ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN—POLONIA
VOL. XL/XLI, 35 SECTIO AAA 1985/1986

Joint Institute for Nuclear Research, Laboratory of Theoretical Physics
Moscow

V. G. SOLOVIEV

Quasiparticle-phonon Nuclear Model

Model jądrowy ze sprzężeniem kwasicząsteczka—fonon

Квазичастично-фононная ядерная модель

1. Introduction

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.

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 quasiparticles with phonons; this fact has been pointed out in refs.[1-6] in 1965-1975. Just the results of these investigations made the basis of the QPNM.

2. Basic assumptions of the quasiparticle-phonon nuclear model (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

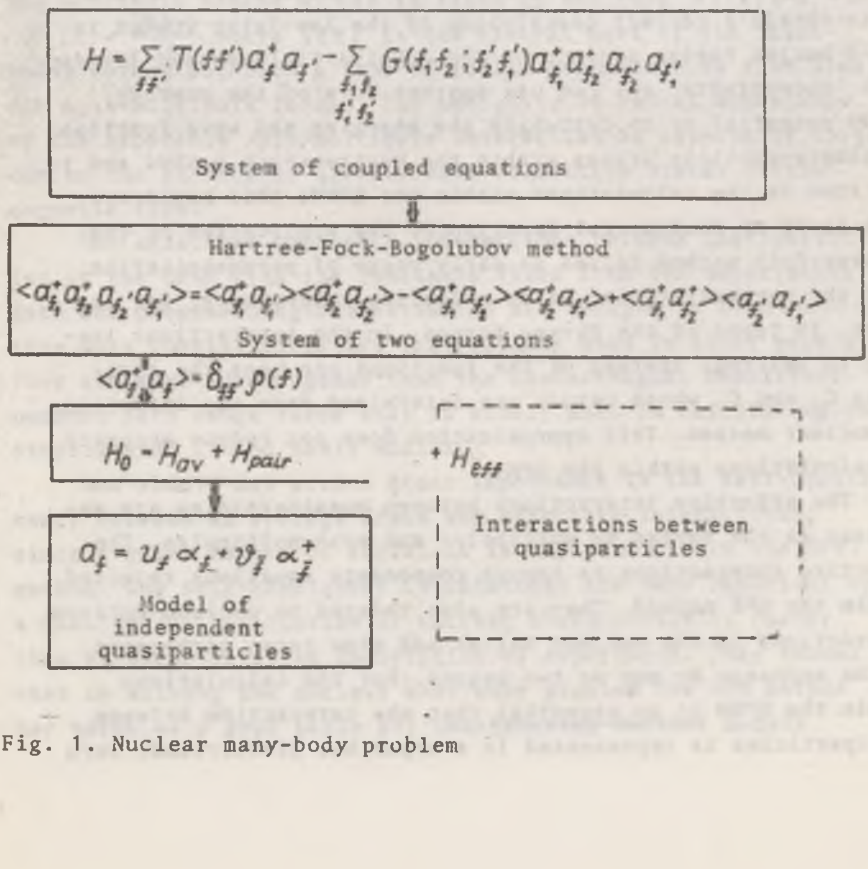

Fig. 1. Nuclear many-body problem

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.

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 Hartree-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 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 interations 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 quasiparticlesin 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 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 $R_\lambda(r) = r^\lambda$ 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.

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 thery [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 introductions, 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

$$H_{QPhNM} = \sum_{jm} \varepsilon_j \alpha^{+}_{jm}\alpha_{jm} + H_{v} + H_{vq} , \qquad (1)$$

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. This is the first specific feature of the QPNM.

