orbital momentum ℓ is captured by the target with spin I_0, the neutron strength function is determined by

$$S_\ell = \sum_{Jj} g(J) S^{Jj}_\ell , \tag{7}$$

where $g(J) = \frac{2J+1}{2(2I+1)(2\ell+1)}$ is the statistical weight, S^{Jj}_ℓ is the partial strength function with the spin of compound-nucleus equal to $\vec{J} = \vec{I}_0 + \vec{\ell} + \frac{\vec{1}}{2} = \vec{I}_0 + \vec{j}$ in the channel j. For the doubly even target $I_0=0$ and $J=j$. Then S^{Jj}_ℓ has the following form:

$$S^{JJ}_\ell = S^J_\ell = \frac{\Sigma_\nu \Gamma^{0\ell}_{n\nu}(J)}{\Delta E} = \frac{\Gamma^{0\ell}_{s.p.}}{\Delta E} u^2_J \int_{\Delta E} C^2_J(\eta)d\eta , \tag{8}$$

where u_J is the Bogolubov transformation coefficient equal to unity for ^{208}Pb, $\Sigma_\nu \Gamma^{0\ell}_{n\nu}$ is the sum of reduced neutron widths in the energy interval ΔE and $\Gamma^{0\ell}_{s.p.}$ is the single-particle reduced neutron width in the form given in ref. [19] for the Saxon-Woods potential. In doubly even compound-nuclei one should substitute $C^2_J(\eta)$ by the strength function $b(\Phi,\eta)$ for the two-quasiparticle components [5]. Then in formula (4) $\Phi_{Ji} = \sum_n u_{n\ell j}\psi^{Ji}_{n\ell j,\, n_0\ell_0 I_0}$ where $n\ell j$ are the quantum

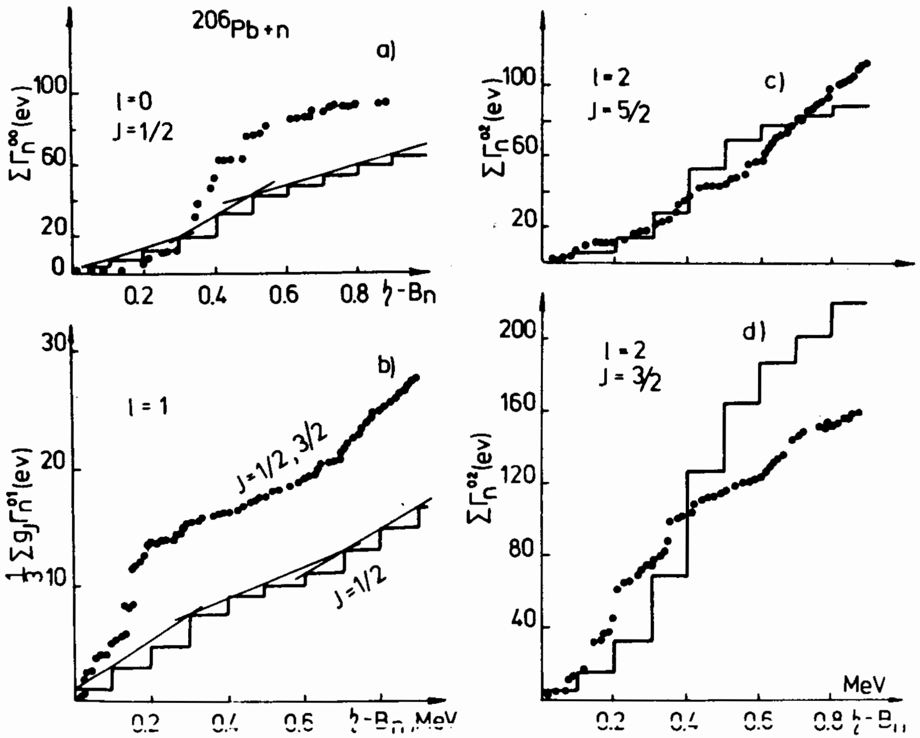

Fig. 1. Plots of the sum of the reduced neutron widths for the ^{206}Pb+n resonances versus neutron energy, the points are the experimental data /10/, the solid line is the calculation, a) for the s-wave resonances, b) for the p-wave resonances, experimental plot for the weighted sum with J = 1/2 and 3/2, calculation for the states with J = 1/2, c) for the d-wave resonances with J = 5/2, d) for the d-wave resonances with J = 3/2.

numbers of signle-particle states, and $\psi^{Jj}_{n\ell j, n_0\ell_0 I_0}$ are the phonon amplitudes.

