NEUTRON ONE-QUASIPARTICLE STATES OF HEAVIEST NUCLEI

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Neutron one-quasiparticle states of heaviest nuclei are calculated within a macroscopic–microscopic approach. Basic characteristics of these states (projection of spin on the symmetry axis, parity, excitation energy, Nilsson label) are given. Much attention is paid to systematics of them (especially of the ground state), as functions of proton number. Other important properties of the analyzed nuclei, as deformation, deformation energy, shell correction to energy and neutron pairing-energy gap parameter, are also given. Heavy and superheavy (even-Z, odd-N) nuclei with proton number $Z = 90$–110 and neutron number N=145–161 are considered. All of them are expected to be deformed. It is obtained that characteristics of the ground states, which are known experimentally, is rather well reproduced.

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1. Introduction

We are recently witnessing intensive experimental studies of single-particle structure of heaviest nuclei (*e.g.* [1–7]). This is connected with a fast progress in synthesis of these nuclei and in detection of their decays. A review of older studies may be found in *e.g.* [8] and of more recent ones in [9]. Theoretical studies are being also done (*e.g.* [10–14]).

The objective of this paper is a theoretical study of neutron single-particle states of heavy and superheavy nuclei. A macroscopic–microscopic approach is applied, which appeared very useful in description of many other properties of these nuclei (*e.g.* [15–19]). The study is performed in a very similar way to that used in our previous analysis of proton single-particle states [14]. Even-Z, odd-N nuclei with $Z = 90$–110 and $N = 145$–161 are considered.

2. Theoretical model

The calculations are done within a macroscopic–microscopic approach. The Yukawa-plus-exponential model [20] is used for the calculation of the macroscopic part of energy of a nucleus, and the Strutinski shell correction is taken for its microscopic part. The Woods–Saxon single-particle potential, with the "universal" variant of its parameters found in [21] and also specified explicitly in [15], is used for description of the single-particle properties of a nucleus. Values of parameters of the macroscopic part of mass are taken the same as in [22], where they were adjusted to experimental masses [23] of even–even heaviest nuclei with atomic number $Z \geq 84$.

A large, 7-dimensional deformation space, $\{\beta_\lambda\}$, $\lambda = 2, 3, \ldots, 8$, is used to obtain the equilibrium deformation of a nucleus. The contribution of an odd nucleon, occupying a single-particle state $|\,\mu\rangle$, to energy of a nucleus is described by the one-quasiparticle energy $E_\mu = \sqrt{(e_\mu - \lambda)^2 + \Delta^2}$. Here, e_μ is the energy of the odd nucleon in the state $|\,\mu\rangle$ and Δ is the pairing-energy gap parameter, calculated in the BCS approximation. Pairing interaction of the monopole type, with the same strength parameters as in [22], is taken. No blocking is used. The calculations are done in a very similar way to that of [14] (*cf.* also [18, 24]).

3. Results

3.1. Equilibrium deformations

As stated in the previous section, equilibrium deformation of a nucleus is calculated in the 7-dimensional deformation space, $\{\beta_\lambda\}$, $\lambda = 2, 3, \ldots, 8$. Non-zero equilibrium deformation parameters of odd multipolarity, $\beta_\lambda^0 \neq 0$, $\lambda = 3, 5, 7$, are obtained, however, only for very light isotopes of the analyzed elements, *e.g.* ^{227}Th, ^{225}U, ^{227}Pu (*cf.* [25]), *i.e.* much lighter than these considered in the present paper. Thus, for all nuclei studied here, only deformations of even multipolarities $\beta_\lambda^0, \lambda = 2, 4, 6, 8$, are different from zero. Their values are given in Table I.

3.2. Deformation energy, shell correction energy and neutron pairing-energy gap

Table I also shows a few other important characteristics of the considered nuclei: deformation energy $E_{\rm def}$, shell correction energy $E_{\rm sh}$ and neutron energy gap parameter Δ_n. The energy $E_{\rm def}$ tells us how well is a nucleus deformed and $E_{\rm sh}$ informs us how much it gains in energy from its shell structure. Value of the parameter Δ_n gives an information how good is the BCS approximation. If Δ_n is not too close to zero, the approximation is good.

One can see in Table I that all considered nuclei are well deformed (as such ones, we consider nuclei with $E_{\rm def} > 2\,{\rm MeV}$ [26]). For most of them $E_{\rm def}$ exceeds 10 MeV and for some of them this energy is even larger than 13 MeV.

Concerning shell correction energy $E_{\rm sh}$, it reflects a general tendency discussed *e.g.* in [15, 16, 27]. For nuclei considered in this paper, $E_{\rm sh}$ takes its maximum (6.4 MeV in absolute value) for the nucleus ^{269}Hs (Z=108), *i.e.* for a neighbor of the doubly magic deformed nucleus ^{270}Hs [15, 27].

What concerns the pairing-energy gap parameter Δ_n, one can see in Table I that it is never equal to zero. The smallest value of it (0.36 MeV) is obtained for the nucleus ^{269}Hs, *i.e.* the nucleus with the largest shell correction $E_{\rm sh}$, which means that it strongly feels the influence of a large energy gap in the neutron single-particle spectrum appearing at the closed deformed shell at $N = 162$. For such a nucleus, the value $\Delta_n = 0.36$ MeV may be considered as a "normal" value, not influenced by the deficiency of the BCS approximation which appears at the pairing interaction strength G close to its critical value $G_{\rm cr}$. A direct check shows that we are really, in this case, in a sufficiently large distance from $G_{\rm cr}$.

3.3. One-quasiparticle states

In this subsection, we present quantum characteristics and excitation energies of 5 lowest neutron states: the ground state and 4 excited states. The quantum characteristics are: projection of the total spin of a state on the symmetry axis Ω and the Nilsson ("asymptotic") quantum numbers $[N\, n_z \Lambda]$, where N is the total number of the oscillator quanta, n_z is the number of quanta along the symmetry axis Oz and Λ is projection of the orbital angular momentum on the symmetry axis. For a shorter notation, we give 2Ω instead of Ω, and do not show explicitly parity π of a state, as it is the same as parity of the number N ($\pi = (-1)^N$). (In the figures, however, we explicitly show also π.)

Characteristics of the ground state (g.s.) of considered nuclei are given in Table I. They are compared with available experimental data, taken from references given in the last column. As usual, data, which are not certain, are put into round brackets. One can see that in most cases, calculated Ω and parity agree with experimental ones. More particularly, of 34 cases, in which experimental indications of the values of Ω and π are given, the agreement appears in 23 cases. In the rest ones, a calculated state with proper Ω and π is often close or even very close in energy to the ground state (*e.g.* ^{241}Cm), but sometimes it is not (*e.g.* ^{255}Fm), as can bee seen in Figs. 3 to 9.

TABLE I

Deformation parameters β_λ^0, deformation energies $E_{\rm def}$, shell correction energies $E_{\rm sh}$, neutron energy-gap parameters Δ_n and the ground-state quantum characteristics: theoretical (th) and experimental (exp) given for even-Z, odd-N nuclei with $N = 145$–161.

Z	A	β_2^0	β_4^0	β_6^0	β_8^0	$E_{\rm def}$	$E_{\rm sh}$	Δ_n	(th)	(exp)	Ref.
—	—	—	—	—	—	[MeV]	[MeV]	[MeV]	g.s.	g.s.	—
					$N = 145$						
90	235	0.219	0.091	−0.007	−0.025	7.9	−1.9	0.55	7[743]	(1+)	[28]
92	237	0.223	0.095	−0.007	−0.026	9.5	−2.4	0.53	7[743]	1+	[28]
94	239	0.229	0.091	−0.011	−0.026	10.7	−2.8	0.51	7[743]	1+	[28]
96	241	0.233	0.081	−0.018	−0.021	11.7	−2.9	0.52	7[743]	1+	[28]
98	243	0.237	0.072	−0.027	−0.018	12.3	−3.0	0.53	1[631]	(1+)	[5, 28]
100	245	0.241	0.062	−0.032	−0.021	12.6	−2.9	0.54	1[631]		
102	247	0.242	0.052	−0.037	−0.014	12.3	−2.4	0.58	1[631]		
					$N = 147$						
92	239	0.231	0.083	−0.018	−0.028	9.6	−2.5	0.49	5[622]	5+	[28]
94	241	0.235	0.081	−0.021	−0.025	10.8	−2.9	0.48	5[622]	5+	[28]
96	243	0.238	0.073	−0.026	−0.021	12.0	−3.2	0.49	5[622]	5+	[28]
98	245	0.242	0.064	−0.034	−0.017	12.7	−3.4	0.50	5[622]	(5+)	[5]
100	247	0.247	0.055	−0.043	−0.015	13.2	−3.5	0.51	5[622]	(7+)	[5]
102	249	0.247	0.044	−0.045	−0.011	12.9	−3.1	0.55	5[622]		
104	251	0.244	0.028	−0.040	−0.008	12.3	−2.7	0.61	5[622]		
106	253	0.243	0.009	−0.038	0.001	11.6	−2.3	0.68	7[624]		
					$N = 149$						
94	243	0.235	0.062	−0.027	−0.013	10.5	−2.8	0.53	7[624]	7+	[28]
96	245	0.238	0.058	−0.031	−0.011	11.7	−3.3	0.53	7[624]	7+	[28]
98	247	0.243	0.050	−0.038	−0.008	12.7	−3.6	0.52	7[624]	(7+)	[28]
100	249	0.247	0.042	−0.046	−0.006	13.2	−3.9	0.52	7[624]	7+	[5, 9]
102	251	0.249	0.029	−0.050	−0.002	13.2	−3.7	0.55	7[624]	7+	[4, 5]
104	253	0.247	0.016	−0.045	0.000	12.8	−3.5	0.57	9[734]		
106	255	0.246	−0.001	−0.043	0.007	12.2	−3.3	0.62	9[734]		
					$N = 151$						
94	245	0.239	0.043	−0.035	−0.002	10.1	−2.9	0.49	9[734]	(9-)	[28]
96	247	0.242	0.041	−0.038	−0.001	11.4	−3.4	0.47	9[734]	9-	[28]
98	249	0.245	0.035	−0.044	0.000	12.4	−4.0	0.44	9[734]	9-	[28]
100	251	0.249	0.029	−0.051	0.002	13.2	−4.4	0.42	9[734]	(9-)	[28]
102	253	0.252	0.019	−0.054	0.005	13.4	−4.5	0.42	9[734]	9-	[5]
104	255	0.249	0.008	−0.050	0.006	13.2	−4.4	0.43	9[734]	9-	[4]
106	257	0.247	−0.006	−0.047	0.011	12.8	−4.3	0.45	9[734]		
					$N = 153$						
94	247	0.243	0.027	−0.042	0.006	9.3	−2.6	0.51	1[620]		
96	249	0.245	0.026	−0.045	0.006	10.5	−3.2	0.49	1[620]	1(+)	[28]
98	251	0.248	0.023	−0.049	0.007	11.6	−3.8	0.47	1[620]	1+	[28]
100	253	0.251	0.017	−0.054	0.005	12.4	−4.3	0.45	1[620]	1+	[28]
102	255	0.254	0.009	−0.059	0.012	12.8	−4.6	0.43	1[620]	(1+)	[28]
104	257	0.252	−0.004	−0.054	0.014	12.8	−4.7	0.43	1[620]	1+	[1]
106	259	0.250	−0.016	−0.051	0.018	12.5	−4.8	0.44	1[620]	(1+)	[28]
108	261	0.243	−0.028	−0.043	0.018	11.6	−4.5	0.47	1[620]		

