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# THE DESCRIPTION OF NUCLEAR STATES IN A WIDE RANGE OF EXCITATION ENERGIES


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**Описание характеристик ядерных состояний в широком диапазоне энергий возбуждения**

Показано, что в рамках квазичастично-фононной модели ядра может быть получено описание малоквазичастичных компонент ядерных состояний при низких, промежуточных и высоких энергиях возбуждения. Для низколежащих состояний вычисляется энергия каждого уровня. Малоквазичастичные компоненты состояний при промежуточных и высоких энергиях возбуждения представляются усредненными в определенных энергетических интервалах, а их характеристики даются в виде соответствующих силовых функций. В рамках этой модели изучена фрагментация одночастичных состояний в деформированных ядрах, исследована зависимость нейтронных силовых функций для реакций однонуклонных передач типа (dp) и (dt) от энергии возбуждения. Рассчитаны s-, p-, d-волновые нейтронные силовые функции при энергии связи нейтрона и получено хорошее согласие с опытом. Получено хорошее описание радиационных силовых функций в сферических ядрах, изучено влияние хвоста гигантского дипольного резонанса на E1-силовые функции. Рассчитаны энергии и $E\lambda$-силовые функции для гигантских мультипольных резонансов в сферических и деформированных ядрах, и получено правильное описание их ширин.

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**The Description of Nuclear States in a Wide Range of Excitation Energies**

It is shown that within the quasiparticle-phonon nuclear model one can obtain the description of few-quasiparticle components of nuclear states at low, intermediate and high excitation energies. For the low-lying states the energy of each level is calculated. The few-quasiparticle components at intermediate and high excitation energies are represented to be averaged in certain energy intervals and their characteristics are given as the corresponding strength functions. The fragmentation of single-particle states in deformed nuclei is studied within this model. The dependence of neutron strength functions on the excitation energy is investigated for the transfer reactions of the type (d,p) and (d,t). The s-, p-, and d-wave neutron strength functions are calculated at the neutron binding energy $B_n$. A satisfactory agreement with experiment is obtained. A correct description of the radiative strength functions in spherical nuclei is obtained. The influence of the tail of the giant dipole resonance on the E1-strength functions is studied. The energies and $E\lambda$-strength functions for giant multipole resonances in spherical and deformed nuclei are calculated. A correct description of their widths is obtained.

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## 1. *QUASIPARTICLE-PHONON NUCLEAR MODEL*

The main assumptions of the semimicroscopic description of the nuclear structure are as follows[1]:

1) The Hartree-Fock-Bogolubov method is used for obtaining the closed system of equations for the density and correlation functions.

2) A representation is chosen where the density matrix is diagonal and the correlation function has a canonical form. In this representation all interactions between nucleons in a nucleus are reduced to the average field and interactions resulting in pairing.

3) The average field is extracted. It is postulated that the choice of an average field corresponds to the aforesaid representation for some doubly even nuclei lying in the $\beta$-stability zone.

4) The interactions resulting in superconducting pairing correlations are introduced.

The excited states are defined as one-, two-, three-, and so on quasiparticle states.

5) The vibrational states are connected with off-diagonal elements of the density matrix. To describe them the multipole-multipole and spin-multipole-spin-multipole forces are introduced.

6) The rotational, quasiparticle and phonon excited states are related to each other by the Coriolis and quasi-particle-phonon interaction.

A quasiparticle-phonon model which is the basis for a unique description of few-quasiparticle components of the wave functions of complex nuclei at low, intermediate and high excitation energies is constructed within the semimicroscopic nuclear theory. The quasiparticle-phonon nuclear model develops from the description of the low-lying nuclear states as quasiparticle and one-phonon states by generalizing the phonons and quasiparticle-phonon interaction.

The quasiparticle-phonon model is based on the following assumptions [2-4.]:

1) The two-quasiparticle and vibrational states are considered to be the one-phonon states.

2) The coupling of single-particle and collective motions is described as the quasiparticle-phonon interaction.

