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STABILITY AND PROPERTIES OF SUPERHEAVY NUCLEI*

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Recent theoretical studies of stability and properties of heavy and superheavy nuclei are described. Such properties as deformations, rotational energies and half-lives with respect to main decay modes are discussed. Even-even nuclei with proton number $Z = 82 - 120$ and neutron number $N = 126 - 190$ are considered.

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1 Introduction

There is a fast progress both in experimental (cf. e.g. the reviews [1–3])and theoretical (cf. e.g. [4–6])studies of superheavy nuclei. The objective of this paper is to discuss recent theoretical results.

We concentrate here on the results obtained in a macroscopic-microscopic approach, which seem to be, at the moment, the most extensive and complete. Still, fully microscopic studies, like those using the Hartree-Fock-Bogolubov or Relativistic Mean Field approaches, are also being done (e.g. [7–10]).

2 Theoretical model

As already stated in the Introduction, we concentrate on the macroscopic-microscopic approach. In this approach, the energy (mass) of a nucleus is composed of two parts: macroscopic and microscopic. The macroscopic part is usually described by the Yukawa-plus-exponential model [11]. The microscopic part is the Strutinski shell correction, based on a model for the internal (microscopic) structure of a nucleus. As this model, we take the Woods-Saxon single-particle potential [12].

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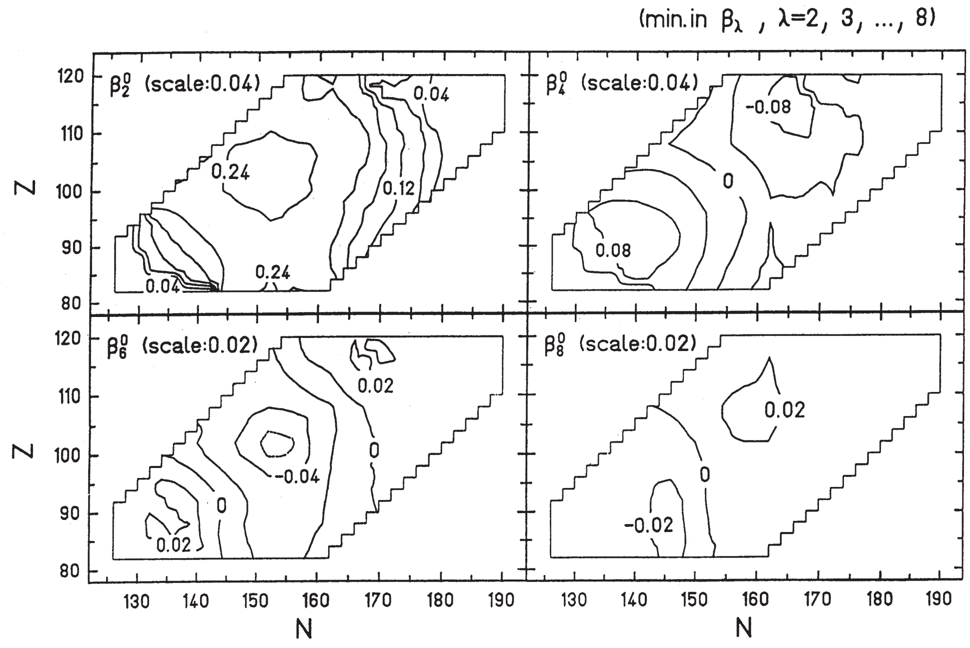

Fig. 1. Contour maps of the equilibrium deformations β^0_λ, $\lambda = 2,\ 4,\ 6,\ 8$, plotted as functions of the proton *Z* and the neutron *N* numbers. Numbers at the contour lines give the values of the deformations. The difference in the values between neighbouring contour lines is specified by the scale [15].

Equilibrium deformations of a nucleus is calculated by minimization of its energy in a multidimensional deformation space [13]. A study performed in [14, 15] has shown that the 4-dimensional deformation space $\{\beta_\lambda\}$, $\lambda = 2,\ 4,\ 6,\ 8$, is sufficient for the heaviest nuclei considered in this paper. Here, β_λ are the usual deformation parameters, appearing in the expression for nuclear radius (in the intrinsic frame of reference) in terms of spherical harmonics.

To obtain the energies of the ground-state rotational band, the moment of inertia of a nucleus is calculated. This is treated in the cranking approximation (cf. e.g. [16–18]).

