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E4-85-706

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QUASIPARTICLE-PHONON NUCLEAR MODEL

Submitted to International School
on Nuclear Structure (Alushta, 1985)

1985

1. Basic assumptions of the quasiparticle-phonon nuclear model (QPNM)

The wave functions of low-lying states have one dominating component: one-quasiparticle in odd-A nuclei and one-phonon or two-quasiparticle in even nuclei. The simplicity of the structure of low-lying states enabled a detailed experimental and theoretical investigation. With increasing excitation energy the density of states in atomic nuclei increases and their structure becomes complicated. From simple low-lying states one passes to more complicated states at intermediate and high excitation energies. In studying the state structure at intermediate and high excitation energy an important role in atomic nuclei is attributed to the fragmentation of single-particle states, i.e. the distribution of the strength of single-particle states over many nuclear levels. In the models of independent particles and quasiparticles the single-particle strength is concentrated on a single level. In the extreme statistical model it is randomly distributed over all nuclear levels. A large region of intermediate and high excitation energies of an atomic nucleus lies between the low-lying states and the states that may be described by the extreme statistical model.

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. Moreover, due to the complication of the state structure there is a large number of components of the wave functions that should be measured experimentally. Complication of the state structure begins at low excitation energies.

The existing theories and computer technique does not allow a correct description of the structure of each level at the excitation energy above 3 MeV, apart from light and magic nuclei. This is caused by the necessity of diagonalizing matrices of an order of 10^{14}–10^{20}. Moreover, one should take into consideration a rough description of nuclear forces and an approximate solution of the nuclear many-body problem. The main reason is that there is no need in calculating each of many millions of components of the wave function of each state since the quantitative data on nuclear structure are available for few-quasiparticle configurations of the wave functions. The most exact experimental data follow from the fragmentation of one-quasiparticle, one-phonon and quasiparticle ⊗ phonon states. The only exception is the high-spin states. At intermediate excitation energies the fragmentation of one-quasiparticle states appears as local maxima or substructures 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 s- and p-wave neutron strength functions. The giant resonances are defined by the position of collective one-phonon states and the widths of giant resonances are due to their fragmentation. The few-quasiparticle components reveal the effects of the shell structure. The problem of the nuclear theory is not so much a more exact solution of the many-body problem in the general form as a more exact description of those nuclear characteristics which are being measured in experiment at present time and would be measured in the nearest future. In describing the fragmentation, an important role is played by the coupling of the single-particle with collective vibrational motions, i.e. to the interaction of qusiparticles with phonons; this fact has been pointed out in refs./1-6/ in 1968-1971. Just the results of these investigations made the basis of the QPNM.

The QPNM was formulated to describe few-quasiparticle components of the wave functions at low, intermediate and high excitation energies/4,7-11/. The fragmentation of one-quasiparticle, one-phonon and quasiparticle ⊗ phonon states over many nuclear levels is described in the framework of the model. Those characteristics of complex nuclei that are defined by these components are calculated.

Now we present the general scheme of solving the many-body nuclear problem (fig. 1) preceding the formulation of the QPNM. The nuclear Hamiltonian in the general form is expressed through the operators of creation a_f^+ and absorption a_f of neutrons and protons and the system of equations is introduced. The Hartree-Fock-Bogolubov approximation (HFB) is used for deriving the closed system of equations. Many equations turn out to be rejected within this approximation. It is assumed that the influence of rejected equations is insignificant; moreover, they can partially be compensated by the effective forces

with constants fixed from the experimental data. The HFB method and the condition under which the density matrix is diagonal allow one to separate an average field and interactions leading to superconducting pairing correlations. Then, using the canonical Bogolubov transformation one is led to the model of independent quasiparticles.

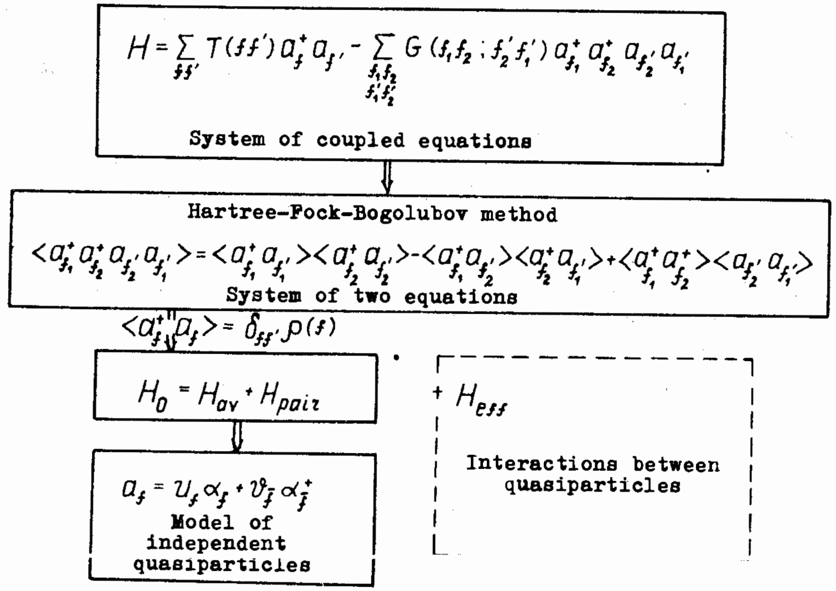

Fig. 1. Nuclear many-body problem

An approximate solution of the nuclear many-body problem symbolically represented in fig. 1, is used to construct the QPNM Hamiltonian. The QPNM Hamiltonian includes an average nuclear field as the Saxon-Woods potential and the superconducting pairing interactions. It also contains the multipole and spin-multipole isoscalar and isovector including charge-exchange interactions in the particle-hole and particle-particle channels as well as the tensor isovector interaction.

The parameters of the Saxon-Woods potential are fixed so as to obtain a correct description of the low-lying states in odd-A nuclei taking account of the quasiparticle-phonon interaction. Undoubtedly, one can use another form of the average field potential or to calculate the energies and wave functions of single-particle states within the Hartree-Fock method and to use them in the calculations within the QPNM; this arbitrariness is of no fundamental importance. The application of the Hertree-Fock method imlies an early stage of parametrization, i.e. the parametrization of an effective interaction, for instance, in terms of the Skyrme forces. In the interactions leading to pairing, instead of the functions one uses the constants G_N and G_Z whose values are determined from the difference of nuclear masses. This approximation does not reduce the accuracy of calculations within the QPM.

