объединенный
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исследований
дубна

E4-80-63

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SHELL STRUCTURE EFFECTS AT HIGH EXCITATIONS AND MANY-QUASIPARTICLE CONFIGURATIONS

Submitted to International Conference on Extremum States in Nuclear Systems, DDR, Dresden.

1980

1. INTRODUCTION

To comprehend the structure of complex nuclei it is useful to represent the wave functions of excited states as an expansion over a number of quasiparticles and phonons. This wave function is constructed in the representation where the density matrix is diagonal for the ground nuclear state. In this representation the wave function of a highly excited state contains thousands of different components. In many cases a highly excited state is produced due to the capture of a nucleon or high-energy γ-ray by the targer-nucleus in the ground zero-quasiparticle or one-quasiparticle state. The expansion of the wave function over a number of quasiparticles and phonons seems to be performed on the basis of the function of the target-nucleus. The square of each coefficient of this expansion determines a fraction of time of the nucleus in this configuration. The fraction of time of the nucleus in the one-quasiparticle or one-phonon configuration decreases exponentially with increasing excitation energy.

The most complete and exact data on the nuclear structure are available for the few-quasiparticle components of the wave functions. These are the data on the fragmentation (distribution of strength) of one-quasiparticle, one-phonon and quasiparticle plus phonon states. The high-spin states are the exception. In the low-lying states the few-quasiparticle configurations give a dominant contribution to the normalization of their wave functions. At intermediate excitation energies the fragmentation of one-quasiparticle states is exhibited in the form of local maxima in the cross sections of the one-nucleon transfer reactions. The fragmentation of the subshells $s_{1/2}$, $p_{1/2}$ and $p_{3/2}$ determines the s- and p-wave neutron strength functions. The giant resonances are determined by the position and collectiveness of the one-phonon states, and the widths of the giant resonances are caused by their fragmentation. The few-quasiparticle components reflect the shell structure effects.

The few-quasiparticle components of the wave functions at low, intermediate and high excitation energies are described within the quasiparticle-phonon nuclear model /1/. Within the model the method of strength functions is used and the fragmentation of one-quasiparticle and one-phonon states over many nuclear levels is calculated. The properties or processes determined by the one-quasiparticle and one-phonon components of the excited state wave functions of complex nuclei are calculated within this model.

The present conference is devoted to the discussion of extreme states in nuclear systems. The aim of my report is to show that the information on the structure of ordinary nuclear states (except for the highspin states) with the excitation energy higher than 2-3 MeV is very scarce. A more thorough study is required for the many-quasiparticle components of the excited state wave functions. One should investigate a subsequent level of the nuclear structure and comprehend the main regularities of the fragmentation of many-quasiparticle states. Further, the transition to the nuclear states, described by the statistical nuclear model, needs elucidation.

2. ONE-QUASIPARTICLE AND ONE-PHONON COMPONENTS IN COMPLEX NUCLEI

Quasiparticle-Phonon Nuclear Model

The model Hamiltonian includes an average field as the Saxon-Woods potential, the superconducting pairing interactions and multipole-multipole and spin-multipole - spin-multipole isoscalar and isovector forces. The study of the lowlying states allowed one to fix the parameters of the Saxon-Woods potential. The second quantization method is used for obtaining the secular equations the solutions of which give the energies of one-phonon states. For each multipolarity several hundreds of roots of the secular equations and the corresponding wave functions are calculated. To describe the one-phonon states with any K^{π} in deformed nuclei and any I^{π} in spherical nuclei, the multipole-multipole and spin-multipole - spin-multipole forces with any λ as well as with large multipolarities are introduced. The quasiparticle-phonon interaction is taken into account. If phonons are fixed, the corresponding parts of the multipole and spin-multipole forces describing the quasiparticle-phonon interactions are uniquely determined. If the secular equations for phonons are solved, all model parameters turn out to be fixed.

The advanrage of the model is that the one-phonon rather than single-particle states are used as the basis of the model. This means that the basis includes the collective vibrational, weakly collective and two-quasiparticle states. The calculations /2/ of the nuclear state density indicate a full phonon space. The characteristics of excited states are described by the method of strength functions [1,3,4].