The $\alpha-$decay half-lives are described by the phenomenological formula of Viola and Seaborg, but with its free parameters readjusted to account for recent data. Details of the calculations are given in [14, 15].

The spontaneous-fission half-lives are analyzed in a dynamical way, with the mass tensor (describing the inertia of a nucleus with respect to its deformation) taken into account. Details of the calculations are given in [19].

3 Some of general results

3.1 Equilibrium deformations

The equilibrium deformations of heaviest nuclei have been studied in [15], as has been already mentioned in sect. 2. The analysis has been performed in the 8-dimensional deformation

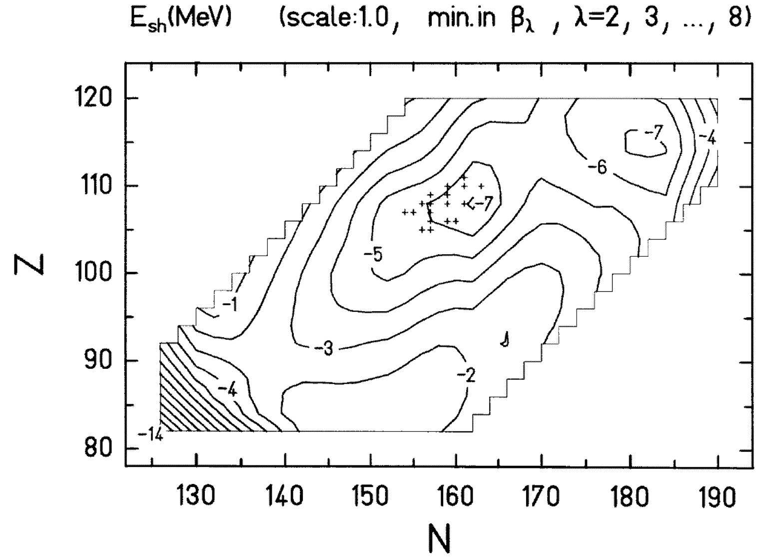

Fig. 2. Contour map of the shell correction to energy, E_{sh}. Crosses denote the heaviest nuclides synthesized up to now [15].

space $\{\beta_\lambda\}$, $\lambda = 2,\ 3,\ \ldots\ 9$. In accordance with [13], it has been found, however, that the odd-multipolarity components β^0_λ, $\lambda = 3,\ 5,\ 7$, of the deformation are different from zero for only a very few of the nuclei (which are situated around radium). Thus, almost all nuclei considered here are reflection symmetric. Due to this, we only show the results for even-multipolarity deformations β^0_λ , $\lambda = 2,\ 4,\ 6,\ 8$. Contour maps of these deformations are given in Fig. 1, taken from [15]. One can see that most of the investigated nuclei are deformed. Only two rather small regions of spherical nuclei, situated around the doubly magic spherical nuclei ^{208}Pb and ^{298}114, appear: a smaller one around ^{208}Pb and a slightly larger region around ^{298}114. The main, quadrupole, component of the deformation, β^0_2, is largest and is positive in the whole region of deformed nuclei. Its value ($\beta^0_2 \approx 0.24$) is about constant in a large part of the region (around its center) and it rapidly decreases as one moves towards the boundaries of this region. The higher-multipolarity components are smaller and they change sign as one moves through the region. The largest β^0_6 (in their absolute values) are obtained for nuclei around ^{254}102, they are negative and equal to about -0.05. The values of β^0_8 are even smaller in their absolute magnitude. The largest β^0_8 are equal to about 0.03 and are obtained for nuclei which are close to the nucleus ^{270}108 (^{270}Hs).

3.2 Shell correction to energy (mass) of a nucleus

Shell correction to the ground-state mass of a heavy nucleus gives us a first orientation in the stability of this nucleus. Fig. 2, taken from [15], shows the shell correction E_{sh} calculated for the large region of nuclei under consideration. One can see that E_{sh} has three minima in this region. The first one, which is the deepest (E_{sh}=–14.3 MeV), is obtained for the doubly magic spherical nucleus ^{208}Pb. The second one (E_{sh}=–7.2 MeV) appears at the nucleus $^{270}108_{162}$, which is predicted [14] to be a doubly magic deformed nucleus. The third minimum, with the same depth ($E_{sh} = -7.2$ MeV) as the former one, is obtained for the nucleus $^{296}114_{182}$, which is close to the nucleus $^{298}114_{184}$ predicted [20, 21] to be a doubly magic spherical nucleus, the next one to the last experimentally known ^{208}Pb.