The s-, p- and d-wave neutron strength functions in the reaction ^{206}Pb+n for the neutron energy of 0-900 keV have been studied experimentally in ref. /10/. Substructures appear in the energy dependence $S^J_\ell(\eta)$. The experimental and calculated energy dependences of the sum of reduced neutron widths for ℓ = 0, 1, 2 in ^{207}Pb are shown in fig. 1. The strength function S^J_ℓ is given by the slope of the curve. The s-wave strength function in ^{207}Pb exhibits significant changes near 300 and 500 keV. The calculated values of $\Sigma\Gamma^{00}_n$ also change the slope at these energies, but they are less pronounced. The

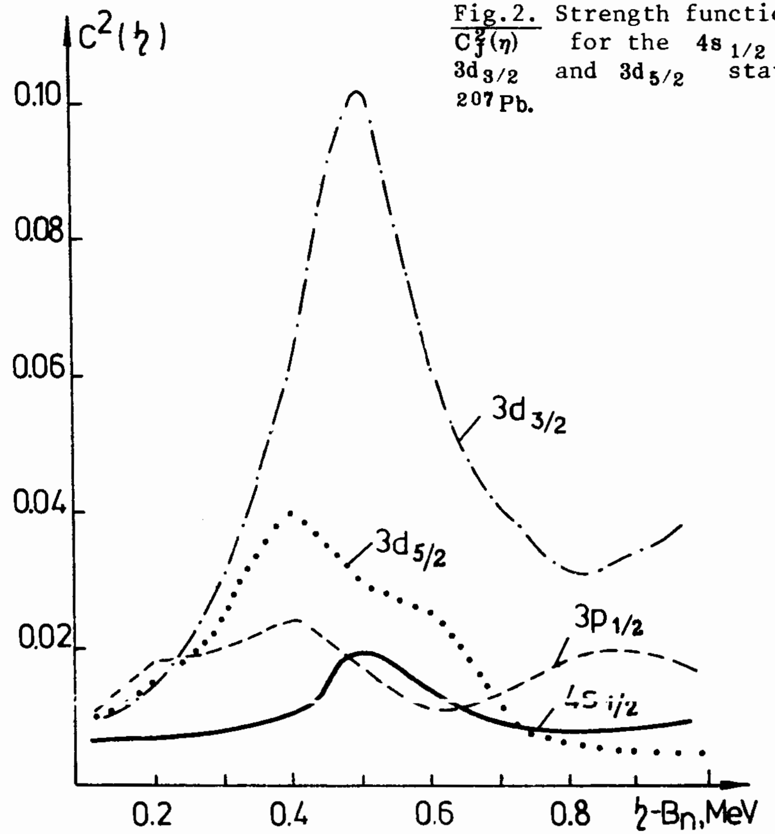

Fig. 2. Strength functions $C^2_J(\eta)$ for the $4s_{1/2}$, $3p_{1/2}$, $3d_{3/2}$ and $3d_{5/2}$ states in ^{207}Pb.

fragmentation of the subshells $4s_{1/2}$, $3p_{1/2}$, $3d_{5/2}$ and $3d_{3/2}$ in the energy interval (0-900) keV above the neutron binding energy B_n is shown in fig. 2. It is seen from this figure that the strength distribution of these states has local maxima. Just this substructure of $C^2_J(\eta)$ manifests itself as the change of slope in the sum of neutron reduced widths $\Sigma\Gamma^{0\ell}_n$.

A similar situation occurs for the p- and d-wave resonances. It is seen from fig. 1 that the experimental p-wave strength function changes considerably near 200 keV and slightly near 700 keV. We have calculated the fragmentation of the $3p_{1/2}$ subshells and have not calculated that of 4p.