Low-lying states. The wave functions of the low-lying states contain one dominating one-quasiparticle component in odd-A nuclei and one dominating one-phonon or two-quasiparticle component in doubly even nuclei. Therefore, the experimental study and theoretical description of the low-lying states has been performed for many nuclei. The quasiparticle-phonon nuclear model describes well the nonrotational states in deformed nuclei [5,6].

With increasing excitation energy the nuclear state density increases and the nuclear structure becomes complicated. The transition from simple low-lying states to more complex ones proceeds at intermediate and high excitation energies. With increasing excitation energy the complication of the state structure proceeds in different ways in magic, vibrational, transition and deformed nuclei. In the study of the structure of states at intermediate and high excitation energy in atomic nuclei of mach importance is the fragmentation of single-particle states, i.e., the distribution of the single-particle strength over many nuclear levels. In the independent-particle and quasiparticle models the single-particle strength is concentrated on a single level. In the extreme statistical model it is distributed at random over nuclear levels. A large region of intermediate and high excitation energies of an atomic nucleus lies between the lowlying states, when the properties of each individual level are studied and the states which can be described by the extreme statistical model, when the individuality of nuclei and the effect of shells disappear. To study the structure of these states, one should investigate the main regularities of the fragmentation of one-quasiparticle and one-phonon states.

The complication of the state structure proceeds at low excitation energies. In odd-A deformed nuclei at the excitation energy more than 0.5 MeV the one-quasiparticle components are mixed with the quasiparticle plus phonon components [5,6]. In odd-A spherical nuclei such admixtures are observed in the ground states. In the nuclei with closed shells the single-particle states are pure up to the excitation energy of 2 and more MeV. The one-nucleon transfer reactions are the important tool for studying the fragmentation of one-quasiparticle states at low and intermidiate extitation energies. The experimental data on the spectroscopic factors or strength functions provide the information on the one-quasiparticle components.

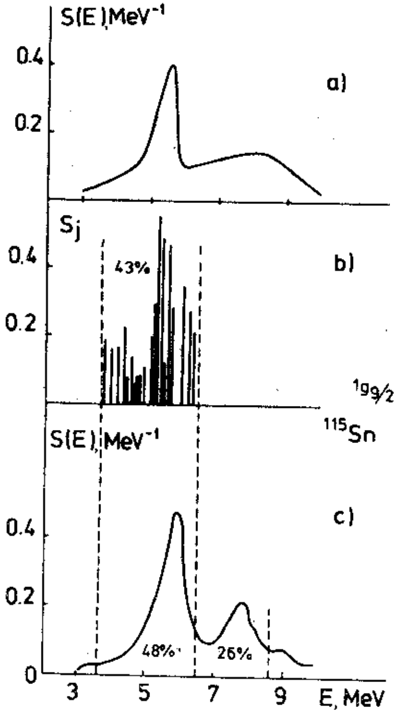

Fig. 1. Fragmentation of the $1g_{9/2}$ state in ^{115}Sn.
a) The experimental data on the spectroscopic strength function S(E), obtained in ref. /9/ (arbitrary units);
b) the experimental data on the spectroscopic factor S_j, obtained in ref. /13/;
c) calculations within the quasiparticle-phonon model performed in ref. /15/.

The fragmentation of one-quasiparticle states in the one-nucleon transfer reactions is intensively studied in spherical nuclei. Valuable information has been obtained on the fragmentation of deep hole states /7-14/. I should like to point out the resonance-like structures in the (p, d) and (^{3}He, α) reactions on the Ni, Zr and Mo isotopes. Interesting data have been obtained on the fragmentation of the subshell $1g_{9/2}$ in the Sn, Te and Pr isotopes.