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 $K^{\pi} = 0^{+}, 1^{+}, 2^{+}, \dots 7^{+}$. In spherical nuclei the multipole forces are used to construct one-phonon states with $J^{\pi} = 1^{-}, 2^{+}, 3^{-}, \dots 7^{-}$ and spin-multipole forces for the states with $J^{\pi} = 1^{+}, 2^{-}, 3^{+}, \dots 7^{-}$.

$$H = H_{av} + H_{pair} + \underbrace{H_M + H_S + H_T}$$

separable form

↓

$$a_f = U_f \alpha_f + v_f \alpha_{\bar f}^+$$

$$\underset{RPA}{\Omega_{\lambda\mu i}} \begin{Bmatrix} \alpha_f^+ & \alpha_{f'}^+ \\ \alpha_{f'} & \alpha_f \end{Bmatrix} \Rightarrow \underset{RPA}{Q_{\lambda\mu i}} \qquad \alpha_f^+ \; \alpha_{f'}$$

np-phonon　　　phonon　　　quasiparticles

RPA-equations, phonon space, all the constants are fixed

↓

$$H_{QPhNM} = \underbrace{\sum_f \varepsilon_f \alpha_f^+ \alpha_f + H_v} + H_{vq}$$

quasiparticle and phonons　　　quasiparticle-phonon interaction

⇓

Approximate solutions

$$\Psi_\nu^o = \left\{ \sum C\alpha^+ + \sum D\,\alpha^+ Q^+ + \sum F \alpha^+ Q^+ Q^+ \right\} \Psi_0 \,,$$

$$\Psi_\nu^{e\text{-}e} = \left\{ \sum R Q^+ + \sum P Q^+ Q^+ \right\} \Psi_0$$

$$\Psi_\nu^{o\text{-}o} = \left\{ \bar{\sum} \bar{R}\, \Omega^+ + \sum \bar{P}\, \Omega^+ Q^+ \right\} \Psi_0$$

$$\delta \left\{ \langle \Psi_\nu | H_{QPhNM} | \Psi_\nu \rangle - \eta_\nu \langle \Psi_\nu | \Psi_\nu \rangle \right\} = 0$$

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

Method of strength functions

$$b(\eta) = \sum \frac{\Delta}{2\pi} \frac{B_\nu}{(\eta - \eta_\nu)^2 + \Delta^2/4} = \frac{1}{\pi} \mathcal{I}m \frac{\bar{P}(\eta + i\Delta/2)}{\mathcal{F}(\eta + i\Delta/2)}$$

Fig. 2. Scheme of calculations within the QPNM

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.

The second specific feature of the model is: 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 the third specific feature of the model. 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.

The fourth specific feature of the model is the use of the strength function method. 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 densities, 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 $\otimes$ 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

$$\Psi_\nu(JM) = C_{J\nu}\Big\{\alpha^+_{JM} + \sum_{\lambda i j} D_j^{\lambda i}(J\nu)[\alpha^+_{jm} Q^+_{\lambda\mu i}]_{JM} + \sum_{\lambda_1 i_1 \lambda_2 i_2 j I} F_{jI}^{\lambda_1 i_1 \lambda_2 i_2}(J\nu)[\alpha^+_{jm}[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{IM'}]_{JM}\Big\}\Psi_0 , \quad (2)$$

$$\Psi_\nu(JM) = \Big\{\sum_i R_i(J\nu) Q^+_{\lambda\mu i} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P_{\lambda_2 i_2}^{\lambda_1 i_1}(J\nu)[Q^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{JM}\Big\}\Psi_0 , \quad (3)$$

$$\Psi_\nu(JM) = \Big\{\sum_i \bar{R}_i(J\nu)\, \Omega^+_{\lambda\mu i} + \sum_{\lambda_1 i_1 \lambda_2 i_2} \bar{P}_{\lambda_2 i_2}^{\lambda_1 i_1}(J\nu)[\Omega^+_{\lambda_1\mu_1 i_1} Q^+_{\lambda_2\mu_2 i_2}]_{JM}\Big\}\Psi_0 \quad (4)$$

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} (1) over (2) or (3) or (4). Using the variational principle and taking into account the normalization of the wave function (2) or (3) or (4), we get the secular equation for the energies of excited states and write it down as

$$\mathcal{F}(\eta_\nu) = 0 \quad (5)$$

We also get the systems of equations for the coefficients of the wave functions (2) or (3) or (4).

