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DESCRIPTION OF NONROTATIONAL STATES IN ^{170,174}Yb

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The calculations of the energies and wave functions of two-quasiparticle and one-phonon states in doubly even deformed nuclei were performed in 1960-75. The available at that time experimental data were well described, and the predictions were made which in many cases were experimentally confirmed. Many experimental data obtained after 1975 and expectation of many data at a new generation of accelerators and detectors show the necessity of a new series of calculations.

A new series of calculations of nonrotational states of doubly even deformed nuclei has been performed within the quasiparticle-phonon nuclear model (QPNM)[1-3]. The isoscalar and isovector particle-hole (p-h) and particle-particle (p-p)[4] multipole interactions are taken into account. The monopole and quadrupole [5] pairing are included. Vibrational states with $K^{\pi} \neq 0^{+}$ and 1^{+} for ^{168}Er, ^{172}Yb and ^{178}Hf were calculated in ref.[6]. The latter contains also the relevant formular and details of calculations.

The present paper is devoted to calculations of nonrotational states with $K^{\pi} \neq 0^{+}$ and 1^{+} in $^{170,174}Yb$ and to comparison of the results of calculations with experimental data.

As in ref.[6], the calculations are made in the QPNM with the monopole and quadrupole pairing and isoscalar and isovector p-h and p-p multipole interactions. We used the single-particle energies and wave functions of the Woods-Saxon potential with the parameter for the zone A=173 fixed in 1969 and listed in refs.[7,8]. The constants of the monopole pairing were chosen by pairing energies. According to ref.[5], the role of the quadrupole pairing in choosing the constant G^{20} is not great. The constants of the isovector interactions are taken equal to $\varkappa_1^{\lambda\mu} = -1.5\,\varkappa_0^{\lambda\mu}$. The quadrupole, octupole and hexadecapole interactions were taken into account. The energies of two-quasiparticle poles were calculated taking account of the blocking effect and the Gallagher - Moszkowski corrections. The constants of the isoscalar p-h interaction were chosen from the condition of reproducing experimental energies of the first $K^{\pi}_{\nu=1}$ nonrotational states; they turned out to be close to the constants used for describing the states of ^{172}Yb in ref.[6]. The constants of the p-p interaction $G^{\lambda\mu} = 0.9\,\varkappa_0^{\lambda\mu}$.

The energies and wave functions of one-phonon states are calculated in the random phase approximation with p-h and p-p interactions. Nonrotational states of doubly even deformed nuclei were calculated with the wave function

$$\Psi_\nu(K_0^{\pi_0}\sigma_0)=\Big\{\sum_{i_0}R_{i_0}^{\nu}Q_{\lambda_0\mu_0 i_0\sigma_0}+\sum_{\substack{\lambda_1\mu_1 i_1\sigma_1\\ \lambda_2\mu_2 i_2\sigma_2}}\frac{(1+\delta_{\lambda_1\mu_1 i_1,\lambda_2\mu_2 i_2})^{-1}}{2\,[1+\delta_{K_0 0}(1-\delta_{\mu_1 0})]^{1/2}} \qquad (1)$$

$$\cdot\,\delta_{\sigma_1\mu_1+\sigma_2\mu_2,\sigma_0 K_0}\,P^{\nu}_{\lambda_1\mu_1 i_1,\lambda_2\mu_2 i_2}\,Q^{+}_{\lambda_1\mu_1 i_1\sigma_1}\,Q^{+}_{\lambda_2\mu_2 i_2\sigma_2}\Big\}\Psi_0 .$$

In the two-phonon terms of the wave function (1) the Pauli principle is taken into account. Using the variational principle we have derived equations for the energies ε_ν and coefficients $R_{i_0}^{\nu}$ and $P^{\nu}_{\lambda_1\mu_1 i_1,\lambda_2\mu_2 i_2}$. For each state ν with energy ε_ν we calculated the structure represented as a contribution (in per cent) of the one-phonon $\lambda\mu i$ and two-phonon $\{\lambda_1\mu_1 i_1,\lambda_2\mu_2 i_2\}$ components to the normalisation of the wave function (1). The results of calculations are listed in tables 1 and 2. They also give (in per cent) the largest two-quasineutron nn and two-quasiproton pp components of the wave functions of one-phonon states $\lambda\mu i$.

