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HEXADECAPOLE STATES IN DEFORMED NUCLEI

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1. Introduction

The quadrupole and octupole vibrational states are the most correctly described in the random phase approximation (RPA) and well studied experimentally among the low-lying states in doubly even nuclei[1-5]. There are numerous experimental data on the low-lying $K^{\pi} = 3^{+}$ and 4^{+} states (K is momentum projection onto the nuclear symmetry axis) in the rare-earth region[4,6-23]. The states with $K^{\pi}=4^{+}$ in Gd and Dy isotopes have large two-quasiparticle components[4,6-8]. The mixing of neutron and proton two-quasiparticle components in the 3^{+} states has been observed in Yb isotopes in transfer reactions [12,13]. In some nuclei in the region A≈170 the states $I^{\pi}K=4^{+}3$ are excited with large cross sections in the reaction (d,d')[12]. According to the experimental data[20] there are strong E4 transitions in the excitation of $I^{\pi}K=4^{+}4$ states in Os isotopes in (α,α') reaction. They indicate the hexadecapole structure of these states.

The available experimental data necessitate studies of hexadecapole states in deformed nuclei. The present paper is aimed at calculating the energies and B(E4)-values for the low-lying nonrotational $K^{\pi}=3^{+}$ and 4^{+} states and elucidating to what extent these states are collective. We also consider the influence of hexadecapole forces on $K^{\pi}=2^{+}$ states, which is concluded from the experimental data of $(\bar{p},\bar{p}')$ reaction for ^{168}Er[26].

It is necessary to investigate hexadecapole states for solving the problem of existence of two-phonon collective states in deformed nuclei. A correct inclusion of the Pauli principle in two-phonon components of the wave function enabled one to make a conclusion about the absence of collective two-phonon states in deformed nuclei[27,28]. The study of $K^{\pi}=4^{+}$ and 3^{+} states enables one to compare[29] the results of calculations within the quasiparticle-phonon nuclear model (QPNM) and the interacting boson model (IBM) (particularly, in the case of introduction of g-boson into the IBM)[23-25].

2. Details of calculations

The Hamiltonian of the quasiparticle-phonon nuclear model (QPNM) consists of an average field of the neutron and proton systems as the Saxon-Woods potential, superconducting pairing correlations and the multipole isoscalar and isovector forces. A phonon basis is constructed in the RPA. Using then the RPA secular equations the QPNM Hamiltonian is transformed to

$$H = \sum_{q\sigma} \varepsilon_q \alpha^{+}_{q\sigma} \alpha_{q\sigma} + H_{\nu} + H_{\nu q} \qquad (1)$$

containing free quasiparticles and phonons and the quasiparticle-phonon interaction $H_{\nu q}$. Here ε_q is the quasiparticle energy, $\alpha^{+}_{q\sigma}$ and $\alpha_{q\sigma}$ are the quasiparticle creation and absorption operators, $q\sigma$ are quantum numbers of single-particle states, $\sigma=\pm 1$.

Hexadecapole nonrotational states with $K^{\pi}=3^{+}$ and 4^{+} are generated by multipole isoscalar and isovector forces with $\lambda=4$. However, as the calculations showed, the role of isovector forces is negligible and one can use formulae given in ref. /28/ for the isoscalar case.

The wave function of a nonrotational excited state of a doubly even nucleus is

$$\Psi_n(K^{\pi}_{\sigma}) = \Big\{ \sum_i R^n_i Q^{+}_{g\sigma} + \sum_{\substack{g_1\sigma_1 \\ g_2\sigma_2}} \frac{\sqrt{1+\delta_{g_1 g_2}}}{2} \delta_{\sigma_1\mu_1+\sigma_2\mu_2,\sigma K} P^n_{g_1 g_2} Q^{+}_{g_1\sigma_1} Q^{+}_{g_2\sigma_2} \Big\} \Psi_0 \qquad (2)$$

with the normalization condition

$$\sum_i (R^n_i)^2 + \sum_{g_1 g_2} \frac{1+\delta_{g_1 g_2}}{2} (P^n_{g_1 g_2})^2 \Big\{ 1 + \frac{1}{1+\delta_{g_1 g_2}} \mathcal{K}^K(g_2 g_1 | g_1 g_2) \Big\} = 1 . \qquad (3)$$