3. Investigations in the QPNM

The results of calculations in the QPNM of the properties of spherical and deformed nuclei defined by the fragmentation of one-quasiparticle, one-phonon and quasiparticle ⊗ phonon configurations were published in many papers, reviews and reports [7-11,18-22] .

The following nuclear characteristics are calculated within the QPNM:

1) Low-lying nonrotational states of deformed nuclei[23-27],

2) fragmentation of one-quasiparticle and two-quasiparticle states in deformed nuclei [17-29],

3) fragmentation of one-quasiparticle states in spherical nuclei [20,22,30-32],

4) fragmentation of two-quasiparticle states in spherical nuclei [10,33],

5) neutron s-, p-, d-wave strength functions in spherical and deformed nuclei [10,17,19,22,32,34],

6) radiative E1-, E2- and M1-strength functions for transitions from neutron resonances to the ground states of spherical and deformed nuclei [35-37],

7) γ-decay of deep hole states [38],

8) photoabsorption cross sections in the region of the giant dipole resonance tail in spherical nuclei [10,32,35-39],

9) positions, widths and transition densities for $E\lambda$- and $M\lambda$-giant resonances in spherical and deformed nuclei [8,10,21,32,32,40,41],

10) strength distribution of the charge-exchange Gamow-Teller and spin-dipole resonances in spherical and deformed nuclei [18,42,43],

11) description of the scattering of photons, electrons and protons with excitation of giant $E\lambda$- and $M\lambda$-resonances [44] 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.

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

The phenomenological interacting boson model (IBM) has been formulated by Arima and Iachello [45] on the basis of the group theory method. This model has first been put forward by Janssen, Jolos and Denau [46]. A considerable contribution to the development of the IBM was made by Szpikowski [47]. To show the efficiency of the QPNM, we shall consider the confrontation between the QPNM and the IBM in describing deformed nuclei [48].

Compare now the description of the $K^{\pi}=0^{+}$, 2^{+}, 4^{+} states of doubly-even deformed nuclei within the IBM and the QPNM. The γ-vibrational states are particle-hole excitations in the QPNM and particle-particle (hole-hole) ones in the IBM. Since in the sd IBM the whole space of two-quasiparticle states with $K^{\pi}=0^{+}$ and 2^{+} is the one entering into one-boson $n_{\gamma}=1$ and $n_{\beta}=1$

states, the interaction between bosons leads to distribution of their strength to the 0^+_3, 0^+_4, 2^+_2 and 2^+_3 states. The wave functions of the 0^+_3, 0^+_4, 0^+_5, 2^+_2, 2^+_3 and 2^+_4 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 is mainly determined by the set of two-quasiparticle components that are absent in the IBM. There is a fundamental difference in describing these states within the QPNM and the IBM.

The inclusion of the g boson in the IBM leads to $K^\pi = 1^+$, 3^+ and 4^+ states containing two-quasiparticle components and to the broadening of the space of two-quasiparticle states with $K^\pi = 0^+$ and 2^+. With the g boson included, some weakly collective states are taken into account in the IBM. These states differ slightly from other weakly collective states which are not taken into account. The inclusion of the g-boson as well as of s′ and d′ bosons contradicts the basic idea of the IBM on the separation of a subspace of collective states. Nevertheless with the g-boson included, the 4^+_1 state has a large two-boson component [49,50]. Among the $K^\pi = 0^+$ and 2^+ states considered, still there are states with large two-phonon configurations.

The existence of collective two-phonon states is the central problem in the study of the structure of nonrotational states of doubly even deformed nuclei. The crucial contradiction between the QPNM on the one hand and the IBM, the Bohr-Mottelson model [51] and its microscopic analogs [52] and the self-consistent-collective-coordinate method[53] on the other hand consists in the existence of two-phonon collective states. According to the QPNM, the deformed nuclei have no two-phonon collective states whereas other models predict their existence.