The calculations taking into account the subshell $3p_{1/2}$ cannot reproduce completely the function $\frac{1}{3}\Sigma_\nu g(J)\Gamma^{01}_{n\nu}$. However, the energy dependence $\frac{1}{3}\Sigma_\nu\Gamma^{01}_{n\nu}$ for the $3p_{1/2}$ resonances is

Table 1

Experimental and calculated values of the strength functions S_ℓ in $^{208,207}Pb + n$

Compound nucleus	Partial wave	$S_\ell \cdot 10^4$	
		exp.	calc.
^{207}Pb	$s_{1/2}$	1.06	0.8
	$d_{3/2}$	1.81	2.4
	$d_{5/2}$	1.24	1.1
	p	0.32	0.2
^{208}Pb	$s_{1/2}$	1.4	1.1
	d	2.8	2.0

similar to the behaviour of the experimental weighted sum of reduced neutron widths for the p-resonances with J=1/2 and 3/2. The calculations give less pronounced change of $S_1^J(J = 1/2)$ near 300 and 700 keV in comparison with the experimental data for J=1/2 and 3/2. There is a change in the d wave strength functions near 400 keV. The change in slope of $\Sigma\Gamma_n^{02}$ versus neutron energy for the $d_{3/2}$ resonances is stronger than for the $d_{5/2}$ resonances. The calculations reproduce the experimental data qualitatively, that is seen from fig.2. The calculated sum of $\Sigma\Gamma_n^{02}$ for the $J^\pi=3/2^+$ states is above the experimental one at the neutron energies E_n>400 keV.

The experimentally determined in ref./10/ values of the average strength functions S_ℓ in the interval E_n=0-900 keV and the calculated values are given in table 1. Our calculations give a fairly good description of the experimental data including the absolute values of the neutron strength functions without a special fitting of the parameters.

The ^{207}Pb+n reaction has been studied in ref./10/ in the energy interval 0-500 keV. Substructures have been observed also in the neutron strength functions. The available experimental data for $\Sigma\Gamma_n^{0\ell}$ for ℓ=0,2 and the results of our calculations are given in fig.3. The change in the s-wave strength function near 450 keV (i.e., change in slope of

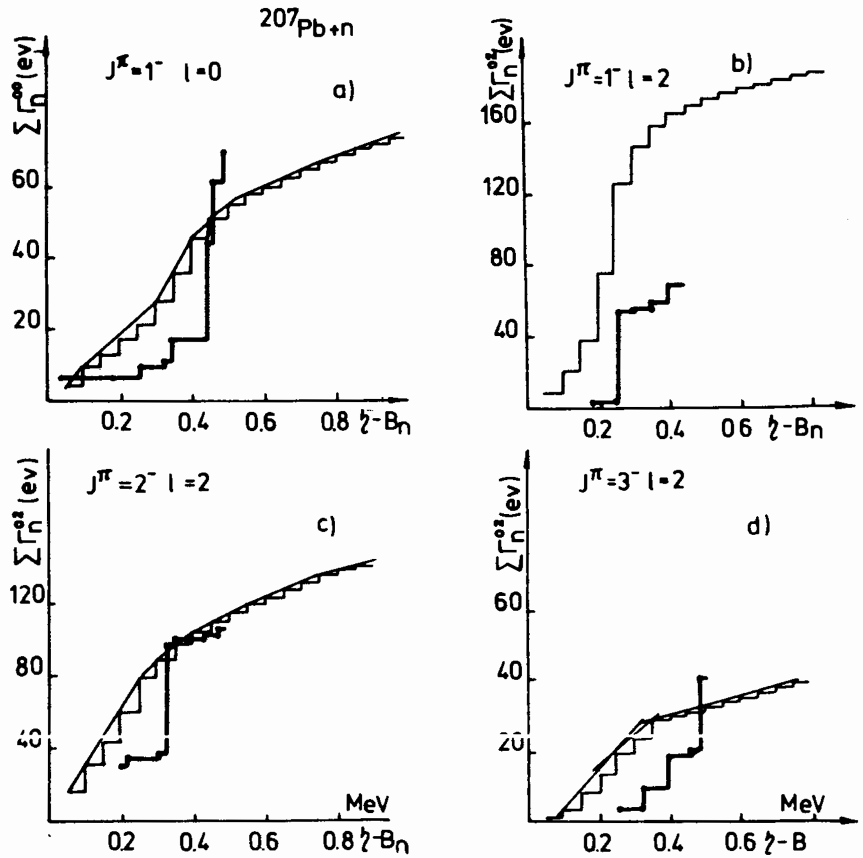

Fig.3. Plots of the sum of reduced neutron widths for the ^{207}Pb+n resonances a) s-wave resonances with $J^\pi=1^-$, d) d-wave resonances with $J^\pi=1^-$, c) d-wave resonances with $J^\pi=2^-$, d) d-wave resonances with $J^\pi=3^-$, the points are the experimental data /10/, the solid lines are our calculations.