The effective interactions between quasiparticles are expressed as the series of multipoles and spin-multipoles. The effective interactions as though compensate equations rejected within the HFB method. They are also related to nucleon-nucleon interactions in the nuclear matter and some terms correspond to the exchange by one or two mesons. For the calculations within the QPNM it is essential that the interaction between quasiparticles is represented in a separable (factorized) form. As is known[12,13] separable potentials are widely used in describing nucleon-nucleon interactions and in studying three-body nuclear systems and lightest nuclei, i.e. separable potentials are used in the cases where the results of calculations are more sensitive to the form of radial dependence of forces in comparison with the calculations of the properties of complex nuclei within the QPNM. It is to be noted that the matrix elements of effective interactions are used in the calculations. The single-particle wave functions truncate a small part of interactions. One can construct separable interactions whose matrix elements are similar to those of more complex forces[14]. It may be assumed that appropriately chosen interactions between quasiparticles in a separable form do not limit the accuracy of calculations.

There is a certain arbitrariness in the radial dependence of separable interactions. The existence of collective vibrational quadrupole and octupole states indicates a maximum on the nuclear surface in the radial dependence of multipole forces. Therefore, for multipole forces $R_\lambda(r)$ is taken in the form of $R_\lambda(r)=r^\lambda$ or $R_\lambda(r)=\frac{\partial V(r)}{\partial r}$ where $V(r)$ is the central part of the Saxon-Woods potential. Such a type of radial dependence is also used for spin-multipole forces. The ambiguity of radial dependence of the separable spin-multipole interaction is especially large due to the absence of clearly seen collective states of the magnetic type.

Since the role of the one-pion (ρ-meson) exchange process at large nucleon-nucleon separations is very high, the QPNM Hamiltonian presented in refs.[7-11] should be added by the isovector tensor interaction in the form

$$H_T^{ph}=\frac{1}{2}(\vec{\tau}^{(1)}\vec{\tau}^{(2)})\sum_{LM}\varkappa_T^L\left\{(S_{LM}^{L-1})^+S_{LM}^{L+1}+(S_{LM}^{L+1})^+S_{LM}^{L-1}\right\}, \tag{1}$$

where

$$(S_{LM}^\lambda)^+=\sum_{jj'mm'}\langle jm|i^\lambda R_\lambda(r)\{\vec{\sigma}\vec{Y}_{\lambda\mu}\}_{LM}|j'm'\rangle a_{jm}^+a_{j'm'}.$$

The effective separable interactions between quasiparticles in the QPNM with the constants fixed from the experimental data and phenomenological estimates are thought to be not weaker than more complex effective interactions used in other papers. They are more advantageous than the Landau-Migdal density-dependent zero range force that is widely used in calculating the structure of closed shell nuclei.

One should not attach great importance to the self-consistency between an average field and effective interactions, since a great number of equations is rejected within the HFB method. The self-consistent calculations are very important by a qualitative description of nuclear characteristics rather than by their detailed description of experiment. They showed that in solving the nuclear many-body problem the HFB method may serve as a good basis for constructing nuclear models.

The scheme of calculations within the QPNM is shown in fig. 2. The explicit form of the model Hamiltonian is given in refs.[7,8] for deformed nuclei and in ref.[9] for spherical nuclei. Transforming the model Hamiltonian by the canonical Bogolubov transformation one passes from the nucleon operators to the quasiparticle α_{jm}^+ and α_{jm} operators. The pairs of operators $\alpha_{jm}^+\alpha_{j'm'}^+$ and $\alpha_{j'm'}\alpha_{jm}$ are expressed through the phonon operators and the quasiparticle operators remain only in the form $\alpha_{jm}^+\alpha_{j'm'}$. Such an inclusion of phonon operators overcomes difficulties with double counting of some diagrams that take place in the nuclear field theory[15]. Then, the RPA equations are solved to determine the energies and wave functions of one-phonon states. All the model parameters are fixed at this stage. By using the experimental data to fix the constants of pairing, multipole and spin-multipole isoscalar and isovector interactions, one as if takes into account the effect of a chain of equations rejected within the HFB method.

The specific feature and advantage of the QPNM is the use of one-phonon states as a basis. This is possible due to the fact that the RPA provides a unique description of collective, weakly collective and two-quasiparticle states. Within the RPA the secular equations of the model Hamiltonian are transformed to the form