One can see in Fig. 2 that some of the already synthesized nuclei profit by 6–7 MeV in their binding energy from the shell correction. They could not exist without this profit, as discussed in [22].

The appearance of the region of nuclei around the second minimum (deformed superheavy nuclei) constitutes the main change in our view of stability of heaviest nuclei in recent years. Before, it was believed for a long time that spherical superheavy nuclei, predicted to be situated around the third minimum, would constitute an island, separated from the usual peninsula of relatively long-lived nuclei by an "ocean" of full instability. After the appearance of deformed superheavy nuclei, however, the peninsula is expected to be extended, to include also the spherical superheavy nuclei.

3.3 Single-particle structure

It is interesting to see the single-particle spectra of the doubly magic nuclei: ^{208}Pb, ^{270}Hs and $^{298}114$, for which the three minima of the shell correction E_{sh} have been obtained in Fig. 2. The spectra are shown in Figs. 3 and 4, for protons and neutrons, respectively. One can see in Fig. 3 large energy gaps at $Z = 82$ (in the spectrum of ^{208}Pb), at $Z = 108$ (in ^{270}Hs) and at $Z = 114$ (in $^{298}114$). In the spectrum of ^{270}Hs, a low density of levels extends from $Z = 106$ to $Z = 110$. For neutrons (Fig. 4), besides a large energy gap obtained at $N = 162$ in the spectrum of ^{270}Hs, a smaller gap at $N = 152$ is also seen. All this finds its reflection in the shell correction to energy E_{sh}, as shown in Fig. 2.

4 Properties of deformed superheavy nuclei

4.1 Half-lives

Theoretical half-lives for nuclei situated around the doubly magic deformed nucleus ^{270}Hs (deformed superheavy nuclei), i.e. around the second minimum in Fig. 2, have been given and extensively discussed in [14, 15, 19]. Here, we only illustrate a comparison of these results with the experimental values obtained for the element 110. This is shown in Fig. 5. The experimental values are taken from [23] for $^{257}110$, from [24] for $^{259,261}110$ and from [25] for $^{263}110$. One can see that the measured values are rather close to the predicted ones. In particular, they seem to confirm the existence of the predicted neutron deformed shell at $N = 162$. They also confirm the prediction that T_{sf} is larger than T_α for respective nuclei, as only α-decay has been observed for them.

4.2 Rotational energies

Nuclei situated around ^{270}Hs, in nuclear chart, and discussed in this section are called "deformed". But the only indication for this are theoretical results. There is no direct experimental evidence for their deformed shapes. Thus, it would be important to obtain such evidence.