$\Sigma\Gamma_n^{00}$ versus η) for the 1^- resonances has been observed. The calculated energy dependence of $\Sigma\Gamma_n^{00}$ also changes but not so abruptly. There are also indications to the substructures in the d-wave neutron scattering /10/. The calculations indicate a sharp, as in the experiment, change of $\Sigma\Gamma_n^{02}$ near 250 keV for the 1^- resonances. Our values of $\Sigma\Gamma_n^{02}$ for the resonances formed by $d_{3/2}$ neutrons are much higher that the experimental data. In the channel with $J^\pi=2^-$ and 3^- the strength functions S_2^J also change near 300 and 400 keV.

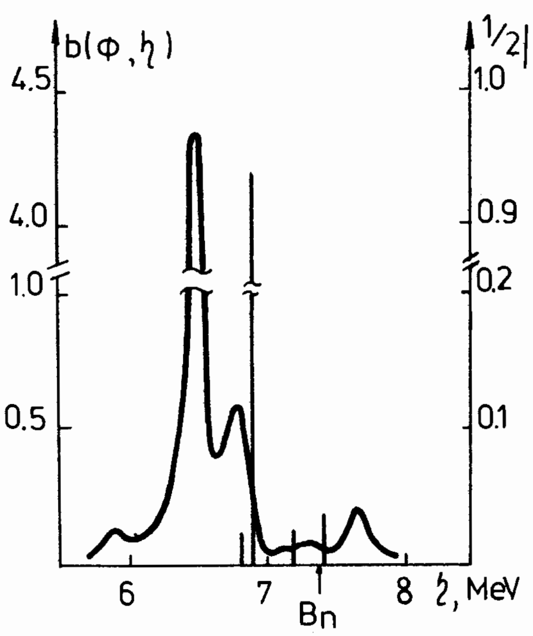

Fig.4. Calculated strength disctibution of the two-quasiparticle neutron state $\{3p_{1/2}, 3d_{3/2}\}$ with $J^{\pi}=1^-$ in ^{208}Pb. The straight lines are the calculations (the right scale). The curve is the calculation of the strength function taking into account the two-phonon components (the left scale). The arrow shows the position of the neutron binding energy.

The changes in slope of $\Sigma\Gamma_n^{0\ell}$ in ^{208}Pb are due to substructures in the fragmentation of the corresponding states. In ^{208}Pb the s-wave strength function is defined by the fragmentation of the two-quasiparticle states $\{3p_{1/2}, 4s_{1/2}\}$, and the d-wave strength functions by the fragmentation of the states $\{3p_{1/2}, 3d_{3/2}\}$ and $\{3p_{1/2}, 3d_{5/2}\}$. In the strength distribution of these states there are local maxima at the energy above B_n. As an example fig.4 shows the strength functions $b(\Phi, \eta)$ calculated with the wave function (1) and the strength distribution over the roots of the RPA equations for the two-quasiparticle states $\{3p_{1/2}, 3d_{3/2}\}$. 92% of strength of this state is concentrated on one level with an energy of 6.9 MeV, and the rest part is distributied over three states. The quasiparticle phonon interaction causes a strong fragmentation of this state. As a result there is a local maximum in the $\{3p_{1/2}, 3d_{3/2}\}$ strength distribution at η=7.45 MeV, which appears in the energy dependence of $\Sigma\Gamma_n^{02}$. There are similar substructures in the $s_{1/2}$ and $d_{5/2}$ channels. The appearance of substructures in the two-quasiparticle state strength distributions in ^{208}Pb at $\eta \approx 7.5$ MeV is due to a strong coupling

of these states with the two-phonon states $\{2^+_1 \otimes 3^-_1\}$ and $\{4^+_1 \otimes 3^-_1\}$ with the calculated energies 7.32 MeV and 7.48MeV, respectively.