$$H_{QPhNM}=\sum_{jm}\varepsilon_j\alpha_{jm}^+\alpha_{jm}+H_v+H_{vq} \tag{2}$$

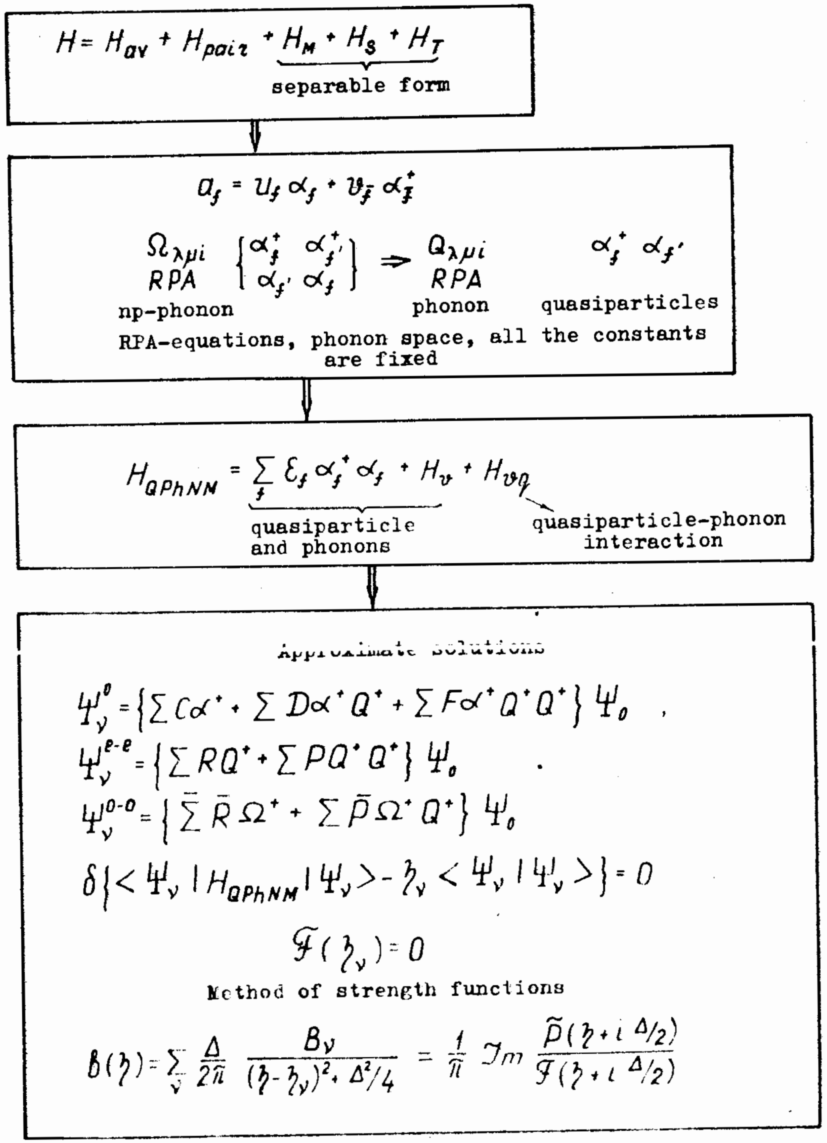

Fig. 2. Scheme of calculations within the QPNM

containing free quasiparticles and phonons and the quasiparticle-phonon interaction H_{vq}. Formula (1) includes also the np phonon operators describing charge-exchange giant resonances and $T_>$ excited states. <u>This is the first specific feature of the QPNM</u>.

The phonon space corresponds to a full space of two-quasiparticle states of the particle-hole-type and some states of the particle-particle-type. A full space of two-quasiparticle states is used when the interactions in the particle-particle channel are taken into account. The multipole forces are used to construct a phonon basis in deformed nuclei for $K^\pi = 0^\pm, 1^\pm, 2^\pm, \ldots 7^\pm$. In spherical nuclei the multipole forces are used to construct one-phonon states with $J^\pi = 1^-, 2^+, 3^-, \ldots 7^-$ and spin-multipole forces for the states with $J^\pi = 1^+, 2^-, 3^+, \ldots 7^-$. For each value of K^π or J^π several hundreds of roots of the secular equations and relevant wave functions are calculated. The calculations of the state density/16/ indicate the completeness of the phonon space. As a result of calculations of the phonon space all the QPNM constants turned out to be fixed.

<u>The second specific feature of the model is</u>: the quasiparticle-phonon interaction is responsible for the fragmentation of quasiparticle and collective motion and thus for the complication of the nuclear state structure with increasing excitation energy.

The excited state wave functions are represented as a series in a number of phonon operators, in odd-A nuclei each term is multiplied by a quasiparticle operator. The approximation consists in the cut-off of this series, that is <u>the third specific feature of the model</u>. The cut-off of the series is the approximation similar to the cut-off of the chain of equations in the HFB approximation. At present our expansion is limited to two phonons, that is demonstrated in the scheme (fig. 2). To elucidate the influence of many-phonon terms of the wave functions on the calculated effects is as difficult as to evaluate the role of neglected in the HFB approximation chains of equations of the many-body problem. It is stated in both the cases that approximate equations describe correctly the properties of nuclear excitations and the terms neglected are partially taken into account by using constants fixed from the experimental data. In the calculations the Pauli principle is taken into account by using exact commutation relations between the phonon and quasiparticle operators.

<u>The fourth specific feature of the model is the use of the strength function method</u>. By using a version of the strength function method developed in refs./7,17/ one can directly calculate the reduced transition probabilities, spectroscopic factors, transition den-

sities, cross sections and other nuclear characteristics without solving the relevant secular equations. The application of the strength function method reduces the computer time by 10^3 times and makes it possible to calculate the fragmentation of one-quasiparticle, quasiparticle ⊗ phonon and one-phonon states for many nuclei. The characteristics of highly excited states are calculated for spherical nuclei with closed and open shells and for deformed nuclei.

The general scheme of calculations within the QPNM is the following. The wave functions of the excited states of odd-A, doubly even and doubly odd spherical nuclei are written as

$$\Psi_\nu(JM) = C_{J\nu}\Big\{\alpha^+_{JM} + \sum_{\lambda i j}\bar{D}_j^{\lambda i}(J\nu)\,[\alpha^+_{jm}\,Q^+_{\lambda\mu i}]_{JM} + \sum_{\lambda_1 i_1 \lambda_2 i_2 j I} F_{jI}^{\lambda_1 i_1 \lambda_2 i_2}(J\nu)[\alpha^+_{jm}[Q^+_{\lambda_1\mu_1 i_1}Q^+_{\lambda_2\mu_2 i_2}]_{IM'}]_{JM}\Big\}\Psi_0\,, \qquad (3)$$

$$\Psi_\nu(JM) = \Big\{\sum_i R_i(J\nu)Q^+_{\lambda\mu i} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P_{\lambda_2 i_2}^{\lambda_1 i_1}(J\nu)[Q^+_{\lambda_1\mu_1 i_1}, Q^+_{\lambda_2\mu_2 i_2}]_{JM}\Big\}\Psi_0\,, \qquad (4)$$

$$\Psi_\nu(JM) = \Big\{\sum_i \bar{R}_i(J\nu)\Omega^+_{\lambda\mu i} + \sum_{\lambda_1 i_1 \lambda_2 i_2}\bar{P}_{\lambda_2 i_2}^{\lambda_1 i_1}(J\nu)[\Omega^+_{\lambda_1\mu_1 i_1}, Q^+_{\lambda_2\mu_2 i_2}]_{JM}\Big\}\Psi_0 \qquad (5)$$

where Ψ_0 is the ground state wave function of a doubly even nucleus (phonon vacuum); α^+_{jm}, $Q^+_{\lambda\mu i}$, $\Omega_{\lambda\mu i}$ are the quasiparticle and phonon creation operators. Then, we find an average value of H_{QPhNM} (2) over (3) or (4) or (5). Using the variational principle and taking into account the normalization of the wave function (3) or (4) or (5), we get the secular equation for the energies of excited states and write it down as

$$\mathcal{F}(\eta_\nu) = 0. \qquad (6)$$

We also get the systems of equations for the coefficients of the wave functions (3) or (4) or (5).