The fragmentation of the neutron hole subshell $1g_{9/2}$ in ^{115}Sn is given in fig.1. Figure 1a) shows the spectroscopic strength function and fig. 1b) the spectroscopic factor; they are obtained in the (^{3}He, α) reaction. Figure 1c) gives the calculations within the quasiparticle-phonon nuclear model. The calculations have used the wave function containing the one-quasiparticle, quasiparticle plus phonon and quasiparticle plus two phonons components. It is seen from fig. 1 that a considerable part of strength of the $1g_{9/2}$ subshell is concentrated at the energy of 5-8 MeV as a narrow and high, and flat and low maxima. The quasiparticle-phonon model describes correctly the fragmentation of the subshell $1g_{9/2}$ in ^{115}Sn.

So, according to ref.[13] in the energy interval from 3.6 to 6.5 MeV 43% of the $1g_{9/2}$ strength is concentrated, while the calculations of ref.[15] give 48%. Neglecting the components of the quasiparticle plus two components wave function, one obtains a larger concentration of the $1g_{9/2}$ strength in this interval[16].

Neutron resonances. Now we pass to neutron resonances, lying above the neutron binding energy. Note, that the most complete and exact experimental data available for the neutron resonances specify their particular place among the highly excited states. The available experimental information on the nuclear structure obtained from the study of the neutron resonances can be interpreted as follows[17]:

1) The reduced neutron widths provide mainly the information on definite one-quasiparticle or two-quasiparticle components of their wave functions;

2) The partial radiative widths for γ-transitions to the ground states provide the data on the one- and three-quasiparticle components of their wave functions;

3) The neutron and radiative strength functions may provide the information on the averaged over some neutron resonance values of the above mentioned components.

4) The α-decays of the neutron resonances and γ-transitions to the excited states involve the components of the neutron resonance wave functions with a large number of quasiparticles. However, these processes give mainly the data on the integral contribution of these components. Thus, almost the whole experimental information on the structure of neutron resonances concerns the few-quasiparticle components of their wave functions. In the complex nuclei the few-quasiparticle components comprise 10^{-3}-10^{-6} part of the normalization of their wave functions. So, we have a trace amount of information about the neutron resonance wave functions.

I should like to note that in the neutron resonances the shells are strongly exhibited and the nonstatistical effects play an important role. A number of characteristics of the neutron resonances are included in the general scheme of nonstatistical calculations within the quasiparticle phonon nuclear model. The fragmentation of one-quasiparticle states allowed one to calculate the s-, p- and d-wave neutron strength functions for odd-A compound nuclei[4,17,18]. The s- and p-wave neutron strength functions and their spin splitting in doubly even spherical nuclei have been calculated using the fragmentation of one-phonon states[19]. The calculations describe well the corresponding experimental data. The partial radiative strength functions for the γ-transitions from the neutron resonances to the ground states are under study.

Above the neutron resonances. It is a common viewpoint that above the neutron resonances the photoabsorption cross section is determined by the giant dipole resonance tail. The influence of the giant dipole resonance (GDR) on the radiative strength functions and the dipole photoabsorption cross sections in spherical nuclei has been studied within the quasiparticle-phonon nuclear model with the wave function containing the one-phonon and two-phonon components [20]. It is shown that in the nuclei with one closed shell the GDR slightly influences the E1-strength function at the energies above the neutron binding energy. The values of the strength functions are determined by the fragmentation of one-phonon states lying at these energies. For the nuclei far from the closed shells the influence of the GDR on the radiative strength functions increases and in ^{136}Ba, ^{144}Nd and ^{146}Nd, for instance, it becomes essential. According to the calculations the substructures should exist in the dipole photoabsorption cross section depending on the excitation energy. The available experimental data [21] confirm the existence of substructures in the energy dependence.

The substructures at the excitation energy of 8 MeV with the width of several hundred KeV have been observed, for instance, in ref. [22] in the cross sections of the (γ, n_0) reaction in ^{117}Sn and ^{119}Sn. Figure 2 shows the experimental data for ^{117}Sn. It is seen from the figure that there is a pronounced substructure and the behaviour of the cross section $\sigma(\gamma n_0)$ differs strongly from the predictions of the Lorenz extrapolation of the GDR. The calculations [23] performed within the quasiparticle-phonon model have shown that this substructure is related to the maxima of the fragmentation of the $2p_{1/2}$ and $2p_{3/2}$ subshells and to the location of the M1 giant resonance in this region. Thus, the substructures of this type are determined by the fragmentation of one-quasiparticle states.