The results of calculations and experimental data from [9,10] for ^{170}Yb are given in table 1. According to the experimental data for the $K_\nu^\pi=2_1^+$ states, B(E2)=2.8 s.p.u. The states 0_2^-, 1_2^- and 2_2^- are collective. It would be interesting to measure B(E3) values for the 3^-K_1 and 3^-K_2 states with $K^\pi=0^-$, 1^- and 2^-. The E2 transition between the states 6_1^- and 4_1^-, observed in ref. [11], confirms the correctness of the calculated two-quasineutron configurations. A large number of states with $K^\pi=0^-$ and 1^- in ^{170}Yb has been observed in the β decay of ^{170}Lu. In ref. [12] there were indications of a possible M0 transitions from the $I^\pi K=0^-0$ state with energy 2.820 MeV to the ground state. The energy centroids of the two-phonon states {201,221}, {221,221}, {301, 321}, {221,331}, {221,301}, {221,311} and others lie above 3 MeV.

The results of calculations and experimental data [13-15] for ^{174}Yb are given in Table 2. The energy of the first $K_\nu^\pi=2_1^+$ state

Table I

Nonrotational states in ^{170}Yb

K_ν^π	Exper. E MeV	Calculation in QPNM: E MeV	B(Eλ) s.p.u.	Structure, %		
2_1^+	1.146	1.1	2.3	221	87	222: 4 {201,221} 3.4
2_1^+		1.5	1.0	222	92	221 : 5
0_1^-	1.512	1.6	2.8	301	98	
0_2^-		2.1	1.4	302	96	
1_1^-	1.364	1.5	0.7	311	99	
1_2^-		2.2	1.0	312	86	313 : 5 314 2 {221,331} 1
2_1^-	1.425	1.6	2.4	321	94	322 2 {201,321} 3
2_2^-	(1.718)	1.9	2.0	322	94	321 2
3_1^-	1.661*	1.6	0.1	331	98	
3_2^-		2.0	0.2	332	96	
3_1^+		1.4	1.3	431	99	
3_2^+		1.7	0.1	432	98	
4_1^+	1.409	1.7	0.001	441	98	
4_2^+		2.3	0.04	442	72	443 26
4_1^-	1.228	1.2		nn 633↑+ 521↓ 100		
6_1^-	1.852	1.8		nn 633↑+ 512↑ 100		
5_1^-		1.9		pp 411↓+ 514↑ 100		
6_2^-		2.0		nn 523↓+ 633↑ 100		
6_1^+		2.1		nn 642↑+ 633↑ 100		
7_1^-	2.19	2.2		pp 523↑+ 404↓ 100		

* $I^\pi=5^-$

Table 2

Nonrotational states in ^{174}Yb

	Experiment E MeV	Calculation in QPNM E MeV	B(Eλ) s.p.u.	Structure, %
2^+_1	1.634	1.6	2.2	221 94 {201,221} 2 221: nn512↑-510↑ 36; nn512↑-521↓ 16
2^+_2	2.172	2.0	0.2	222 99
0^-_1	1.710	1.7	1.0	301 99 301:nn 514↓-633↓44;pp404↓-523↓ 1
0^-_2		2.2	0.5	302 99 302: pp 404↓- 523↑ 43
1^-_1		1.8	0.1	311 99
1^-_2		1.9	0.8	312 98
2^-_1	1.318	1.2	1.6	321 98 321: nn 624↑- 512↑ 92; pp 514↑- 402↑ 1
2^-_2		2.7	1.7	322 85 {201,321} 3 {204,321} 4
3^-_1	1.851	2.0	4.0	331 98 331:nn615↓-512↓ 25; pp514↓-411↓ 25
3^-_2	(2.050)	2.2	0.2	332 98 332: nn 633↓- 521↓ 92
3^+_1	1.606	1.5	1.4	431 99 431 : pp 404↓- 411↓ 61; nn 512↑+ 521↓ 23; nn 514↓- 521↓ 10; nn 505↑- 512↑ 1
3^+_2	(2.284)	1.9	0.1	432 99 432 : pp 404↓- 411↓ 34; nn 512↑+ 521↓ 60
4^+_1		1.8	0.01	441 99
4^+_2		1.9	0.001	442 99
6^+_1	1.518	1.5		nn 512↑+ 514↓ 100
7^-_1		1.6		nn 512↑+ 624↑ 100
7^-_2		1.7		nn 514↓+ 633↑ 100
8^-_1		1.8		nn 514↓+ 624↑ 100
5^-_1	1.885	1.9		pp 411↓+ 514↑ 78; nn 521↓+ 624↑ 21
5^-_2	2.379	2.2		pp 411↓+ 514↑ 21 nn 521↓+ 624↑ 77
6^-_1		2.0		nn 633↑+ 512↑ 100

