SENSITIVITY OF CALCULATED PROPERTIES OF SUPERHEAVY NUCLEI TO VARIOUS CHANGES*

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Ground-state properties of heaviest nuclei are recalculated within a macroscopic–microscopic approach. Both macroscopic and microscopic parts of energy are modified. Such properties as deformation, masses, neutron separation energies, α-decay energies and half-lives are studied. A large region of even–even nuclei with proton, Z=82–128, and neutron, N=126–188, numbers is considered.

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1. Introduction

An impressive progress in the synthesis and experimental studies of the heaviest nuclei (*e.g.* [1–4]) requires intensive theoretical studies of them. These studies are needed for predictions of the properties of not yet observed superheavy nuclei and also for the interpretation of already existing experimental results. The latter especially concerns experiments in which the observed genetic chains are not linked to already known nuclei [2, 4].

The objective of this paper is to recalculate properties of superheavy nuclei within a macroscopic-microscopic model, but introducing changes in both macroscopic and microscopic parts of the model, with respect to previous calculations. The comparison of obtained results with previous ones [5,6] gives us an idea of their sensitivity to these changes.

In optimization of parameters of macroscopic part of energy, a more recent data for nuclear masses [7] are taken than in the previous studies. Also, another way of adjusting the pairing forces strength is used in the microscopic part.

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Such properties as deformation, mass, neutron separation energy, α-decay energy and half-life are studied. Even–even nuclei with proton number Z=82–128 and neutron number N=126–188 are considered.

Description of the calculations are given in Sect. 2 and the results are presented in Sect. 3.

2. Description of the calculations

The analysis is performed in a similar way to that used in Refs. [5,6]. A large, 7-dimensional deformation space $\{\beta_\lambda\}$, λ=2,3,...,8, is used in the analysis. Mass (energy) of a nucleus is calculated by a macroscopic–microscopic method, with the Yukawa-plus-exponential model [8] taken for the macroscopic, and the Strutinski shell correction used for the microscopic, parts of the energy. The Woods–Saxon single-particle potential, with the "universal" variant of its parameters found in [9] and also specified explicitly in [6], is taken as a basis for the shell correction.

The macroscopic part is (*cf. e.g.* Refs. [8,10–12])

$$\begin{aligned} &M_{\rm macr}(Z,N,\beta_\lambda^0) = M_H Z + M_n N - a_v(1-\kappa_v I^2)A \\ &+a_s(1-\kappa_s I^2)A^{2/3}B_1(\beta_\lambda^0) + a_0 A^0 + c_1 Z^2 A^{-1/3} B_3(\beta_\lambda^0) - c_4 Z^{4/3} A^{-1/3} \\ &+f(k_{\rm F} r_p) Z^2 A^{-1} - c_a(N-Z) - a_{\rm el} Z^{2.39}\,, \end{aligned} \tag{2.1}$$

where $M_{\rm H}$ is mass of the hydrogen atom, M_n is mass of neutron, I=$(N$–$Z)/A$ is the relative neutron excess, $A = Z + N$ is the mass number of a nucleus. The functions $B_1(\beta_\lambda)$ and $B_3(\beta_\lambda)$ describe the dependence of the surface and Coulomb energies, respectively, on the deformation β_λ, and β_λ^0 is the value of the deformation at equilibrium. The range of the Yukawa–plus–exponential potential, appearing in B_1 is: $a = 0.68$ fm, and the range of Yukawa function generating the nuclear charge distribution, appearing in B_3, is: $a_{\rm den} = 0.70$ fm [10]. The coefficients c_1 and c_4 and the function $f(k_{\rm F} r_p)$ have the same form and values as in [10,11], with the proton root-mean square radius $r_p = 0.80$ fm and the nuclear-radius constant $r_0 = 1.16$ fm. The electron binding constant is $a_{\rm el} = 1.433 \times 10^{-5}$ MeV [10,11]. We adopt here the values of the parameters a_s and κ_s of the surface term, adjusted in [10] to large heights of experimental fission barriers of relatively light nuclei. The values are: a_s=21.13 MeV, κ_s=2.30. The four parameters: a_v, κ_v, a_0, c_a, are treated as free parameters, which are adjusted to masses of even–even nuclei. We find that the reduction of the number of these parameters to 3: a_v, κ_v, a_0 (*i.e.* assuming $c_a = 0$) leaves the mass rms deviations almost unchanged. We also find that the Wigner term [10,11] may be disregarded as well in a study of masses of considered nuclei. Adjustment of the parameters to experimental masses [7] of heaviest nuclei ($Z \geq 84$)

leads to the values:

$$a_v = 16.0643, \quad \kappa_v = 1.9261, \quad a_0 = 17.926\,. \tag{2.2}$$

These values are obtained when, additionally, some care is taken to get not too large deviations from experimental masses of also lighter nuclei, and not only of considered heavy nuclei.