3) The main approximation is chosen as to obtain the most correct description of few-quasiparticle components rather than of the whole wave function.

The wave functions of highly excited states of complex nuclei comprise several millions of components. It is very difficult to find the wave function of each state. This is demonstrated for light nuclei in ref. [5] where the matrices of a very high order have been diagonalized when calculating the energies and wave functions. The investigations within the approach based on the operator form of the wave function [6] have shown that such characteristics of highly excited states as the photoexcitation total cross sections, spectroscopic factors of the one-nucleon transfer reactions, neutron strength functions, partial radiative strength functions for direct transitions to the low-lying states and others are determined by the few-quasiparticle components of their wave functions. The problem is essentially simplified if only few-quasiparticle components of the wave functions are to be well described in a certain energy interval. In this case one should use different types of the strength functions. Within the quasiparticle-phonon model the fragmentation (distribution of strength) of one-quasiparticle, one-phonon and quasiparticle plus phonon states over many nuclear levels can be calculated.

The model Hamiltonian includes the average field for protons and neutrons, superconducting pairing interactions and multipole-multipole and spin-multipole-spin-multipole forces.

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 $K^{\pi}$ in deformed nuclei and any $I^{\pi}$ in spherical nuclei, the multipole-multipole and spin-multipole-spin-multipole forces with any $\lambda$ as well as with large multipolarities are introduced.

Now let us formulate the following rules for the description of one-phonon states:

1) For the states with fixed $K^{\pi}$ in deformed nuclei and $I^{\pi}$ in spherical nuclei, the following equations are solved: a) The secular equations with the multipole-multipole forces. b) The secular equations with the spin-multipole-spin-multipole forces if the multipole forces do not exist or they are of higher multipolarity.

2) The interaction in the particle-hole channel is taken into account.

3) The interaction in particle-particle channel is taken into account in the calculation of: a) the $0^+$ states in all nuclei, b) the $2^+$ states in individual spherical nuclei.

4) For the one-phonon states with fixed $K^{\pi}$ or $I^{\pi}$ the equations with the forces minimal multipolarity are calculated. When calculating $B(E\lambda)$-values all the states with $I=\lambda$ and different values of $K$ are taken into account.

5) The isoscalar constants $\kappa_0^{(\lambda)}$ for $\lambda = 2$ and 3 are determined from the first state energy, and for $\lambda \geq 4$ they are taken from the phenomenological estimate so small as to prevent the lowering and strong collectiveness of the first states.

6) The ratio of $\kappa_1^{(\lambda)} / \kappa_0^{(\lambda)}$ is determined: a) from the position of the corresponding isovector resonance, b) from the phenomenological estimates. The good agreement of the calculated density of nuclear states with the experimental data at the neutron binding energy $B_n$ justifies the completeness of the phonon space /7/.

The wave function of highly-excited states in doubly even nuclei comprises one-phonon, two-phonon, three-phonon and so on terms.

The wave function components which differ by one phonon are related by the interaction of quasiparticle with phonons. If phonons are fixed, the corresponding parts of the multipole-multipole and spin-multipole-spin-multipole forces which describe the quasiparticle-phonon interactions are uniquely determined. If the secular equations for phonons are solved, all model parameters turn out to be fixed. The larger the quasiparticle-phonon interaction connecting, for instance, the one-quasiparticle and quasiparticle plus phonon states the stronger a phonon is collectivized.

The quasiparticle-phonon interaction has the following advantages as compared to other types of effective interaction:

1) A consistent description of quasiparticle and phonon states and their coupling.

2) A unique choice of the form and constants of the interaction.

3) Applicability for the description at low, intermediate and high excitation energies.

## 2. *LOW-LYING STATES*

The low-lying nonrotational states in doubly even deformed nuclei are well described as the two-quasiparticle and one-phonon states [1,8-10]. The admixtures to the two-quasiparticle states with energies up to (2-2.5)*MeV* are small [11]. The admixtures of the two-phonon components to the first vibrational states do not exceed as a rule (5-10)% [12]. The description of the wave functions of the first vibrational states can be improved by taking into account a large number of two-phonon components. The contribution of the one-phonon component to the normalization condition is more than 90%.