According to the QPNM, in the two-phonon configurations the Pauli principle shifts the energy centroid by 1-2 MeV towards higher energies with respect to the energy sum of two RPA phonons. As a result, the energy centroid of a two-phonon state becomes larger than 3 MeV. At an energy above 3 MeV a two-phonon state should be fragmented over many nuclear levels. The conclusion on the absence of two-phonon collective states in deformed nuclei has been made in ref.[26] on the basis of the above reasoning.

From the analysis of experimental data it has been concluded [54] that there are no reliably determined two-phonon collective states in deformed nuclei. Numerous experimental investigations in recent years did not lead to the detection of two-phonon states.

The comparison of the results for the nonrotational states with $K^{\pi}=0^{+}$, 2^{+} and 4^{+} calculated within various models between themselves and with the experimental data will be performed for ^{168}Er. The choice of ^{168}Er is caused by the rich experimental data [55-58] and numerous calculations [26,27,48-50, 53,57-59]. The results of calculations for ^{168}Er in the sd IBM [57-59] and sdg IBM [49] contradict the experimental data on 0_3^+, 0_4^+, 2_2^+, 2_3^+ and 2_4^+ states. In a new version of the sdg IBM [50] four types of the interaction with new parameters have additionally been introduced into the Hamiltonian. As a result, some discrepancies with the experimental data including those on the 0^+ state excitations in the (tp) reaction were removed. Nevertheless, in the calculations [50] one of the two states 0_3^+ or 0_4^+ as well as of $K^{\pi}=2_2^+$ or 2_3^+ is a two-phonon state, which contradicts the experimental data. Moreover, according to ref. [56] , the 2_4^+ state having a large two-quasiparticle pp411↑ +411↓ component cannot exist within the sdg IBM [50]. Following ref.[50], the $K^{\pi}=4_1^+$ state has a two-phonon nature and the $K^{\pi}=4^+$ state with a large one-phonon hexadecapole component lies at 3.8 MeV. In all the calculations within the sd and sdg IBM the 4_1^+ state is the two-phonon one.

The comparison of different models should be performed for many deformed nuclei in the rare-earth and actinide regions so that the specific features of one nucleus could not distort the general picture. Thus, there are still discrepancies between the sdg IBM and the experimental data in describing the $K^{\pi}=4_1^+$ and 4_2^+ states in ^{156,158}Gd and ^{160,164}Dy and the $K^{\pi}=3_1^+$ and 3_2^+ states in ^{172,174}Yb. The sdg IBM encounters difficulties in describing the $K^{\pi}=2_2^+$ states with large B(E2)-values that are present in many nuclei. The absence of two-phonon 0^+{301, 301} states in the Th and U isotopes, in which there is no stable octupole deformation, is yet to be explained within the IBM, the Bohr-Mottelson model, the method used in ref.[53] and other models. It would be more correct to formulate the IBM so as to provide a unique description of states with positive and negative parity. Such a model there might be the spdfg IBM. It should contain a large number of states in the energy interval 1.5-2.5 MeV, whose wave functions have dominating two-boson components. May the existence of these states be consistent with the available experimental data?

It should be noted that the structure of nonrotational states of doubly even deformed nuclei in the rare-earth and actinide regions is correctly described within the QPNM. In these calculations new interaction parameters are not introduced and, as rule, one uses the single-particle energies and wave functions as well as the one-phonon RPA states calculated more than 15 years ago. The results obtained within the QPNM automatically, can be obtained in the IBM by introducing new parameters.

Further investigations of the structure of deformed nuclei need experiments on measurement of the contribution of two-quasiparticle components to the wave functions of rotational bands based on $K_n^\pi = 0_3^+, 0_4^+, 0_5^+, 2_2^+, 2_3^+, 2_4^+, 3_1^+, 3_2^+, 4_1^+, 4_2^+$ etc. and on search for two-phonon collective states.

Conclusion

Within the quasiparticle-phonon nuclear model one can calculate many properties of complex nuclei at low, intermediate and high excitations 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.

