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SEMI-MICROSCOPIC DESCRIPTION OF NEUTRON AND RADIATIVE STRENGTH FUNCTIONS

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Полумикроскопическое описание нейтронных
и радиационных силовых функций

В рамках полумикроскопического подхода проведены расчеты нейтронных и радиационных силовых функций. Получено хорошее согласие с экспериментальными данными.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Soloviev V.G., Voronov V.V. **E4 - 10506**

Semi-Microscopic Description of Neutron and
Radiative Strength Functions

A new method for calculating the neutron and radiative strength functions with the model based on the quasiparticle-phonon interaction is suggested. A good description of the neutron strength functions in deformed nuclei and E1-strength functions for the transitions to the ground state in semi-magic nuclei is obtained. The experimental detection of few-quasiparticle components of the neutron resonance functions is discussed.

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

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1. INTRODUCTION

A unified description of few-quasiparticle components of the wave functions in complex nuclei at low, intermediate and high excitation energies is obtained in the framework of the semi-microscopic nuclear model [1-4]. For the first time this model was used for the calculation of nuclear state densities taking into account the rotational and vibrational motions. The description of the density of nuclei from $A=50$ to $A=250$ at the neutron binding energy is in good agreement with experiment [5]. Some general and important properties of neutron resonances were investigated within the approach based on the operator form of the wave functions of highly excited states [6,7]. For instance, the cases when the neutron valence model is valid for the γ-transitions from neutron resonances are studied [8]. Investigation of the fragmentation of single-particle states [9] allowed the calculation of neutron strength functions [10-12]. The calculation of the fragmentation of one-phonon states gives a possibility of obtaining the radiative strength functions [13].

In this report we present the calculated results of the neutron and E1-radiative strength functions. We also study the influence of giant multipole resonances on the energy dependence of radiative strength functions. The ways of experimental detection of many-quasiparticle components of the wave functions of neutron resonances are discussed.

2. FRAGMENTATION OF SINGLE-PARTICLE STATES AND NEUTRON STRENGTH FUNCTIONS

The fragmentation of one-quasiparticle states in odd-A deformed nuclei is studied in the framework of the above mentioned model based on the quasiparticle-phonon interaction. It is shown that the fragmentation strongly depends on the positions and quantum numbers of single-particle states and on the characteristics of collective excitations of the nucleus. The distribution differs in form from the Breit-Wigner curve. This result disagrees with the conventional idea but it is in agreement with the distribution form calculated by a simple model in ref. [14].

A method for calculating different types of strength functions related to the fragmentation of single-particle states was developed in ref. [11]. The strength functions of one-nucleon transfer reactions of the type (d,p),(d,t) and (d,n),(d, ^{3}He) on doubly even targets were obtained at intermediate excitation energies.

The calculation of the fragmentation of single-particle states made it possible to formulate an essentially new method for calculating the neutron strength functions at the neutron binding energy B_n. The method is developed in detail for nuclei with odd number of neutrons (even-even targets). A part of the calculated results for deformed nuclei is given in Table 1. The experimental data are taken from ref. /15/. It

Table 1

Neutron strength functions at $\eta = B_n$

Compound nucleus	B_n MeV	$S_0 \cdot 10^4$ Exp.	$S_0 \cdot 10^4$ Calc.	$S_1 \cdot 10^4$ Exp.	$S_1 \cdot 10^4$ Calc.	$S_2 \cdot 10^4$ Calc.
^{155}Sm	5.819	1.8±0.5	1.0		1.1	1.2
^{159}Gd	6.031	1.5±0.2	1.1	$2.8^{+1.4}_{-1.0}$	1.6	1.0
^{161}Gd	5.650	1.8±0.4	1.0	$0.88^{+0.84}_{-0.47}$	1.1	1.2
^{161}Dy	6.448	2.0±0.36	1.5	-	0.5	1.5
^{163}Dy	6.253	1.88	1.8	1.4	0.7	3.7
^{165}Dy	5.635	1.7	1.8	1.3	0.6	3.6
^{169}Er	5.997	1.5	3.4	0.7	0.5	6.8
^{171}Er	5.676	1.54	3.5	0.8	0.7	5.2
^{183}W	6.187	2.1±03	4.6	0.3±0.1	0.8	2.0
^{231}Th	5.09	1.3	1.1	-	0.7	4.0
^{233}Th	4.96	0.9	0.8	0.5-1.6	0.6	6.0
^{233}U	5.88	0.95	0.9	-	0.8	4.0
^{235}U	5.27	1.13±0.4	1.3	-	1.2	5.8
^{237}U	5.30	1.3±0.2	1.2	2.3±0.6	1.1	4.6
^{239}U	4.78	1.1±0.1	1.5	1.7±0.3	0.8	3.8
^{241}Pu	5.41	0.94±0.9	0.9	2.8	1.0	3.4
^{243}Pu	5.05	0.9±0.1	1.4	-	1.4	4.0
^{245}Cm	5.696	1.1±0.2	1.6	-	0.7	3.0

