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The present paper is devoted to a rather widely discussed recently problem about an interaction of vibrational and two-quasiparticle excitations in even-even atomic nuclei.

The semimagic and neighbouring to them nuclei have such an energy gap that the two-phonon and two-quasiparticle states have nearly the same excitation energies. If so, even not very strong interaction may cause sensible mixing of these excitations and complicating of the structure of "true" states.

Within the framework of superfluid nuclear model /9/ the above situation has been investigated already for deformed nuclei /1/. For spherical nuclei such investigations have been made quite recently /2-4/. There it has been shown that the admixture of noncollective components may be rather significant.

The account of the above admixture in the structure of "two-phonon" states is of importance not only in itself. If the only collective degrees of freedom (for anharmonic terms of Hamiltonian not higher than those cubic in the number of phonon operators) are allowed for in calculations then, as is known /7,8/, the energy of 2^+_2 level is very high, the quantity $B(E2, 0^+_{g.s.} \to 2^+_2)$ is larger by an order than the experimental one and the sequence of levels in triplet $0^+_1, 4^+_1, 2^+_2$ is given strictly.

In papers /7/ it is pointed out that inclusion of the noncollective components into the wave function of $2^+_2, 4^+_1$ states can improve a theoretical description.

We have calculated characteristics of a series of 2^+ and 3^- levels in the isotones N=80,82,84. . The energies of states, probabilities of electromagnetic transitions, quadrupole moments have been computed. All the details of calculations and arguments for basic approximations can be found in paper /3/ We give here only the expression for the state wave function $\Psi_\nu(IM)$

$$\Psi_\nu(IM) = \{ \sum_i C_i^\nu Q^+_{IMi} + \sum_{\substack{\lambda_1\mu_1 i_1 \\ \lambda_2\mu_2 i_2}} \Delta^{\lambda_2 i_2}_{\lambda_1 i_1}(I\nu) <\lambda_1\mu_1\lambda_2\mu_2 | IM> Q^+_{\lambda_1\mu_1 i_1} \times$$

$$\times Q^+_{\lambda_2\mu_2 i_2} \} |0>_{ph} \qquad (1)$$

and the secular equation for the energy $\eta_{I\nu}$ of this state:

$$\det\{(\omega_{Ii} - \eta_{I\nu})\delta_{ii'} - K(ii')\} = 0. \qquad (2)$$

The following conventions are used in (1), (2): $Q^+_{\lambda\mu i}$, $Q_{\lambda\mu i}$ are, respectively, the phonon creation and annihilation operators with moment and projection λ, μ and number i; ω_{Ii} is the energy of phonon with quantum numbers IMi, $<\lambda_1\mu_1\lambda_2\mu_2 | IM>$ - the Clebsch-Gordan coefficient, ν -the number of root of eq. (2).

Note that $I, \lambda_1, \lambda_2 = 2,3$. The expression for coefficients $K(ii')$ can be found in paper /3/. The operator of $E\lambda$-transition which we have employed in calculations of probabilities of the electric transitions and quadrupole moments is taken from book /9/ (Chapter 6, Sect. 3). The wave function (1) which includes the components not higher than two-phonons permits one to calculate states with an excitation energy not higher than 2.5-3.0 MeV for positive parity and 3.5-4.0 MeV for negative parity. Accordingly, the summation over i in (1) is restricted, $i \leq 4$.

The Hamiltonian of spherical nucleus consists of average field for neutron and proton systems and the following residual interactions: pairing, quadrupole-quadrupole and octupole-octupole.

The average field is described by the Saxon-Woods potential with the following parameters:

a) for the proton system: $A=141$; $Z=59$; $r_0=1.24$ fm, $V_0=58.0$ MeV, $\kappa=0.349$ fm^2, $\alpha=1.587$ fm^{-1};

b) for the neutron system with $N>82$: $A=137$, $r_0=1.28$ fm, $V_0=43.4$ MeV, $\kappa=0.413$ fm^2, $\alpha=1.613$ fm^{-1},

c) for the neutron system with $N<82$: $A=141$, $r_0=1.27$fm, $V_0=46.5$ MeV, $\kappa=0.409$ fm^2, $\alpha=1.613$ fm^{-1}.

Here A is the atomic number, Z - the proton number, $R=r_0A^{1/3}$ - the potential radius, V_0 - the potential depth, κ - the constant of spin-orbital part of the potential, α - the parameter of diffusion of the potential boundary.