It 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. S o l o v i e v V. G.: Phys.Lett. 1965, 16, 308-311; Phys.Lett. 1966, 21, 320-322.
2. S o l o v i e v V. G.: Nuclear Structure Dubna Symposium 1968, IAEA, Vienna, 101-118.
3. S o l o v i e v V. G.: Theory of Complex Nuclei, M. Nauka, 1971.
4. S o l o v i e v V. G.: Izv.Akad.Nauk SSSR, ser.fiz. 1971, 35, 666-677; 1974, 38, 1580-1587.
5. S o l o v i e v V. G.: Proceedings of the School on Nuclear Structure, Alushta 1972, 77-123, JINR D-6465 Dubna, 1972; S o l o v i e v V. G., M a l o v L. A.: Nucl.Phys.A, 1972, 196, 443-451.
6. S o l o v i e v V. G.: in "Neutron Capture Gamma-Ray Spectroscopy", 99-117, Reactor Centrum Nederland, Petten, 1975.
7. S o l o v i e v V. G.: Part. and Nucl., 1978, 9, 580-622. S o l o v i e v V. G.: Nucleonica, 1978, 23, 1149-1178.
8. M a l o v L. A., S o l o v i e v V. G.: Part. and Nucl., 1980, 11, 301-341.
9. V d o v i n A. I., S o l o v i e v V. G.: Part. and Nucl., 1983, 14, 227-285.
10. V o r o n o v V. V., S o l o v i e v V. G.: Part. and Nucl., 1983, 14, 1381-1442.
11. V d o v i n A. I. et al.: Part. and Nucl., 1985, 16, 245-279.
12. B r o w n G. E., J a c k s o n A. D.: The Nucleon-Nucleon Interaction, North-Holland P.C. Amsterdam, 1976.
13. T a b a k i n F.: Ann.Phys. 1964, 30, 51-63. S c h m i d E., Z i e g e l m a n n H.: The Quantum Mechanical Three-Body Problem, Pergamon Press, Braunschweig, 1974.
14. K n ü p f e r W., H u b e r M. G.: Phys.Rev.C, 1976, 14, 2254-2268.
15. B e s D., B r o g l i a R. A. et al.: Nucl.Phys.A, 1976, 260, 77-94.

16. V d o v i n A. I. et al.: Part. and Nucl., 1976, 7, 952-988.
17. M a l o v L. A., S o l o v i e v V. G.: Nucl.Phys.A, 1976, 270, 87-107.
18. S o l o v i e v V. G.: Proceedings of the School on Nuclear Structure, Alushta 1980, 57-88, JINR D4-80-385; Alushta 1985, 8-26, JINR D4-85-851, Dubna.
19. V o r o n o v V. V.: Proceedings of IV School on Neutron Physics, 105-116, JINR D3,4-82-704, Dubna, 1982. S t o y a n o v Ch.: ibid., 87-104.
20. S t o y a n o v Ch., V d o v i n A. I.: In proc. School on Nuclear Structure, Alushta 1985, 27-50, JINR D4-85-851, Dubna.
21. S o l o v i e v V. G.: In Proc. Symposium Nuclear Excited States, 87-89, Publ. Wydawnictwo Univ.Lodzkiego, Lodz, 1985.
22. S o l o v i e v V. G.: In Proc. Intern. Symposium Neutron Indused Reactions, 155-173, Reidel Publ. C., Dordrecht, 1985. V d o v i n A. I., S t o y a n o v Ch.: ibbid., 188-199.
23. S o l o v i e v V. G.: Atomic Energy Rew. 1965, 3, 2, 117-193.
24. G r i g o r i e v E. P., S o l o v i e v V. G.: Structure of Even Deformed Nuclei, M., Nauka, 1974. I v a n o v a S. P. et al.: Part. and Nucl., 1976, 7, 450-498.
25. G a r e e v F. A. et al.: Part. and Nucl., 1973, 4, 357-455.
26. S o l o v i e v V. G., S h i r i k o v a N. Yu.: Z.Phys.A. 1981, 301, 263-269. S o l o v i e v V. G., S h i r i k o v a N. Yu.: Yad.Fiz., 1982, 36, 1376-1386.
27. N e s t e r e n k o V. O., S o l o v i e v V. G., S u s h k o v A. V., S h i r i k o v a N.Yu.: Yad.Fiz., 1986, 44, 1443-1450.
28. V d o v i n A. I. et al.: Izv. Akad. Nauk SSSR, ser.fiz., 1985, 49, 834-842.
29. N g u y e n D i n h V i n h, S o l o v i e v V. G.: Yad. Fiz., 1986, 43, 1162-1168.
30. S o l o v i e v V. G., S t o y a n o v Ch., V d o v i n A. I.: Nucl.Phys.A, 1980, 342, 261-282.