The anharmonic effects are more important in spherical nuclei than in deformed ones. Nevertheless, in the first $2^+$ and $3^-$ states the one-phonon components are dominating [13]. The description of the wave functions of the $2^+$ and $3^-$ states is somewhat improved by taking into account a large number of the two-phonon components. In some spherical nuclei with unfilled shells, when calculating the energies and wave functions of the $2^+$ and $3^-$ states, one should take into account the multipole-multipole forces in the particle-particle channel [14,15].

The wave functions of the low-lying states of odd A-nuclei comprise the one-quasiparticle and quasiparticle plus phonon components [1,16]. The quasiparticle-phonon interaction is of great importance. This is confirmed by the calculations in ref. [17] and by the analysis of the experimental data in ref. [18] In deformed nuclei one should take into account the Coriolis forces. A sufficiently good description of the low-lying states can be obtained if the quasiparticle-phonon interaction and Coriolis forces are taken into account simultaneously [19]. It is shown in ref. [20] that at an energy of 1 *MeV* and higher the components of the wave function of quasiparticle plus two phonons-type are rather important.

The interaction of a quasiparticle with one definite phonon can be described more correctly than within the quasiparticle-phonon model [4]. However, one should take into account the interaction of quasiparticle with a large number of phonons. The necessity to use a large phonon space increases with increasing energy of the states studied.

In ref. [21] the energies of the one-particle states are extracted from the experimental data in the region $150 < A < 190$. The superconducting pairing correlations are taken into account, and the contribution from the coupling between the rotational and vibrational motions is subtracted. In ref. [22] the energies of one-quasiparticle states are reproduced from the experimental data for nuclei with $A > 228$. Under such a reproduction the most difficulties are caused by the states with complex structure the wave functions of which have several large components.

On the basis of the solution of the model with four levels and constant forces the authors of ref. [22] stated that the calculations [16,17] with the quasiparticle-phonon interaction, overestimate the lowering of the low-lying states which arise from the particle-hole interactions and that the Pauli principle is violated. In accordance with this statement we want to mention the paper [23] which investigated the role of nonpole terms in the corresponding secular equations. The necessity of taking into account these terms was pointed out in ref. [22]. In ref. [23] it was shown that the influence of nonpole terms reduces the energies of collective states of the quasiparticle plus phonon type (by less than 10%). The nonpole terms weakly influence the energies of states close to one-quasiparticle states and, practically, do not change the structure of nonrotational states in odd- A nuclei. In [22] a formula was derived which related the energy of the system of odd number of particles with that of the system of even number of particles. The nonpole terms play an important role in it. When describing the energies of excited states of odd-A nuclei one should calculate the differences of energies of the ground and excited states. In these differences the nonpole terms are practically cancelled. So, there are no grounds for the statement [22] that the role of the quasiparticle-phonon interaction in the calculations [17] is overestimated. Most important is that the quasiparticle-phonon interaction correctly describes the fragmentation of single-particle states, whereas the energy shifts are not so important.

In the calculations [17] a large number of single-particle levels was used. Of most importance are the collective phonons the wave functions of which comprise a large number of two-quasiparticle components. The violation of the Pauli principle is not essential since it can occur only in a very small number of three-quasiparticle components (the total number of very large) over which the quasiparticle plus phonon terms are expanded. It should be noted that inaccuracies which occur if the nonpole terms of the secular equations are neglected and the Pauli principle is approximately taken into account are less than those caused by the description of an average field as the Saxon-Woods potential and others.

Note, that one should carefully evaluate the accuracy of the description of the excited state energies and wave functions in complex nuclei by analyzing simple models, as it was done in [22]. In simple models the coherent effects are shaded by noncoherent corrections. One cannot trace their changes caused by the increasing number of single-particle states and phonons which is necessary when passing to higher energies.

