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ON THE ROLE OF HIGH MULTIPOLARITY INTERACTIONS IN DEFORMED NUCLEI

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In describing collective vibrational states effective spin independent central interactions are expanded over series in multipoles λ . In deformed nuclei, collective vibrational states are specified by the multipolarity λ and its projection μ ($\mu \equiv K$). In doubly even nuclei there are collective quadrupole with λ = 2 and octupole with λ = 3 states. In deformed nuclei they are well described in the RPA (see Soloviev (1976)). The wave functions of one-phonon states are a superposition of two-quasineutron nn and two-quasiproton pp components. According to the experimental data measured by Walker et al. (1982) and Burke et al. (1978) there are collective hexadecapole states with $K^{\pi} = 3^{+}$ in nuclei with $A \approx 170$ and with $K^{\pi} = 4^{+}$ in the Os isotopes. Hexadecapole states in doubly even deformed nuclei have rather well been described by Nesterenko et al. (1986) within the quasiparticle-phonon nuclear model (Soloviev 1978, 1987, 1989 and Soloviev and Shirikova 1986).

There are experimental indications of a strong mixing of two-quasiproton and two-quasineutron components in the states with large K in doubly even deformed nuclei. They have been analysed by Sood and Sheline (1989). Large matrix elements responsible for such a mixing have not yet been explained theoretically. It is interesting to elucidate the role of high multipolarity interactions in deformed nuclei. The present letter is aimed at studying the mixing of two-quasineutron and two-quasiproton states, caused by the interactions with multipolarities $\lambda \geq 4$.

Soloviev and Shirikova (1989) have obtained a good enough description of nonrotational states in ^{168}Er, ^{172}Yb and ^{178}Hf within the QPNM. They have also succeeded in desoribing the mixing of two-quasiproton and two-quasineutron components in the states $K^{\pi}_{\nu} = 4^-_1$ and 4^-_2 in ^{168}Er (see also Karadjov et al. 1989). In the calculations of quadrupole with $K^{\pi} = 2^+$, octupole and hexadecapole states, the isoscalar constants $\varkappa_0^{\lambda\mu}$ were chosen in the interval (0.015 – 0.025) fm^2 MeV^{-1}. The present calculations are perfomed in the RPA with the parameters of the Woods–Saxon potential and pairing, as in Soloviev and Shirikova (1989) with $\varkappa_0^{\lambda\mu} = (0.020 - 0.024)$ fm^2 MeV^{-1}; the radial dependence of multipole interactions is taken in the form $\partial V(r)/\partial r$ where $V(r)$ is the central part of the Woods–Saxon potential. The results of calculations and experimental data (Gallagher and Nielsen, 1962; Ward and Chu, 1975; Khoo et al., 1972; Hammer et al. 1973; Kaffrell and Kurcewicz, 1975; Burke et al. 1985a,b; Greenwood et al. 1978) are listed in the table. Each one-phonon state is provided with experimental and calculated energies and contributions (in per cent) of the largest two two-quasiparticle components to the normalisation of their wave functions.

The mixing of the two-quasineutron nn 514↓+624↑ and the two-quasiproton pp 404↓ +514↑ states in ^{178}Hf is described by taking the interaction with multipolarity $\lambda\mu = 98$ into account. It is seen from the table that a good description of the experimental data on the energies and structure of the $K^{\pi}_{\nu} = 8^-_1$ and 8^-_2 states has been obtained at $\varkappa_0^{98} = 0.024$ fm^2 MeV^{-1}. Note that at $\varkappa_0^{98} = 0.020$ fm^2 MeV^{-1} the mixing is somewhat lower, namely 80% and 20%. The corresponding neutron and proton

Table. Mixing of two-quasiproton and two-quasineutron configurations in deformed nuclei

Nuclei	$\lambda\mu$ / K^{π}_{ν}	E, MeV exp.	E, MeV calc.	1 configuration % exp.	1 configuration % calc.	2 configuration % exp.	2 configuration % calc.
^{178}Hf	98			pp 404↓+ 514↑		nn 514↓+ 624↑	
	8^-_1	1.147	1.11	34±4	25	(66)	75
	8^-_2	1.479	1.42	(66)	75	34±4	24
^{176}Hf	66			pp 404↓+ 402↑		nn 514↓+ 512↑	
	6^+_1	1.333	1.35	62	26	38	73
	6^+_2	1.762	1.75	38	71	62	27
	98			pp 404↓+ 514↑		nn 514↓+ 624↑	
	8^-_1	1.559	1.52	95 (86±6)	86		14
	8^-_2		1.84		14		86
	77			nn 514↓+ 633↑		nn 512↑+ 624↑	
	7^-_1	1.860	1.76	∼100	99.7		0.04
	7^-_2		1.81		0.2		99.8
^{174}Yb	55			pp 411↓+ 514↑		nn 521↓+ 624↑	
	5^-_1	1.885	1.9	46±2	78		21
	5^-_2	2.379	2.2	54±2	21		77
^{168}Er	54			nn 633↑+ 521↓		pp 411↓+ 523↑	
	4^-_1	1.094	1.0	70	81	25	18
	4^-_2	1.905	1.6	30	18	60	80
^{158}Gd	44			pp 413↓+ 411↑		nn 523↓+ 521↑	
	4^+_1	1.380	1.32	is large	94	is noticeable	4
	4^+_2	1.920	1.9		4	75	95
	54			nn 521↑+ 642↑		pp 532↑+ 411↑	
	4^-_1	1.636	1.66	72	92		6
	4^-_2		1.86		7		87

matrix elements are large. The important role of interactions with such a high multipolarity as $\lambda = 9$ with projection $\mu = 8$ with the constant $\varkappa_0^{98}$ close in value to $\varkappa_0^{22}$, $\varkappa_0^{33}$ and $\varkappa_0^{44}$, with which Soloviev and Shirikova (1989) obtained a good description of quadrupole, octupole and hexadecapole states of ^{178}Hf, was unexpected. It is to be noted that in spite of the fact that the 8^-_1 and 8^-_2 states are not pure two-quasiparticle states, the isomeric state with $K^\pi = 16^+$ and energy 2.447 MeV in ^{178}Hf is a pure four-quasiparticle states p 514↑+ p404↓+ n 514↓+ n 624↑. This is due to the fact that the total strength of the configurations nn 514↓+ 624↑ and pp 514↑+ 404↓ is concentrated in the two levels 8^-_1 and 8^-_2 .

