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ON THE STRUCTURE OF NONROTATIONAL STATES OF DEFORMED NUCLEI

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Low-lying nonrotational states of even-even deformed nuclei are treated as two-quasiparticle or collective vibrational states[1-4]. Within the microscopic approach in the random-phase approximation (RPA) states $\lambda\mu i$ are calculated with fixed multipolarities $\lambda\mu, \mu \equiv K$, and the number of roots i of the secular equation equals the number of two-quasiparticle neutron and proton states. The first excited ($i=1$) $K^{\pi}=2^+_1$ and 0^+_2-states are collective γ- and β-vibrational states, further ($i=2, 3, 4, \ldots$) there occur slightly collective states, and finally, collective states forming giant resonances. The wave function is a superposition of two-quasiparticle particle-hole components. The wave function of the first collective states contains the large number of two-quasiparticle components. However, only a small part of the space of two-quasiparticle states is taken into consideration.

A more exact description of the nonrotational states of deformed nuclei is given by the quasiparticle-phonon nuclear model (QPNM) [5,6]. The model wave function is there written as a sum of one- and two-phonon components, and the Pauli principle is exactly taken into account in the two-phonon components. As is shown in[6], the first excited state with a fixed K^{π}-value is collective (the contribution of the one-phonon state with $i=1$ exceeds 80-90%), the contribution to the wave functions of the second, third, and other states from the one-phonon components with $i=2, 3, \ldots$ exceeds 80%. In ref.[6] the conclusion is made that the collective two-phonon states should not exist in deformed nuclei that is confirmed by the experimental data. According to new experimental data[7], the state $I^{\pi}=4^+$ 2.03 MeV in ^{168}Er earlier specified by K=4 and interpreted in[8,9] as a two-phonon state has K=0 and is not a two-phonon state.

In recent years a lot of calculations has been made within the interacting boson model (IBM)[10]. In that model the states $K^{\pi}=0^+$

and 2^+ are described with the help of their approximate classification[9,11,12] in terms of the numbers n_β of β- and n_γ of γ-vibrational phonons. For the first $K^{\pi}=2^+_1$ γ-vibrational states $n_\gamma=1$, for the second 2^+_2 $n_\gamma=1$ and $n_\beta=1$, etc., whereas for the first excited $K^{\pi}=0^+_2$ β-vibrational states $n_\beta=1$, for 0^+_3 $n_\gamma=2$, for 0^+_4 $n_\beta=2$, and so on. In IBM the states 2^+_1 and 0^+_2 have almost the same two-quasiparticle components as the one-phonon γ- and β-vibrational states in RPA. The microscopic description of γ- and β-vibrational states in IBM and QPNM is similar. A drawback of the phenomenological IBM is that it cannot use the experimental data from (dp) and (dt) reactions on the quasiparticle structure of phonons.

There is a strong distinction in the description of the structure of some states of even-even deformed nuclei in IBM and in QPNM. In IBM the wave functions of $K^{\pi}=2^+_2, 2^+_3, \ldots, 0^+_3, 0^+_4, \ldots 4^+_2, \ldots$ consist of components $n_\gamma=2$, $n_\beta=2$, $n_\gamma=1$, and $n_\beta=1$ and have no two-quasiparticle or one-phonon components, while in QPNM these functions contain large one-phonon ($i=2, 3, \ldots$) components and have no large two-phonon components. Within the microscopic approach in IBM account is taken only of the small part of two-quasiparticle states contained in the γ- and β-vibrational phonons. In QPNM the structure of the above states is defined by another set of two-quasiparticle states absent in IBM. What of these two descriptions is more correct, can be verified by experimental data on the structure of the above states obtained mainly from the one- and two-nucleon transfer reactions. Experimental data for ^{168}Er and ^{158,156}Gd[7,13-16] and results calculated in QPNM[6,17] for ^{168}Er and ^{158}Gd are presented in the Table. There are also reported the available data showing the value of one-phonon components and their structure. For ^{168}Er and ^{158,156}Gd the energy and structure of γ- and β-vibrational states are well described by QPNM and are not listed in the Table.

Experimentally, ^{168}Er is most thoroughly studied[13]. Rotational bands based on states $K^{\pi}=0^+_3$, 0^+_4 and 2^+_2 get much excited in the (tp) reaction. The ^{169}Tm ($\vec{t}\alpha$) ^{168}Er data show that 0^+_4 1.834 MeV state has the large two-quasiparticle configuration pp411↓ -411↑. This means that the wave functions of these states have large one-phonon components. The state $K^{\pi}=4^+_1$ 2.056 MeV decays into the band with $K^{\pi}=4^-$, 1.094 MeV and according to[7] has no large two-phonon (221,221) components. The wave functions calculated in QPNM[6,17] and listed in the Table for states of ^{168}Er have large one-phonon components, whereas the above states calculated in IBM[11,12] consist of two and three bosons, i.e., they possess large components $n_\gamma=2$, $n_\beta=2, n_\gamma=1$ and $n_\beta=1$, etc., and have no one-phonon components.