The following nuclear characteristics are calculated within the QPNM:

1) Low-lying nonrotational states of deformed nuclei/18-21/,

2) fragmentation of one-quasiparticle and two-quasiparticle states in deformed nuclei/17-22/,

3) fragmentation of one-quasiparticle states in spherical nuclei/23-25/,

4) fragmentation of two-quasiparticle states in spherical nuclei/10-26/,

5) neutron s-, p-, d-wave strength functions in spherical and deformed nuclei/10,17,25,27/,

6) radiative E1-, E2- and M1-strength functions for transitions

from neutron resonances to the ground states of spherical and deformed nuclei/28-30/,

7) photoabsorption cross sections in the region of the giant dipole resonance tail in spherical nuclei/10,25,28,31/,

8) positions, widths and transition densities for $E\lambda$ - and $M\lambda$ - giant resonances in spherical and deformed nuclei/8,10,25,28,32,33/,

9) strength distribution of the charge-exchange Gamow-Teller and spin-dipole resonances in spherical and deformed nuclei/34,35/,

10) description of the scattering of photons, electrons and protons with excitation of giant $E\lambda$ - and $M\lambda$-resonances/36/ and others.

A rather good description of the relevant experimental data is obtained. Some predictions are made. The calculations are performed with the same model parameters for each group of nuclei. After fixation of the phonon space the model has no any free parameters.

In these lectures the application of the QPNM is given for two cases for the description of the fragmentation of charge-exchange resonances in spherical nuclei and for the description of vibrational low-lying states in doubly even deformed nuclei and comparison of the QPNM results with the interacting boson model (IBM). Part of the results obtained within the QPNM will be presented in the lectures by Ch.Stoyanov/37/.

2. Fragmentation of charge-exchange collective states

In recent years much attention has been paid to the study of giant charge-exhange resonances. Only part of the charge-exchange resonance strength is observed experimentally as compared to the relevant sum rules. The fragmentation of these states due to the coupling with 2p-2h configurations and to the mixing with Δ -isobar-nucleon hole configurations is the reason for the quenching of strength in the region of maximum. The influence of admixtures of 2p-2h configurations has been studied in refs./38-41/ and other papers. The fragmentation of charge-exchange phonons is studied within the QPNM. A general method of introducing charge-exchange phonons in the QPNM is expounded in ref./42/. The fragmentation of the Gamow-Teller resonance in some spherical nuclei has been described in refs./34,41/.

It is assumed in some papers, for instance in ref./39/, that the inclusion of tensor forces in calculating the fragmentation of the Gamow-Teller resonance leads to a shift of a considerable part of its strength towards high excitation energies. Within the QPNM the influence of tensor forces can be studied if the model Hamiltonian is added by the term (1). For the spin-multipole states with $L^{\pi} = 1^+, 2^+, 3^+ ...$ a simultaneous inclusion of spin-multipole with $\lambda = \pm 1$ and tensor forces leads to the following secular equation for the energies ω_{Li} of one-phonon states:

$$\left| \begin{array}{ll} \varkappa_1^{L-1L} X_{(+)}^{L-1Li} + \varkappa_T^L X_{(+)}^{L\pm 1Li} - 1 & \varkappa_1^{L+1L} X_{(+)}^{L\pm 1Li} + \varkappa_T^L X_{(+)}^{L-1Li} \\ \varkappa_1^{L-1L} X_{(+)}^{L\pm 1Li} + \varkappa_T^L X_{(+)}^{L+1Li} & \varkappa_1^{L+1L} X_{(+)}^{L+1Li} + \varkappa_T^L X_{(+)}^{L\pm 1Li} - 1 \\ \varkappa_1^{L-1L} X_{(+-)}^{L-1Li} + \varkappa_T^L X_{(+-)}^{L\pm 1Li} & \varkappa_1^{L+1L} X_{(+-)}^{L\pm 1Li} + \varkappa_T^L X_{(+-)}^{L-1Li} \\ \varkappa_1^{L-1L} X_{(+-)}^{L\pm 1Li} + \varkappa_T^L X_{(+-)}^{L+1Li} & \varkappa_1^{L+1L} X_{(+-)}^{L+1Li} + \varkappa_T^L X_{(+-)}^{L\pm 1Li} \\ \varkappa_1^{L-1L} X_{(+-)}^{L-1Li} + \varkappa_T^L X_{(+-)}^{L\pm 1Li} & \varkappa_1^{L+1Li} X_{(+-)}^{L\pm 1Li} + \varkappa_T^L X_{(+-)}^{L-1Li} \\ \varkappa_1^{L-1L} X_{(+-)}^{L\pm 1Li} + \varkappa_T^L X_{(+-)}^{L+1Li} & \varkappa_1^{L+1Li} X_{(+-)}^{L+1Li} + \varkappa_T^L X_{(+-)}^{L\pm 1Li} \\ \varkappa_1^{L-1L} X_{(-)}^{L-1Li} + \varkappa_T^L X_{(-)}^{L\pm 1Li} - 1 & \varkappa_1^{L+1Li} X_{(-)}^{L\pm 1Li} + \varkappa_T^L X_{(-)}^{L-1Li} \\ \varkappa_1^{L-1L} X_{(-)}^{L\pm 1Li} + \varkappa_T^L X_{(-)}^{L+1Li} & \varkappa_1^{L+1Li} X_{(-)}^{L+1Li} + \varkappa_T^L X_{(-)}^{L\pm 1Li} - 1 \end{array} \right| = 0, \quad (7)$$

where

$$X_{(\pm)}^{\lambda Li} = \frac{1}{2L+1} \sum_{j_p j_n} \frac{(f^{\lambda L}(j_p j_n) v_{j_p j_n}^{(\pm)})^2 \varepsilon_{j_p j_n}}{\varepsilon_{j_p j_n}^2 - \Omega_{Li}^2},$$

$$X_{(\pm)}^{L\pm 1Li} = \frac{1}{2L+1} \sum_{j_p j_n} \frac{f^{L-1L}(j_p j_n) f^{L+1L}(j_p j_n) (v_{j_p j_n}^{(\pm)})^2 \varepsilon_{j_p j_n}}{\varepsilon_{j_p j_n}^2 - \Omega_{Li}^2},$$

$$X_{(+-)}^{\lambda Li} = \frac{1}{2L+1} \sum_{j_p j_n} \frac{(f^{\lambda L}(j_p j_n))^2 v_{j_p j_n}^{(+)} v_{j_p j_n}^{(-)} \Omega_{Li}}{\varepsilon_{j_p j_n}^2 - \Omega_{Li}^2},$$

$$X_{(+-)}^{L\pm 1Li} = \frac{1}{2L+1} \sum_{j_p j_n} \frac{f^{L-1L}(j_p j_n) f^{L+1L}(j_p j_n) v_{j_p j_n}^{(+)} v_{j_p j_n}^{(-)} \Omega_{Li}}{\varepsilon_{j_p j_n}^2 - \Omega_{Li}^2}.$$

Assuming that $\varkappa_T^L = 0$ one gets an equation for spin-multipole forces with $\lambda = L \pm 1$. Rejecting also the components with $\lambda = L+1$ one arrives at the RPA equations that are used for the study of the Gamow-Teller resonance. The calculations have shown that the inclusion of tensor forces somewhat changes the RPA solutions.

