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Abstract

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Octupole States of Even-Even Nuclei in the Region $150 \leq A \leq 176$

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In recent years, a semimicroscopic approach to the study of collective nonrotational states of deformed nuclei has become widespread. In ([1]), a method is described for studying quadrupole and octupole excited states within the framework of the superfluid model, and experimental data on such states are systematized. Works ([2–8]) are devoted to calculations of the energies of octupole states, their structure, and the reduced transition probabilities to these states within the method of approximate second quantization. In these calculations, interactions leading to paired correlations of the superconducting type and multipole-multipole interactions are taken into account. Calculations of octupole-state energies that take account of the surface delta interaction are presented in ([9]).

In all these calculations, the energies and wave functions of one-particle levels of the Nilsson potential were used. However, to increase the accuracy of these calculations it is necessary to use a better description of the mean field. This can be done by switching to the use of one-particle energies and wave functions of the Saxon–Woods potential, which has a number of advantages in comparison with the Nilsson potential. In works ([10,11]), for the study of the characteristics of one-phonon states, one-particle energies and wave functions of the Saxon-Woods potential, calculated in ([12]), were used for the first time.

In the present work, the Saxon–Woods scheme has been used in calculating the energies and structure of octupole states of even-even nuclei in the region $150 \leq A \leq 176$. In these calculations, the formulas and computer programs applied were the same as in ([10]). The calculations were carried out for a large number of deformed even-even nuclei.

Since the energies and wave functions of one-particle states of the Saxon–Woods potential depend on the mass number A, the entire region of nuclei studied was divided into zones with $A = 155$ and $A = 165$. For the neutron system an additional zone with $A = 173$ was introduced. Calculations in the zones $A = 155$ and $A = 165$ were performed at deformation $\beta_0 = 0.31$, and in the zone $A = 173$ at $\beta_0 = 0.26$. In solving the secular equations, 50 neutron and 43 proton one-particle levels of the mean field were taken into account. The levels

of the lowest shells were not included: in the neutron system up to $N = 3$, and in the proton system up to $N = 2$.

The constant of the octupole-octupole interaction was chosen so as to obtain the best agreement of the calculated energy values of the first octupole states with the corresponding experimental data. Taking into account the decrease of the constant $\chi^{(3)}$ with increasing A, it was taken to be

$$\chi^{(3)} = (4.24 - 4.06)\ \text{MeV/cm}^6$$

for states with $K^\pi = 1-$ and $2-$, and equal to

$$\chi^{(3)} = (4.46 - 4.26)\ \text{MeV/cm}^6$$

for states with $K^\pi = 0^-$. Thus, the constant $\chi^{(3)}$ for states $K^\pi = 0^-$ is 1.05 times larger than for states $K^\pi = 1^-$ and 2^-.

In calculating the reduced probabilities of electric $E3$ transitions, the value of the effective charge $e^{(3)}_{\text{eff}}$ was taken equal to 0.2 ($e_n = e_{\text{eff}};\ e_p = 1 + e_{\text{eff}}$). The quantities $B(E3)$ are given in single-particle units $B_{sp}(E3) = 4.2\,A^2e^2 10^{-79}$ cm^6.

Table 1

Energies of the first and second octupole states with $K^\pi = 0^-, 1^-$, and 2^- (in MeV)

A	Nucleiment	$K^\pi = 0^-$, experiment	$K^\pi = 0^-$, calculation $i = 1$	$K^\pi = 0^-$, calculation $i = 2$	$K^\pi = 1^-$, experiment	$K^\pi = 1^-$, calculation $i = 1$	$K^\pi = 1^-$, calculation $i = 2$	$K^\pi = 2^-$, experiment	$K^\pi = 2^-$, calculation $i = 1$	$K^\pi = 2^-$, calculation $i = 2$
155	^{150}Nd	–	1.05	2.30	–	1.39	2.37	–	1.62	2.34
155	^{152}Sm	0.966	0.99	1.85	1.511	1.32	2.11	–	1.63	2.38
155	^{154}Sm	0.920	0.98	1.85	1.474	1.37	2.04	–	1.55	2.50
155	^{156}Sm	–	1.02	2.24	–	1.47	2.00	–	1.40	2.36
155	^{154}Gd	1.241	1.10	1.84	1.509	1.38	2.06	1.720	1.37	2.36
155	^{156}Gd	–	1.09	2.21	–	1.41	2.06	–	1.31	2.40
155	^{158}Gd	–	1.13	2.05	–	1.51	2.05	–	1.20	2.29
155	^{160}Gd	–	1.27	2.05	–	1.76	2.06	–	1.14	2.11
155	^{156}Dy	–	1.21	2.30	–	1.49	1.78	–	1.31	2.34
155	^{158}Dy	–	1.20	2.21	–	1.50	1.78	–	1.25	2.33
155	^{160}Dy	–	1.24	2.07	1.285	1.57	1.77	1.264	1.15	2.20
165	^{162}Dy	1.275	1.31	2.05	–	1.83	1.91	1.148	1.05	1.95
165	^{164}Dy	–	1.57	2.40	–	1.59	1.91	0.977	1.09	1.87