TABLE I cont.

Z	A	β_2^0	β_4^0	β_6^0	β_8^0	$E_{\rm def}$	$E_{\rm sh}$	Δ_n	(th)	(exp)	Ref.
—	—	—	—	—	—	[MeV]	[MeV]	[MeV]	g.s.	g.s.	—
					$N=155$						
94	249	0.240	0.016	−0.041	0.011	8.3	−2.3	0.61	1[620]		
96	251	0.243	0.016	−0.043	0.011	9.4	−2.8	0.60	1[620]	(1+)	[28]
98	253	0.246	0.012	−0.048	0.012	10.5	−3.4	0.58	1[620]	(7+)	[28]
100	255	0.250	0.006	−0.053	0.014	11.3	−4.0	0.56	1[620]	7+	[28]
102	257	0.253	−0.003	−0.056	0.019	11.8	−4.3	0.54	1[620]	(7+)	[28]
104	259	0.251	−0.015	−0.053	0.021	11.9	−4.6	0.54	1[620]		
106	261	0.249	−0.027	−0.050	0.025	11.9	−5.0	0.54	1[620]		
108	263	0.245	−0.041	−0.040	0.025	11.1	−4.9	0.56	1[620]		
					$N=157$						
96	253	0.237	0.002	−0.043	0.020	8.3	−2.5	0.62	11[725]		
98	255	0.245	−0.002	−0.047	0.020	9.3	−3.0	0.60	11[725]	(9+)	[28]
100	257	0.249	−0.007	−0.052	0.022	10.1	−3.6	0.57	11[725]	(9+)	[28]
102	259	0.252	−0.016	−0.055	0.026	10.7	−4.2	0.54	11[725]	(9+)	[28]
104	261	0.251	−0.026	−0.052	0.029	10.9	−4.6	0.52	11[725]		
106	263	0.250	−0.037	−0.050	0.032	11.1	−5.1	0.51	11[725]		
108	265	0.245	−0.049	−0.039	0.030	10.5	−5.2	0.54	11[725]		
110	267	0.234	−0.050	−0.028	0.023	8.5	−4.1	0.59	3[622]		
					$N=159$						
98	257	0.237	−0.016	−0.037	0.019	8.2	−2.9	0.58	9[615]		
100	259	0.244	−0.021	−0.045	0.025	9.0	−3.5	0.54	7[613]		
102	261	0.243	−0.029	−0.044	0.026	9.7	−4.1	0.52	7[613]		
104	263	0.245	−0.038	−0.044	0.029	10.1	−4.8	0.49	7[613]		
106	265	0.247	−0.047	−0.045	0.034	10.3	−5.4	0.47	7[613]		
108	267	0.240	−0.059	−0.034	0.032	9.9	−5.7	0.50	7[613]		
110	269	0.232	−0.063	−0.022	0.027	8.1	−4.8	0.54	9[615]		
					$N=161$						
100	261	0.233	−0.037	−0.031	0.022	8.1	−3.7	0.43	9[615]		
102	263	0.235	−0.042	−0.032	0.024	8.8	−4.3	0.41	9[615]		
104	265	0.237	−0.049	−0.033	0.026	9.3	−5.1	0.39	9[615]		
106	267	0.238	−0.057	−0.033	0.030	9.6	−5.8	0.37	9[615]		
108	269	0.237	−0.067	−0.026	0.031	9.5	−6.4	0.36	9[615]		
110	271	0.230	−0.072	−0.017	0.028	7.8	−5.6	0.38	9[615]		

Table II gives quantum characteristics and excitation energies of the lowest four neutron one-quasiparticle states of considered nuclei, in addition to the ground state. Here, the structure of the states is better described than in Table I, as three main components of each state, instead of only one, are specified. These are the components in the expansion of a given state (Ω,π) in terms of pure harmonic oscillator (h.o.) states. Magnitude of the contribution of a component to the state is given (in %) by square of the amplitude of this component. Sum of the contributions of all components

TABLE II

Quantum characteristics $2\Omega[N\,n_z\Lambda]$ of three main components (and their contributions given in %) of the ground state (g.s.) and of four excited states of (even-Z, odd-N) nuclei with neutron number N = 145–161. For an excited state, the excitation energy is also given (in MeV).

Z	A	g.s.	1	2	3	4
				N=145		
90	235	7[743] 58	1[631] 38 0.05	5[622] 47 0.12	7[624] 50 0.53	5[633] 57 0.57
		7[723] 16	1[611] 11	5[633] 14	7[633] 13	5[642] 14
		7[734] 10	1[640] 11	5[422] 8	7[613] 10	5[613] 12
92	237	7[743] 59	1[631] 39 0.04	5[622] 47 0.14	7[624] 51 0.57	5[633] 58 0.58
		7[723] 16	1[611] 11	5[633] 13	7[633] 13	5[642] 14
		7[734] 10	1[640] 10	5[422] 8	7[613] 10	5[613] 12
94	239	7[743] 59	1[631] 39 0.02	5[622] 48 0.16	7[624] 57 0.59	5[633] 60 0.62
		7[723] 15	1[611] 11	5[633] 12	7[633] 12	5[642] 14
		7[734] 10	1[640] 10	5[422] 9	7[613] 7	5[613] 11
96	241	7[743] 59	1[631] 39 0.00	5[622] 50 0.14	7[624] 65 0.52	5[633] 61 0.67
		7[723] 15	1[640] 10	5[633] 10	7[633] 12	5[642] 14
		7[734] 10	1[611] 10	5[422] 9	7[604] 6	5[613] 10
98	243	1[631] 39	7[743] 58 0.02	5[622] 51 0.14	7[624] 70 0.48	1[501] 45 0.53
		1[640] 11	7[723] 14	5[422] 10	7[633] 11	1[701] 22
		1[611] 10	7[734] 10	5[633] 9	7[604] 5	1[301] 19
100	245	1[631] 39	7[743] 58 0.05	5[622] 52 0.14	1[501] 47 0.37	7[624] 72 0.44
		1[640] 10	7[723] 14	5[422] 10	1[701] 21	7[633] 10
		1[611] 9	7[734] 10	5[633] 8	1[301] 18	7[604] 5
102	247	1[631] 38	7[743] 58 0.06	5[622] 53 0.10	1[501] 48 0.26	7[624] 74 0.32
		1[640] 11	7[723] 14	5[422] 10	1[701] 21	7[633] 10
		1[611] 8	7[734] 11	5[633] 7	1[301] 18	7[604] 4
				N=147		
92	239	5[622] 49	7[624] 60 0.26	7[743] 58 0.26	1[631] 39 0.34	9[734] 72 0.47
		5[633] 10	7[633] 12	7[723] 15	1[611] 10	9[714] 10
		5[422] 9	7[613] 6	7[734] 10	1[640] 10	9[725] 8
94	241	5[622] 50	7[624] 64 0.25	7[743] 58 0.30	1[631] 40 0.34	9[734] 72 0.43
		5[633] 10	7[633] 11	7[723] 15	1[611] 10	9[714] 9
		5[422] 9	7[604] 6	7[734] 10	1[640] 10	9[725] 8
96	243	5[622] 51	7[624] 69 0.21	1[631] 39 0.31	7[743] 58 0.32	9[734] 72 0.37
		5[422] 10	7[633] 11	1[640] 10	7[723] 14	9[714] 9
		5[633] 9	7[604] 5	1[611] 10	7[734] 10	9[725] 8
98	245	5[622] 52	7[624] 72 0.17	1[631] 39 0.30	9[734] 73 0.31	7[743] 58 0.34
		5[422] 10	7[633] 10	1[640] 10	9[714] 8	7[723] 14
		5[822] 8	7[604] 5	1[611] 9	9[725] 7	7[734] 10
100	247	5[622] 53	7[624] 74 0.14	9[734] 73 0.24	1[631] 39 0.30	7[743] 57 0.37
		5[422] 10	7[633] 10	9[714] 8	1[640] 10	7[723] 13
		5[822] 8	7[604] 4	9[725] 7	1[611] 8	7[734] 10
102	249	5[622] 53	7[624] 75 0.09	9[734] 72 0.19	1[631] 37 0.25	7[743] 57 0.34
		5[422] 11	7[633] 10	9[714] 8	1[640] 11	7[723] 13
		5[822] 7	7[604] 4	9[725] 7	1[611] 8	7[734] 11

TABLE II cont.