In describing the fragmentation of charge-exchange phonons the wave function is written in the form (5) and the variational principle is used to find the secular equation and equations for $\bar{R}_i(J\nu)$ and $\bar{P}_{\lambda_2 i_2}^{\lambda_1 i_1}$. Then, the strength functions of (p,n) and (n,p) reactions are calculated. Fig. 3 shows the results of calculations of (p,n) reaction with excitation of the Gamow-Teller resonance in ^{140}Ce /34/. In comparison with the RPA calculations the quasiparticle-phonon interaction

leads to the decrease of strength in the region of resonance maximum from 81% to 46% of 3(N-Z), to the increase of strength in the low-energy region from 12% to 30% and to its increase in the regions above the resonance maximum from 7% to 24%. The strength shifted to the region above the resonance maximum is insufficient to explain the relevant experimental data. A similar picture takes place for other spherical nuclei.

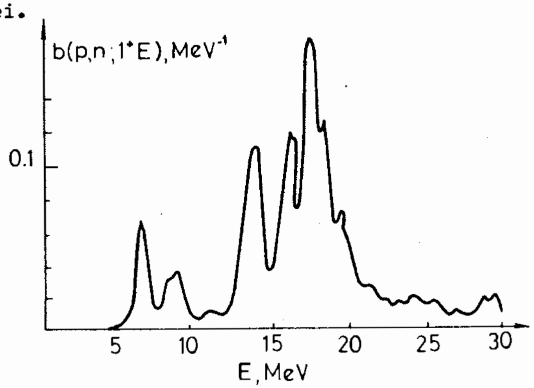

Fig. 3. Fragmentation of the Gamow-Teller resonance in ^{140}Ce

The quasiparticle-phonon interaction causes a strong fragmentation of spin-dipole one-phonon states /34/. The strength of these states is considerably redistributed within the region of the RPA solutions though the strength of spin-dipole states is not greatly shifted from the resonance region towards high excitation energies.

A further study of the fragmentation of charge-exchange one-phonon states within the QPNM will be performed along the following lines: 1) improvement of the description of the fragmentation taking into account a part of three-phonon terms of the wave functions by formulae given in ref. /43/; 2) for the states of the magnetic type and first of all for the Gamow-Teller resonance the inclusion of the tensor force together with the spin-multipole forces with $\lambda = L-1$ and $\lambda = L+1$; 3) elucidation of the influence of the radial dependence of effective interactions.

3. Confrontation between the QPNM and IBM in describing deformed nuclei

The phenomenological interacting boson model (IBM) has been formulated by Arima and Iachello /44/ on the basis of the group theory method. They introduced two types of bosons; s-bosons with $J = 0$ and quadrupole d-bosons (d_μ, $\mu = 0, \pm 1, \pm 2$) and assumed that 0^+ and 2^+

collective nucleon pairs play a dominating role for the description of quadrupole collective states. They used a finite boson expansion of the Schwinger-type and the SU(6) approximation. Bosons are expressed through correlated nucleon pairs, therefore the IBM is related with the shell model. However, the IBM is based on a very small part of the shell model fermion space. The IBM is widely used for analysing the experimental data of the energies and E2 transition probabilities for a large number of spherical, transitional and deformed nuclei. The IBM allowed one to describe the spectra of transitional nuclei that could not be reproduced in other models. However, a good description of the energies and E2 transitions does not imply a correct description of the structure of these collective states. Apart from the integral characteristics there are also differential ones of vibrational states which are exhibited in the one-nucleon transfer reactions and β - and γ -transitions to these states. The calculations within the IBM were enormous that in some cases they fall outside the range of its applicability. The anharmonic corrections are thought to be not very large in deformed nuclei, therefore each wave function of an excited state has one dominating component.

Doubly even deformed nuclei possess low-lying two-quasiparticle and vibrational states. The collective $K^{\pi}=2_1^+$ γ-vibrational, $K^{\pi}=0_2^+$ β-vibrational and $K^{\pi}=0_1^-$, 1_1^-, 2_1^- and 3_1^- octupole states and $B(E\lambda)$-values of their excitation are well described as the one-phonon states[3,18,19]. The one-phonon wave functions are the superpositions of two-quasiparticle components. The experimental data available for some nuclei confirm that the largest components of the wave functions of the first one-phonon states are correctly described.

According to the generally accepted treatment there should exist one-, two- and three-phonon states in doubly even spherical and deformed nuclei. In refs.[21,45] the effect of the Pauli principle on excited states in two-phonon components of the wave functions has been studied within the QPNM taking into consideration many complex diagrams. It was concluded in ref.[21] that the collective two-phonon states should not exist in deformed doubly even nuclei. It should be emphasized that A.Bohr and B.Mottelson[46] try to uphold the generally accepted treatment assuming the existence of collective two-phonon states in deformed nuclei.

For the description of doubly even deformed nuclei within the QPNM the wave function (4) is usually taken as a sum of 5-10 one-phonon terms and a great number (10^2 10^3) of two-phonon terms. According to the calculations performed the components $\lambda\mu i$ =221 and 201 con-

tribute more than 80% to γ -vibrational $K^{\pi}=2_1^+$ and β -vibrational $K^{\pi}=0_2^+$ states. The states 2_2^+, 2_3^+, 2_4^+, 0_3^+, 0_4^+, 0_5^+, 4_1^+ and 4_2^+ have dominating components $\lambda\mu i$ =222, 223, 224, 202, 203, 204, 441, 442. Up to the excitation energy of 2 MeV an admixture of two-phonon collective components does not exceed 10%. The states with $K^{\pi}=3_1^+$ and 3_2^+ are as a rule two-quasiparticle. It can be stated that up to the energies (2.0-2.3) MeV the wave functions of nonrotational states have one dominating one-phonon component; they are shown in fig. 4.