Thus, one may conclude that the low-lying states can easily be studied experimentally and described theoretically. This is due to the fact that each of the wave functions has one dominating component which can be measured and described.

### *3. INTERMEDIATE EXCITATION ENERGIES*

With increasing excitation energy the state density of atomic nuclei increases and their 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 is not the same for the states with different spins and in different nuclei.

In the study of the structure of states at intermediate and high excitation energy in atomic nuclei of much importance is the single-particle fragmentation, that is 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 chaotically distributed over all nuclear levels.

A large region of intermediate and high excitation energies of an atomic nucleus lies between the low-lying states, when the properties of each individual level are studied and the states which may be described by the extreme statistical model, when the individuality of nuclei and the effect of shells disappear. The experimental study of the state structure of this region encounters great difficulties. It is practically impossible to measure the characteristics of each of many thousands levels. Due to the complication of the state structure a large number of characteristics for each level should be measured experimentally. To study the state structure at intermediate and high excitation energies, one should not describe each level. The investigations within the model with the wave function involving the one-phonon and two-phonon components showed that if the constants of the quadrupole and octupole interactions are increased by (2-5)% then the structure of the first and a number of the second states with $K^{\pi} = 0^+, 2^+, 0^-, 1^-, 2^-, 3^-$ changes a little, whereas the structure of most of the third and higher states changes very strongly.

Thus, one may conclude that it is impossible to describe correctly the structure of each nuclear level at the excitation energy higher than 2-3 *MeV*.

To study the state structure at intermediate and high excitation energies, one should clarify the general regularities of the fragmentation of one-, two- and many-quasiparticle states. The one-nucleon transfer reactions are the important tool in the study of the fragmentation of one-quasiparticle states at intermediate excitation energies. First of all it is necessary to measure experimentally and to describe theoretically the strength functions of the one-nucleon transfer reactions which provide information on one-quasiparticle components averaged over several excited states. In ref.[24] at attempt was made to obtain information on neutron strength functions in deformed nuclei. In refs.[25,26], the information about deep hole states in spherical nuclei was obtained. Of most interest is the experimental measurement of strength functions for the one-nucleon transfer reactions with the fixed transfer angular momentum $\ell$ or to the final states with the fixed $I$.

To describe the characteristics of excited states at intermediate and high excitation energies the method of strength functions is effectively used. To illustrate this let us consider the fragmentation of one-quasiparticle states in deformed nuclei. The wave function of odd-$A$ nucleus is

$$\Psi_i(K^\pi) = \frac{1}{\sqrt{2}} \sum_\sigma \{ \sum_s C_s^i \alpha_{s\sigma}^+ + \sum_g D_g^i (\alpha^+ Q^+)_g +$$

$$+ \frac{1}{\sqrt{2}} \sum_G F_G^i (\alpha^+ Q^+ Q^+)_G \} \Psi_0 , \qquad (1)$$

where $\Psi_0$ is the wave function of the ground state of a doubly even nucleus having one nucleon less than the studied one; $Q_g^+$ is the phonon creation operator; $\alpha_{s\sigma}^+$ is the quasiparticle creation operator; $i$ is the number of a state; $g = s\lambda\mu n$, $G = s\lambda_1\mu_1 n_1 \lambda_2 \mu_2 n_2$ where $n$ is the number of the root of the secular equation for the one-phonon state of multipolarity $\lambda\mu$. The set of quantum numbers for a single-particle state is denoted by $(s\sigma)$, $\sigma = \pm 1$. The system of basic equations is given in ref.[27]. The secular equation for defining the energies $\eta_i$ can symbolically be written as

$$\mathcal{F}_s(\eta_i) = 0. \qquad (2)$$

For intermediate and high excitation energies the results of calculation of the characteristics for each state can hardly be represented clearly. For instance, in $^{239}U$ at excitation energies of (3-5) *MeV*, 10-20 poles (and the corresponding solutions) of the quasiparticle plus phonon-type are in the interval of 100 *keV*. Therefore, when calculating the fragmentation of one-quasiparticle states[28], the sums of the type $\sum_i (C_{s\sigma}^i)^2$ have been calculated for the states lying in the interval 200 *keV*, and the results have been represented as a histogram. The energy of each state has been found, the components (many thousands of them) of the wave functions have been calculated and the value of one of them only has been used. Only a small part of information obtained has been used. Therefore, it became necessary to construct such a mathematical apparatus which could be used for the calculation of aquired quantities in a certain interval of excitation energies. Such an apparatus is the method of strength functions, i.e., the method of direct calculation of averaged characteristics without a detailed calculation of each state.