Z	A	g.s.	1	2	3	4
				N=147 (continuation)		
104	251	5[622] 53	7[624] 76 0.03	9[734] 72 0.15	1[631] 35 0.16	7[743] 57 0.29
		5[422] 11	7[633] 10	9[725] 8	1[640] 11	7[723] 14
		5[822] 7	7[604] 3	9[714] 7	1[431] 8	7[734] 12
106	253	7[624] 76	5[622] 52 0.01	9[734] 71 0.09	1[631] 31 0.10	1[501] 52 0.16
		7[633] 11	5[422] 12	9[725] 8	1[640] 12	1[701] 19
		7[844] 4	5[842] 8	9[954] 7	1[431] 8	1[301] 18
				N=149		
94	243	7[624] 71	9[734] 72 0.10	5[622] 50 0.11	7[743] 57 0.50	1[631] 37 0.54
		7[633] 11	9[714] 8	5[422] 10	7[723] 14	1[640] 10
		7[604] 5	9[725] 8	5[633] 9	7[734] 11	1[611] 9
96	245	7[624] 72	9[734] 72 0.08	5[622] 51 0.10	1[631] 37 0.53	7[743] 57 0.53
		7[633] 10	9[714] 8	5[422] 11	1[640] 10	7[723] 14
		7[604] 5	9[725] 8	5[822] 8	1[611] 9	7[734] 11
98	247	7[624] 74	9[734] 72 0.06	5[622] 52 0.09	1[631] 37 0.52	7[743] 57 0.55
		7[633] 10	9[714] 8	5[422] 11	1[640] 11	7[723] 14
		7[604] 4	9[725] 7	5[822] 8	1[611] 8	7[734] 11
100	249	7[624] 75	9[734] 72 0.04	5[622] 52 0.08	1[631] 36 0.51	7[743] 56 0.56
		7[633] 10	9[714] 7	5[422] 11	1[640] 11	7[723] 13
		7[604] 4	9[954] 7	5[822] 8	1[431] 8	7[734] 11
102	251	7[624] 76	9[734] 72 0.02	5[622] 53 0.07	1[631] 34 0.44	7[743] 56 0.52
		7[633] 10	9[954] 8	5[422] 11	1[640] 11	7[723] 13
		7[844] 4	9[725] 7	5[822] 8	1[431] 8	7[734] 11
104	253	9[734] 71	7[624] 76 0.01	5[622] 52 0.07	1[631] 32 0.33	1[501] 50 0.38
		9[725] 8	7[633] 10	5[422] 12	1[640] 11	1[701] 20
		9[954] 8	7[844] 4	5[842] 8	1[431] 8	1[301] 18
106	255	9[734] 71	7[624] 75 0.08	5[622] 52 0.11	1[501] 51 0.23	1[631] 29 0.26
		9[725] 8	7[633] 11	5[422] 12	1[701] 19	1[640] 11
		9[954] 8	7[844] 5	5[842] 9	1[301] 18	1[431] 8
				N=151		
94	245	9[734] 71	7[624] 73 0.16	5[622] 50 0.39	1[620] 44 0.49	7[613] 55 0.55
		9[725] 8	7[633] 10	5[422] 11	1[420] 10	7[813] 15
		9[714] 8	7[604] 4	5[822] 8	1[820] 8	7[413] 13
96	247	9[734] 71	7[624] 74 0.17	5[622] 51 0.38	1[620] 44 0.54	7[613] 56 0.64
		9[725] 8	7[633] 10	5[422] 11	1[420] 10	7[813] 14
		9[714] 7	7[604] 4	5[822] 8	1[820] 8	7[413] 13
98	249	9[734] 71	7[624] 75 0.17	5[622] 51 0.36	1[620] 45 0.59	3[622] 52 0.72
		9[954] 8	7[633] 10	5[422] 12	1[420] 11	3[422] 8
		9[725] 7	7[604] 4	5[822] 8	1[820] 8	3[631] 7
100	251	9[734] 71	7[624] 75 0.18	5[622] 52 0.33	1[620] 46 0.63	3[622] 53 0.76
		9[954] 8	7[633] 10	5[422] 12	1[420] 11	3[422] 8
		9[725] 7	7[844] 4	5[842] 8	1[820] 8	3[631] 7

TABLE II cont.

Z	A	g.s.	1	2	3	4
				N=151 (continuation)		
102	253	9[734] 71	7[624] 76 0.20	5[622] 52 0.32	1[620] 47 0.66	1[501] 47 0.71
		9[954] 8	7[633] 10	5[422] 12	1[420] 11	1[701] 20
		9[725] 7	7[844] 5	5[842] 9	1[820] 8	1[301] 18
104	255	9[734] 70	7[624] 75 0.25	5[622] 52 0.32	1[501] 49 0.58	1[631] 31 0.63
		9[954] 8	7[633] 10	5[422] 12	1[701] 20	1[640] 11
		9[725] 8	7[844] 5	5[842] 9	1[301] 18	1[431] 8
106	257	9[734] 70	7[624] 75 0.32	5[622] 51 0.34	1[501] 50 0.41	1[631] 28 0.51
		9[954] 8	7[633] 10	5[422] 13	1[701] 19	1[640] 11
		9[725] 8	7[844] 5	5[842] 10	1[301] 18	1[431] 8
				N=153		
94	247	1[620] 44	3[622] 50 0.09	7[613] 56 0.15	9[734] 70 0.17	11[725] 81 0.33
		1[420] 11	3[422] 8	7[813] 15	9[954] 8	11[925] 5
		1[820] 8	3[631] 8	7[413] 13	9[725] 8	11[945] 5
96	249	1[620] 44	3[622] 51 0.09	7[613] 57 0.18	9[734] 70 0.23	11[725] 81 0.30
		1[420] 11	3[422] 8	7[813] 14	9[954] 8	11[925] 5
		1[820] 8	3[631] 7	7[413] 13	9[725] 8	11[945] 5
98	251	1[620] 45	3[622] 52 0.08	7[613] 58 0.22	11[725] 81 0.28	9[734] 70 0.30
		1[420] 11	3[422] 8	7[813] 14	11[945] 5	9[954] 8
		1[820] 8	3[631] 7	7[413] 13	11[925] 5	9[725] 8
100	253	1[620] 46	3[622] 53 0.07	11[725] 82 0.25	7[613] 59 0.26	9[734] 70 0.39
		1[420] 11	3[422] 8	11[945] 5	7[813] 14	9[954] 8
		1[820] 8	3[631] 7	11[925] 5	7[413] 13	9[725] 7
102	255	1[620] 46	3[622] 53 0.06	11[725] 82 0.22	7[613] 60 0.37	9[734] 70 0.47
		1[420] 11	3[422] 8	11[945] 6	7[813] 13	9[954] 9
		1[840] 9	3[842] 8	11[925] 5	7[413] 12	9[725] 7
104	257	1[620] 46	3[622] 52 0.05	11[725] 82 0.15	7[613] 60 0.36	9[734] 69 0.48
		1[420] 11	3[422] 9	11[945] 6	7[813] 13	9[954] 9
		1[840] 9	3[842] 8	11[925] 5	7[413] 13	9[725] 8
106	259	1[620] 45	3[622] 52 0.05	11[725] 81 0.09	7[613] 61 0.37	9[734] 69 0.47
		1[420] 12	3[422] 9	11[945] 7	7[413] 13	9[954] 9
		1[840] 10	3[842] 9	11[925] 5	7[813] 12	9[725] 8
108	261	1[620] 43	11[725] 81 0.03	3[622] 50 0.04	7[613] 61 0.29	9[734] 68 0.40
		1[420] 12	11[945] 7	3[422] 9	7[413] 13	9[725] 9
		1[840] 10	11[925] 5	3[842] 9	7[813] 12	9[954] 8
				N=155		
94	249	1[620] 43	3[622] 49 0.02	7[613] 56 0.06	11[725] 81 0.14	9[615] 78 0.39
		1[420] 11	3[422] 9	7[813] 15	11[925] 5	9[624] 6
		1[820] 8	3[631] 8	7[413] 13	11[945] 5	9[815] 4
96	251	1[620] 43	3[622] 50 0.02	7[613] 57 0.07	11[725] 81 0.12	9[615] 79 0.40
		1[420] 11	3[422] 9	7[813] 14	11[945] 5	9[624] 6
		1[840] 8	3[631] 8	7[413] 13	11[925] 5	9[815] 4
98	253	1[620] 44	3[622] 51 0.01	11[725] 81 0.10	7[613] 58 0.10	9[615] 81 0.44
		1[420] 11	3[422] 9	11[945] 6	7[813] 14	9[624] 6
		1[840] 9	3[842] 8	11[925] 5	7[413] 13	9[815] 4

TABLE II cont.