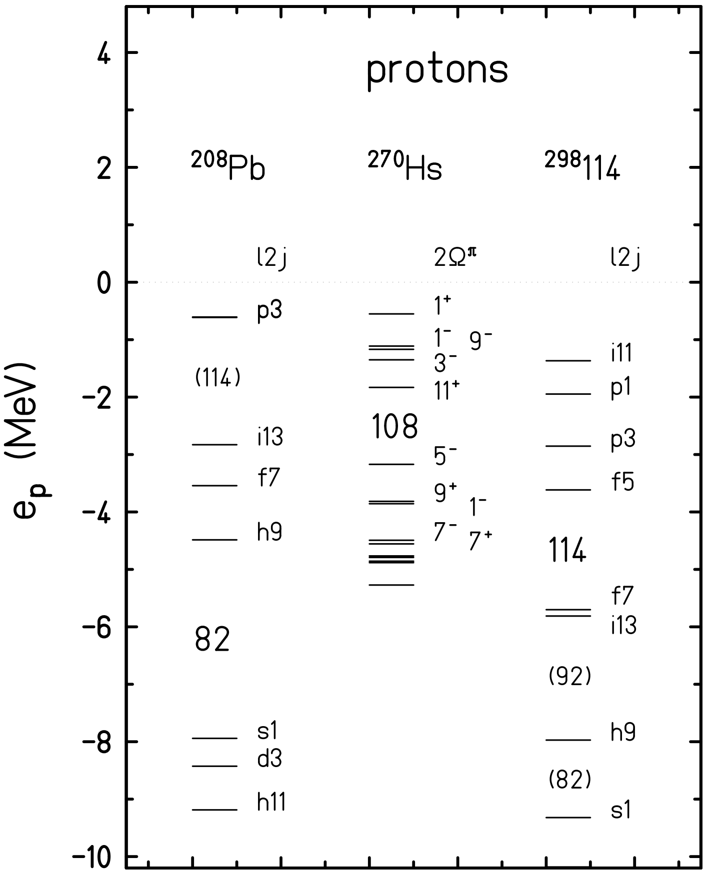

Fig. 3. Proton single-particle levels calculated for the doubly magic nuclei: ^{208}Pb, ^{270}Hs and ^{298}114. Spectroscopic symbol for the orbital angular momentum l and total spin (multiplied by two) $2j$ are given at each level of the spherical nuclei ^{208}Pb and ^{298}114. Projection of spin (multiplied by two) 2Ω and parity π are shown at each level of the deformed nucleus ^{270}Hs.

A direct evidence for the stable deformation of a nucleus is the observation of a rotational band in its spectra. The heaviest nuclei, for which such bands have been observed up to now, are the isotopes of fermium: ^{254,256}Fm [26]. Very recently, a rotational band has been also seen for ^{254}No [27]. Here, we would like to show what rotational energies may be expected for superheavy nuclei, up to those of the element 114.

To specify the energies of the ideal rotational band, it is enough to give the energy of any state of the band. For even-even nucleus, this may be e.g. the first state: 2^+. To obtain this energy, we calculate the moment of inertia of the nuclei. As we are interested in the ground-state rotational bands, we analyze the ground-state moments of inertia. This quantity is calculated in almost the same way as used and described e.g. in [16–18], the differences concerning only some details of the calculations. For example, we use the Woods-Saxon single-particle potential, instead of the

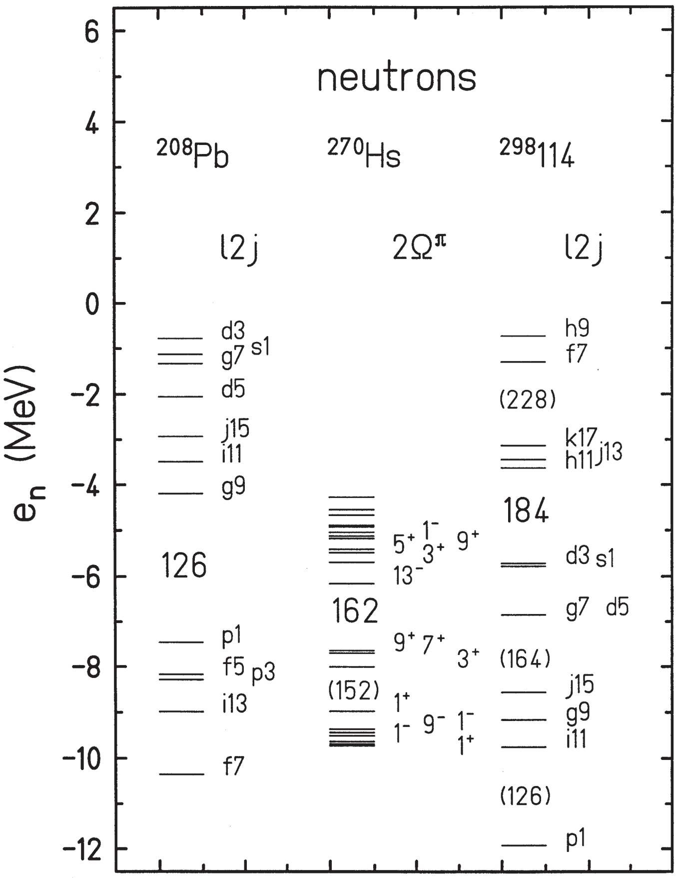

Fig. 4. Same as in Fig. 3, but for neutrons.

Nilsson potential taken in those papers. The results obtained for the energy of the first 2^+ state, E_{2+}, are shown in Fig. 6.