Now we shall compare the description of β - and γ -vibrational states within the QPNM and IBM. Since the one-phonon components = 201 and 221 are dominating, the QPNM does not provide a considerably better description of 0_2^+ and 2_1^+ states in comparison with the RPA calculations. The wave functions of 0_2^+ and 2_1^+ states are the superposition of a large number of two-quasiparticle components of the particle-hole type. Note, that for the description of 0_1^+ and 2_1^+ states only a small part of the space of two-quasiparticle states is taken into account. In the IBM the one-boson components n_β =1 and n_γ =1 dominate in the wave functions of 0_2^+ and 2_1^+ states. The particle-particle components in the wave functions of these states dominate at the beginning of the region of deformed nuclei, whereas the hole-hole components at the end. Due to the particle-particle structure of n_γ =1 operator at the beginning of the region of deformed nuclei the 2_1^+ states may be well excited in reactions of the type (d,p) or (He,d) and should not be excited (or slightly excited) in the reactions of the type (d,t) or (d,^{3}He). The success of the IBM in describing the integral characteristics of 0_2^+ and 2_1^+ states is obvious, especially as concerns the E2 transitions to the ground state band and between the bands constructed on 0_2^+ and 2_1^+ states. These states are treated differently within the QPNM and IBM.

Compare the description of $K^{\pi}=0_3^+$, 0_4^+, 0_3^+, 2_2^+, 2_3^+, 2_4^+ so on states. In the QPNM the states 0_3^+, 0_4^+, 0_5^+ have large (80-95)% one-phonon components $\lambda\mu i$ = 202, 203, 204 and the states 2_2^+, 2_3^+, 2_4^+ large one-phonon components $\lambda\mu i$ =222, 223, 224. In some cases a mixture of one-phonon components is observed. It is to be noted that in describing these states the space of two-quasiparticle states became broader in comparison with that determining 201 and 221 phonons. These states should not have large collective two-phonon components and first of all those constructed of 201 and 221 phonons. The available experimental data[47,48] do not contradict this conclusion. Moreover, according to the new experimental data[49] the state $K^{\pi}=4^+$ with an energy of 2.03 MeV in ^{168}Er which has been thought to be K=4 and treated in refs.[46-50] as the two-phonon state has K=0 and is not two-phonon.

In the IBM the dominating components of the wave functions are: $n_\gamma=1$, $n_\beta=1$ for 2^+_1 states, $n_\gamma=3$ for 2^+_3, $n_\gamma=2$ for 0^+_3 and $n_\beta=2$ for 0^+_4 states. The main part of the strength of one-boson states $n_\gamma=1$, $n_\beta=1$ is concentrated in 2^+_1 and 0^+_2 states and only a small fraction of their strength is attributed to 2^+_2, 2^+_3, 0^+_3 and 0^+_4 states. This means that the dominating components of the wave functions of 2^+_2, 2^+_3, 0^+_3 and 0^+_4 states are the two- and three-boson ones and the contribution of one-boson and thereby two-quasiparticle components is very small. These components are shown in fig. 4. From the microscopic point of view, within the IBM only a small part of the space of two-quasiparticle states entering into the wave functions β-$(n_\beta=1)$ and γ $(n_\gamma=1)$ -vibrational states is taken into consideration. With g -boson the space of two-quasiparticle states becomes broader. However, according to the calculations/51/ for ^{168}Er the weight of g -boson in 2^+_2, 2^+_3, 0^+_3 and 0^+_4 states does not exceed 30% and the two- and three-boson components are still dominating.

As a result we state that the wave functions of 2^+_2, 2^+_3, 2^+_4, 0^+_3, 0^+_4, 0^+_5 states in the IBM have large two- and three-boson components and in the QPNM they have large one-phonon components with i = 2,3,4 and have no pronounced two-phonon collective components. In the QPNM the structure of these states is mainly determined by the set of two-quasiparticle components that is not available in the IBM. As it has been mentioned in ref./52/ there is fundamental difference in describing these states within the QPNM and the IBM.

We shall consider $K^\pi = 4^+_1$ and 4^+_2 states. According to the calculations within the QPNM the one-phonon components $\lambda\mu i$ =441 and 442 dominate in the wave functions of 4^+_1 and 4^+_2 states; the contribution of two-phonon components {221,221} does not exceed (1-5)%. In the IBM the 4^+ state is treated as the two-boson $n_\gamma=2$ state. According to the calculations of ref./51/ for ^{168}Er the weight of g -boson in the wave functions of 3^+_1, 4^+_1 and 4^+_2 states does not exceed 30%. This means that the two-boson $n_\gamma=2$ components are dominating. There is an essential difference in describing 4^+_1 as well as 3^+_1, 3^+_2 and 4^+_2 states within the QPNM and IBM. The wave functions of these states should contain large two-quasiparticle components or large two-phonon components.

Summing up the above discussion we may state that in describing nonrotational states with $K^\pi = 0^+$, 2^+, 3^+ and 4^+ of deformed doubly even nuclei with excitation energies in the range of 1.5-2.5 MeV three basic models are confronted: the Bohr-Mottelson model with its microscopic analogue, the QPNM and the IBM. According to the QPNM the collective two-phonon states should not exist in doubly even deformed

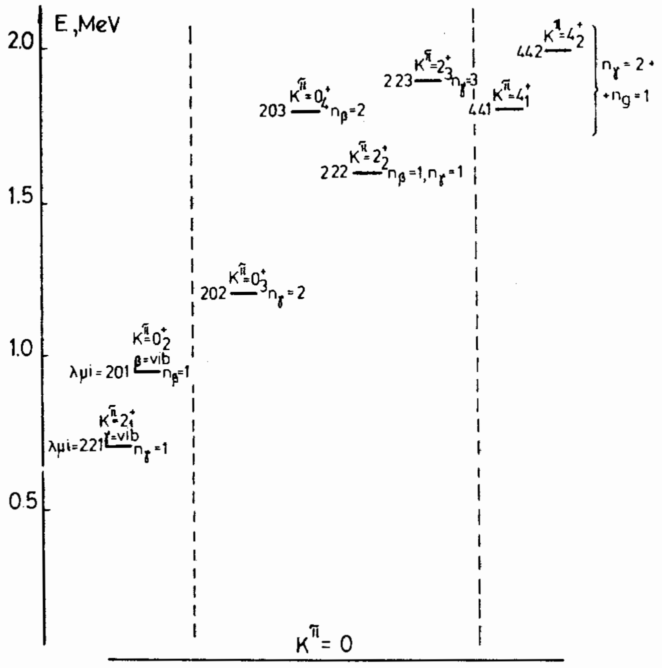

Fig. 4. Scheme of excitations of deformed nuclei. States with K^π = 2^+_1, 0^+_2; 0^+_3, 0^+_4, 2^+_2, 2^+_3 and 4^+_1, 4^+_2. A dominating constant is attributed for each level: on the left according to the QPNM and on the right to the IBM.