is seen from Table 1 that a good description of the s and p-wave strength functions is obtained. Table 1 also gives the calculated results of the d-wave strength functions for which there are only preliminary and poor experimental data. Note, that an accuracy of these calculations is limited, mainly, by that for the single-particle wave functions (in particular, for quasi-bound states) of the Saxon-Woods potential.

3. FRAGMENTATION OF THE ONE-PHONON STATES AND THE RADIATIVE STRENGTH FUNCTIONS

To study the giant multipole resonances in spherical nuclei, a modified version of our model taking into account the isoscalar and isovector components of multipole-multipole strength is used in ref.[16]. We use the apparatus[16] for calculating the E1-strength functions for the transitions from the ground states of doubly even spherical nuclei. The wave function of the neutron resonance is

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

where Q^+_{JMi} is the phonon production operator, and Ψ_0 is the ground state function. Following ref.[13] to calculate the radiative strength functions, we use the method (see ref.[11]) which allows the calculation of average values without solving the secular equations. The strength function for the

E1 -transitions to levels in the energy interval $E-\Delta/2, E+\Delta/2$ has the following form:

$$b(E1,E) = \frac{1}{2\pi}\sum_{\nu}\frac{\Delta}{(E-E_\nu)^2+\Delta^2/4} B(E1, 0^+_{g.s.} \to 1^-_\nu) . \quad (2)$$

The radiative width for the E1-transitions from the 1^- levels to the ground state is defined as:

$$\Gamma_{\gamma_0} = 0{,}35 E^3_\gamma \overline{B(E1,\uparrow)} \ \mathrm{eV}, \quad (3)$$

where $B(E1,\uparrow)$ is obtained from (2) and is given in units e^2f^2m, and E is given in MeV. We use the following definitions of the radiative strength functions

$$K_{E1} = \sum_{\Delta} \Gamma_{\gamma_0}/(E^3 A^{2/3}\Delta), \quad (4)$$

$$S_\gamma = \sum_{\Delta} \Gamma_{\gamma_0}/\Delta ,$$

where Γ_{γ_0} is in eV, E_γ is in MeV and Δ is in MeV or eV.

The calculated values of S_γ , $\langle\Gamma_{\gamma_0}\rangle$ and K_{E1} in ref. /13/, and the experimental data /17-20/ are given in Tables 2,3. The parameters are taken the same as in ref. /16/ $\Delta = 0.5$ MeV. The values averaged over doubly even isotopes are given for Sn. Table 2 shows that a good description of the radiative strength functions is obtained.

To illustrate the influence of the averaging interval Δ on the calculated results, Table 3 gives the values of $\langle\Gamma_{\gamma_0}\rangle$,

Table 2

E1-Radiative strength function

Nuclei	E, MeV	$S_\gamma \times 10^5$		
		Experiment	Reference	Calculation
^{56}Fe	11.2	3.5	17	3.5
^{90}Zr	8.7	4.3		4.5
	10.0	10.2		48
	11.3	18.1	20	24.0
	11.6	22.9		20.5
	11.9	24.0		25.0
	12.1	15.3		40.3
Sn	6.2	1.4		1.8
	6.4	3.2	20	2.0
	7.0	3.5		3.8
	8.6	12.9		14.7
	9.1	13.7		35.9

Table 3

Average E1-radiative widths and strength functions

Nuclei	E, MeV	Experiment			Calculation					
		$\langle\Gamma_{\gamma 0}\rangle$, eV	$K_{E1} \times 10^3$	Refer.	Δ=2 MeV		Δ=1.0 MeV		Δ=0.5 MeV	
					$\langle\Gamma_{\gamma 0}\rangle$ eV	$K_{E1} \times 10^3$	$\langle\Gamma_{\gamma 0}\rangle$ eV	$K_{E1} \times 10^3$	$\langle\Gamma_{\gamma 0}\rangle$ eV	$K_{E1} \times 10^3$
^{56}Fe	11.2	0.435		17	0.2		0.3		0.38	
^{138}Ba	8.6	3.3	4 ± 1	18	2.2	2.5	3.5	3.9	5.0	5.6
^{140}Ce	9.08	1.7	2.2	19	2.7	3.9	1.9	2.8	1.5	2.1

Δ for three nuclei calculated with Δ from 0.5 MeV to 2.0 MeV. It is seen from this table that $\langle\Gamma_{\gamma 0}\rangle$, K_{E1} changes by a factor of about 2 with increasing Δ from 0.5 MeV to 2 MeV.