Z	A	g.s.	1	2	3	4
				N=155 (continuation)		
100	255	1[620] 45	3[622] 52 0.01	11[725] 81 0.08	7[613] 59 0.14	9[615] 82 0.50
		1[420] 11	3[422] 9	11[945] 6	7[813] 14	9[624] 5
		1[840] 9	3[842] 8	11[925] 5	7[413] 13	9[815] 4
102	257	1[620] 45	3[622] 52 0.00	11[725] 81 0.05	7[613] 60 0.20	9[615] 84 0.55
		1[420] 12	3[422] 9	11[945] 7	7[813] 13	9[624] 5
		1[840] 9	3[842] 9	11[925] 5	7[413] 13	9[815] 3
104	259	1[620] 44	3[622] 51 0.00	11[725] 81 0.03	7[613] 60 0.21	9[615] 85 0.51
		1[420] 12	3[422] 9	11[945] 7	7[413] 13	9[624] 5
		1[840] 10	3[842] 9	11[925] 5	7[813] 13	9[835] 3
106	261	1[620] 43	3[622] 50 0.00	11[725] 81 0.01	7[613] 61 0.22	9[615] 85 0.48
		1[420] 12	3[842] 9	11[945] 7	7[413] 13	9[624] 5
		1[840] 10	3[422] 9	11[925] 5	7[813] 12	9[835] 4
108	263	1[620] 42	3[622] 48 0.00	11[725] 80 0.00	7[613] 60 0.17	9[615] 85 0.34
		1[420] 12	3[842] 10	11[945] 7	7[413] 13	9[624] 5
		1[840] 11	3[422] 9	11[925] 5	7[813] 12	9[835] 5
				N=157		
96	253	11[725] 80	7[613] 57 0.00	3[622] 48 0.02	1[620] 42 0.05	9[615] 82 0.19
		11[945] 6	7[813] 14	3[422] 9	1[420] 12	9[624] 6
		11[925] 6	7[413] 13	3[842] 8	1[840] 9	9[815] 4
98	255	11[725] 81	7[613] 58 0.02	3[622] 50 0.03	1[620] 43 0.07	9[615] 83 0.24
		11[945] 6	7[813] 14	3[422] 9	1[420] 12	9[624] 5
		11[925] 5	7[413] 13	3[842] 9	1[840] 10	9[815] 4
100	257	11[725] 81	7[613] 59 0.04	3[622] 50 0.04	1[620] 43 0.08	9[615] 84 0.28
		11[945] 7	7[813] 14	3[422] 9	1[420] 12	9[624] 5
		11[925] 5	7[413] 13	3[842] 9	1[840] 10	9[815] 4
102	259	11[725] 81	3[622] 50 0.06	7[613] 60 0.06	1[620] 43 0.09	9[615] 85 0.32
		11[945] 7	3[842] 9	7[813] 13	1[420] 12	9[624] 5
		11[925] 5	3[422] 9	7[413] 13	1[840] 10	9[835] 4
104	261	11[725] 80	3[622] 50 0.05	7[613] 60 0.06	1[620] 43 0.08	9[615] 85 0.28
		11[945] 8	3[842] 10	7[413] 13	1[420] 12	9[624] 5
		11[925] 5	3[422] 9	7[813] 13	1[840] 11	9[835] 4
106	263	11[725] 80	3[622] 49 0.04	7[613] 60 0.06	1[620] 42 0.06	9[615] 85 0.25
		11[945] 8	3[842] 10	7[413] 13	1[420] 12	9[835] 5
		11[925] 5	3[422] 9	7[813] 12	1[840] 11	9[624] 5
108	265	11[725] 80	3[622] 47 0.01	7[613] 60 0.02	1[620] 40 0.02	9[615] 85 0.12
		11[945] 8	3[842] 10	7[413] 13	1[420] 12	9[835] 6
		11[925] 5	3[422] 9	7[813] 12	1[840] 11	9[624] 5
110	267	3[622] 46	7[613] 59 0.00	1[620] 39 0.01	11[725] 79 0.02	9[615] 85 0.04
		3[842] 10	7[413] 14	1[420] 12	11[945] 7	9[624] 5
		3[422] 10	7[813] 12	1[840] 11	11[925] 5	9[835] 5

TABLE II cont.

Z	A	g.s.	1	2	3	4
				N=159		
98	257	9[615] 84	7[613] 57 0.00	11[725] 80 0.03	3[622] 47 0.11	1[620] 40 0.16
		9[624] 5	7[813] 14	11[945] 7	3[422] 10	1[420] 12
		9[815] 4	7[413] 14	11[925] 6	3[842] 9	1[840] 10
100	259	7[613] 58	9[615] 84 0.05	11[725] 80 0.08	3[622] 48 0.19	1[620] 41 0.24
		7[813] 14	9[624] 5	11[945] 7	3[842] 10	1[420] 12
		7[413] 13	9[835] 4	11[925] 6	3[422] 9	1[840] 10
102	261	7[613] 59	9[615] 85 0.04	11[725] 80 0.11	3[622] 48 0.20	1[620] 41 0.24
		7[413] 13	9[624] 5	11[945] 7	3[842] 10	1[420] 12
		7[813] 13	9[835] 4	11[925] 6	3[422] 10	1[840] 11
104	263	7[613] 59	9[615] 85 0.04	11[725] 80 0.15	3[622] 47 0.23	1[620] 41 0.27
		7[413] 13	9[835] 5	11[945] 8	3[842] 10	1[420] 12
		7[813] 13	9[624] 5	11[925] 5	3[422] 10	1[840] 11
106	265	7[613] 59	9[615] 84 0.05	11[725] 79 0.21	3[622] 47 0.28	1[620] 40 0.31
		7[413] 13	9[835] 6	11[945] 8	3[842] 10	1[420] 12
		7[813] 12	9[624] 5	11[925] 5	3[422] 9	1[840] 11
108	267	7[613] 59	9[615] 84 0.01	11[725] 79 0.19	3[622] 45 0.19	1[620] 38 0.21
		7[413] 13	9[835] 6	11[945] 8	3[842] 10	1[420] 12
		7[813] 12	9[624] 5	11[925] 6	3[422] 10	1[840] 11
110	269	9[615] 84	7[613] 58 0.01	3[622] 43 0.11	1[620] 37 0.12	11[725] 78 0.16
		9[835] 6	7[413] 14	3[842] 10	1[420] 12	11[945] 8
		9[624] 5	7[813] 12	3[422] 10	1[840] 11	11[925] 6
				N=161		
100	261	9[615] 84	7[613] 57 0.15	11[725] 79 0.24	3[622] 45 0.33	1[620] 38 0.38
		9[624] 5	7[413] 14	11[945] 7	3[842] 10	1[420] 12
		9[835] 5	7[813] 14	11[925] 6	3[422] 10	1[840] 11
102	263	9[615] 84	7[613] 57 0.13	11[725] 79 0.29	3[622] 45 0.36	1[620] 38 0.40
		9[624] 5	7[413] 14	11[945] 7	3[842] 10	1[420] 12
		9[835] 5	7[813] 14	11[925] 6	3[422] 10	1[840] 11
104	265	9[615] 84	7[613] 58 0.11	11[725] 79 0.33	3[622] 45 0.38	1[620] 38 0.42
		9[835] 5	7[413] 14	11[945] 8	3[842] 10	1[420] 12
		9[624] 5	7[813] 13	11[925] 6	3[422] 10	1[840] 11
106	267	9[615] 84	7[613] 58 0.08	11[725] 78 0.38	3[622] 45 0.41	1[620] 38 0.44
		9[835] 6	7[413] 14	11[945] 8	3[842] 10	1[420] 12
		9[624] 5	7[813] 13	11[925] 6	3[422] 10	1[840] 11
108	269	9[615] 83	7[613] 58 0.05	3[622] 43 0.34	11[725] 78 0.35	1[620] 37 0.36
		9[835] 7	7[413] 14	3[842] 11	11[945] 8	1[420] 12
		9[624] 5	7[813] 12	3[422] 10	11[925] 6	1[840] 11
110	271	9[615] 83	7[613] 57 0.02	3[622] 42 0.19	1[620] 35 0.20	11[725] 77 0.26
		9[835] 7	7[413] 14	3[842] 10	1[420] 12	11[945] 8
		9[624] 5	7[813] 12	3[422] 10	1[840] 11	11[925] 6

is 100%, as each state is normalized to unity. The components are given in the sequence of decreasing contributions. Knowledge of such structure of a state is important for interpretation and predictions of α decay of odd-A nuclei. Usual Nilsson label (asymptotic quantum numbers) of a state (Ω,π)is the h.o. state which gives the largest contribution to this state.

One can see in Table II that the main component may give as large as 85%, but also as small as 28% contribution. Usually, the main contribution significantly differs in its magnitude from the next one, but the second and the third contributions are already comparable with each other.