Here $Q^{+}_{g\sigma}$ is the phonon creation operator, $g=\lambda\mu i$, $i=1,2,\ldots$ are numbers of the roots of secular equations in the RPA, Ψ_0 is the ground state wave function of a doubly even nucleus, $n=1,2,\ldots$ is number of the state with given K. The notation and equations for the energies of excited states and the amplitudes R^n_i and $P^n_{g_1 g_2}$ are given in ref. /28/. It should be noted that these equations were derived by taking strict account of the Pauli principle in the two-phonon components of the wave function (2).

The calculations have been performed with the parameters of the Saxon-Woods potential from refs. /30,32/. The single-particle spectrum was taken from the bottom of the potential well up to +5 MeV. The pairing interaction constants were chosen according to pairing energies and the constants of residual multipole-multipole forces were adjusted so as to reproduce of experimental energies of the lowest nonro-

tational states using the wave function (2), for the isovector forces $\varkappa_1^{(\lambda\mu)} = -1.2\varkappa_0^{(\lambda\mu)}$ /30/. The radial dependence of residual forces was taken in the form $R(r) = \frac{\partial V(r)}{\partial r}$ where $V(r)$ is the spherical Saxon-Woods potential. The multipolarities $\lambda\mu$ =20,22,30,31,32,43,44 were taken into account, 10 RPA-phonons were used for each multipolarity. The reduced $E\lambda$ transition probabilities were calculated in the adiabatic approximation with $e_{eff}=0.1$. The two-quasiparticle state energies were calculated taking account of the blocking effect and the Gallagher-Moszkowski corrections. The latter was calculated by formula $\Delta\varepsilon_{qq'} = \varkappa_{\sigma\sigma}\langle q|\sigma_z|q\rangle\langle q'|\sigma_z|q'\rangle$ where $\varkappa_{\sigma\sigma}=0.26$ MeV is the constant of the isovector spin-spin interaction /31/ and $\langle q|\sigma_z|q\rangle$ is the single-particle matrix element.

The energies and wave functions of $K^{\pi}_n = 3^{+}_1$, 3^{+}_2, 4^{+}_1 and 4^{+}_2 states have been calculated with the constants $\varkappa_0^{(43)}=0.015\,\frac{fm^2}{MeV}$ and $\varkappa_0^{(44)} = 0.022\,\frac{fm^2}{MeV}$. The difference in values of the constants $\varkappa_0^{(43)}$ and $\varkappa_0^{(44)}$ is caused by the inclusion of only particle-hole excitations in the calculations of hexadecapole states and by that number of matrix elements of the particle-hole type at $\lambda\mu=44$ is less than at $\lambda\mu=43$ (for matrix elements of the particle-particle type we have an inverse case). The single-particle matrix elements of hexadecapole forces are close in value at different values of μ but on the average the particle levels have larger values of K than the hole ones. The calculations have shown that the use of an incomplete single-particle basis ($E_q < +5$ MeV) results in $\varkappa_0^{(42)} < \varkappa_0^{(43)}$. If the calculations are performed with the forces $R(r) = r^{\lambda}$ the relevant value of $\varkappa_0^{(44)}$ we used turns out to be larger than in ref. /30/ in describing the giant hexadecapole resonance.

3. Properties of $K^{\pi}=3^{+}$ and 4^{+} states

Now we consider the low-lying states with $K^{\pi}=3^{+}$ and 4^{+}. The results of calculations and experimental data /4,6-23/ are shown in table 1. It includes the experimental energies, state structure and contribution of one-phonon components as well as the values calculated within the QPNM, namely reduced probabilities of E4 transitions to $4^{+}K$ states from the ground one, contributions of one-phonon configurations, the largest two-quasiparticle components. In the table phonons are denoted by $\lambda\mu i$, their contribution to the wave function normalization is given in per cent. To denote the neutron (nn) and proton (pp) components the asymptotic quantum numbers $Nn_z\Lambda$ ($\uparrow$ for $K=\Lambda+\frac{1}{2}$ and $\downarrow$ for $K=\Lambda-\frac{1}{2}$) were used.