Let us consider the fragmentation of the single-particle state.

Now we construct the function

$$\Phi_{s_0}(\eta) = \sum_i (C^i_{s_0})^2 \rho(\eta_i - \eta), \tag{3}$$

where

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

The way of presentation of the results of calculation depends on the value of the energy interval of averaging $\Delta$. By introducing the parameter $\Delta$ one can take into account phenomenologically the influence of many-phonon components of the wave functions. In this case it is necessary to calculate the parameter $\Delta$. Using the theory of residues the function $\Phi_{s_0}(\eta)$ is expressed in terms of the contour integral around the poles which are the roots of eq. (2). Considering that the contour integral over infinite radius circle is equal to zero, one passes to two contour integrals around the poles $\eta + i\Delta/2$ and $\eta - i\Delta/2$. As a result of calculation[4], one gets

$$\Phi_{s_0}(\eta) = \frac{1}{\pi} \mathrm{Im} \left\{ \frac{1}{\mathcal{F}_{s_0}(\eta + i\Delta/2)} \right\}, \tag{5}$$

similarly one can calculate the strength functions of the one-nucleon transfer reactions, of the $b(E\lambda, \eta)$ $E\lambda$-transitions and others.

When calculating the strength functions one should not diagonalize the matrices of a very high rank the elements of which are the sums of complex functions. One should calculate their imaginary parts at different energies. This is much easier and reduces the computational time approximately by a factor of $10^3$. In so doing one can calculate different characteristics of many nuclei at intermediate and high excitation energies.

The basic regularities of the fragmentation of one-quasiparticle states in deformed nuclei are formulated within the quasiparticle-phonon nuclear model [27,29]. The fragmentation of deep hole states is studied in spherical nuclei. The neutron strength functions are calculated at the neutron binding energy $B_n$ in the tin and tellurium isotopes [30] and in many deformed odd-A-nuclei [27]. The s- and p- wave neutron strength functions are sufficiently well described. The d-wave strength functions are calculated, for which there are only preliminary experimental data.

The partial radiative strength functions [31,32] are calculated and the influence of the giant dipole resonance on E1-strength functions [33] is studied within the quasiparticle-phonon nuclear model. To calculate the E1-strength functions for the transitions from the ground states of doubly even spherical nuclei the formulae of ref. [34] are used. The wave function of an excited state can be written as

$$\Psi_i(JM) = \{ \sum_n R_n(J\,i) Q^+_{JMn} + \sum_{\substack{\lambda_1 n_1 \\ \lambda_2 n_2}} P^{\lambda_1 n_1}_{\lambda_2 n_2}(Ji) \times$$

$$\times [Q^+_{\lambda_1 \mu_1 n_1} Q^+_{\lambda_2 \mu_2 n_2}]_{JM} \} \Psi_0 . \qquad (6)$$

The quantity $R^2_n(J_i)$ determines the contribution of the one-phonon components $n$ to the normalization condition of the wave function (6). The secular equations defining the energies $\eta_{Ji}$ of states $i$ and the quantities $R^2_n(J_i)$ are given in [34].