Therefore, our new method for calculating the radiative strength functions gives a correct description of them. This method does not contain any new parameters.

The reactions (γ,γ') are widely used to measure the partial widths $\Gamma_{\gamma 0}$ in the excitation of individual levels. Table 4 shows the experimental data[21] of $\Gamma_{\gamma 0}$ quantities and the calculated results[13]. The calculated values are larger approximately by an order of magnitude than the experimental ones. In these experiments the $\Gamma_{\gamma 0}$-quantities of random excited states are measured, whereas we have calculated the averaged values. This discrepancy should not be considered very seriously. The experimental study of the reactions (γ,γ') with the state excitation in an energy interval of several keV is of great interest.

Table 4

E1-Partial widths

Nuclei	Experiment		Calculation	
	E, MeV	$\Gamma_{\gamma 0}$, meV	E, MeV	$\Gamma_{\gamma 0}$, meV
^{118}Sn	6.988	128±3	6.38	534
^{120}Sn	7.696	70±20	7.76	775
^{140}Ce	5.66	12±2	5.74	158

4. THE INFLUENCE OF THE GIANT DIPOLE RESONANCE ON THE RADIATIVE STRENGTH FUNCTIONS

The radiative strength functions have been analyzed in reviews [22-25]. To study the radiative strength functions the Brink-Axel treatment is often used according to which the dependence of the radiative widths on the γ-quanta energy is defined by the Lorentz distribution of the giant dipole resonance (GDR) tail. In this case the photoabsorption cross-section is the following:

$$\sigma_{\gamma t}(E_\gamma) = \frac{\sigma_o E_\gamma^2 \Gamma_o^2}{(E_\gamma^2 - E_o^2)^2 + E_\gamma^2 \Gamma_o^2}, \qquad (5)$$

where E_o is the GDR energy and Γ_o is its width. It is assumed that the Lorentz form fits well the energy dependence in nuclei far from the closed shells. The analysis of the radiative strength functions has shown [24] that the Lorentz extrapolation of GDR overestimates the values of strength functions in the low-energy region for nuclei near closed shells.

Our model allows the calculation of the fragmentation of the one-phonon state strength in the region of giant resonances. Therefore, there is a possibility of studying the influence of GDR on the E1-strength functions. According to [20], the average photoabsorption cross-section is related to the average radiative E1 width in the following way:

$$\sigma_{\gamma t} = 1{,}15 \cdot 10^{-7} \sum_\Delta \Gamma_{\gamma o} / (E_\gamma^2 \Delta), \qquad (6)$$

where E_γ is in MeV, $\Gamma_{\gamma 0}$ and Λ are in eV or in MeV. Using formulae (2) and (3), we can write $\sigma_{\gamma t}$ as follows:

$$\sigma_{\gamma t} = 2.02 E_\gamma \, b(E1, E_\gamma) \quad \text{mb}. \tag{7}$$

In a general case $b(E1,E_\gamma)$ has a more complicated form [16].

Note that formula (5) is a particular case of (7) and it can be obtained under the following assumptions: a) GDR is formed by one collective one-phonon state, b) all the matrix elements entering into the secular equations are equal to each other, c) the density of two-phonon poles is proportional to $E^{1/2}$. These assumptions are not valid in a real case. It is shown in [16] that GDR exhibits several collective one-phonon states in spherical nuclei and a great number of them in deformed nuclei.