When adjusting the pairing forces strength to odd–even mass differences, the usual assumption that such a difference is directly equal to the pairing energy gap is relaxed. With the isotopic-dependent form of the monopole type pairing strength

$$AG_l = g_{0l} + g_{1l}I\,, \tag{2.3}$$

the result is

$$\begin{aligned} g_{0n} &= 17.67 \text{ MeV}, \quad g_{1n} = -13.11 \text{ MeV}, \quad \text{for } l = n \text{ (neutrons)} \\ g_{0\mathrm{p}} &= 13.40 \text{ MeV}, \quad g_p = 44.89 \text{ MeV}, \quad \text{for } l = p \text{ (protons)}\,. \end{aligned} \tag{2.4}$$

Here A is the mass number of a nucleus and $I = (N - Z)/A$ is its relative neutron excess.

α-decay half-lives T_α are calculated according to the phenomenological formula of Viola and Seaborg with the same parameters as in Ref. [5].

3. Results

Results of the calculations are presented in Table I for superheavy nuclei with Z=106–120.

The first three columns specify proton Z, neutron N and mass A numbers of a nucleus. In column 4, the main (quadrupole) component β_2^0 of the equilibrium deformation of a nucleus is given. Column 5 gives mass (more exactly: mass excess) M of a nucleus. For very heavy nuclei considered in the Table, there are only very few for which masses have been measured. These are: ^{260}Sg and ^{264}Hs. Their measured masses are: 106.60 MeV and 119.61 MeV [7], respectively. One can see that they are very close to the calculated ones.

Column 6 presents neutron separation energy S_{n}. This quantity is important for estimates of the decay probability of a compound nucleus (*e.g.* Refs. [13–15]).

TABLE I

Quadrupole deformation parameter β_2^0, mass M, neutron separation energy $S_{\rm n}$, α-decay energy Q_α and half-life T_α calculated for even–even superheavy nuclei.

Z	N	A	β_2^0	M	S_n	Q_α	$Q_\alpha^{\rm pre}$	T_α	$T_\alpha^{\rm pre}$
—	—	—	—	MeV	MeV	MeV	MeV		
106	150	256	0.247	105.73	9.01	9.97	10.19	5.0 ms	1.3 ms
106	152	258	0.248	105.58	8.56	9.61	9.90	48 ms	7.4 ms
106	154	260	0.248	106.68	8.01	9.95	9.96	5.4 ms	5.1 ms
106	156	262	0.249	108.33	7.73	9.49	9.60	0.11 s	52 ms
106	158	264	0.246	110.39	7.53	8.94	9.06	5.2 s	2.1 s
106	160	266	0.240	112.89	7.26	8.42	8.54	4.5 m	1.7 m
106	162	268	0.233	115.73	7.05	7.89	8.05	6.7 h	1.7 h
106	164	270	0.224	120.27	6.21	8.74	8.66	23 s	43 s
106	166	272	0.213	125.29	6.10	8.50	8.46	2.4 m	3.2 m
106	168	274	0.199	130.63	5.98	8.12	8.11	56 m	58 m
108	154	262	0.244	119.01	8.54	11.00	11.02	47 μs	42 μs
108	156	264	0.242	119.69	8.24	10.59	10.69	0.48 ms	0.26 ms
108	158	266	0.242	120.80	8.05	10.04	10.20	13 ms	4.8 ms
108	160	268	0.237	122.31	7.78	9.49	9.65	0.46 s	0.16 s
108	162	270	0.233	124.18	7.54	8.87	9.13	42 s	6.0 s
108	164	272	0.225	127.95	6.54	9.80	9.79	61 ms	63 ms
108	166	274	0.217	132.25	6.44	9.55	9.58	0.31 s	0.26 s
108	168	276	0.205	136.91	6.31	9.19	9.22	3.83 s	3.2 s
108	170	278	0.180	141.82	6.24	8.77	8.77	92 s	89 s
110	156	266	0.234	133.83	8.67	12.40	12.17	0.13 μs	0.38 μs
110	158	268	0.232	134.05	8.52	11.93	11.76	1.2 μs	2.9 μs
110	160	270	0.228	134.59	8.32	11.36	11.24	23 μs	44 μs
110	162	272	0.226	135.47	8.11	10.74	10.80	0.74 ms	0.52 ms
110	164	274	0.217	138.18	7.06	11.57	11.39	7.7 ms	20 μs
110	166	276	0.208	141.46	6.90	11.09	11.03	0.10 ms	0.14 ms
110	168	278	0.188	145.44	6.46	10.76	10.52	0.64 ms	2.8 ms
110	170	280	0.163	149.25	6.64	9.91	9.84	0.12 s	0.19 s
110	172	282	0.128	153.13	6.66	8.89	8.86	3.0 m	3.5 m
112	162	274	0.219	148.45	8.62	11.44	11.67	53 μs	16 μs
112	164	276	0.208	150.12	7.50	12.22	12.13	0.98 μs	1.5 μs
112	166	278	0.204	152.46	7.31	11.86	11.83	5.9 μs	6.8 μs
112	168	280	0.197	155.29	7.10	11.40	11.36	66 μs	83 μs
112	170	282	0.145	158.33	7.21	10.46	10.65	15 ms	4.8 ms
112	172	284	0.129	161.43	7.04	9.76	9.80	1.5 s	1.1 s
112	174	286	0.100	164.90	6.80	9.35	9.35	26 s	27 s

TABLE I cont.