One can see that two minima of E_{2+} are obtained for the considered nuclei. One of them (41.7 keV) is obtained for the nucleus ^{254}No, and the other (40.0 keV) for ^{270}Hs. It is interesting to note that the positions of the minima do not coincide with the positions of maxima of deformations β_λ (in their absolute values), $\lambda = 2,\ 4,\ 6,\ 8$. Only the position of the first minimum is close to that of the maximum of β_6 (in its absolute value). It looks then that deformations β_λ of various multipolarities are important and only the superposition of them gives the final result. This is illustrated in Fig. 7, where the dependence of E_{2+} on the maximal multipolarity λ_{max} of the deformations β_λ taken into account is shown, for the nucleus ^{254}No. It is seen that besides β_2, also β_6 is important for the final value of E_{2+}, for this nucleus. This illustrates the importance of

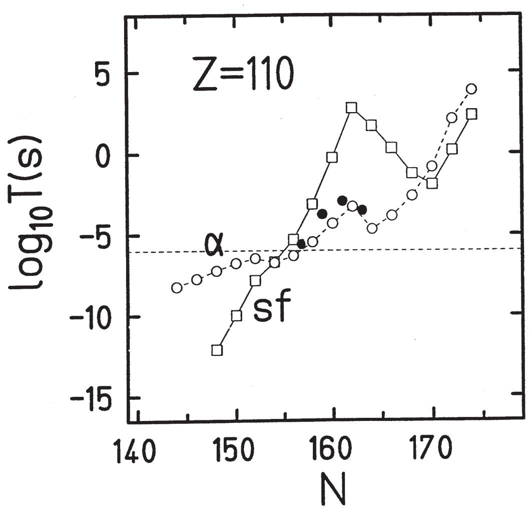

Fig. 5. Comparison between predicted theoretically (open cirles) and measured (full circles) α-decay half-lives, for isotopes of the element 110.

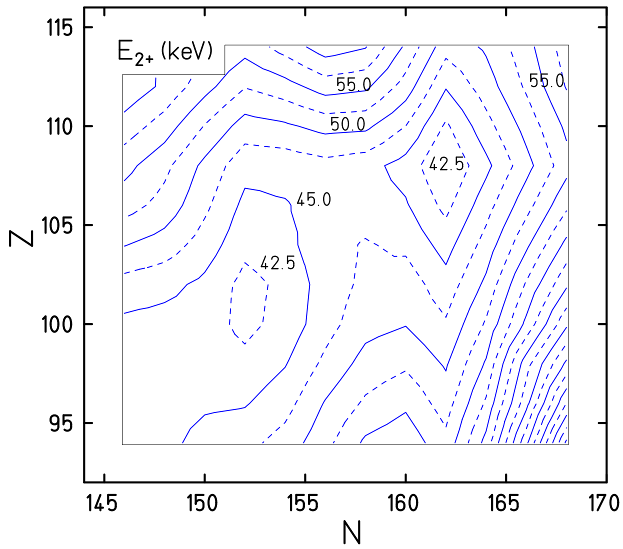

Fig. 6. Contour map of calculated energy E_{2+} of the first rotational state 2^+.

using sufficiently large deformation space, to obtain proper E_{2+}.

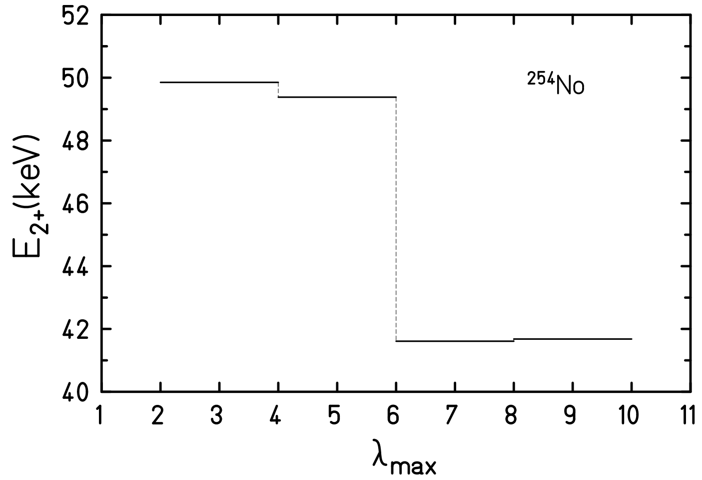

Fig. 7. Dependence of the rotational energy E_{2+} on the maximal multipolarity λ_{max} of the deformations β_λ taken into account, calculated for the nucleus ^{254}No.

5 Half-lives for "spherical" superheavy nuclei

We discuss here half-lives of nuclei situated around the third minimum in Fig. 2, i.e. around the hypothetical doubly magic spherical nucleus ^{298}114. Certainly, only nuclei close to this nucleus are expected to be spherical; this is the reason for which we put the word "spherical" in the title of the section into quotation marks. The half-lives have been recently calculated in [28, 29] in a dynamical way, using 3-dimensional deformation space $\{\beta_\lambda\}$, $\lambda = 2,\ 4,\ 6$.