The calculated and experimental neutron strength functions for the compound-nucleus ^{208}Pb are given in table 1. Ignoring the possible effects of substructure in ref. /10/ there has been obtained the total d-wave strength function between 180-480 keV as $S_2 \approx 2.8\cdot10^{-4}$. Our calculations by formula (5-1) give $S_2=2\cdot10^{-4}$ for the energy interval 200-500 keV. If the averaging is performed over the interval (0-800) keV, we get $S_2=1,4\cdot10^{-4}$. We find $S_0=1,1\cdot10^{-4}$, and the experimental value is $S_0=1.4\cdot10^{-4}$, if substructure is ignored. The difference between the experimental and theoretical values of the strength functions for $d_{3/2}$ in ^{207,208}Pb can be diminished by changing the parameters of the Saxon-Woods potential.

4. GIANT QUADRUPOLE AND OCTUPOLE RESONANCES IN ^{208}Pb

Our RPA calculations show that the most part of strength of the giant isoscalar quadrupole resonance is concentrated on one collective level. For the radial dependence of the multipole forces $R(r)=r^{\lambda}$ the resonance energy is 9.2 MeV and 76.3% of the isoscalar energy weighted sum rule (EWSR) is exhausted. We have calculated EWSR as in ref. /6/ using the uniform distribution for $\langle r^{2\lambda-2}\rangle_{g.s.}$ at $R_0=1.2A^{1/3}$ fm. For the radial dependence $R(r)=\partial V/\partial r$ the GDR energy is 10.1 MeV and EWSR is exhausted by 72%. It should be noted that the calculations of the states of other multipolarities with both types of the radial dependence $R(r)$ are very similar.

The E2 strength functions calculated with the wave function (1) are shown in fig.5. The isoscalar quadrupole resonance strength is fragmented in the interval (8-11) MeV, in the calculations with $R(r)=\partial V/\partial r$ this fragmentation being more strong. The results of calculation of the GDR depend on the radial form of the quadrupole-quadrupole forces. In the case of $R(r)=\partial V/\partial r$ for the E2 strength centroid energy is $\bar{E}_x$=9.5 MeV, and the isoscalar EWSR is exhausted by 66%. The substructures are observed near 8.8, 9.5, 10.4 and 10.8 MeV. The calculations of ref. /20/ give $\bar{E}_x$=11.2 MeV and the EWSR is exhausted by 72%. The experimental papers on excitation of the isoscalar quadrupole resonance in the (α, α') and (d, d') reactions in ^{208}Pb give for $\bar{E}_x$=10.5-10.9 MeV, and the EWSR is exhausted by (60-80)%. A large number of 2^+ states in the excitation energy interval of 8-12 MeV has been observed in the electron scattering from ^{208}Pb /14/.

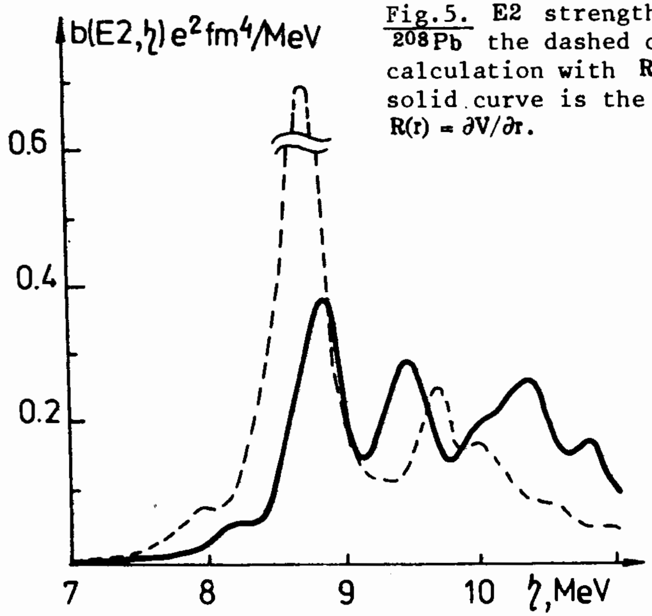

Fig.5. E2 strength functions in ^{208}Pb the dashed curve is the calculation with $R(r) = r^{\lambda}$ the solid curve is the calculation with $R(r) = \partial V/\partial r$.