In the Gd and Dy isotopes there are one or two $K^{\pi}=4^+$ states with an energy less than 2 MeV/4,6-8/. According to the calculations these states are slightly collectivized, for which B(E4)=0.1÷0.4 spu. The two-quasiparticle neutron configuration nn523↓+521↑ appears in the excitation of $K^{\pi}=4^+$ states in (d,p), (d,t) reactions and β-decay of the au type. Of great importance is the proton configuration pp413↓+ +411↑ in (t,α) reactions. It should be noted that ^{164}Dy and ^{166}Er have almost four-quasiparticle $K^{\pi}=3^+$ and 4^+ states (for instance the 4_2^+ state in ^{164}Dy shown in table 1)/4/.

In ^{166,168}Er the calculations with $\varkappa_0^{(44)}=0.022$ fm^2/MeV provide energies by 0.5 MeV higher than the experimental values and B(E4)<0.1 spu. In ^{168}Er according to the calculations with $\varkappa_0^{(44)}=0.022$ fm^2/MeV there are two states 4_1^+ and 4_2^+ with energies 2.57 and 2.59 MeV. For their wave functions the calculations give mixing of phonons 441 and 442 with structure 441:nn514↓+521↓- 99.8% and 442:nn512↑+521↑ -99.7%. In order the energy of the 4^+ state in ^{168}Er be equal to 2 MeV, one has to take $\varkappa_0^{(44)}=0.035$ fm^2/MeV. In this case the collectivity of the 4^+ state will explicitly be overestimated (see table 1).

In the Sm, Gd and Dy isotopes there are no reliable data on $K^{\pi}=3^+$ states with an energy less than 2 MeV. The analysis of (d,d') reaction with excitation of $I^{\pi}K=4^+3$ states allowed one to make a conclusion on the existence of collective hexadecapole 3_1^+ states in nuclei with N=98-104 and Z=68-72/12/. Our calculations performed with fixed value of the constant $\varkappa_0^{(43)}=0.015$ fm^2/MeV confirm the conclusion on the collectivity of 3^+ states in these nuclei. It is seen from table 1 that the energies of 3_1^+ and 3_2^+ states are qualitatively described in the Er, Yb and Hf isotopes. If in ^{168}Er B(E4) is equal to 0.8 spu, in $^{168-174}$Yb and ^{174,176,178}Hf it takes the valuee from 1.0 to 1.7 spu.

In ^{172,174}Yb there are two $K^{\pi}=3^+$ states with the wave functions consisting of the mixing of two-quasiparticle neutron and proton configurations. This is shown in table 1. The mixing of the neutron nn512↑+521↓ and proton pp404↓-411↓ configurations in 3^+ states in ^{172}Yb has experimentally been observed in ref./13/. The value of the neutron component has been confirmed in ref./12/. The results of calculations of the contribution of neutron and proton configurations to the 3^+ states in ^{172}Yb coincide with the experimental data/12,13/.

The hexadecapole collective $K^{\pi}=4^+$ states have been observed experimentally/20,21/ in Os isotopes. The results of calculations presented in table 1 indicate that beginning from ^{178}Hf the collectivity of 4^+ states increases. In ^{186,188}Os we have B(E4)=4 spu that are

Table 1. Results of calculations for low-lying $K^{\pi}=3^+$ and 4^+ states in rare-earth nuclei