nuclei, though their existence is predicted by the Bohr-Mottelson model and in the IBM they are treated as two-boson components. Moreover, according to the QPNM the wave functions of each of the states with $K^{\pi} = 2^+_1, 2^+_2, 2^+_3, 0^+_3, 0^+_4, 0^+_5, 4^+_1$ and 4^+_2 (K - projection of momentum onto the nuclear symmetry axis, $i = 1, 2, \dots$) has one dominating one-phonon component, whereas the IBM predicts a two- and three-boson component as dominating. Thus the treatment of these states differs qualitatively within the QPNM and IBM. It should be emphasized that there are no reliable experimental data on collective two-phonon states in deformed nuclei. The recent experimental data indicate that they are correctly described within the QPNM. Further experimental investigations are necessary to elucidate the structure of nonrotational states of deformed nuclei and to settle contradiction between three models.

Conclusion

Within the quasiparticle-phonon nuclear model one can calculate many properties of complex nuclei at low, intermediate and high excitation energies. Part of these calculations has already been performed. The fact that within the QPNM one can get a good description of many nuclear characteristics in a sufficiently wide energy interval using one set of parameters indicates that it correctly reproduces the basic features of the nuclear many-body problem. The model makes it possible to calculate many nuclear characteristics and cross sections of a large number of reactions for spherical nuclei with $A > 50$. It is obvious that for further calculations more complicated versions of the model will be used by including new terms in the functions and by taking account of new forces. The study of fragmentation of quasiparticle ⊗ phonon states and the calculation of γ-decay of deep hole states and relative strength functions are the problems to be solved in the nearest future.

In should be noted that the main contribution to the wave functions of highly excited states comes from many-quasiparticle and many-phonon components. At present there is no information on the values and distributions of many-quasiparticle components of the wave functions of highly excited states. Certainly we shall witness in future the manifestation of new properties of highly excited states defined by many-quasiparticle components.

References:

1. Soloviev V.G., Phys.Lett., 1965, v. 16, p. 308; Phys.Lett., 1966, v. 21, p. 320.
2. Soloviev V.G., Nuclear Structure Dubna Symposium 1968, IAEA, Vienna, p. 101.
3. Соловьев В.Г., Теория сложных ядер, М., Наука, 1971.
4. Соловьев В.Г., Изв. АН СССР, сер.физ., 1971, т. 35, с. 666; 1974, т. 38, с. 1580.
5. Соловьев В.Г., в трудах Школы по Структуре ядра, Алушта, 1972, с. 77, изд. ОИЯИ, Д-6465, Дубна, 1972.
   Soloviev V.G., Malov L.A., Nucl.Phys.A, 1972, v. 196, p. 443.
6. Soloviev V.G., in:"Neutron Capture Gamma-Ray Spectroscopy, p. 99, Reactor Centrum Nederland, Petten, 1975.
7. Соловьев В.Г., ЭЧАЯ, 1978, т. 9, с. 580.
   Soloviev V.G., Nucleonica, 1978, v. 23, p. 1149.
8. Малов Л.А., Соловьев В.Г., ЭЧАЯ, 1980, т. 11, с. 301.
9. Вдовин А.И., Соловьев В.Г., ЭЧАЯ, 1983, т. 14, с. 327.
10. Воронов В.В., Соловьев В.Г., ЭЧАЯ, 1983, т. 14, с. 1381.
11. Вдовин А.И. и др., ЭЧАЯ, 1985, т. 16, с. 245.
12. Браун Дж.Е., Джексон А.Д., Нуклон-нуклонные взаимодействия, М., Атомиздат, 1979.
13. Tabakin F., Ann.Phys., 1964, v. 30, p. 51.
   Шмидт Э., Цигельман Х., Проблема трех тел в квантовой механике, М., Наука, 1979.
14. Knüpfer W., Huber M.G., Phys.Rev.C. 1976, v. 14, p. 2254.
15. Bes D., Broglia R.A. et al., Nucl.Phys.A, 1976, v. 260, p. 77.
16. Вдовин А.И. и др., ЭЧАЯ, 1976, т. 7, с. 952.
17. Malov L.A., Soloviev V.G., Nucl.Phys.A, 1976, v. 270, p. 87.
18. Soloviev V.G., Atomic Energy Rew., 1965, v. 3, n. 2, p. 117.
19. Григорьев Е.П., Соловьев В.Г., Структура четных деформированных ядер, М., Наука, 1974.
   Иванова С.П. и др., ЭЧАЯ, 1976, т. 7, с. 450.
20. Гареев Ф.А. и др., ЭЧАЯ, 1973, т. 4, с. 357.
   Soloviev V.G., Nesterenko V.O., Bastrucov S.I., Z.Phys.A, 1983, v. 309, p. 353.
21. Soloviev V.G., Shirikova N.Yu., Z.Phys.A. 1981, v. 301, p. 263.
   Соловьев В.Г., Ширикова Н.Ю., ЯФ, 1982, т. 36, с. 1376.
22. Вдовин А.И. и др. Изв. АН СССР, сер.физ., 1985, т. 49, с. 834.
23. Soloviev V.G., Stoyanov Ch., Vdovin A.I., Nucl.Phys.A, 1980, 342, 261.
24. Chan Zuy Khuong, Soloviev V.G., Voronov V.V., J.Phys.G: Nucl.Phys. 1981, 7, 151.