Table. Structure of some states of deformed nuclei

Nucleus	K^π	experiment[7,13-16] E, MeV	experiment[7,13-16] structure	QPNM calculation[6,17] E, MeV	QPNM calculation[6,17] structure
^{168}Er	0_3^+	1.422	(tp) 10% of ground state	1.6	202 93% * 202: nn521↑ −521↑ 6%
	0_4^+	1.834	(tp) 2,4% of ground state (tα) pp411↓ −411↓ large	1.9	203 96% 203: pp411↓ −411↓ 30%
	2_2^+	1.848	(tp) 60% of 2^+ ground state	1.7	222 98% 222: nn512↑−521↓ 90%
	2_3^+	1.930		1.9	223 96%
	4_1^+	2.056	no large two-phonon component	1.8	441 83% {221,221} 1%
^{158}Gd	0_3^+	1.452	$B(E2)=19e^2b^2$ (pt) 23% of gr.st.	1.8	202 96% 202: nn521↑ −521↑ 69%
	0_4^+	1.743	(tα) pp411↑− 411↑ large	2.0	203 37%; 205 51% 203: pp411↑ −411↑ 45%
	4_1^+	1.380	(tα) pp411↑ +413↓ large	1.5	441 96% 441: pp411↑ +413↓ 95%
	4_2^+	1.920	(dp) nn521↑+523↓ large	1.7	442 92% 442: 521↑ +523↓ 90%
^{156}Gd	0_3^+	1.168	$B(E2)=15e^2b^2$ excited in (dp) and (dt) reactions		
	0_4^+	1.715	excited in (dt) reaction		
	2_2^+	1.828			
	4_1^+	1.510	pp411↑ +413↓ large		
	4_2^+	1.861	(dt) nn521↑ +523↓ **large**		

* The phonon is denoted by $\lambda\mu i$, its contribution to the wave-function normalization is given in %, neutron nn and proton pp components are represented by asymptotic quantum numbers $Nn_z\Lambda$ (↑ for K = =Λ+1/2, ↓ for K = Λ −1/2).

In both the isotopes ^{158}Gd and ^{156}Gd there were experimentally observed three bands constructed on excited $K^\pi=0^+$ states, and in both the nuclei states 2^+0_2 and 2^+0_3 have large B(E2)-values for transitions into the ground states. According to the IBM calculations /15,16/ only one of the states, either 2^+0_2 or 2^+0_3, has the large B(E2)-value, but not both simultaneously. For 0_3^+ and 0_4^+ states experiment gives large one-phonon components. The two-quasiparticle configuration pp411↓ −411↓ in 0_4 of ^{158}Gd is clearly seen in the (tα) reaction. States $K^\pi=4_1^+$ and 4_2^+ in both the nuclei possess large two-quasiparticle components pp411↑ +413↓ and nn521↑ +523↓, respectively.

From the experimental data on states $K^\pi=0_3^+$, 0_4^+, 2_2^+, 4_1^+ and 4_2^+ presented in the Table it is clear that their wave functions contain large one-phonon or two-quasiparticle components which are qualitatively well described by QPNM and are not reproduced by IBM. States of this type are also observed in other nuclei, e.g., in Yb and Hf isotopes. The same concerns $K^\pi=3^+$ and other states. The agreement of the IBM calculations with experimental data on energies and B(E2)-values is not sufficient: the structure of states should be described correctly. The states with large one-phonon components (except 0_2^+, 2_1^+ and 4_1^+, with the g-boson being included) are to be removed from the IBM calculations. The main defect of IBM, the consideration of a small part of the space of two-quasiparticle states, cannot be eliminated by an optimal choice of parameters. Note that in the spherical nuclei states of the above considered type are higher than the two-phonon states, and the contradictions mentioned have not yet been observed there.

A further study of the structure of even-even deformed nuclei requires experimental measurements of the contribution of two-quasiparticle components to the wave functions of rotational bands constructed on $K^\pi=0_3,\ldots$, $2_2^+\ldots$, $3_1^+,\ldots$, $4_1^+\ldots$, and other states at energies 1.5-2.5 MeV and search for two-phonon collective states.

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О структуре неротационных состояний деформированных ядер

Согласно экспериментальным данным волновые функции ряда $K^{\pi} = 0^+_3, 0^+_4, 2^+_2, 2^+_3, 4^+_1, 4^+_2$ состояний в деформированных ядрах имеют большие однофононные или двухквазичастичные компоненты, что качественно согласуется с квазичастично-фононной моделью ядра и противоречит модели взаимодействующих бозонов.

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