Giant resonances. The position of the giant resonances is determined by the corresponding one-phonon states. The fragmentation of one-phonon states forms the widths of the giant resonances in spherical nuclei [20,24-28]. In the deformed nuclei the giant resonance widths are determined by the one-phonon states [28-32]. This is due to the fact that the subshells are splitted because of the deformation and this splitting is more important than the fragmentation of one-phonon states [33]. The quasiparticle-phonon interaction becomes stronger with increasing excitation energy. It diminishes and in some cases suppresses the high-energy part of the giant resonance. This suppression is shown in fig. 3. It is seen from this figure that

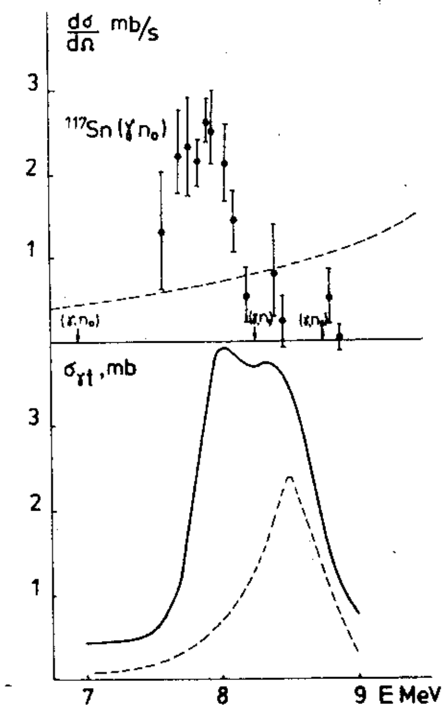

Fig. 2. Dipole photoabsorption cross section $\sigma_{\gamma t}$ in ^{117}Sn.
a) The experimental data [22] on the (γ, n_0) reactions, the arrows show the reaction thresholds; the dashed line denotes the Lorentz extrapolation of the giant dipole resonance;
b) the results of calculations [23] including $\sigma_{\gamma t}$ (E1) for the transitions $3s_{1/2} \rightarrow 2p_{1/2}$ and $3s_{1/2} \rightarrow 2p_{3/2}$, $\sigma_{\gamma t}$ (M1); the dashed curve denotes the cross section $\sigma_{\gamma t}$ (M1).

in the RPA calculations there is a strongly-collectivized M2-one-phonon state at an energy of about 20 MeV. The quasiparticle-phonon interaction causes such a strong fragmentation of this phonon state that it almost disappears.

Thus, the position and widths of the giant $E\lambda$ - and $M\lambda$ -resonances are determined by the one-phonon components of the wave functions of highly excited states.

Conclusion. In this section I have demonstrated that the most reliable nuclear properties are determined by the few-quasiparticle components of the wave functions at low, intermediate and high excitation energies; they reflect the effect of shells.

3. MANY-QUASIPARTICLE COMPONENTS OF THE EXCITED STATE WAVE FUNCTIONS

Definition. By many-quasiparticle components we mean the components of the excited state wave functions containing more than three quasiparticle operators or more than one quasiparticle and one phonon. These are components with four, five,