A	Nucleiment	$K^\pi = 0^-$, experiment	$K^\pi = 0^-$, calculation $i = 1$	$K^\pi = 0^-$, calculation $i = 2$	$K^\pi = 1^-$, experiment	$K^\pi = 1^-$, calculation $i = 1$	$K^\pi = 1^-$, calculation $i = 2$	$K^\pi = 2^-$, experiment	$K^\pi = 2^-$, calculation $i = 1$	$K^\pi = 2^-$, calculation $i = 2$
165	^{160}Er	–	1.31	2.16	–	1.63	2.16	–	1.87	2.39
165	^{162}Er	–	1.29	2.04	–	1.65	2.15	–	1.65	2.42
165	^{164}Er	1.386	1.37	2.07	–	1.85	2.02	–	1.48	2.18
165	^{166}Er	1.663	1.64	2.41	–	1.59	2.45	1.460	1.47	1.99
165	^{168}Er	–	1.78	2.69	–	1.82	2.03	–	1.87	2.12
165	^{170}Er	–	1.85	2.44	–	1.37	2.31	–	1.81	2.37
165	^{166}Yb	–	1.35	1.95	–	1.83	2.02	–	1.49	2.18
165	^{168}Yb	–	1.56	2.24	–	1.58	2.40	–	1.48	1.98
165	^{170}Yb	1.364	1.66	2.33	–	1.81	2.03	–	1.89	2.12
173	^{172}Yb	–	1.62	2.15	–	1.35	2.41	–	1.57	2.57
173	^{174}Yb	–	1.67	2.43	–	1.63	1.93	1.321	1.27	2.78
173	^{176}Yb	–	2.08	2.51	–	1.55	2.37	–	1.27	2.43
173	^{170}Hf	–	1.58	2.27	–	1.49	1.89	–	1.19	1.79
173	^{172}Hf	–	1.73	2.19	–	1.49	1.62	–	1.39	1.99
173	^{174}Hf	–	1.65	2.17	–	1.35	1.49	–	1.35	1.99
173	^{176}Hf	1.722	1.68	2.60	–	1.49	1.63	1.280	1.15	1.91

Part of the results obtained is presented in Tables 1 and 2. It is seen from the tables that the calculated energies of the octupole states and the values $B(E3)$ agree fairly well with the corresponding experimental data ([13], [14]).

The data obtained show that, for most nuclei, the octupole states with $K^\pi = 0^-$ are more strongly collectivized than the states with $K^\pi = 1^-$ and 2^-. Analysis of the component composition of the octupole states and of the reduced transition probabilities shows that in ^{150}Nd and in the Sm and Gd isotopes the first levels $K^\pi = 0^-, 1^-$, and 2^- are very strongly collectivized; a large number of two-quasiparticle states contributes to their wave functions.

It should be noted that, according to these calculations, the collectivization of the $K^\pi = 1^-$ and 2^- states has increased strongly in comparison with the calculations ([6]) carried out with the Nilsson scheme.

For the Dy isotopes, a decrease in the collectivization of the $K^\pi = 1^-, 2^-$ states is characteristic in comparison with the $K^\pi = 0^-$ states. For the $K^\pi = 1^-$ states there is a noticeable decrease in collectivization with increasing N, so that in ^{164}Dy the contribution

of the first pole in this state is 97.8%. The states $K^\pi = 2^-$ are collectivized substantially more strongly than according to the data of ([6]), obtained with

the Nilsson scheme. Thus, in ^{162}Dy and ^{164}Dy the contribution of the first pole to the wave function of the state $K^\pi = 2^-$ is 50%, whereas according to calculations with the Nilsson scheme it was 97%.

Table 2

Reduced probabilities of $B(E3, O_g \to 1 = 3, K)$-transitions from the ground state to octupole states with $K^\pi = 0^-, 1^-$, and 2^- with $e_{\text{eff}} = 0.2$ (in single-particle units)