It is interesting to see how representative is the Nilsson label for the structure of a given state. An inspection to Table II indicates that it represents this structure quite well. We mean by this that if two states, in two different nuclei, have the same Nilsson label (*i.e.* the same h.o. state, which gives the largest contributions to them), these contributions are of a comparable magnitude and the next contributing states are also the same and of similar contributions to these states. And this is, to a large extent, independent of how different are nuclei, in which the states appear, and of how different are the excitation energies of these states. An example of this may be the states 7+, which appear in ^{249}Pu at the excitation energy $E_{\rm exc} = 60$ keV and in ^{261}Sg at the excitation energy $E_{\rm exc} = 220$ keV. Both nuclei have neutron number $N = 155$. One can see in the Table that the structure of these states is similar (the same 3 main components with similar contributions). One should add that deformations of these nuclei differ from each other. Although quadrupole components of the deformations are similar (β_2^0=0.240 and 0.249, respectively), the hexadecapole ones are quite different ($\beta_4^0 = 0.016$ and -0.027, respectively).

To get an orientation, how well the calculated spectra reproduce experimental ones, we show Figs. 1 and 2. One can see that usually the discrepancy in energy of the lowest states does not exceed about 300 keV. Average discrepancy for the lowest six excited states of ^{245}Cm, shown in Fig. 1, is 165 keV, and for four exited states of ^{249}Cf, shown in Fig. 2, is 235 keV.

Figs. 3 to 11 illustrate the dependence of the neutron spectra on proton number Z (or mass number A) for the isotones with $N = 145$ to $N = 161$. Here, all states with the excitation energy up to about 1 MeV are shown. Behavior of each level with changing Z is shown. Generally, larger the excitation energy, stronger is the dependence on Z. In particular, the ground state remains usually the same for a rather long chain of isotones.

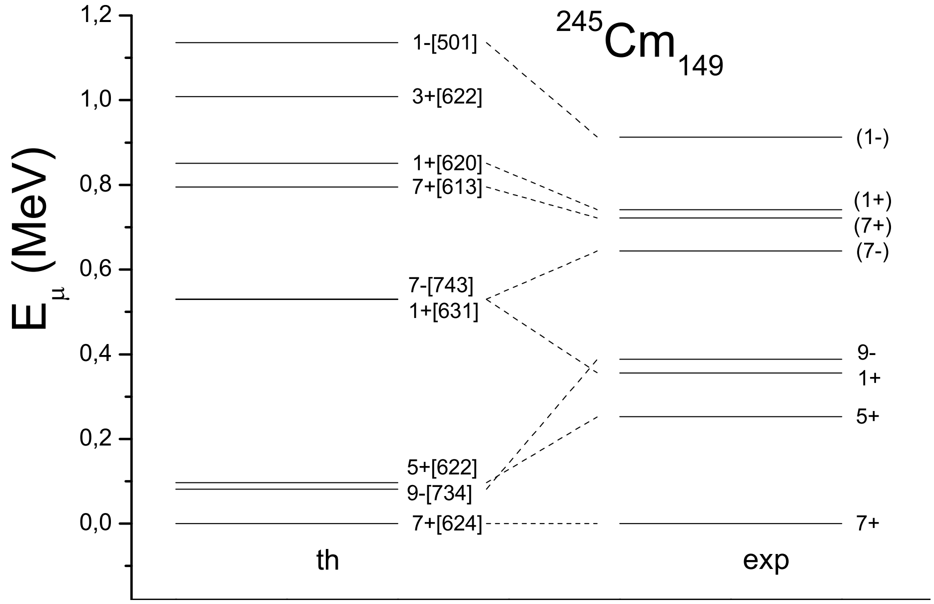

Fig. 1. Comparison between theoretical and experimental single-neutron spectra for the nucleus ^{245}Cm.

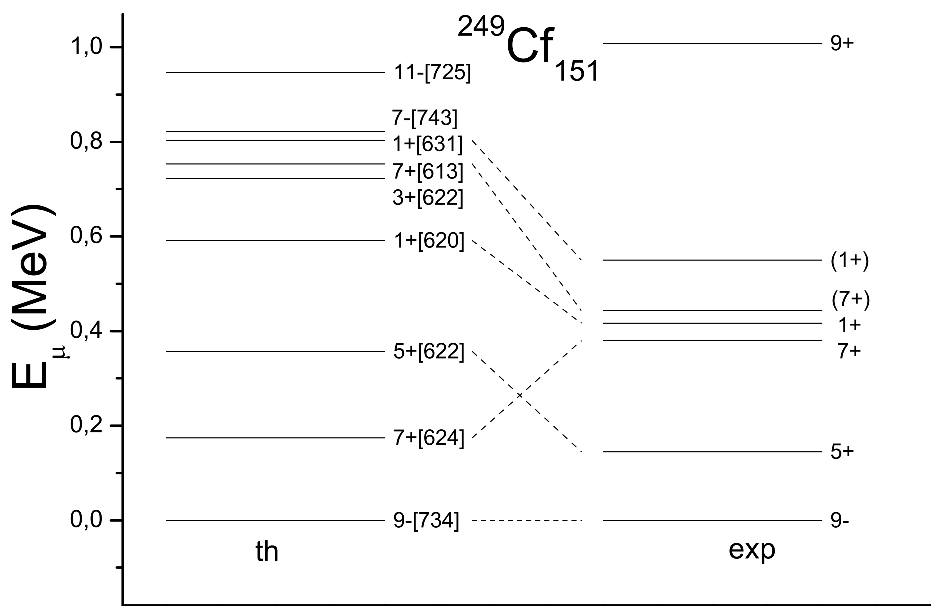

Fig. 2. Same as in Fig. 1, but for ^{249}Cf.

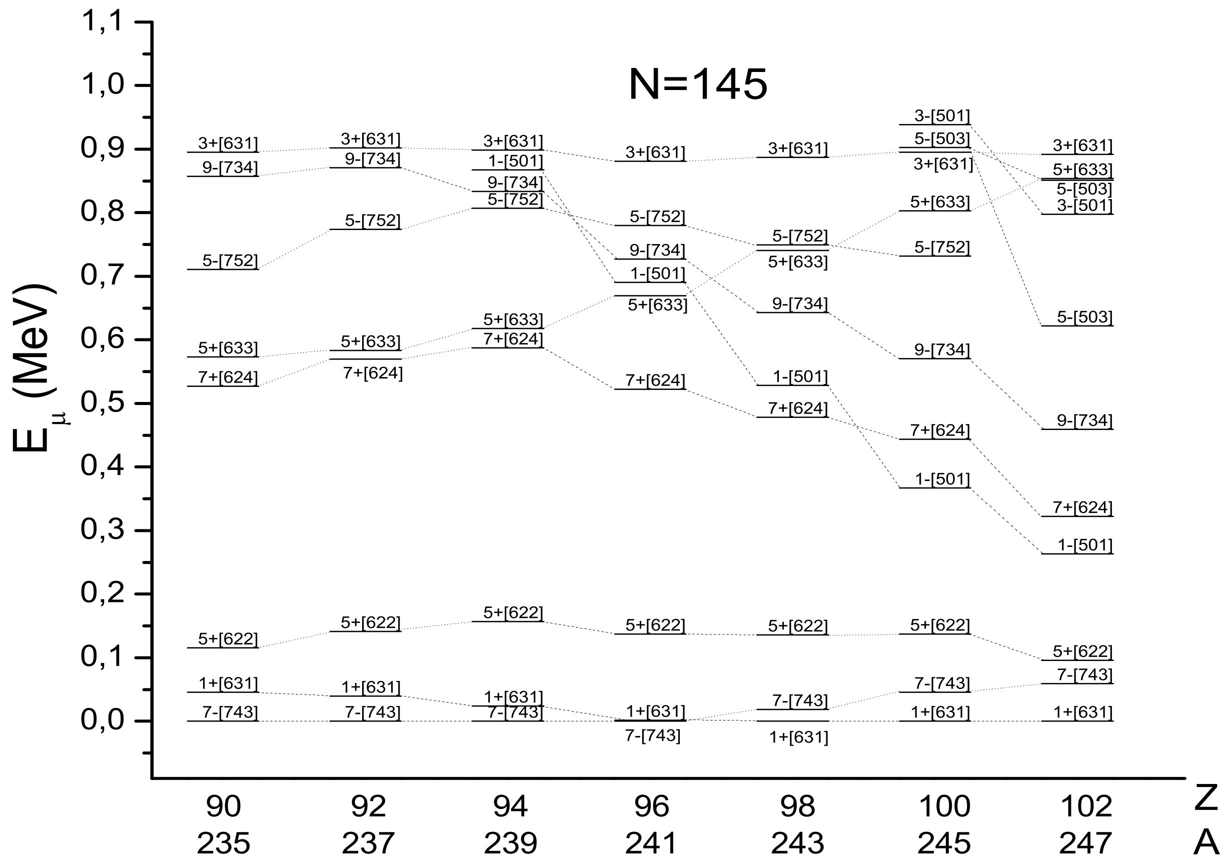

Fig. 3. Systematics of one-quasiparticle neutron states calculated for odd-A isotones with neutron number $N = 145$.