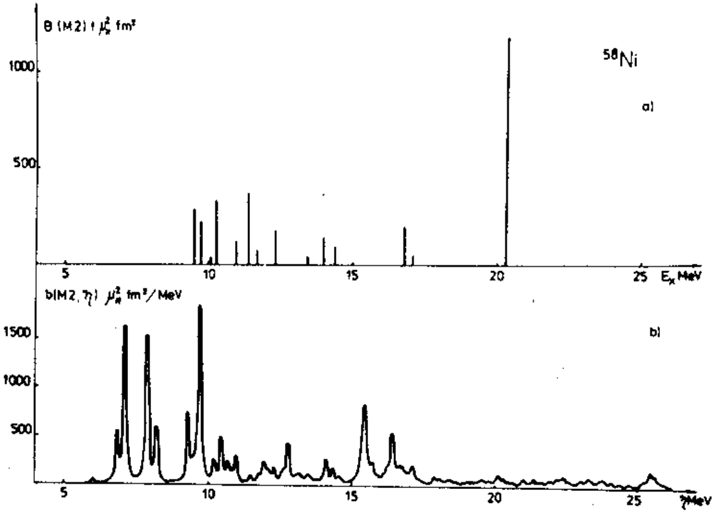

Fig. 3. The M2-resonance in ^{58}Ni calculated in ref.[26],
a) the RPA calculations,
b) the strength function b (M2, E), calculated taking into account the quasiparticle-phonon interaction.

ten or several dozens of quasiparticles or with two, three, etc., phonons. At present the information on the many-quasiparticle components is so scarce that all the components with a different number of quasiparticles can be considered together. Certainly, the behaviour of four-quasiparticle, five-quasiparticle, etc., components of the excited state wave functions will be studied separately in future.

With increasing excitation energy the density of levels increases exponentially and the contribution of few-quasiparticle components to the normalization of the wave functions decreases exponentially. According to the estimates of refs.[17,34-36] in nonmagic nuclei with $A > 100$ the contribution of one-quasiparticle components to the normalization of the neutron resonance wave functions is 10^{-4}-10^{-7}. The statistical nuclear model is valid for such small components of the wave functions. Figure 4 shows the decrease in the contribution of one-quasiparticle components to the normalization of the wave functions with increasing excitation energy. Our detailed information on the nuclear state structure also decreases exponentially with increasing excitation energy. The exceptions are the doubly magic nuclei and the nuclei differing from them by one nucleon.

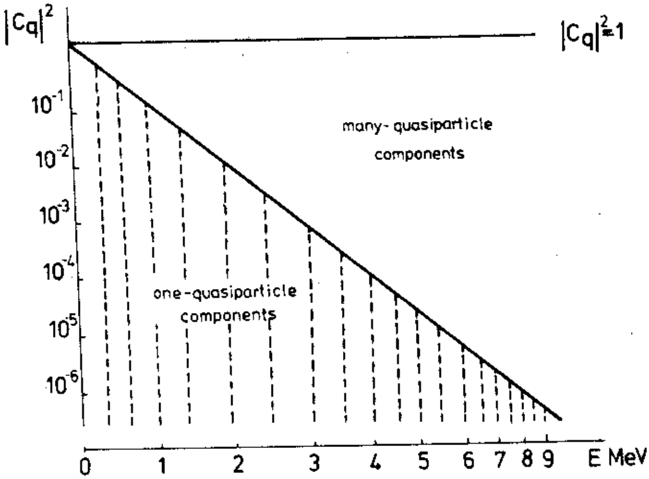

Fig. 4. Decrease in the contribution of the one-quasiparticle component $|Cq|^2$ to the normalization of the wave functions with increasing excitation energy.

Neutron resonances. The analysis of the experimental data on the neutron resonances [34-36] has shown that one cannot yet choose between two extreme cases of the behaviour of many-quasiparticle components of their wave functions, the first case is when there are many-quasiparticle components and the second when the many-quasiparticle components are small and distributed at random. The possible experimental detection of large many-quasiparticle components of the neutron resonance wave functions has been discussed in refs. [17,35]. The most direct and available way for detecting large many-quasiparticle components is the measurement of the probabilities for the E1-, M1- and E2-transitions from the neutron resonances to the states with an energy by (1-2) MeV lesser. Let, for instance, the state have a large eight-quasiparticle component. Among the states lying by 1-2 MeV lower with $\Delta I = 0, \pm 1$ there is a state with a large six-quasiparticle component (these six quasiparticles enter into the eight-quasiparticle component). Then the γ-transition probability should be equal in the order of magnitude to the single-particle transition probability. The detection of such γ-transitions or γ-cascades, the reduced transition probabilities of which are not very small, will indicate the existence of large many-quasiparticle components.