The choice of these parameters was made on the basis of papers [10]. Single-particle schemes and matrix elements of multipole operators were calculated by the program of paper [11].

The constants of pairing interaction were chosen to ensure the correct description of pair energies [9,12]. In calculations only the levels of open shell were involved. The values obtained for the correlation function and chemical potential are in good agreement with the results of papers [12]. The constants of quadrupole-quadrupole and octupole-octupole forces were taken for each nucleus in such a way that the values of η_{21} and η_{31} coincide with the experimental energies of 2_1^+ and 3_1^- levels, respectively. The effective charge used for describing the electromagnetic transitions and quadrupole moments is taken to equal 0.6 for all nuclei.

Calculating energies of two-quasiparticle states in the isotones N=80,84 we have taken the blocking effect [9] into account. The account of this effect results in decreasing of energies of two-quasiparticle states by 200-400 keV as compared to the values calculated with the correlation function of the ground state. The main result of this decreasing is just the energy lowering of the second and higher roots of eq. (2) and change of the structure of their wave functions. An example of the above changes is given in Table 1 (for ^{140}Nd and ^{144}Nd). Allowing for the blocking effect has caused the energy lowering of the second 2^+ levels by 100-250 keV. Note also should be made that the blocking effect changes the

Table 1

The influence of blocking effect on the energy and structure of the wave function of the states with $I^{\pi}=2^{+},3^{-}$ in isotones N=80,84

Nucleus	I_i^{π}	E KeV exp.	Without blocking effect		With blocking effect	
			ω KeV theory	Structure of the wave funct.	ω KeV theory	Structure of the wave function
^{144}Nd	2_1^+	697	723	81.1% Q^+_{21} + 9.3% Q^+_{21} Q^+_{21}	704	83.7% Q^+_{21} + 10% Q^+_{21} Q^+_{21}
	2_2^+	1556	1852	7.6% Q^+_{21} + 63.1% Q^+_{22} + + 1.2% Q^+_{23} +1.3% Q^+_{24} + 25% Q^+_{21} Q^+_{21}	1715	3.4% Q^+_{21} +82.6% Q^+_{22} + 10.7%Q^+_{21} Q^+_{21}
	3_1^-	1510	1484	66.7%Q^+_{31} +4.4%Q^+_{33} +26%Q^+_{21} Q^+_{31}	1505	69.7%Q^+_{31} 24.2%Q^+_{21} Q^+_{31} +3.5% Q^+_{33}
	3_2^-	2776	3110	2.8%Q^+_{31} +70.5%Q^+_{32} +14.4%Q^+_{33} +0.4%Q^+_{21} Q^+_{31} +5.8%Q^+_{21} Q^+_{32} + + 3.6% Q^+_{21} Q^+_{33}	2995	1.8%Q^+_{31} +80%Q^+_{32} +8%Q^+_{33} +1%Q^+_{21} Q^+_{31} + 4.2% Q^+_{21} Q^+_{32}
^{140}Nd	2_1^+	775	783	78.6%Q^+_{21} + 15.2% Q^+_{21} Q^+_{21}	731	77% Q^+_{21} + 14.3% Q^+_{21} Q^+_{21}
	2_2^+	1490	2069	9% Q^+_{21} + 30% Q^+_{22} +11% Q^+_{23}+ + 34.6% Q^+_{24} + 6.8% $Q^+_{21}$$Q^+_{21}$	1822	11.6% Q^+_{21} + 47.5% Q^+_{22} + 9.7% Q^+_{23} + + 17.6% Q^+_{24} + 8.9% Q^+_{21} Q^+_{21}

structure of phonons themselves, as well, especially the noncollective ones, and, besides, diminishes slightly the strength of interaction between quasiparticles and phonons.

The numerical results are presented in Tables 2 (for states with $I^{\pi}=2^{+}$) and 3 (for those with $I^{\pi}=3^{-}$). The experimental data are taken from papers /14–19/. At first we will say a few words concerning the general properties of the results obtained. Mainly we shall speak about 2^{+} levels where we have more experimental information.