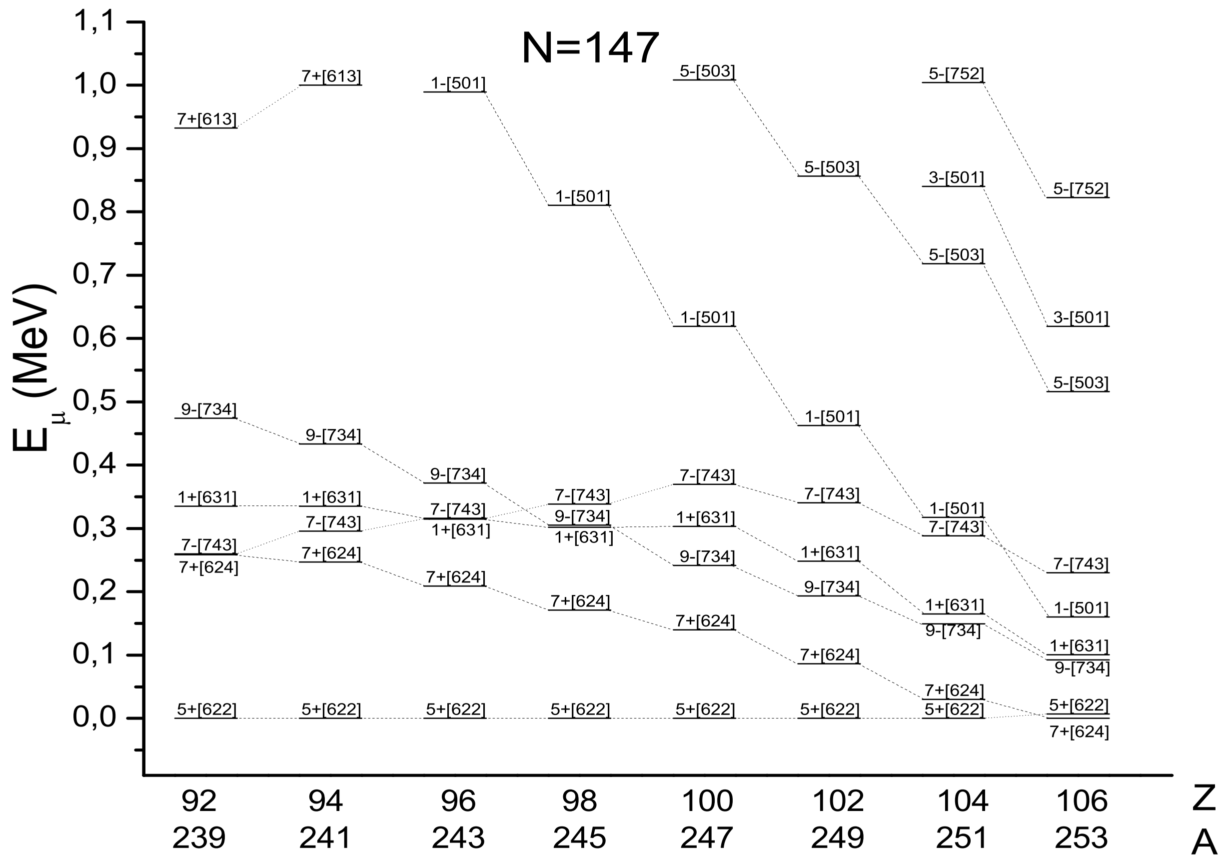

Fig. 4. Same as in Fig. 3, but for $N = 147$.

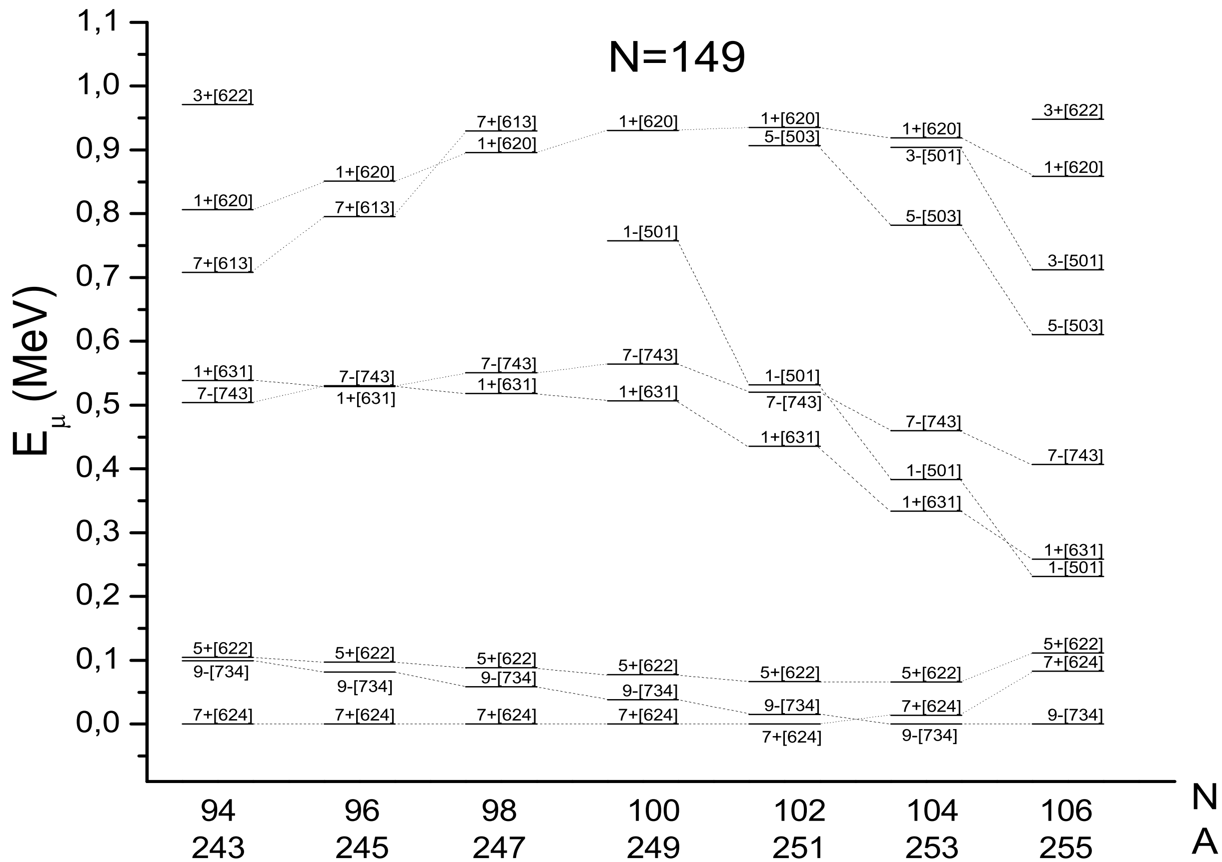

Fig. 5. Same as in Fig. 3, but for $N = 149$.

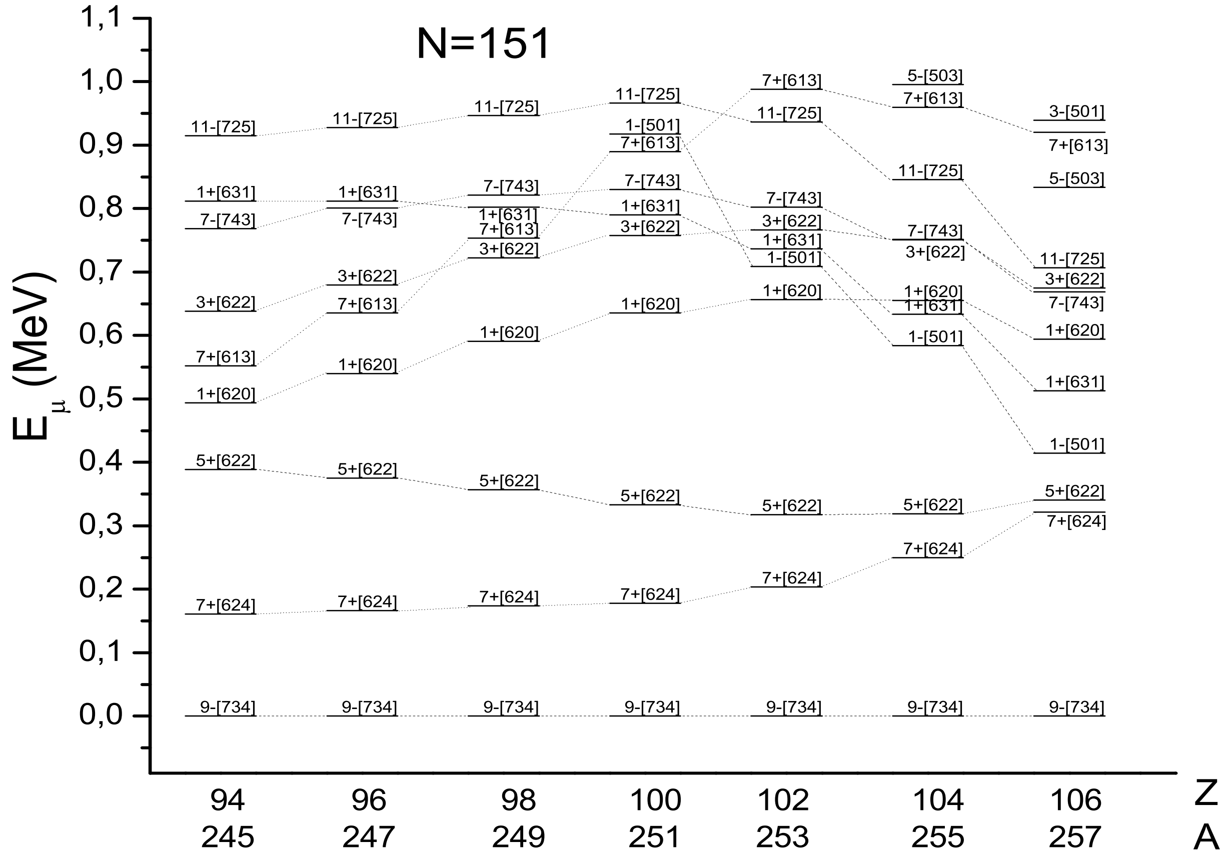

Fig. 6. Same as in Fig. 3, but for $N = 151$.