With this model one can calculate the fragmentation of one-phonon states over many nuclear levels. The fragmentation of one-phonon states allows one to calculate the reduced $E\lambda$-transition probabilities and the total photoexcitation cross sections from the ground states of doubly even nuclei. Neglecting the terms $\sim a^+a$ in the $E\lambda$-transition operator, the radiative $E\lambda$-strength functions and the average cross sections of the dipole photoabsorption can be written as follows:

$$b(E\lambda,\eta)=\frac{\Delta}{2\pi}\sum_i \frac{B(E\lambda,0^+_{g.s.}\to\lambda i)}{(\eta-\eta_{\lambda i})^2+\Delta^2/4}, \tag{7}$$

where the summation $i$ is taken over the states in the interval from $\eta-\Delta/2$ to $\eta+\Delta/2$,

$$B(E\lambda,0^+_{g.s.}\to\lambda i)=\Big|\sum_n R_n(\lambda i)\sqrt{B(E\lambda,0^+_{g.s.}\to\lambda n)_{RPA}}\Big|^2, \tag{8}$$

where $B(E\lambda,0^+_{g.s.}\to\lambda n)_{RPA}$ is the reduced $E\lambda$-transition probability calculated in the one-phonon approximation;

$$\sigma_{\gamma t}(E)=4.025\,\frac{E}{\Delta}\int_{E-\Delta/2}^{E+\Delta/2} b(E1,\eta)\,d\eta \quad \text{mb}. \tag{9}$$

In refs. [31,32] the $E1$- and $E2$-radiative strength functions are calculated for the transitions from ground states to the levels near $B_n$. A good agreement of theory with experiment is obtained. This agreement is not trivial since the calculations have no free parameters.

In refs. [32,33] the dipole photoabsorption cross sections are calculated. They study also the influence of the giant dipole resonance (GDR) on it. The results of calculation of the cross section $\sigma_{\gamma t}$ for $^{140}$Ce and the experimental data [35] for the natural cerium are given in *Fig. 1*. The experimental cross section $\sigma_{\gamma t}(E)$ has a maximum at an energy of 7.8 *MeV*, and the calculated cross section has a higher maximum at an energy of 8 *MeV*. In calculations the fragmentation of one-phonon states is much weaker in single-closed-shell nuclei than in nuclei far from the closed shells. This is the reason for the appearance of such a large peak at an energy of 8 *MeV*. The increase of the cross section at an energy

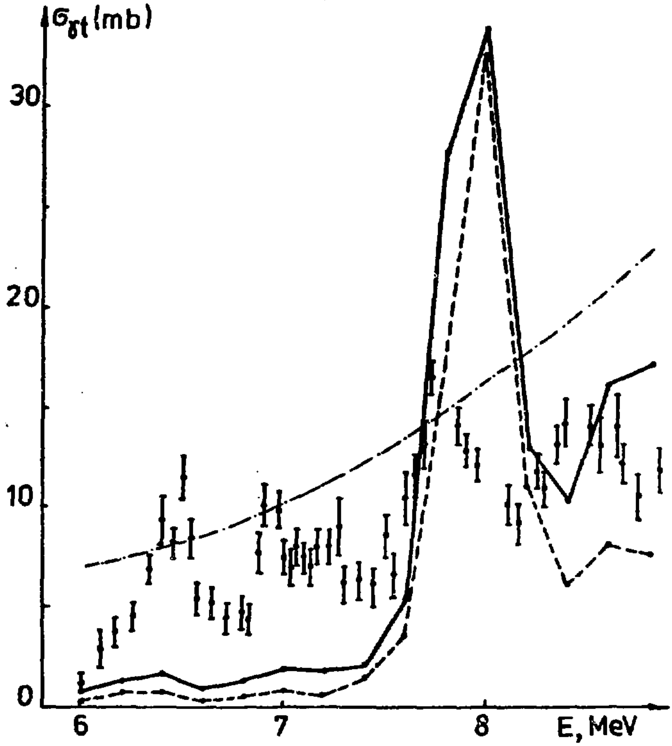


*Fig. 1. Dipole photoabsorption cross sections in* $^{140}$Ce *. The experimental data are obtained in ref.* [35] *for natural cerium. The calculation* [33] *with* $\Delta$ = *0.2 MeV taking into account GDR are given by solid line whereas without taking into account by the dashed line. The Lorentz curve (dash-dot line) is calculated in ref.* [35] *with* $E_0$ = *15 MeV,* $\Gamma$ = *4.35 MeV and* $\sigma$ = *360 mb.*