31. C h a n Z u y K h u o n g, S o l o v i e v V. G., V o r o n o v V. V.: J.Phys.G: Nucl.Phys. 1981, 7, 151-163.
V d o v i n A. I., N g u y e n D i n h T h a o, S o l o v i e v V. G., S t o y a n o v Ch.: Yad.Fiz., 1983, 37, 43-51.
S t o y a n o v Ch., V d o v i n A. I.: Phys.Lett.B, 1983, 130, 134-138.
V d o v i n A. I., S t o y a n o v Ch.: Yad.Fiz., 1985, 41, 1134-1140.
32. S o l o v i e v V. G., S t o y a n o v Ch., V o r o n o v V. V.: Nucl.Phys.A, 1983, 399, 141-162.
33. S o l o v i e v V. G., S t o y a n o v a O., V o r o n o v V. V.: Nucl.Phys.A, 1981, 370, 13-29.
V o r o n o v V. V.: J.Phys.G: Nucl.Phys., 1983, 9, L273-L277.
34. V o r o n o v V. V., Z h u r a v l e v I. P.: Yad.Fiz., 1983, 38, 52-58.
D a m b a s u r e n D. et al.: J.Phys.G: Nucl.Phys., 1976, 2, 25-31.
V o r o n o v V. V., S o l o v i e v V. G., S t o y a - n o v a O.: Yad.Fiz., 1980, 31, 327-334.
35. V o r o n o v V. V., S t o y a n o v Ch.: Nucl.Phys. 1985, 11, L97-L100.
S o l o v i e v V. G., S t o y a n o v Ch., V o r o n o v V. V.: Nucl.Phys.A, 1978, 304, 503-519.
36. S o l o v i e v V. G., S t o y a n o v Ch.: Nucl.Phys.A, 1982, 382, 206-220.
37. M a l o v L. A., M e l'i e v F. M., S o l o v i e v V. G.: Z.Phys.A, 1985, 320, 521-527.
38. P o n o m a r e v V. Yu., S o l o v i e v V. G., S t o y a n o v Ch., V d o v i n A. I.: Preprint JINR E4-86-396, Dubna, 1986.
39. V o r o n o v V. V., D a o T i e n K h o a: Izv.Akad. Nauk SSSR, ser.fiz., 1984, 48, 2008-2015.
40. S o l o v i e v V. G., S t o y a n o v Ch., V d o v i n A. I.: Nucl.Phys.A, 1977, 288, 376-396.
P o n o m a r e v V. Yu. et al.: Nucl.Phys.A, 1979, 323, 446-460.
V o r o n o v V. V. et al.: Yad.Fiz., 1984, 40, 683-689.

V d o v i n A. I.: Izv. Akad Nauk SSSR, ser.fiz., 1979, 43, 2018-2032.

41. P o n o m a r e v V. Yu., S t o y a n o v Ch., V d o v i n A. I.: J.Phys.G: Nucl.Phys. 1882, 8, L77-L83.
P o n o m a r e v V. Yu.: ibid., 1984, 10, L177-L181.
P o n o m a r e v V. Yu., S t o y a n o v Ch., V d o v i n A. I.: Z. Phys.A, 1982, 308, 157-163.