Z	N	A	β_2^0	M	S_n	Q_α	$Q_\alpha^{\rm pre}$	T_α	$T_\alpha^{\rm pre}$
—	—	—	—	MeV	MeV	MeV	MeV		
114	168	282	0.186	166.97	7.52	12.09	12.13	6.1 μs	4.9 μs
114	170	284	0.149	169.24	7.40	11.53	11.51	0.11 ms	0.12 ms
114	172	286	0.086	171.61	7.46	10.86	10.84	5.2 ms	5.6 ms
114	174	288	0.086	174.18	7.27	10.32	10.32	0.14 s	0.14 s
114	176	290	0.000	177.39	6.78	10.07	10.12	0.75 s	0.52 s
116	170	286	0.078	181.79	8.21	12.39	12.34	4.3 μs	5.5 μs
116	172	288	0.077	183.21	7.87	11.54	11.56	0.38 ms	0.33 ms
116	174	290	0.076	185.12	7.60	11.08	11.17	5.0 ms	3.1 ms
116	176	292	0.056	187.66	7.12	11.06	11.07	5.7 ms	5.5 ms
116	178	294	0.009	190.56	7.13	10.74	10.69	39 ms	52 ms
118	172	290	0.080	196.61	8.27	12.40	12.46	13 μs	9.5 μs
118	174	292	0.079	197.78	7.96	12.15	12.27	48 μs	25 μs
118	176	294	0.077	199.65	7.42	12.11	12.19	58 μs	38 μs
118	178	296	0.039	202.15	7.28	12.06	12.07	74 μs	71 μs
118	180	298	0.017	204.96	7.06	11.98	11.96	0.12 ms	0.13 ms
120	174	294	0.084	212.27	8.37	13.24	13.42	0.67 μs	0.28 μs
120	176	296	0.085	213.43	7.75	13.23	13.40	0.70 μs	0.31 μs
120	178	298	0.054	215.52	8.02	13.44	13.36	0.26 μs	0.37 μs
120	180	300	0.009	217.69	7.39	13.11	13.10	1.2 μs	1.3 μs
120	182	302	0.000	220.46	7.09	13.08	13.07	1.4 μs	1.5 μs

α-decay energy Q_α is given in column 7. Values of this energy calculated in a previous work [5], $Q_\alpha^{\rm pre}$, are shown in column 8 for comparison. One can see that these previous values are quite close to the present ones. Experimental values of Q_α are known for the nuclei ^{260}Sg, ^{266}Sg and ^{264}Hs. They are: 9.92 MeV, 8.76 MeV and 10.59 MeV [7], respectively. One can see that the values for ^{260}Sg and ^{264}Hs are very close to the calculated ones, while the value for ^{266}Sg differs from the theoretical value by about 0.3 MeV.

Recently, Q_α has been also measured for the nuclei ^{284}112, ^{288}114 [4,16] and ^{292}116 [4,17]. The respective values are: 9.30 MeV, 9.98 MeV [16] and 10.71 MeV [17]. One can see that these values are by about 0.4 MeV smaller than the calculated ones. Very recently, Q_α have been also measured for the nuclei ^{266}Hs and ^{270}110 [18]. The respective values are: 10.34 MeV and 11.20 MeV [18]. Thus, the first one is by about 0.3 MeV larger, while the second is by about 0.2 MeV smaller than the calculated ones.

α-decay half-lives T_α are shown in column 9. Values calculated previously [5], $T_\alpha^{\rm pre}$, are also given (column 10) for comparison. One can see that the present values are close to the previous ones. Experimental values of T_α are known for the nuclei: ^{260}Sg and ^{264}Hs. They are: 9.5 ms and 1.1 ms [7], respectively. One can see that they are quite close to the calculated values. Recently, T_α has been also measured for the nuclei ^{284}112, ^{288}114 [4,16] and ^{292}116 [4,17]. The respective values are: 9.8 s, 1.9 s [16] and 33 ms [17]. Thus, they are by about 6-14 times larger than the calculated ones. Very recently, T_α have been also found experimentally for the nuclei ^{266}Hs and ^{270}110 [18]. The respective values are: 2.3 ms and 100 μs [18]. Thus, the first one is about 6 times smaller, while the second one is about 4 times larger than the respective calculated values.

Concluding, one can say that the recalculated values of α-decay energies Q_α and half-lives T_α are quite close to the previous ones [5]. The discrepancy between them and experimental results obtained recently is of about (0.2–0.5) MeV for Q_α and by about a factor of (4–14) for T_α.

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