The results are shown in Fig. 8, taken from [29]. The isotopes with the neutron number N=176–184 of the elements 110–118 are considered in the figure. Only for the element 114, the isotope with N=186 is also shown, to see the behaviour of the half-lives above the shell closure at N=184. The role of the dimension of the deformation space admitted in the analysis of spontaneous fission has been discussed in [30].

One can see that the fission half-life is longer than that of α-decay for all considered isotopes of the elements 112–118. The opposite relation is only obtained for the three lightest isotopes of the element 110. As illustrated for the element 114, the half-lives decrease above the shell closure at N=184, with the fission half-life decreasing especially fast.

One can also see in Fig. 8 that the longest half-lives, with respect to both decay modes, are expected to appear for nuclei around the nucleus ^{292}110 and to be of the order of one hundred years. As the nucleus ^{292}110 is expected to be β-stable (e.g. [31]), these longest half-lives are expected to be the total half-lives. Nuclei with so long half-lives could be accumulated (in distinction to those situated around the doubly magic deformed nucleus ^{270}Hs, which have short half-lives). This would give a chance for extensive studies of physical and chemical properties of these exotic nuclei and elements. Certainly, on the condition that cross sections for their synthesis appear sufficiently large.

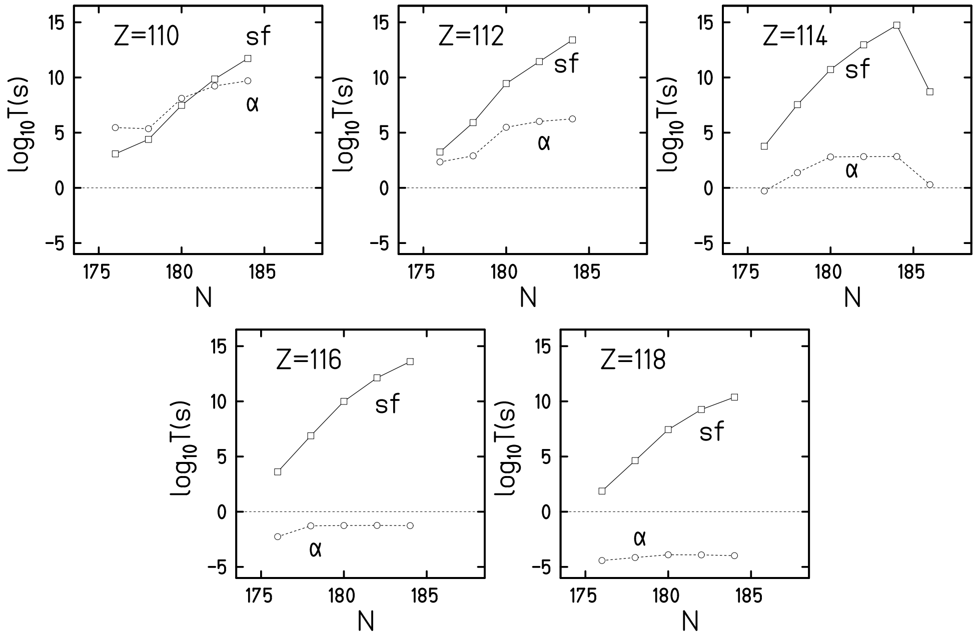

Fig. 8. Logarithm of the calculated spontaneous-fission (sf) and α-decay (α) half-lives (given in seconds), as function of the neutron number *N*, for the elements: 110–118 [29].

Fission half-lives of "spherical" superheavy nuclei have been also considered recently in [32] applying the approach used in [19], i.e. the dynamics in two-dimensional deformation space. They have been also studied in [33].