42. K u z m i n V. A., S o l o v i e v V. G.: J.Phys. G: Nucl. Phys., 1984, 10, 1507-1522; 1985, 11, 603-612.

43. S o l o v i e v V. G., S u s h k o v A. V., S h i r i k o v a N. Yu.: Z.Phys. A, 1984, 316, 65-74.

44. R e i f R. et al.: J.Phys.G: Nucl.Phys. 1982, 8, 257-265.
A k u l i n i c h e v S. V. et al.: Yad.Fiz., 1978, 28, 883-892.
P o n o m a r e v V. Yu.: Yad.Fiz., 1985, 41, 79-84.
A k u l i n i c h e v S. V., S h i l o v V. M.: Yad.Fiz., 1978, 27, 670-678.

45. A r i m a A., I a c h e l l o F.: Phys.Rev.Lett., 1975, 35, 1069-1072; Ann. of Phys. 1976, 99, 253-317.

46. J a n s s e n D., J o l o s R. V., D ö n a u F.: Nucl. Phys.A, 1974, 224, 93-115.

47. S z p i k o w s k i S., G o z d z A.: Nucl.Phys.A, 1980, 340, 76-92.
G o z d z A., S z p i k o w s k i S., Z a j a c K.: Nucleonica, 1980, 25, 1055-1064.

48. S o l o v i e v V. G.: Pis'ma ZhETPh, 1984, 40, 398-401.
S o l o v i e v V. G.: Z.Phys.A, 1986, 324, 393-401.

49. W u H u a - C h u a n, Z h o X i a o - Q i a n: Nucl.Phys. A, 1984, 417, 67-76.

50. Y o s h i n a g a N., A k i y a m a Y., A r i m a A.: Phys.Rev.Lett., 1986, 5, 1116-1119.
A k i y a m a Y., H e y d e K., A r i m a A., Y o s h i n a g a N.: Phys.Lett.B, 1986, 173, 1-4.

51. B o h r A., M o t t e l s o n B.: Nuclear Structure, 2, Benjamin, INC, London, 1975; Physica Scripta, 1982, 25, 28-36.

52. M a t s u o M., M a t s u y a n a g i K.: Prog.Theor.Phys., 1985, 74, 1227-1244.

54. P e k e r L. K., H a m i l t o n J. H.: Future Directions in Studies of Nuclei far from Stability, ed. Hamilton,

Amsterdam, North-Holland P.C., 1980, 323-335.
55. D a v i d s o n W. F. et al.: Phys.Lett.B, 1983, 136, 161-166.
56. B u r k e D. G. et al.: Nucl.Phys.A, 1985, 445, 70-92.
B u r k e D. G., M a d d o c k B. L., D a v i d s o n W. F.: Nucl.Phys.A, 1985, 442, 424-459.
57. D a v i d s o n W. F., W a r n e r D. D., C a s t e n R. F. et al.: J.Phys.G: Nucl.Phys. 1981, 7, 455-528; 843.
B u r k e D. G., D a v i d s o n W. F., C i z e w s k i J. A. et al.: Can. J.Phys., 1985, 63, 1309-1319.
58. G o v i l I. M., F u l b r i g h t H. W., C l i n e D. et al.: Phys.Rev.C, 1986, 33, 793-803.
59. W a r n e r D. D., C a s t e n R. F., D a v i d s o n W. F.: Phys.Rev.C, 1981, 24, 1713-1727.

STRESZCZENIE

W pracy przedyskutowano założenia modelu kwazicząstkowo-fononowego (QPNM) oraz zastosowanie tego przybliżenia w opisie wielu własności jąder atomowych. Przedstawiono także porównanie QPNM z modelem oddziałujących bozonów (IBM).

Р Е З Ю М Е

В работе рассматриваются основы квазичастично-фононной модели (QPNM) и применение этого приближения для описания многих свойств атомных ядер. Приводится тоже сравнение QPNM с моделью взаимодействующих бозонов (IBM).