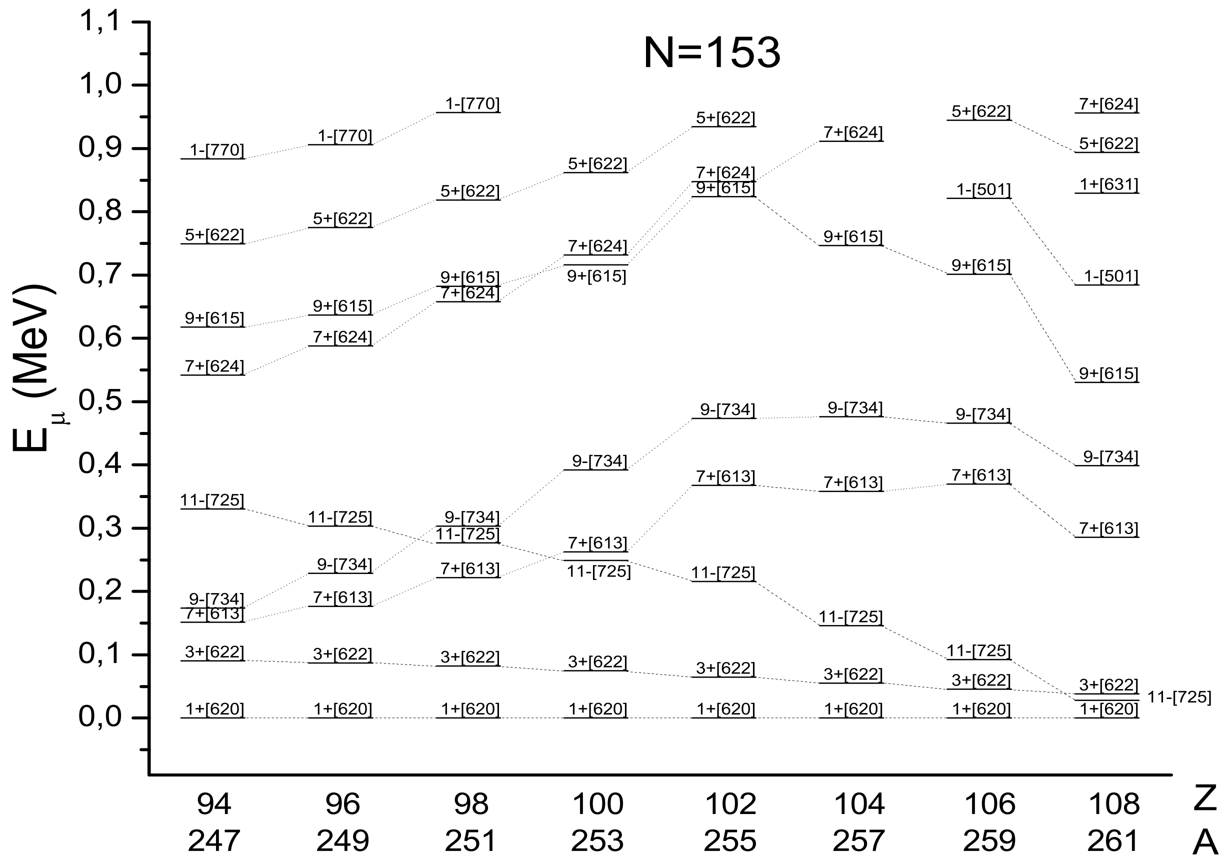

Fig. 7. Same as in Fig. 3, but for $N = 153$.

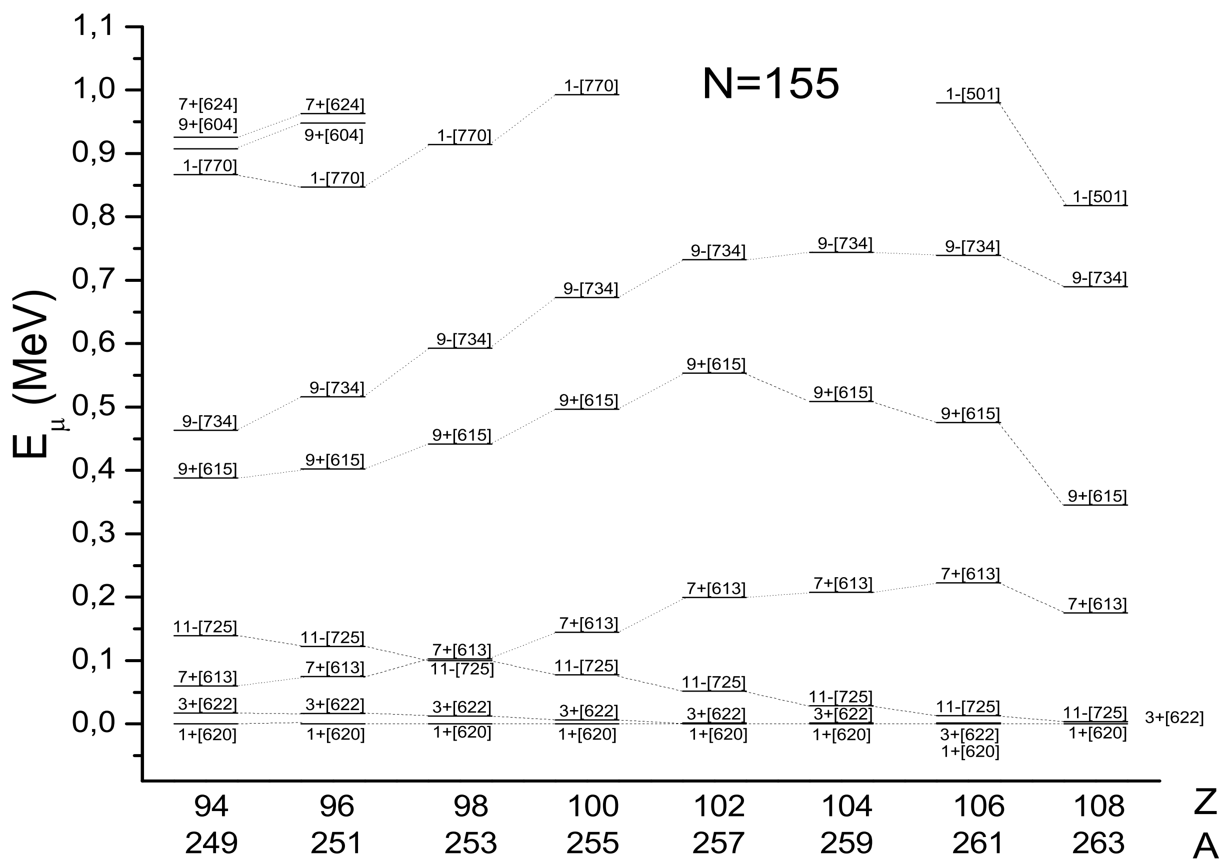

Fig. 8. Same as in Fig. 3, but for $N = 155$.