Nucleus	K_n^{π}	Experiment: E, MeV	Experiment: structure	Calculations in the QPNM: E, MeV. B(E4), spu.	Calculations in the QPNM: structure
1	2	3	4	5	6
^{158}Gd	4_1^+	1.380	(t,α), pp411↑+413↓ is large	1.2	441 95%, {221,221} 3.3%
				0.4	441: pp413↓+411↑ 85%
					nn523↓+521↑ 13%
	4_2^+	1.920	(d,p), nn521↑+523↓ is large	1.7	442 98%
				0.01	442: nn523↓+521↑ 87%
					pp413↓+411↑ 12%
^{160}Gd	4_1^+	1.184		1.2	441 93%, 442 3%, {221,221} 1%
				0.3	441: nn523↓+521↑ 53%
					pp413↓+411↑ 46%
^{158}Dy	4_1^+	1.895	logft=4.9: nn521↑+523↓ is large	2.2	441 92%, 442 6%
				0.4	441: pp413↓+411↑ 36%
					nn523↓+521↑ 28%
^{160}Dy	4_1^+	1.694	logft=4.7: nn521↑+523↓ is large	1.7	441 98%, {221,221} 0.6%
				0.1	441: nn521↑+523↓ 85%
	4_2^+	2.096	logft=5.8	2.0	442 85%, {201,442} 6%
				0.1	442: nn642↑+651↑ 74%
					nn523↓+521↑ 8%
^{162}Dy	4_1^+	1.535	(d,t), nn521↑+523↓ is large	1.7	441 98%
				0.2	441: nn523↓+521↑ 92%

continuation of table 1

1	2	3	4	5	6
^{164}Dy	4^+_1	2.194	logft=5.6	2.2	441 99%
				0.3	441: pp413↓+411↑ 66%
					nn523↓+521↑ 30%
	4^+_2	2.206	logft=5.0:{ pp523↑-411↑ +	2.6	{321,761} 100%
			+ *nn633↑+523↓} is large*		*321: pp523↑-411↑ 73%*
					761: nn523↓+633↑ 100%
^{166}Er	4^+_1	1.976		2.0	441 95%, {221,221} 0.8%
					441: nn523↓+521↑ 52%
					nn633↑+660↑ 8%
^{168}Er	3^+_1	1.653	(d,d') is large for 4^+3_1	1.6	431 99%
				0.8	431: nn512↑+521↓ 90%
	4^+_1	2.055	no large two-phonon components	2.0	441 94%, {221,221} 1%
				3.3	441: nn514↓+521↓ 18%
					pp413↓+411↑ 9%
^{170}Er	3^+_1	1.217	(d,d') is large for 4^+3_1	1.2	431 99%
				0.6	431: nn512↑+521↓ 94%
^{168}Yb	3^+_1	1.452	(d,d') is large for 4^+3_1	1.6	431 98%
			(α,2n) } nn 20%	1.6	431: pp404↓-411↓ 61%
			g_k- factor } pp 80%		nn512↑+521↓ 13%
^{170}Yb	3^+_1	<1.470	(d,d') is large for 4^+3_1	1.3	431 99%
				1.4	431: nn512↑+521↓ 66%
					pp404↓-411↓ 24%

continuation of table 1

1	2	3	4	5	6
^{172}Yb	3^+_1	1.172	(d,d') is large for 4^+3_1	1.3	431 99%
			(d,t), (d,p), nn512↑+521↓ 75%	1.3	431: nn512↑+521↓ 68%
			(p,α) } nn512↑+521↓ 73%		pp404↓-411↓ 20%
			magn.mom. } pp404↓-411↓ 27%		
	3^+_2	1.663	(d,t),(d,p), nn512↑+521↓ is noticeable	1.6	432 100%
			(p,α), pp404↓-411↓ 26%	0.4	432: pp404↓-411↓ 52%
					nn512↑+521↓ 30%
	4^+_1	2.073	(p,α), pp404↓+411↓ is noticeable	1.94	441 99%
				$3\cdot10^{-4}$	441: pp404↓+411↓ 99%
^{174}Yb	3^+_1	1.606	(d,d') is large for 4^+3_1	1.4	431 99%
				1.3	431: nn514↓-521↓ 45%
					pp404↓-411↓ 39%
	3^+_2	2.016	(p,t)	1.8	432 100%
				0.1	432: nn514↓-521↓ 52%
					pp404↓-411↓ 40%
^{174}Hf	3^+_1	1.303	(d,d') is large for 4^+3_1	1.3	431 99%
				1.0	431: nn512↑+521↓ 75%
^{176}Hf	3^+_1	1.578	(d,d') is large for 4^+3_1	1.3	431 99%
			(d,t'), nn514↓-521↓ is large	1.2	431: nn514↓-521↓ 72%
					pp404↓-411↓ 12%
	4^+_1	1.888	(d,t), nn514↓+521↓ is large	1.7	441 100%
				0.01	441: nn514↓+521↓ 99%
^{178}Hf	4^+_1	1.514	(d,p)	1.8	441 95%, {221,221} 3%
				0.4	441: nn514↓+510↑ 89%