Вдовин А.И., Нгуен Динь Тхао, Соловьев В.Г., Стоянов Ч., ЯФ, I983, 37, 43.
Stoyanov Ch., Vdovin A.I., Phys.Lett.B, 1983, 130, 134.
Вдовин А.И., Стоянов Ч., ЯФ, I985, т. 4I, с. II34.
25. Soloviev V.G., Stoyanov Ch., Voronov V.V., Nucl.Phys.A, 1983, v. 399, p. 141.
26. Soloviev V.G., Stoyanova O., Voronov V.V., Nucl.Phys.A, 1981, A370, 13.
Voronov V.V., J.Phys.G: Nucl.Phys., 1983, 9, L273.
Воронов В.В., Журавлев И.П., ЯФ, I983, 38, 52.
27. Dambasuren D. et al., J.Phys.G: Nucl.Phys., 1976, v. 2, p. 25.
Воронов В.В., Соловьев В.Г., Стоянова О., ЯФ, I980, т. 3I, с. 327.
Voronov V.V., Stoyanov Ch., J.Phys.G: Nucl.Phys., 1985, v. 11, p. L97.
28. Soloviev V.G., Stoyanov Ch., Voronov V.V., Nucl.Phys.A, 1978, v. 304, p. 503.
29. Soloviev V.G., Stoyanov Ch., Nucl.Phys.A, 1982, v. 382, p. 206.
30. Malov L.A., Meliev F.M., Soloviev V.G., Z.Phys.A, 1985, v. 320.
31. Воронов В.В., Дао Тиен Кхоа, Изв. АН СССР, сер.физ., I984, т. 48, с. 2008.
32. Soloviev V.G., Stoyanov Ch., Vdovin A.I., Nucl.Phys.A, 1977, v. 288, p. 376.
Ponomarev V.Yu. et al., Nucl.Phys.A, 1979, v. 323, p. 446.
Воронов В.В. и др. ЯФ, I984, т. 40, с. 683.
Вдовин А.И., Изв. АН СССР, сер.физ., I979, т. 43, с. 20I8.
33. Ponomarev V.Yu., Stoyanov Ch., Vdovin A.I., J.Phys.G: Nucl.Phys. 1982, v. 8, p. L77.
Ponomarev V.Yu., idem, 1984, v. 10, p. L177.
Ponomarev V.Yu., Stoyanov Ch., Vdovin A.I., Z.Phys.A, 1982, v.308, p. 157.
34. Kuzmin V.A., Soloviev V.G., J.Phys.G: Nucl.Phys., 1984, v. 10, p. 1507; 1985, v. 11, p. 603.
35. Soloviev V.G., Sushkov A.V., Shirikova N.Yu., Z.Phys.A, 1984, v. 316, p. 65.
36. Reif R. et al., J.Phys.G: Nucl.Phys. 1982, v. 8, p. 257.
Акулиничев С.В. и др. ЯФ, I978, т. 28, с. 883.
Пономарев В.Ю., ЯФ, I985, т. 4I, с. 79.
Акулиничев С.В., Шилов В.М., ЯФ, I978, т. 27, с. 670.
37. Стоянов Ч., IУ школа по нейтронной физике, Дубна, I982, ОИЯИ, Д3,4-82-704, Дубна, I982.
38. Fiegig H.R., Wambach J. Nucl.Phys.A, 1982, v. 386, p. 381.
Adashi S. Phys.Lett.B, 1983, v. 125, p. 5.
Muto K. et al. Phys.Lett.B., 1982, v. 118, p. 261.

39. Bertsch G.F., Hamamoto I. Phys.Rev.C, 1982, v. 26, p. 1323.
40. Wambach J., Schweisinger B. International Symposium of "Highly Excited States and Nuclear Structure" - HESANS-83" Orsay, France, p. 87, 1984.
Knüpfer W., Metsch B.C., idem, p. 171, 1984.
41. Soloviev V.G., idem, p. 112, 1984.
42. Соловьев В.Г., ТМФ, I983, т. 57, с. 438.
43. Соловьев В.Г., ЯФ, I984, т. 40, с. II63.
44. Arima A., Iachello F., Phys.Rev.Lett., 1975, v. 35, p. 1069; Ann. of Phys. 1976, v. 99, p. 253.
45. Джолос Р.В. и др. ТМФ, I979, т. 40, с. 245.
Jolos R.V. et al., Z.Phys., 1980, v. A295, p. 147.
46. Bohr A., Mottelson R.B., Physica Scripta, 1982, v. 25, p. 17.
47. Peker L.K., Hamilton J.H., Future Directions in Studies of Nuclei far from Stability, ed. Hamilton, Amsterdam, North-Holland P.C., 1980, p. 323.
48. Warner D.D. et al., Phys.Rev.C., 1983, v. 27, p. 2292.
49. Kleppinger E.W., Yates S.M., Phys.Rev.C, 1983, v. 28, p. 943.
Davidson W.F. et al., Phys.Lett.B, 1983, v. 130, p. 161.
Burke D.G. et al., Nucl.Phys.A, 1985, v. 442, p. 424.
Davidson W.F., Dixon W.R., Storey R.S., Can.J.Phys. 1984, v. 12, p. 1538.
50. Dumitrescu T.S., Hamamoto I., Nucl.Phys.A, 1982, v. 38, p. 205.
51. Wu Hua-Chuan, Zhou Xiao-Qian, Nucl.Phys.A, 1984, v. 417, p. 67.
52. Соловьев В.Г., Письма в ЖЭТФ, I984, т. 40, с. 398.

Received by Publishing Department
on October 3,1985.

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Соловьев В.Г. E4-85-706

Квазичастично-фононная модель ядра

Изложены основные положения квазичастично-фононной модели ядра /КФМЯ/ и даны два ее применения. Описано введение тензорных сил в КФМЯ и приведены результаты изучения фрагментации зарядово-обменных резонансов в сферических ядрах. Дано описание низколежащих $K^{\pi}=0^+$, 2^+, 3^+ и 4^+ состояний в четно-четных деформированных ядрах и выполнено сопоставление результатов, рассчитанных в КФМЯ, с результатами, полученными в модели взаимодействующих бозонов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1985

Soloviev V.G. E4-85-706

Quasiparticle-Phonon Nuclear Model

Basic assumption of the quasiparticle-phonon nuclear model (QPNM) and its two applications are presented. The introduction of tensor forces in the QPNM is described and the results of studying the fragmentation of charge-exchange resonances in spherical nuclei are given. The low-lying $K^{\pi}=0^+$, 2^+, 3^+ and 4^+ states in doubly even deformed nuclei are described. The results calculated in the QPNM are compared with those obtained in the interacting boson model.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1985