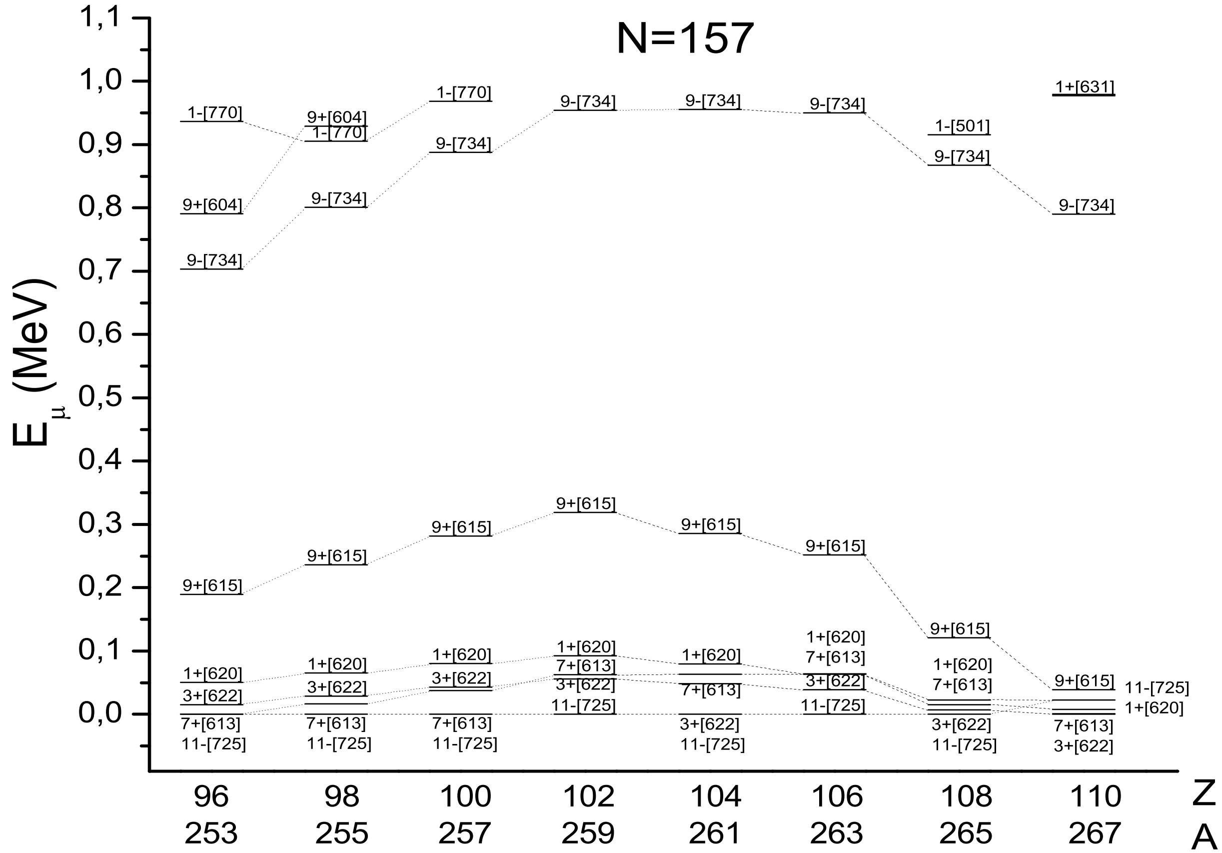

Fig. 9. Same as in Fig. 3, but for $N = 157$.

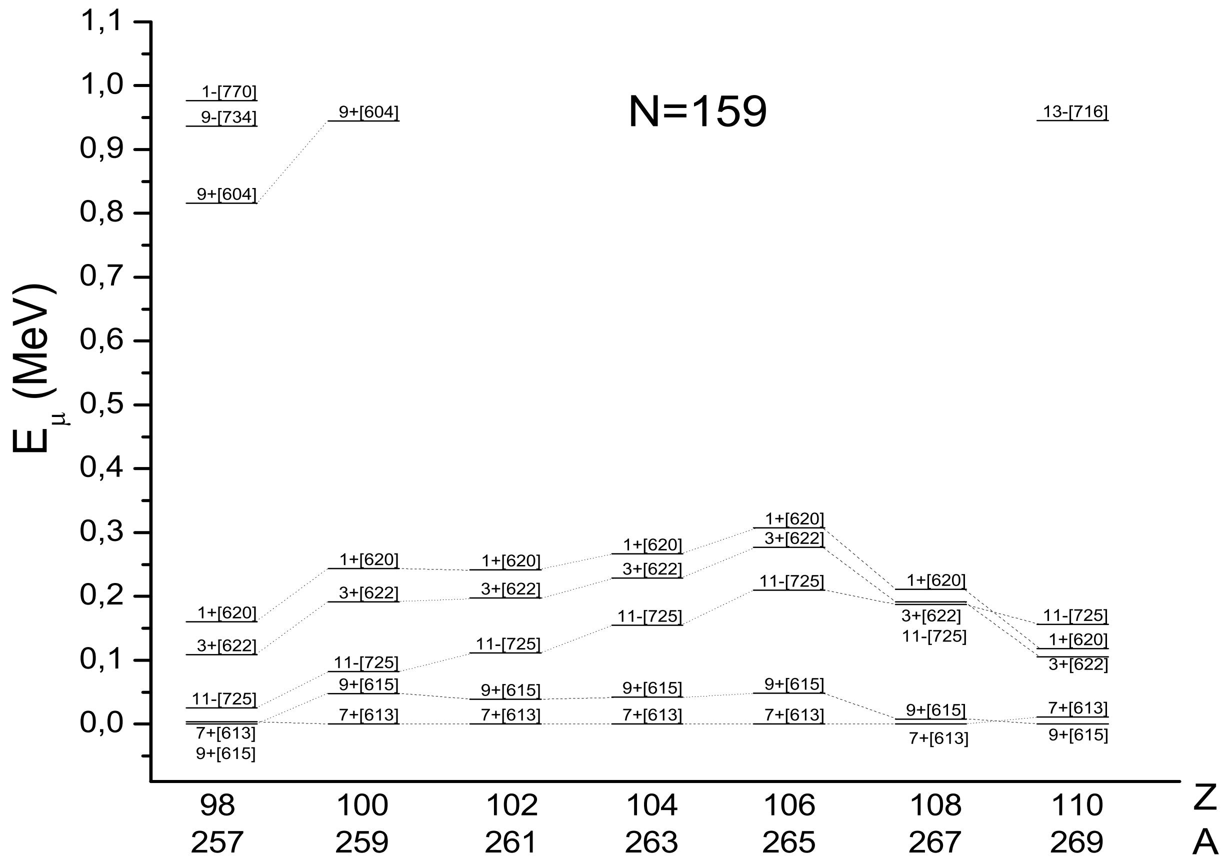

Fig. 10. Same as in Fig. 3, but for $N = 159$.

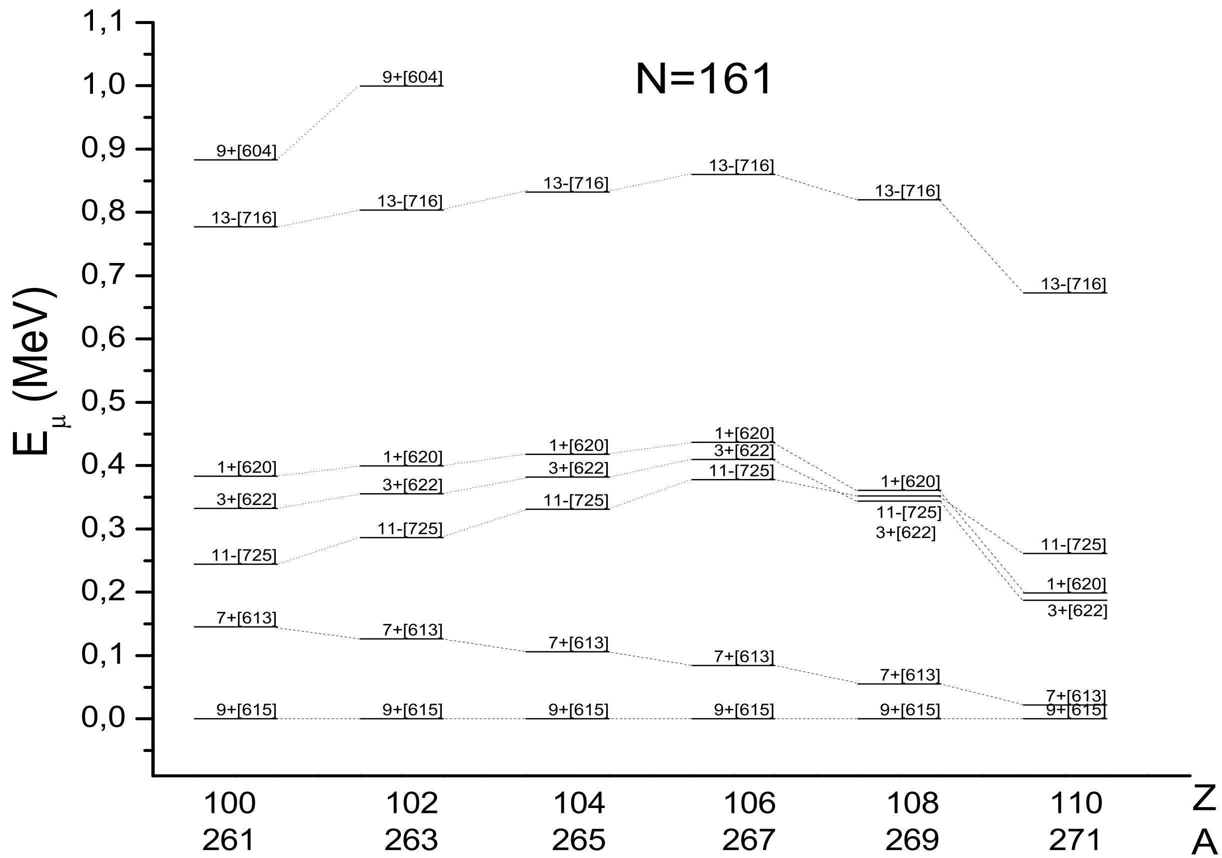

Fig. 11. Same as in Fig. 3, but for $N = 161$.

4. Conclusions

The following conclusions may be drawn from our study:

1. Heavy and superheavy nuclei with proton number $Z = 90$–110 and neutron number $N = 145$–161, analyzed in the present paper, are well deformed;
2. For all of them, pairing energy strength G is larger than its critical value $G_{\rm cr}$ (characteristic for the BCS approach) and rather distant from it. Due to this, the BCS approximation, used in the paper, is justified;
3. Quantum characteristics Ω and π of most experimentally known ground states of analyzed nuclei are reproduced by the calculations;
4. Energies of known lowest neutron excited states are reproduced by the applied model within an average accuracy of about 200 keV;
5. The Nilsson label (asymptotic harmonic oscillator (h.o.) quantum numbers) of a given nuclear single-particle state is quite representative for the structure of this state, even if the contribution of the asymptotic h.o. state to the given state is not large. This means that if two given states, in two different nuclei, have the same Nilsson label, the next h.o. components of the given states are usually the same and with similar contributions to these states. At least as far as three main components (analyzed in the present paper) are considered. This conclusion is important for the analysis of α decay of odd-A nuclei.

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