A	Nuclei	$B(E3)$, experiment $I_1^\pi = 3^-$	$B(E3)$, experiment $I_2^\pi = 3^-$	$B(E3)$, experiment $I_3^\pi = 3^-$	$B(E3)$, calculation $K^\pi = 0^-$, $i = 1$	$B(E3)$, calculation $K^\pi = 0^-$, $i = 2$	$B(E3)$, calculation $K^\pi = 1^-$, $i = 1$	$B(E3)$, calculation $K^\pi = 1^-$, $i = 2$	$B(E3)$, calculation $K^\pi = 2^-$, $i = 1$	$B(E3)$, calculation $K^\pi = 2^-$, $i = 2$
155	^{150}Nd	–	–	–	10,7	0,2	9,9	0,3	7,0	0,03
155	^{152}Sm	14,7	8,2	–	10,7	0,1	9,4	0,1	6,9	0,04
155	^{154}Sm	8,1	6,0	–	10,6	0,1	6,9	0,1	6,9	0,01
155	^{156}Sm	–	–	–	9,5	0,02	4,4	0,3	6,4	0,01
155	^{154}Gd	16	4,5	–	9,3	0,06	8,7	0,002	6,8	0,02
155	^{156}Gd	11	4,2	–	9,1	0,001	6,3	0,01	7,1	0,2
155	^{158}Gd	6,6	2,2	5	8,3	0,6	3,9	0,3	7,0	0,1
155	^{160}Gd	6,9	2	2,7	6,9	1,3	2,8	0,002	6,2	0,002
155	^{156}Dy	18	–	–	7,8	0,2	7,5	0,2	6,2	0,2
155	^{158}Dy	15	–	–	7,6	0,001	5,2	0,006	6,5	0,4
155	^{160}Dy	11	–	–	6,8	0,8	2,9	0,01	6,6	0,1
165	^{162}Dy	8,7	2,5	1,7	7,8	2,5	1,9	0,002	5,9	0,1
165	^{164}Dy	6,0	3,0	0,8	8,7	0,6	0,2	0,02	4,8	0,2
165	^{160}Er	–	–	–	8,2	0,01	4,2	0,4	4,7	0,01
165	^{162}Er	12	2,1	–	7,6	1,0	2,4	0,6	4,1	0,001
165	^{164}Er	8,1	3,6	1,1	6,4	2,6	1,6	0,04	3,3	0,01
165	^{166}Er	6,1	3,0	2,2	7,6	0,7	0,2	1,9	2,4	0,003
165	^{168}Er	3,3	3,0	1,9	7,3	0,2	0,5	0,02	2,2	0,07
165	^{170}Er	1,1	3,6	2,7	5,4	0,3	0,2	0,01	1,7	0,6
165	^{166}Yb	–	–	–	5,7	0,8	2,0	0,04	3,3	0,01
165	^{168}Yb	7,3	3,7	–	5,9	0,3	0,3	2,4	2,3	0,003
165	^{170}Yb	6,2	4,6	–	5,1	1,2	0,6	0,03	2,0	0,1
173	^{172}Yb	2,6	1,4	4,8	1,7	1,2	0,3	0,05	2,1	0,3
173	^{174}Yb	4,0	4,8	–	0,7	2,3	0,02	0,3	1,4	1,5
173	^{176}Yb	2,6	3,4	–	0,5	1,2	0,01	0,2	0,6	0,4
173	^{170}Hf	–	–	–	5,5	0,1	0,01	0,9	5,2	0,1
173	^{172}Hf	–	–	–	3,8	0,08	0,01	0,6	4,2	0,03
173	^{174}Hf	–	–	–	1,3	0,9	0,3	0,003	3,4	0,2

A	Nuclei	$B(E3)$, experiment $I_1^\pi = 3^-$	$B(E3)$, experiment $I_2^\pi = 3^-$	$B(E3)$, experiment $I_3^\pi = 3^-$	$B(E3)$, calculation $K^\pi = 0^-$, $i = 1$	$B(E3)$, calculation $K^\pi = 0^-$, $i = 2$	$B(E3)$, calculation $K^\pi = 1^-$, $i = 1$	$B(E3)$, calculation $K^\pi = 1^-$, $i = 2$	$B(E3)$, calculation $K^\pi = 2^-$, $i = 1$	$B(E3)$, calculation $K^\pi = 2^-$, $i = 2$
173	^{176}Hf	–	–	–	0,6	3,3	0,01	0,03	2,4	0,6

In the Er, Yb, and Hf isotopes the collectivization of the state $K^\pi = 1^-$ decreases substantially, so that for most isotopes this state is close to a two-quasiparticle one. In ^{168}Er the energy of this state lies rather high; however, if the calculation were carried out with the Saxon–Woods scheme for $A = 168$, the energy would drop noticeably. It should be noted that in $^{172-176}$Yb and ^{174,176}Hf the state $K^\pi = 0^-$ is less collectivized than in the other nuclei.

On the basis of the investigations carried out, it may be concluded that octupole states in the region $150 \leq A \leq 176$ are satisfactorily described by the method of approximate second quantization within the framework of the superfluid model of the nucleus. The use of wave functions and single-particle energies of the Saxon–Woods potential makes it possible to carry out the calculations more consistently, without any arbitrariness. In comparison with calculations based on the Nilsson potential, the calculations performed give, for a number of nuclei, more collective octupole states.

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Note: Figure translations are in progress. See original paper for figures.