continuation of table 1

1	2	3	4	5	6
	3^+_1	1.828		1.7 1.0	431 99% 431: pp404↓-411↓ 79%
^{184}W	3^+_1	1.425		1.2 0.8	431 96% 431: nn503↑+510↑ 91%
^{186}Os	4^+_1	1.352	B(E4) is large in (α,α')	1.2 4.0	441 90%, {201,441} 3%, {221,221} 1% 441: pp402↑+402↓ 56% nn514↓+510↑ 13%
^{188}Os	4^+_1	1.280	B(E4) is large in (α,α')	1.0 4.0	441 89%, {201,441} 3%, {221,221} 1% 441: pp402↑+402↓ 62%

probably overestimated. For a better description of the experimental data one should reduce $\varkappa_0^{(44)}$ by (5-10)%. Note that ^{188}Os is a transitional nucleus and the description of $K^\pi_n=0^+_2$ and 2^+_1 states in it is rough, whereas the 4^+_1 state is not very collective and can be described sufficiently well.

Thus, the general picture of hexadecapole 3^+ and 4^+ states in the region $158 \leq A \leq 188$ is the following. The Gd and Dy isotopes contain almost two-quasiparticle 4^+ states with an energy from 1.1. to 2.2 MeV. The nuclei ^{168,170}Er, ^{168,170,172,174}Yb and ^{174,176,178}Hf have collective 3^+ states with B(E4)=0.8÷1.7 spu. In heavy Hf and W isotopes the collectivity of 4^+ states increases and it appears to be large in Os isotopes. The hexadecapole states can correctly be described with the fixed values of the constants $\varkappa_0^{(43)}$ and $\varkappa_0^{(44)}$.

The calculations reproduce the dominating two-quasiparticle components of $3^+_1 4^+$states obtained experimentally as well as the mixing of neutron and proton two-quasiparticle components of 3^+ states in Yb isotopes /12,13/. It should be noted that in those nuclei where the low-lying 3^+ and 4^+ states have not been observed experimentally the calculated energies of the lowest two-quasiparticle states with $K^\pi=3^+$ and 4^+ are usually higher than 2 MeV.

All the calculated states 4^+_1 and 4^+_2 have small two-phonon components, especially {221,221}. The present calculations confirm the conclusion made in refs. /27,28/ about the absence of collective two-phonon states in deformed nuclei.

4. Influence of hexadecapole forces on the states with $K=2^+$

Hexadecapole forces with $\lambda\mu=42$ may contribute to the states with $K^\pi=2^+$.

In the calculations for the states with $K^\pi=2^+$ we have simultaneously taken into account both the quadrupole $\lambda\mu=22$ and hexadecapole $\lambda\mu=42$ forces. The state energies were found from the secular equation of the fourth order, the amplitudes of the two-quasiparticle components of one-phonon states comprise quadrupole and hexadecapole parts as it is shown in table 2. Since value of the constant $\varkappa_0^{(42)}$ is unknown the calculations were made for some values of $\varkappa_0^{(42)}$ in the region $0 \leq \varkappa_0^{(42)} \leq 0.015$ fm^2/MeV (as has been mentioned above, one should expect that $\varkappa_0^{(42)} < \varkappa_0^{(43)}$, where $\varkappa_0^{(43)}=0.015$ fm^2/MeV).The constant $\varkappa_0^{(22)}$ was chosed by fitting the $K^\pi_n=2^+_1$ state energy.