Let us discuss the energy dependence of the $\sigma_{\gamma t}$ cross-section. The experimental $\sigma_{\gamma t}$ measured in [20] for the natural tin in the region of 6-10 MeV, are given in Fig. 1. Fig. 1 also shows our calculated results of $\sigma_{\gamma t}$ (continuous line) averaged over even-even tin isotopes in the interval of A from 116 to 124 which comprise 82% of the natural tin. The dashed line represents the results of extrapolation by the Lorentz formula in ref. [20]. The experimental cross-section $\sigma_{\gamma t}$ is 50% higher than the Lorentz extrapolation. The calculated cross-section $\sigma_{\gamma t}$, integrated over the energy region, is 15% larger than the experimental one. Fig. 2 shows the calculated photoexcitation cross-section for some tin

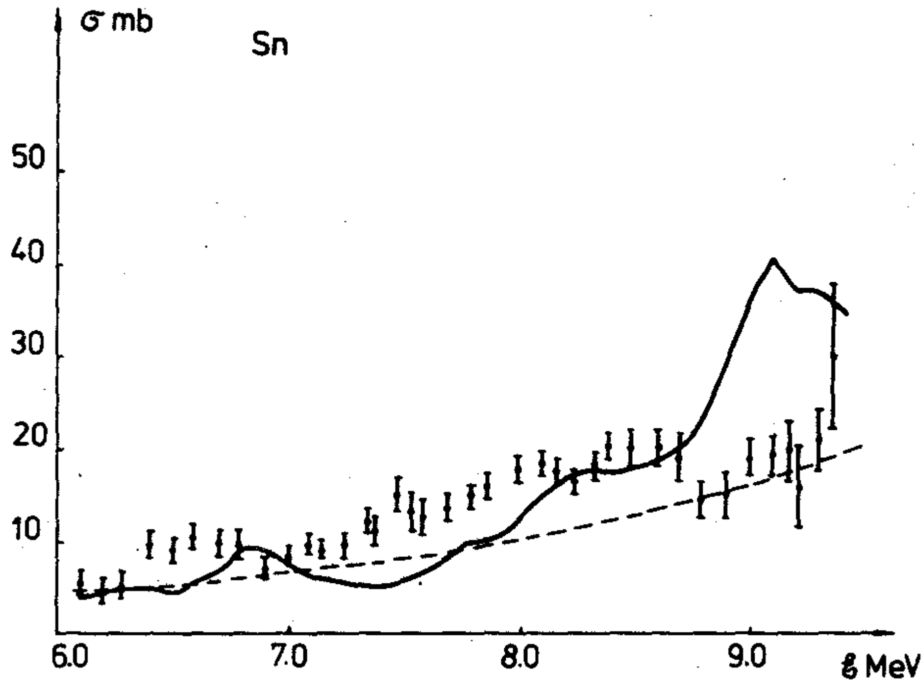

Fig. 1. Photoexcitation cross-section for the natural tin.