Inclusion of the noncollective components into the structure of wave function of the 2^{+} states, as was expected, results in a sensitive improvement of description of energies of the 2_2^{+} levels. For instance, in ^{144}Nd nucleus for the same parameters the energy of the second 2^{+} level appears to be equal to 2429 keV when we allow for the collective components in (1) only, and this one equals 1715 keV when switching on the noncollective components (experimental value for this level is 1556 keV). Analogously, also the description of probabilities of E2 transitions $2_2^{+}\rightarrow 0^{+}_{g.s.}$ becomes better. However, the decrease of quantities resulting from the insertion of noncollective components into the wave function of 2^{+} states proves to be not always sufficient for correct description of experimental data. For a series of nuclei where the quasiparticle-phonon interaction is strong, the component $Q^{+}_{21}Q^{+}_{21}$ appears to be suppressed in the structure of 2^{+}_{2} states that results in nonrealistically small value of $B(E2,2_2^{+}\rightarrow 2_1^{+})$.

Now we discuss in more detail the structure of studied states in various nuclei, starting from the levels $I^{\pi}=2^{+}$.

In the isotones $N=82$ the structure of these states is rather simple and reduces, as a rule, to a single component Q^{+}_{2i}. The reason for this is the high energy and weakened collectivization of the 2^{+}_{1} state in semimagic nuclei. On the one hand, the two-phonon pole of secular eq. (2) appears to be much higher that the two-quasiparticle ones, and, on the other hand, the quasiparticle-phonon interaction proves to be weak. As a result, the intensive mixing of various types of excitations emerges

Table 2

Calculated results of the properties of excited states with $I^{\pi}=2^{+}$ in isotones N=80,82,84

Nucleus	i	$E(2_i^+)$ Kev		$B(E2,0_{gs}^+\to 2_i^+)e^2b^2$		$Q_2(2_i^+)$ e·b		$B(E2,2_1^+\to 2_i^+)e^2b^2$
		exp.	theor.	exp.	theor.	exp.	theor.	theor.
^{134}Xe	I	847	8I9	-	0,36	-	0,27	
	2	I6I3	I493	-	0,02	-	-0,I7	0,075
^{136}Ba	I	8I8	8I5	0,42	0,42	0,43	0.46	
	2	I55I	I7II	-	0.06	-	-0.I2	0.042
	3	208I	I858	-	0.0004	-	-0.I5	0.0002
^{138}Ce	I	789	792	-	0.46	-	0.58	
	2	I5II	I825	-	0.07	-	-0.0I4	0.02
^{140}Nd	I	755	73I	-	0.46	-	0.63	
	2	I490	I822	-	0.08	-	-0.0I6	0.0I4
^{134}Te	I	I278	I262	-	0.I7	-	-0.34	
	2	-	2030	-	0.007	-	-0.25	0.0002
^{136}Xe	I	I3I3	I335	-	0.30	-	-0.I2	
	2	?	2I07	-	0.004	-	-0.23	3xI0^{-5}
	3	2640	2265	-	0.008	-	-0.I9	2xI0^{-4}
^{138}Ba	I	I436	I454	0.38	0.37	-0.07 $\pm 0.I5$	0.II	
	2	22I8	2I6I	-	5xI0^{7}	-	-0.I3	0.00I
^{140}Ce	I	I596	I569	0.29	0.40	-	0.23	
	2	2348	2246	-	3xI0^{-5}	-	-0.03	0.002
	3	2522	2269	-	0,000I	-	-0.05	4xI0^{-4}
^{142}Nd	I	I576	I576	0.39	0.47	-	0.32	
	2	2385	2380	-	0.003	-	0.02	IxI0^{5}
	3	2583	2405	-	0.002	-	0.08	0.002
^{144}Sm	I	I659	I669	0,25	0.56	-	0.27	
	2	2450	2589	-	5xI0^{-4}	-	0.07	0.002
	3	2800	2652	-	0.33	-	0.34	0.03
^{146}Gd	I	I570	I587	-	0.73	-	-0.2I	
	2	-	257I	-	0.002	-	0.I	0.I3
^{142}Ce	I	64I	662	0.46	0.32	-0.I2	-0.40	
	2	I536	I665	-	0.I6	-	0.I4	0.024
^{144}Nd	I	697	704	0.5I	0.3I	-0.23	-0.39	
	2	I556	I7I5	-	0.I6	-	0.I7	0.025
^{146}Sm	I	747	73I	-	0.29	-	-0.45	
	2	I648	I903	-	0.I9	-	0.24	0.0I5
	3	2I57	2438	-	0.03	-	0.06	7xI0^{-5}

only in the structure of states corresponding to the high roots of eq. (2). The value of the component $Q^+_{21} Q^+_{21}$ becomes noticeable (10-20%) only in the wave function of the 2^+_3 state and only for ^{142}Nd and ^{144}Sm nuclei.