The most promising method for determining the values of the many-quasiparticle components in the neutron resonance wave functions is the study of the (n, γ, α) reaction with the estimation of the γ-transition intensity. The available experimental data on the (n, γ, α) reactions on the resonance [37] and thermal [38] neutrons do not allow to conclude about the values of the largest many-quasiparticle components. The integral contribution of the many-quasiparticle components can be obtained from the study of the partial γ-transitions from the neutron resonances to the excited states.

High-spin states. The wave functions of the high-spin states at intermediate excitation energies have been assumed [34] to have sufficiently large many-quasiparticle components. This assumption is based on the fact that quasiparticle-phonon interactions at these energies cannot distructure the many-quasiparticle states so strongly as the one-quasiparticle states. It has been stated in refs. [34-36] that the non-rotational states with high spins should be rather pure many-quasiparticle states. Indeed, these high-spin states clearly exhibit the quasiparticle structure. So, the four-, five-, and six-quasiparticle states are observed with large K in the deformed nuclei [39-41] and large I in the spherical nuclei [42]. The energies of these states in the deformed nuclei are close to the energies calculated within the model of independent quasiparticles [5]. Thus, the main contribution to the wave functions of the non-rotational high-spin states is given by many-quasiparticle components.

Giant resonances on the excited states. The problem of many-quasiparticle components is related with that of the giant resonances constructed on the excited states. According to the Brink-Axel hypothesis a whole series of the giant multipole and spin-multipole resonances should be constructed on each excited state. So, the giant resonances having the two-phonon structure are constructed on the one-phonon state, the three-phonon giant resonances on the two-phonon states and so on. Perhaps, this hypothesis correctly reflects, in general, the situation with the many-quasiparticle and many-phonon states.

The giant dipole resonances constructed on the one-phonon states in the deformed nuclei have been calculated in ref. [43]. The wave function of the one-phonon state is added by the two-phonon components. The addition of the two-phonon components did not cause the broadening of the GDR constructed on this state in comparison with the GDR constructed on the one-phonon state. This means that if the anharmonicity of the vibrational states is not large, the Brink-Axel hypothesis on the giant resonances on the vibrational states is fulfilled. One should correctly take into account the Pauli principle for the calculation of the giant resonances [44]. The investigations [45] have shown that some two-phonon states are rather strongly influenced by the Pauli principle.

It should be noted that the experimental and theoretical study of the giant resonances constructed on the excited states is a further important stage in studying the structure of highly-excited states.

An important information about many-quasiparticle components of the wave functions can be obtained from the study of the (n, α) reactions [46] and α-decays of the giant resonances. It is shown in ref. [47] that the giant isoscalar quadrupole resonance in ^{58}Ni decays mainly by emission of α-particles.

Direct many-particle transfer reactions. The most reliable and rich information about the many-quasiparticle components of the excited state wave functions can be obtained from the spectroscopic factors of the many-nucleon reactions on spherical and deformed nuclei. A great progress in the experimental study of three and four nucleon transfer reactions has been achieved in recent years [48]. Of much importance are the (p, α) reactions on spherical nuclei [49,50]. I should like to mention also the $(^6Li, d)$ [51] and $(^4He, ^8He)$ [52] reactions. Undoubtedly, the detection of the spectroscopic factors in the many-particle transfer reactions encounters great difficulties.

The many-nucleon transfer reactions are the basic method for studying the many-quasiparticle components of the excited state wave functions. Therefore, a great progress is expected in the experimental study of the many-nucleon transfer reactions on a large number of spherical and deformed nuclei and in the development of the theory of these reactions.

4. CONCLUSION

There is an enormous and absolutely unstudied level of the nuclear structure, the many-quasiparticle and many-phonon components of the excited state wave functions of complex nuclei. Many investigations are to be carried out for the study of ordinary nonextreme and nonhighspin states of atomic nuclei. The investigation of extreme states in the nuclear systems is very popular and interesting. But it is only a part of the general problem of the study of the nuclear structure. The general picture of the nuclear structure cannot be developed without studying the many-quasiparticle configurations.

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Received by Publishing Department
on January 28 1980.