According to the experimental data (Khoo et al. 1972) two $K^\pi = 6^+$ configurations nn 514↓+ 512↑ and pp 404↓+ 402↑ in ^{176}Hf are mixed. The calculated energies of the 6^+_1 and 6^+_2 states and the mixing are close to the experimental ones. However, the calculated structure of the first state is close to the second experimentally observed one and vice versa. This discrepancy is due to the energies of single-particle states. It has been disregarded in the proton scheme that, according to the experimental data, in ^{175}Lu the p 402↑ state has a smaller energy than the p 514↑ state. Therefore, the energy of the two-quasiproton state pp 404↓+ 402↑ turned out to be larger than that of the two-quasineutron state nn 514↓+ 512↑ . Maybe this is due to the fact that the calculations were performed with the parameter of the hexadecapole deformation $\beta_4 = -0.03$ and according to the experimental data (Nettles et al., 1988) $\beta_4 = -0.16$.

According to the calculations, the $K^\pi = 8^-_1$ and 8^-_2 states in ^{176}Hf have the energies 1.52 and 1.84 MeV. In comparison with ^{178}Hf, the configurations pp 404↓+ 514↑ and nn 514↓+ 624↑ are somewhat less mixed. The description of the structure of the first 8^-_1 state is in agreement with experimental data by which the contribution of the configuration pp 404↓+ 514↑ equals (86±6)%. It would be interesting to detect experimentally the second 8^-_2 state. According to the calculations, in ^{176}Hf there are 7^-_1 and 7^-_2 states with the energies 1.76 and 1.81 MeV. Despite the proximity of the energies of these states the two-quasineutron configurations nn 514↓+ 633↑ and nn 512↑+ 624↑ are not practically mixed. Both the corresponding neutron matrix elements are not large.

The mixing of the two-quasiproton pp 411↓+ 514↑ and two-quasineutron nn 521↓+ 624↑ configurations has been observed in the states 5^-_1 and 5^-_2 with the energies 1.885 and 2.379 MeV in ^{174}Yb by studying the β decay of ^{174}Tm. From our calculations in the RPA with the interactions $\lambda\mu = 55$ it follows that the mixing is smaller than in experiment. If one takes $\varkappa_0^{55} = 0.026$ fm^2 MeV^{-1} the mixing of these configurations increases up to 72% and 27%. The mixing of the configurations nn 633↑+ 521↓ and pp 411↓+ 523↑ in the states $K^\pi_\nu = 4^-_1$ and 4^-_2 in ^{168}Er has first been calculated by Karadjov et al. (1989) and refined in our present calculations.

According to the analysis, made by Greenwood et al. (1978) of the (d,p) reactions and γ-transitions between the states $K^\pi_\nu = 4^+_1$ with the energy 1.380 MeV, 4^+_2 with 1.920 MeV and 4^-_1 with 1.636 MeV in ^{158}Gd, the above-mentioned states are not pure two-quasiparticle states. The wave function of the 4_1^+ state has the dominating component pp 413↓+ 411↑ and small admixture nn 521↑+ 523↓. It follows from the (dp) reaction that the contribution of the configuration nn 521↑+ 642↑ to the normalisation of the wave function of the 4_1^- state equals 72% and of the configuration nn 521↑+ 523↓ to the 4_2^+ state equals 75%. In this case, one can easily explain the E1 transition between the states 4_2^+ and 4_1^- as n 523↓→n 642↑. It follows from the E1 transition $4_1^- \to 4_1^+$ that the 4_1^- state has admixtures of the configuration pp 532↑+ 411↑. It is seen from the table that according to the calculations in the states 4_1^+, 4_2^+, 4_1^- and 4_2^- one can observe a small mixing of the two-quasineutron and two-quasiproton configurations which is in agreement with the available experimental data.

Based on the calculations we may assert that a qualitatively correct description is obtained of the experimental data on the mixing of two-quasineutron and two-quasiproton configurations with large K by taking account of high multipolarity interactions. Note that mixing like that depends strongly on the energies of single-particle states; in the calculations we have used the single-particle energies and wave functions of the Woods-Saxon potential with the parameters fixed in the 1968-70-ties.

From the above-made studies we can assert that in the case where the energies of two-quasineutron and two-quasiproton states with the same values of K^π are close and the relevant matrix elements are not small, high multipolarity interactions with $\lambda = 5 \div 9$ play an important role in the mixing of these states. In these cases, one should take high multipolarity interactions into account.

Maybe the necessity of including high multipolarity interactions is related to the inclusion (Cwick and Nazarewicz, 1989) of higher multipolarity deformations β_5, β_6 and β_7 stabilizing energy minimum for the nuclei with $Z \sim 58$ and $N \sim 88$ and improving the agreement between measured and calculated ground state spins and electromagnetic moments in neighbouring odd-A Cs and Ba isotopes.

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