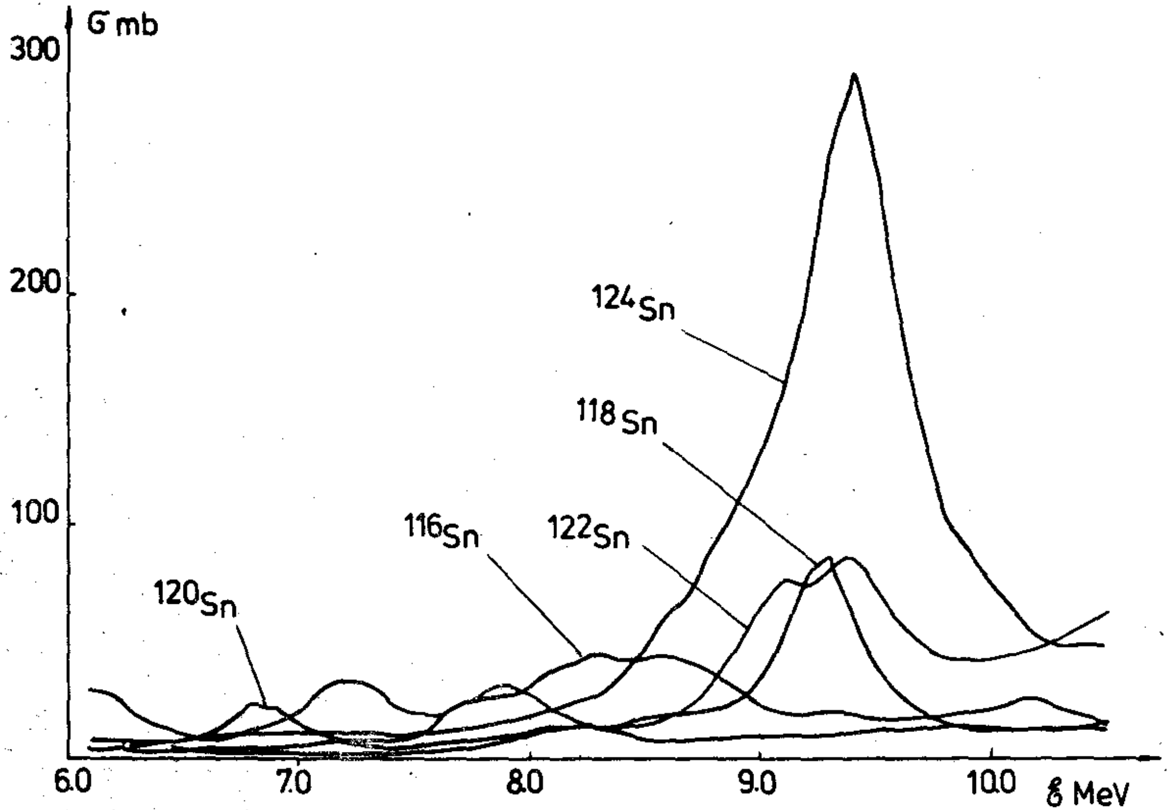

Fig. 2. Photoexcitation cross-section for even-even Sn isotopes.

isotopes. It is seen from fig. 2 that $\sigma_{\gamma t}$ are specified by individual structural peculiarities of nuclei. A good agreement of theoretical and experimental values for the integrated cross-section of the dipole photoabsorption shows that our model correctly describes the distribution of the strength of E1-transitions within the range of excitation energies of 6-10 MeV.

To clarify the mechanism of formation and distribution of dipole excitation strength in the 6-10 MeV region, we have calculated the values of $b(E1,E_\gamma)$ with and without the contribution of GDR. Fig. 3 gives an example for ^{118}Sn. The dashed-dotted line corresponds to the calculations when 7 most collective states including GDR from the energy region of (10-20)MeV are taken into account. In this case $S_{en.w.} = \sum_\nu E_{\gamma\nu} B(E1,E_\nu) = 3.93\ e^2 fm^2 MeV$. The calculation including 10 one-phonon states from the energy region of 6-10 MeV ($S_{en.w.} = 2.0$) are denoted by the dashed line. The continuous line shows the calculation including the most collective states, 4 from the region of (6-10)MeV and 6 from the region of (10-20)MeV. In this case $S_{en.w.} = 1.8$. It is seen from Fig. 1 and the values of the energy weighted sum rule $S_{en.w.}$ that the behaviour of $b(E1,E_\gamma)$ and $\sigma_{\gamma t}(E_\gamma)$ as a function of energy is mainly defined by the fragmentation of one-phonon 1^- states in the region studied. Without taking into account one-phonon states near the binding energy B_n, GDR overestimates the strength of dipole transitions for the neutron resonances in semi-magic nuclei under investigation. This overestimation is higher in

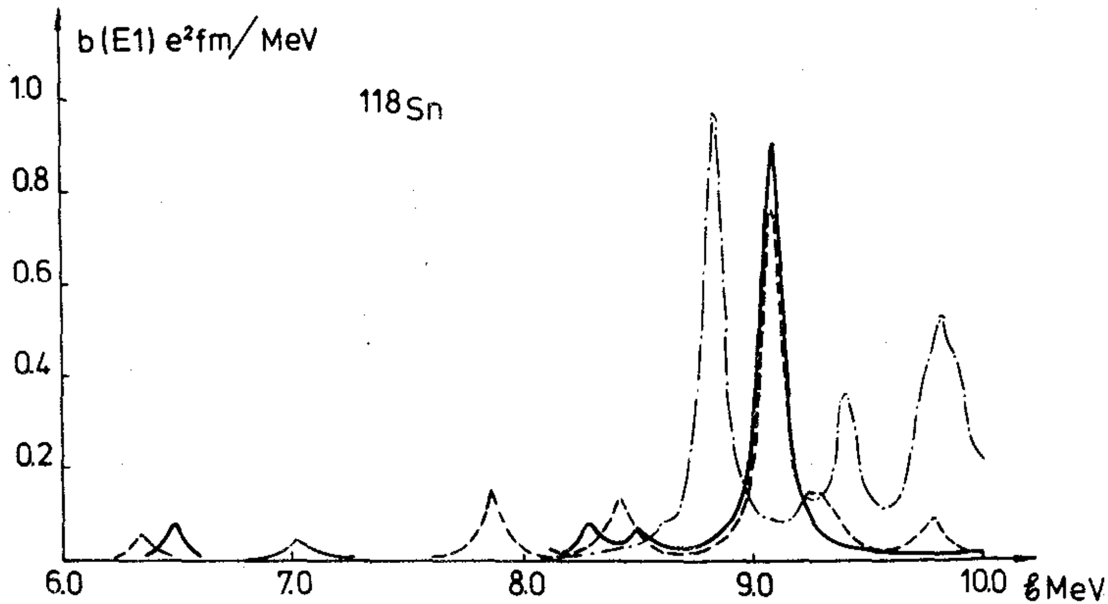

Fig. 3. The strength function $b(E1,E_{\gamma})$ of the nucleus ^{118}Sn.