higher than 8.2 MeV is correctly demonstrated in calculations. The calculated cross sections are smaller than the experimental ones at an energy less than 7.5 *MeV*. Perhaps the peaks observed in [35] at the energies 6.5 and 7 *MeV* are due to the impurities of other cerium isotopes. Figure 1 shows also the results for the case when the phonons forming GDR have not been taken into account. It is seen from Fig. 1 that the cross section $\sigma_{\gamma t}$ is slightly influences by GDR. However, the role of GDR increases at an excitation energy higher than 8 *MeV*.

The energy dependence of the total dipole photoabsorption cross section differs strongly from the Lorentzian curve. Thus, we may conclude that the representation of the photoabsorption cross section near $B_n$ as the Lorentzian is rather rough. One can clearly see the substructures in the total dipole photoabsorption cross section. The calculations show that such substructures should exist. However, the calculations are not sufficiently accurate to predict the exact location of them.

Thus, within the quasiparticle-phonon nuclear model one can calculate a number of nuclear properties at intermediate excitation energy.

## 4. *HIGHLY EXCITED STATES*

It may be expected that the highly excited states, i.e., the states lying above the nucleon binding energy in complex nuclei may exhibit a variety of properties as compared to the low-lying states. It should be noted that the study of the structure of highly excited states is in the initial stage. Much progress has been achieved in the study of states with very high spins. The peculiarities of the fragmentation of a few-quasiparticle components are the giant multipole resonances. The main characteristics of the giant dipole resonance are studied rather well in many nuclei from light to the heaviest ones. In recent years other multipole resonances are studied experimentally.

The quasiparticle-phonon model is used for the description of giant multipole resonances. In refs. [36–39] the giant multipole resonances in deformed nuclei have been calculated in the one-phonon approximation. The energies and widths of the dipole isovector and quadrupole isoscalar resonances have been described sufficiently well in many deformed nuclei in the rare-earth and actinide regions. Different components with respect to $K$ result in the splitting of the giant dipole resonance and broadening of the quadrupole resonance. The giant quadrupole isovector resonance clearly manifests itself. There are three peaks of the giant octupole resonance: the low-energy octupole resonance, the isoscalar and isovector ones. The giant resonances of high multipolarity are calculated, the experimental study of which is of great importance. The giant resonances in deformed nuclei consist of a large number of collective one-phonon states which determined their widths /40/. It should be noted that the calculations with the wave function of type (6) containing two-phonon components, do not noticeably change the widths of giant resonances in deformed nuclei calculated in the one-phonon approximation.

The form of the giant multipole resonances is thought to be well described by the Breit-Wigner formula with the widths $\Gamma$. Such a form is obtained under the assumption that a resonance is formed by one collective state. It follows from the calculations that in complex nuclei the giant multipole resonance is formed by many collective states. Owing to the fragmentation the number of these states is so large that one thinks it to be one resonance. The giant multipole resonances in complex nuclei have a very complicated form, and the width $\Gamma$ cannot be exactly determined for them. Therefore one should better introduce the energy regions of location of the giant multipole resonances rather than their widths. The notion of width $\Gamma$ is conventional especially as the form of the giant resonances is an envelope of a large number of states with small proper widths. Usually, the widths $\Gamma$ of the giant multipole resonances are not related to the lifetime of the states lying in the region of their location.

The calculation of the giant multipole resonances in the one-phonon approximation in spherical nuclei gives a correct resonance position but gives no correct values of the resonance widths. To describe the resonance widths it is necessary to calculate the fragmentation of one-phonon states over many levels and to find the strength functions $b(E\lambda, E)$ specifying the location of the giant multipole resonances. This problem has been solved within the quasiparticle-phonon model in ref.[34].