They observed a rather strong fragmentation of strength with individual centers of gravity around $E_x \approx 8.9$, 10.2, 10.6 and perhaps 11.2 MeV. The experimental data on the fragmentation of E2 strength is qualitatively similar to our calculations with $R(r) = \partial V/\partial r$. However, the experimentally measured strength exhausts only $(29\,^{+11}_{-8})$% of the EWSR. The calculations performed in this paper in the frame of the $1p-1h + 2p-2h$ TDA employing the MSI-interaction [21] give $\bar{E}_x$=9.6 MeV and the EWSR is exhausted by 30%. About 45% of the strength is shifted up to excitation energies between 12 and 20 MeV where it rests in many weakly excited states. Neither our calculations nor the calculations of refs. [20,22] taking into account the $2p-2h$ configurations give such a strong fragmentation of the E2 strength. Our calculations of the isoscalar GDR give the results similar to those obtained in [20].

In ref. [23] the distribution of the quadrupole isoscalar strength is measured in the energy interval of (4-8.17) MeV in ^{208}Pb. The sum of reduced E2 transition probabilities $\Sigma B(E2)$ =480 $e^2 fm^4$ has been obtained for the states lying below the neutron binding energy without taking into account the 2^+_1 level. Our calculations with $R(r) = r^{\lambda}$ give $\Sigma B(E2)$ =900 $e^2 fm^4$, and with $R(r)=\partial V/\partial r$ we get $\Sigma B(E2)$ = =465 $e^2 fm^4$. A group of states with noticeable B(E2) -values

Table 2

Distribution of the octupole strength in ^{208}Pb

	E, MeV		EWSR%	
	Exp.	Calc.	Exp.	Calc.
3^-_1	2.61	2.4	20	21.3
LEOR	4.7	4.78	1.5	0.93
	4.96	4.99	1.6	0.3
	5.34	5.33	2.5	2.61
	5.58	5.76	7.1	3.32
HEOR	17.5	17.4	60	58.3

at the energies (7.8-8.2) MeV is also observed experimentally. It has been obtained [48] that for them $\Sigma B(E2) = 541 e^2 fm^4$. Our calculations indicate also a certain concentration of the E2 strength in this interval. We obtain $\Sigma B(E2)$ =410 $e^2 fm^4$ in the calculations with $R(r) = r^{\lambda}$ and $\Sigma B(E2)$ =240 $e^2 fm^4$ with $R(r) = \partial V/\partial r$.

For the isovector quadrupole resonance we get $\bar{E}_x$=21.3 MeV and the EWSR is exhausted by 70%. The experiment [12] gives $\bar{E}_x$=21.5 MeV and the EWSR is exhausted by 80%.

The experimental data have recently been obtained from the α-particle scattering from ^{208}Pb for the low-lying octupole resonance [15] (LEOR) and high-lying isoscalar octupole resonance [13] (HEOR). Four 3^- levels have been observed in the energy interval (4.5-5.7) MeV. The experimental data and the results of our calculations for the octupole strength distribution in ^{208}Pb are shown in table 2. The calculations for the LEOR give a good agreement with experiment for the level energies, but the EWSR is exhausted by 1.8 times as less as in experiment. The results of our calculations for the HEOR are in good agreement with the experimental data [13]. In the deuteron scattering it has been obtained [12] that the HEOR is at $\bar{E}_x$ =17.8 MeV and the EWSR is exhausted by 12%. The latter contradicts the data of paper [13] and our calculations.

CONCLUSION

So, within the quasiparticle-phonon nuclear model one can correctly describe the neutron-strength-function energy dependence in $^{207,208}Pb$ and the quadrupole and octupole strength distribution for ^{208}Pb,using the same Hamiltonian parameters.

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Воронов В.В., Соловьев В.Г., Стоянов Ч. О фрагментации малоквазичастичных компонент высоковозбужденных состояний $^{207,208}Pb$ E4-82-389

В рамках квазичастично-фононной модели ядра рассчитаны s-, p- и d-волновые нейтронные силовые функции в ядрах $^{207,208}Pb$. Получено качественно правильное описание их энергетической зависимости. Объяснена тонкая структура изоскалярного квадрупольного резонанса и получено согласующееся с экспериментальными данными описание LEOR и HEOR в ^{208}Pb.

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Soloviev V.G., Stoyanov Ch., Voronov V.V. Fragmentation of Few-Quasiparticle Components of Highly Excited States in $^{207,208}Pb$ E4-82-389

The s-, p- and d-wave neutron strength functions are calculated for $^{207,208}Pb$. Their energy dependence is correctly described. The fine structure of the isoscalar quadrupole resonance is explained and the description of the LEOR and HEOR in ^{208}Pb is obtained in agreement with the experimental data.

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

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