nuclei with stronger anharmonicity. For instance, in ^{140}Ce the strength of dipole transitions decreases by a factor of 1.6 when one-phonon states 1^- near B_n are taken into account.

From the above investigation we may conclude that for the neutron resonances in semi-magic nuclei the values of radiative E1 -strength functions are mainly defined by the fragmentation of one-phonon 1^-states near B_n. To describe quantitatively the E1 -strength functions, one should take into account the 1^- one-phonon states near B_n and the collective states including GDR.

5. THE STRUCTURE OF NEUTRON RESONANCES

Concerning the available experimental information on the nuclear structure obtained in the study of the characteristics of neutron resonances, the following conclusions are made in ref. /2/:

i) From the reduced neutron widths mainly the information about certain one-, or two-quasiparticle components of their wave functions is obtained;

ii) From the partial radiational widths for γ-transitions to the ground states, one can extract the data on one- and three-quasiparticle or two-quasiparticle components of their wave functions;

iii) From the neutron and radiational strength functions the information about averaged over a number of neutron resonances values of the above components can be obtained;

iv) In the processes of α-decays of neutron resonances and γ-transitions from them to the excited states there take part the components of the neutron resonance wave functions with a larger number of quasiparticles. However, from these processes we can obtain the data only on the integral contribution of such components.

Therefore, almost the whole experimental information about the structure of neutron resonances is the information on the few-quasiparticle components of their wave functions only. In complex nuclei the few-quasiparticle components are of 10^{-3} - 10^{-6} part of the normalization of their wave functions. Indeed, we have a very insignificant experimental information about the wave functions of neutron resonances. Therefore, we can make the following conclusions:

1) Statistical regularities concern only the few-quasiparticle components of the wave functions of neutron resonances.

2) Nonstatistical effects manifesting themselves in neutron resonances concern only the behaviour of few-quasiparticle components of their wave functions. These effects allow one to state, as it was done by R.E.Crien et al./19/,the violation of the Bohr hypothesis on the compound states.

3) One has no right to extent the regularities concerning only a small part of the wave function to the whole wave function. Such an extension is in fact made in the statistical description of the structure of neutron resonances.

4) One may state that there is no experimental confirmation of the applicability of the N.Bohr hypothesis on the compound states to the neutron resonances.

5. Up to now the processes related to few-quasiparticle components of the wave functions of neutron resonances have been discussed. In ref.[7] the problem on the magnitude of many-quasiparticle components of the wave functions was raised. The assumption was also made that the wave functions at the intermediate excitation energy and neutron resonances have sufficiently large many-quasiparticle components. This is due to the fact that the interactions between quasiparticle and the quasiparticle-phonon interaction at these energies cannot fragmentate many-particle states so strongly as the single-particle states.

The methods of experimental detection of large many-quasiparticle components of the wave functions of neutron resonances were discussed in refs.[7,9,10]. Presently, the most available way of determination of the largest many-quasiparticle components is the study of E1, M1, and E2-transitions from the neutron resonances to the states with an energy less by (1.0-1.5) MeV than their energy. The probabilities of such transitions can be evaluated in the study of the subsequent α-decay of an excited state, fission or neutron emission. The observation of such γ-transitions or γ-cascades, the reduced probabilities of which are close to the single-particle ones, gives evidence to the existence of large many-quasiparticle components in the neutron resonance wave functions. The study of γ-transitions from the neutron resonances to the states at intermediate excitation energy gives the information on the values of individual four- and six-quasiparticle components.

The most promising method of measuring the values of the largest components of neutron resonance wave functions is the study of the reaction (n,γ,α) with the subsequent evaluation of intensities of γ-transitions between the neutron resonances and states lying lower by (1-2) MeV. The experimental results of Popov and collaborators /25/ show that there are relatively large components in the wave functions of these states.

I should like to emphasize that for the study of the state structure at intermediate and high excitation energy the answer to the question whether there are large many-quasiparticle components in the neutron resonance wave functions is of fundamental importance.

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