The important role of the quasiparticle-phonon interaction is demonstrated by the calculation of the giant isovector dipole and isoscalar quadrupole resonances. The RPA calculations (*fig. 2a*) show that the giant E1 - resonance in $^{124}$Te is formed by a large number of collective states in the region of 12-19 *MeV*. The one-phonon $1^-$ states of an energy up to 30 *MeV* in $^{124}$Te exhaust 98% of the energy weighted sum rule (EWSR), the collective states in the interval 12-20 *MeV* - 84%, and the most collective of them - 57% of the EWSR .

The quasiparticle-phonon interaction results in a noticeable broadening of the resonance, as is seen from *fig. 2b* in ref.[34].

In ref.[33] the phonon space has been expanded, and the spin-multipole phonons have been described more correctly. The calculated values $b(E1,E)$ of ref.[33] are given in *Fig. 2c*. The width and form of the giant dipole resonance are described correctly. This conclusion follows from the comparison with the experimental data of ref.[41]. In the calculations the central peak is higher and the fine structure is more clearly seen than in the experiment. This is obviously due to the fact that many-phonon components are not taken into account in the wave function (6).

The widths and forms of the giant dipole resonance in $^{124}$Te represented in *Fig. 2c* are better described than in *Fig. 2b*. This testifies to the fact that to describe the form of giant multipole resonances, one should take into account besides strongly collectivized low-lying phonons a large number of weakly collectivized phonons, i.e., a large phonon space is necessary. In ref.[33] the dipole resonances are also calculated in $^{140}$Ce and $^{142}$Ce . The widths of these resonances are well described. According to the calculations the width of the giant dipole resonance in $^{142}$Ce is by approximately 1 *MeV* larger than in $^{140}$Ce, what is in good agreement with the experimental data[41].

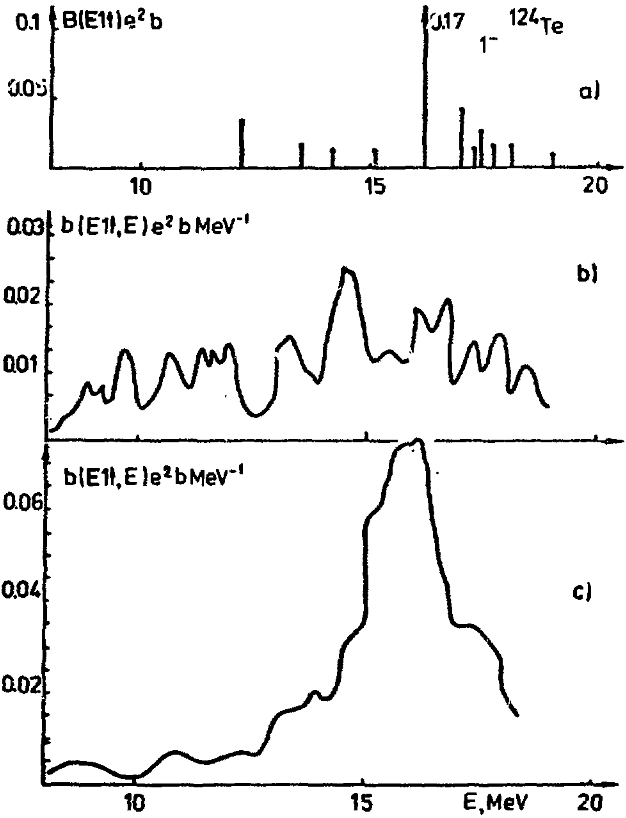


*Fig. 2. Dipole isovector resonance in* $^{124}$Te: *a) calculation* /34/ *in the one-phonon approximation; b) calculation* /34/ *with* $\Lambda$ = *0.4 MeV taking into account the quasiparticle-phonon interaction; c) calculation* /33/ *with* $\Lambda$=*0.4 MeV taking into account the quasiparticle-phonon interaction and using a large phonon space.*

Based on the calculation of the strength functions b(E$\lambda$ ,E) in deformed and spherical nuclei, one can conclude that the widths of the giant multipole resonances can be correctly described within the quasiparticle-phonon nuclear model.

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