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References

[1] S. Hofmann: *Rep. Prog. Phys.* **61** (1998) 639

[2] Yu.Ts. Oganessian: *in Proc. 4th Intern. Conf. on Dynamical Aspects of Nuclear Fission, Casta-Papiernicka (Slovakia) 1998* World Scientific, Singapore 1999 *(to be published)*

[3] F.P. Hessberger: *Acta Phys. Slov.* **49** (1999) 43

[4] P. Möller and J.R. Nix: *J. Phys. G* **20** (1994) 1681

[5] A. Sobiczewski: *Usp. Fiz. Nauk* **166** (1996) 943 ; (*English translation: Physics-Uspekhi* **39** (1996) 885

[6] A. Sobiczewski: *in Proc. R.A. Welch Foundation 41st Conf. on Chemical Research: "The Transactinide Elements", Houston (USA) 1997* R.A. Welch Foundation, Houston 1997, ch. 13

[7] J.-F. Berger et al: *in* Extremes of Nuclear Stucture. *Proc. 24th Intern. Workshop, Hirschegg (Austria) 1996 (Eds. H. Feldmeier, J. Knoll, W. Nörenberg).* GSI, Darmstadt 1996, p. 43.

[8] G.A. Lalazissis, M.M. Sharma, P. Ring and Y.K. Gambhir: *Nucl. Phys. A* **608** (1996) 202

[9] S. Ćwiok et al.: *Nucl. Phys. A* **611** (1996) 211

[10] K. Rutz et al.: *Phys. Rev. C* **56** (1997) 238

[11] H.J. Krappe, J.R. Nix, A.J. Sierk: *Phys. Rev. C* **20** (1979) 992

[12] S. Ćwiok et al.: *Com. Phys. Comm.* **46** (1987) 379

[13] A. Sobiczewski, Z. Patyk, S. Ćwiok, P. Rozmej: *Nucl. Phys. A* **485** (1988) 16

[14] Z. Patyk, A. Sobiczewski: *Nucl. Phys. A* **533** (1991) 132

[15] R. Smolańczuk, A. Sobiczewski: *in* Low Energy Nuclear Dynamics. *Proc. XV Nucl. Phys. Conf., St. Petersburg (Russia) 1995 (Eds. Yu.Ts. Oganessian, W. von Oertzen, R. Kalpakchieva).* World Scientific, Singapore 1995, p. 313

[16] A. Sobiczewski, S. Bjornholm, K. Pomorski: *Nucl. Phys. A* **202** (1973) 274

[17] K. Pomorski et al.: *Nucl. Phys. A* **205** (1973) 433

[18] K. Pomorski, A. Sobiczewski: *Acta Phys. Pol. B* **9** (1978) 61

[19] R. Smolańczuk, J. Skalski, A. Sobiczewski: *Phys. Rev. C* **52** (1995) 1871

[20] A. Sobiczewski, F.A. Gareev, B.N. Kalinkin: *Phys. Lett.* **22** (1966) 500

[21] H. Meldner: *Ark. Fys.* **36** (1967) 593

[22] Z. Patyk, A. Sobiczewski, P. Armbruster, K.-H. Schmidt: *Nucl. Phys. A* **491** (1989) 267

[23] A. Ghiorso et al.: *Phys. Rev. C* **51** (1995) R2293

[24] S. Hofmann et al.: *Z. Phys. A* **350** (1995) 277 ; **350** (1995) 281

[25] Yu.A. Lazarev et al.: *Phys. Rev. C* **54** (1996) 620

[26] *Table of isotopes, 8th edition. (Eds. R.B. Firestone, V.S. Shirley), vol. 2.* J. Wiley, New York 1996

[27] T.L. Khoo: *private communication (1998)*

[28] R.A. Gherghescu, Z. Patyk, A. Sobiczewski: *Acta Phys. Pol. B* **28** (1997) 31

[29] R.A. Gherghescu, Z. Patyk, J. Skalski, A. Sobiczewski: *in* Research with Fission Fragments. *Proc. Intern. Workshop Benediktbeuern (Germany) 1996 (Eds. T. von Egidy, D. Habs, F.J. Hartmann, K.E.G. Löbner, H. Nifenecker).* World Scientific, Singapore 1997, p. 116

[30] R. Smolańczuk, H.V. Klapdor-Kleingrothaus, A. Sobiczewski: *Acta Phys. Pol. B* **24** (1993) 685

[31] W.D. Myers, W.J. Swiatecki: Nucl. Phys. A **601** (1996) 141

[32] R. Smolańczuk: *Phys. Rev. C* **56** (1997) 812

[33] A. Staszczak et al.: *in Proc. 3rd Int. Conf. Dynamical Aspects of Nuclear Fission*, Casta-Papiernicka (Slovakia) 1996 Eds. J. Kliman, B.I. Pustylnik). JINR, Dubna 1996, p. 22