The theoretical and experimental values of energies of the 2^+_2 levels are in satisfactory agreement, except for ^{136}Xe nucleus where the 2^+_2 state itself was not observed, (apparently it should have an energy of 2.1-2.3 MeV as the analysis of experimental data on the neighbouring isotones $N=82$ evidences). Energies of the 2^+_3 levels are systematically lower (by 100-300 keV) than experimental values which is due to inexactitude of the single-particle level scheme. Experimental knowledge on the electromagnetic characteristics of levels is rather poor. The data available (on the 2^+_1 levels only) are in quite good agreement with our calculations. Note that the sign and magnitude which we have found for quadrupole moment of various 2^+ levels for a single nucleus in the isotones $N=82$, do not obey the rule stated by authors of the paper /7/, viz: $\text{sign}\, Q_2\,(2^+_1) = -\,\text{sign}\, Q_2\,(2^+_2)$ and $|Q_2(2^+_1)| < |Q_2\,(2^+_2)|$. No experimental data exist on the electromagnetic characteristics of higher 2^+ levels. We have compared our results with theoretical calculations of the paper /13/. There all 2^+ levels were treated as one-phonon, the Tamm-Dankoff method was used and effective forces were chosen either of a Gaussian type or in a form of the surface δ-interaction. As compared to our results the authors of ref. /13/ give much larger probabilities of $E2$-transitions from the 2^+_2 levels into the ground state and very small transitions $2^+_2 \to 2^+_1$. Besides, we have opposite signs of quadrupole moments of the 2^+_1-levels.

The structure of wave functions of states $I^\pi = 2^+$ in the isotones $N = 80, 84$ is more interesting. The quasiparticle-phonon interaction is here rather strong so that the ratio $\omega_{21}/\eta_{21} =$ 1.2-1.5. As a result, the two-phonon pole is located very close to the two-quasiparticle ones and in the wave function of 2^+ level a considerable admixture of both the noncollective components and two-phonon ones is observed. In the structure of 2^+_1 level the main component is Q^+_{21}, from others only the two-phonon component, Q^+_{21} Q^+_{21}, can be observed (it amounts to 10-15%). The description of energies of 2^+ levels should be recognized as satisfactory though for 2^+_2 levels the energy values obtained are higher than experimental ones. For some nuclei there is an experimental information, though rather poor, on the quadrupole moments and electromagnetic transitions. Our results for the 2^+_1 levels agree quite well with these data. The matter is worse with the 2^+_2 levels. Here, of course, no direct experimental information is available on the transition probabilities but for the nuclei ^{136}Ba, ^{134}Xe /16/ and ^{144}Nd /17/ the ratio $\frac{B(E2, 2^+_2 \to 0^+_{g.s.})}{B(E2, 2^+_2 \to 2^+_1)}$ is known which equals approximately 0.02-0.04 for all the three nuclei. Our results give correctly this ratio only for ^{134}Xe. As to the nuclei ^{136}Ba and ^{144}Nd our value is larger by an order, and even more, than the experimental one. For ^{136}Ba -nucleus the reason is obviously that the description of the transition $2^+_2 \to 0^+_{g.s.}$ is bad. This follows from comparison of our calculations with those performed by the Alaga model /5/, viz; we obtain the same values for $B(E2, 2^+_2 \to 2^+_1)$ and the values differing by an order for $B(E2, 2^+_2 \to 0^+_{g.s.})$. In this connection one should point out a rather strong sensitiveness of the results to a choice of the signle-particle level scheme. In Table 4 we present the calculations for some nuclei with $N=80,84$ with changed single-particle schemes (for $N=80$ the scheme is taken from ref. /6/) In this consideration not only the description of energies of the 2^+_2 levels becomes much better but also the results have been distinctly improved for electromagnetic transitions and quadrupole moments in the isotones $N=84$. Thus, the ratio $\frac{B(E2, 2^+_2 \to 0^+_{g.s.})}{B(E2, 2^+_2 \to 2^+_1)}$ in ^{144}Nd becomes six times smaller.