The results of calculations for the $K^\pi_n=2^+_1$ state in ^{168}Er are shown in table 2. It is seen that with increasing hexadecapole constant $\varkappa_0^{(42)}$, the collectivity of states decreases and its structure

Table 2. Contribution of hexadecapole forces with $\lambda\mu$=42 to $K^{\pi}_{n}=2^{+}_{1}$ state in ^{168}Er. The B(E2,$0^{+}0_{1}\to 2^{+}2_{1}$)-values, contributions to the state normalization of the dominating neutron nn523↓-521↓ and proton pp411↑+411↓ components, quadrupole ($\lambda\mu$=22) and hexadecapole ($\lambda\mu$=42) parts of the amplitudes of these components

$\varkappa_0^{(22)}$	$\varkappa_0^{(42)}$	B(E2) spu.	nn523↓-521↓			pp411↑+411↓		
			22	42	Contrib. to normal %	22	42	Contrib. to normal %
0.023	0	5.9	1	–	20%	1	–	48%
0.020	0.010	4.5	0.65	0.35	28%	0.80	0.20	42%
0.019	0.012	4.0	0.57	0.43	31%	0.70	0.30	41%
0.016	0.015	2.9	0.39	0.61	34%	0.49	0.51	37%

changes. At $\varkappa_0^{(42)}>0.010$ fm^2/Mev hexadecapole forces contribute greatly to the amplitudes of two-quasiparticle components.

Recently, it has been shown that experimental results on the excitation of the $I^{\pi}K=4^{+}2$ state of γ-vabrational band in ^{168}Er in ($\bar{p},\bar{p}'$) reaction can be explained only if hexadecapole forces are introduced/26/. These data may be considered as an experimental evidence of the influence of hexadecapole forces on the properties of $K^{\pi}=2^{+}$ states. The results of our calculations obtained at reasonable values of $\varkappa_0^{(42)}$ are in qualitative agreement with experiment/26/.

5. Conclusion

The low-lying nonrotational hexadecapole states with $K^{\pi}=3^{+}$ and 4^{+} in the region $158\leq A\leq 188$ are described within the QPNM at fixed values of the constants of the hexadecapole interaction $\varkappa_0^{(42)}=0.015$ fm^2/MeV and $\varkappa_0^{(44)}=0.022$ fm^2/MeV. The description is in qualitative agreement with available experimental data. It is shown that in 4^{+}_{1} and 4^{+}_{2} states the two-phonon components, in particular {221,221}, are small. This confirms the conclusion made in refs./27,28/ on the absence of collective two-phonon states in deformed nuclei. The results of calculations for $K^{\pi}_{n}=2^{+}_{1}$ states in ^{168}Er, in which the forces with $\lambda\mu$=22 and 42 have simultaneously been taken into account, are in qualitative agreement with experimental data/26/ on a considerable contribution of hexadecapole forces to $K^{\pi}=2^{+}$ states.

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Гексадекапольные состояния в деформированных ядрах

В рамках квазичастично-фононной модели ядра при фиксированных значениях констант гексадекапольного взаимодействия получено качественно правильное описание низколежащих неротационных гексадекапольных состояний с $K^{\pi}=3^{+}$ и 4^{+} в области $158 \leq A \leq 188$. Показано, что в 4^{+}_{1}- и 4^{+}_{2}-состояниях двухфононные компоненты малы /<10%/. Продемонстрировано, что гексадекапольные силы могут давать заметный вклад в $K^{\pi}=2^{+}$-состояния.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Hexadecapole States in Deformed Nuclei

The low-lying nonrotational hexadecapole states with $K^{\pi}=3^{+}$ and 4^{+} in the $158 \leq A \leq 188$ region are described within the quasiparticle-phonon model at fixed values of the hexadecapole interaction constants. The description is in qualitative agreement with the available experimental data. It is shown that the two-phonon components are small (< 10%) in 4^{+}_{1} and 4^{+}_{2} states. It is found that hexadecapole forces considerably influence the properties of $K^{\pi}=2^{+}$ states.

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

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