increased in comparison with $^{170,172}Yb$, which is correctly described in the QPNM. The experimental value B(E2) = 1.7 s.p.u. does not contradict the calculated one. According to the experimental data /16/, the contribution to the 2^+_1 state of the configuration nn 512↑- 510↑ is about 75% which is considerably larger than the calculated one. According to the calculations, among the $K^\pi = 0^-$ states the most collective is the fourth 0^-_4 state with B(E3)=3.6 s.p.u. and energy about 3 MeV; for the 0^-_3 state B(E3) = 1.0 s.p.u. There are no experimental data on the $K^\pi = 1^-$ states; according to the calculations, the most collective is the fifth 1^-_5 and sixth 1^-_6 states with energies about 3 MeV and B(E3) ≈ 1 s.p.u. The calculated value of B(E3) for excitation of $I^\pi K_\nu = 3^- 2_1$ is much smaller than B(E3) = 4.1 s.p.u. given in ref. /16/.

The states $K^\pi_\nu = 3^+_1$ and 3^+_2 turn out to be one-phonon $\lambda\mu i$ = = 431 and 432 with admixtures about 1%. The component structure given in the table does not contradict the experimental data /13/ on g_K and (dp) reaction. A small admixture of the configuration nn 505↑- 512↑ in the 3^+_1 state testifies to a possible E1 transition to the 2^-_1 state. The 4^+_1 and 4^+_2 states are almost two-quasiparticle states pp 404↓+ 411↓ and nn 514↓+ 521↓.

The state $K^\pi_\nu = 6^+_1$ with energy 1.518 MeV is excited in the (dp) reaction and its calculated structure does not contradict the experimental data. It would be expedient to observe experimentally the levels with $K^\pi_\nu = 7^-_1$, 7^-_2, 8^-_1 and 6^-_1 predicted in Table 2.

The β^- decay of ^{174}Tm from the state with $K^\pi = 4^-$ and configuration p 411↓+ n 514↓ to the levels of ^{174}Yb has been studied in ref. /17/. It was obtained that log ft = 4.73 for the transitions to the state $K^\pi_\nu = 5^-_1$ with energy 1.885 MeV and log ft = 4.67 to the state 5^-_2 with energy 2.379 MeV. Based on these data it was concluded that the two-quasiproton configuration pp 411↓+ 514↑ enters into the 5^-_1 state with the weight 46% and into the 5^-_2 state with the weight 64%. Multipole interactions with $\lambda\mu$ =55 with the constant $\varkappa_0^{55} = \varkappa_0^{22}$ have been taken into account in ref. /18/, and the mixing of the quasiproton pp 411↓+ 514↑ with the quasineutron nn 521↓+ 624↑ configurations, shown in table 2, was obtained. With increasing $\varkappa_0^{55}$ by 15%, the mixing of these configurations increases up to 72% and 27%. It has been stated in ref. /18/ that in the cases where the energies of two-quasiproton and two-quasineutron states with the same K^π are close and the corresponding matrix elements are large, high multipole interactions with $\lambda = 5 \div 9$ play an important role in the mixing of these states.

Table 3

Number of nonrotational $K^{\pi}=0^-$ and 1^- states

Energy interval	^{170}Yb Exper.	^{170}Yb Calcul.	^{174}Yb Calcul.
up to 2 MeV	2	2	3
2.0 - 3.0 MeV	17	13	7
3.0 - 3.4 MeV	16	14	9
Total up to 3.4 MeV	35	29	19

In the β^+ decay of ^{170}Lu the authors of refs.[9,10] observed a large number of states with $K^{\pi}=0^-$ and 1^- of ^{170}Yb, lying in the energy interval from 2.0 to 3.4 MeV. The number of $K^{\pi}=0^-$ and 1^- states of ^{170}Yb obtained from the experimental data [9,10] and the results of calculations are given in table 3. Of course, there is some uncertainty in the experimental data due to the errors in identifying the values of I^{π} to the levels. We should like to note some arbitrariness in the results of calculations. Thus, in the energy interval from 3.4 to 3.5 MeV there are five states with $K^{\pi}=0^-,1^-$ and small change of the parameters of the Woods - Saxon potential can shift some of them towards lower energies. Nevertheless, the results of calculations agree with the experimental data for ^{170}Yb in the interval 2.0 - 3.4 MeV where there is an anomalously large number of states with $K^{\pi}=0^-$ and 1^-. For comparison, Table 3 contains the calculated number of $K^{\pi}=0^-$ and 1^- states in ^{174}Yb; it turned out to be 1.5 times smaller than in ^{170}Yb.

In conclusion, we should like to note that nonrotational states with $K^{\pi}\neq 0^+$ and 1^+ in ^{170}Yb and ^{174}Yb are reasonably well described within the QPNM. Further experimental investigation of excited states of these nuclei is needed.

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