The present experimental information on 3^- states in the nuclei of interest is much more scanty than for 2^+ levels. The second 3^- levels are known only in two nuclei, ^{144}Nd and ^{144}Sm (their energy agrees rather well

Table 3

Calculated results of the properties of excited states with $I^{\pi}=3^{-}$ in isotones N=80,82,84

Nucleus	i	$E(3^-_i)$ kev		$B(E3,0^+_{gs}\rightarrow 3^-_i)e^2b^3$		$Q_2(3^-_i)e{\cdot}b$
		exp.	theor.	exp.	theor.	theor.
^{I42}Ce	I	I653	I654	I.I3	0.I5	0.70
	2	-	3II4	-	0.00I	0.34
^{144}Nd	I	I5I0	I505	0.26	0.I8	0.68
	2	2776	2995	-	0.00I	0.40
^{146}Sm	I	I38I	I399	-	0.2I	0.65
	2	-	2832	-	0.022	0.I4
^{136}Xe	I	3277	3288	-	0.035	0.68
	2	-	3575	-	0.0006	0.28
^{138}Ba	I	288I	2857	-	0.089	0.64
	2	-	34I9	-	0.0004	0.32
^{140}Ce	I	2464	2422	0.76	0.I5	0.59
	2	-	3280	-	0.0005	0.39
^{142}Nd	I	2084	204I	0.44	0.I9	0.59
	2	-	3I49	-	0.0009	0.39
^{144}Sm	I	I809	I846	-	0.24	0.52
	2	3227	3059	-	0.00I	0.45
^{146}Gd	I	I586	I6I4	-	0.32	0.38
	2	-	303I	-	0.00I	0.53
^{136}Ba	I	2532	25I0	-	0.II	0.67
	2	-	3230	-	0.002	0.32

Table 4

Calculated results of the properties of excited states with $I^\pi = 2^+$ in isotones $N = 80, 84$ for changed single-particle level scheme

Nucleus		$E(2_i^+)$	keV	$B(E2, 0_1^+ \to 2_i^+)\, e^2b^2$		$Q_2(2_i^+)\, e\cdot b$		$B(E2, 2_1^+ \to 2_i^+)\, e^2b^2$
		exp.	theor.	exp.	theor.	exp.	theor.	theor.
^{138}Ce	I	789	77I	-	0.38	-	-0.42	
	2	I5II	I444	-	0.I8	-	0.23	0.07
^{136}Ba	I	8I8	794	0.42	0.36	+0.43	-0.44	
	2	I55I	I5I0	-	0.II	-	0.I0	0.04
	3	208I	I689	-	0.003	-	0.29	0.004
^{144}Nd	I	697	678	0.5I	0.49	-0.23	-0.2I	
	2	I556	I488	-	0.I2	-	0.2I	0.I3
^{142}Ce	I	64I	656	0.46	0.48	-0.I2	-0.23	
	2	I536	I469	-	0.II	-	0.I9	0.I2

with our calculation). However, in a number of cases we obtain the probabilities of E3 transitions $0^+_{g.s.} \to 3^-_1$ much smaller than experimental values, but these data are known with large errors and are not very reliable. For ^{142}Nd, , e.g., in paper [19] the value $B(E3, 0^+_{g.s.} \to 3^-_1) = 0.24\ e^2 b^3$ is given. Note also should be made that the probabilities of these transitions calculated in paper [13] appear to be even smaller by one order than our values.

The quasiparticle-phonon interaction influences the structure of 3^- states not less than that of 2^+ states. The component $Q^+_{21} Q^+_{31}$ is large in the wave function of 3^-_1 level. Even in the isotones $N=82$ it amounts to 10% and in other nuclei its value reaches 20-30%. This results in a significant magnitude of $Q_2(3^-_1)$ which experimental measurement would be of interest. To the structure of 3^-_2 states the main contribution comes from the noncollective phonons Q^+_{32} and Q^+_{33}. The change of single-particle schemes does not practically affect the properties of 3^- states, therefore the correspondong results are omitted here.

Thus, we could see that the interaction of collective and two-quasiparticle excitations is considerable in the nuclei we have discussed. It complicates the state structure even at excitation energies 1.5-2.0 MeV. Insertion of the noncollective components into the wave function has made it possible to improve the description of energies and electromagnetic characteristics of the 2^+ levels. The above improvement was sufficient not all the time. This is partly due to the inexact knowledge on the single-particle level scheme; in other cases the more complicated wave function must be used. No doubt, the problem remains open concerning the role of residual forces of another type, e.g., of quadrupole interaction in the particle-particle channel [20]. To analyze the noncollective components the study seems to be necessary of those processes which are more directly connected with the differential structure of states, e.g., of β -decay.

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