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STRUCTURE OF HEAVIEST NUCLEI * **

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Theoretical studies of the structure and the properties of heavy and superheavy nuclei are described. Such properties as mass 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. Main results obtained in recent years (in a macroscopic-microscopic approach) are illustrated.

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1. Introduction

The objective of this paper is to illustrate theoretical results on the ground-state structure and properties of heavy and superheavy nuclei, obtained in recent years. The essential role of shell effects in this structure and in the properties of these nuclei is particularly stressed. Such properties as mass, modes of decay and respective half-lives are discussed. Even-even nuclei with proton number $Z = 82 - 120$ and neutron number $N = 126$–190 are considered.

We concentrate on the studies performed in a macroscopic-microscopic approach (*e.g.* [1–3], *cf.* also the reviews [4–6]), which seem to be, at the moment, most complete. Some properties of heaviest nuclei have been, however, also studied by fully microscopic methods, like Hartree–Fock–Bogolubov, Relativistic Mean Field and Skyrme–Hartree–Fock approaches (*e.g.* [7–9]).

The theoretical studies are closely connected with, and motivated by, an intensive experimental activity in this field (*e.g.* [10–15]). The three new

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elements: 110, 111, 112 and new (heavy) isotopes of the elements 106 (Sg), 107 (Bh), 108 (Hs) and 109 (Mt) have been obtained in these experiments. In Section 5, we make a short note on the present state of the experimental studies and on their perspectives for the nearest future.

2. Essential role of shell effects

Shell effects are important for all nuclei. Their role for the heaviest nuclei is, however, essential, as many of them would not exist at all without these effects [16].

The analysis of shell effects, performed in [16], has shown that these effects elongate the α-decay half-lives T_α by up to about 5 orders of magnitude, and the spontaneous-fission half-lives T_{sf} by up to about 15 orders of magnitude.

A particular feature of the considered region of nuclei is that some deformed nuclei show shell effects which are similarly strong as the effects observed in spherical magic nuclei, i.e. that we observe deformed shells in these nuclei. Specifically, effects of the deformed neutron shell at the neutron number $N = 152$ are experimentally observed for a long time. There is also an increasing experimental evidence for the existence of even stronger deformed shells at $N = 162$ and $Z = 108$, predicted theoretically. The nucleus $^{270}108$ (^{270}Hs) is expected theoretically [2, 17] to be a doubly magic deformed nucleus. To get in a theory, however, these strong shells in a deformed nucleus, one needs to allow the nucleus to deform as it likes, to take the shape comfortable for it. In other words, one needs to consider the properties of a nucleus in a sufficiently large, multidimensional deformation space [2, 18, 19].

3. Theoretical model

As mentioned 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 [20]. The microscopc 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 [21].

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 [2, 22].

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 [3].

The 4-dimensional deformation space $\{\beta_\lambda\}$, $\lambda = 2, 4, 6, 8$, is used, where 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.

4. Illustration of theoretical results

4.1. 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. Figure 1, taken from [22], shows the shell correction, $E_{\rm sh}$, calculated for the large region of nuclei under consideration. One can see that $E_{\rm sh}$ has three minima in this region. The first one, which is the deepest ($E_{\rm sh}$=–14.3 MeV), is obtained for the doubly magic spherical nucleus ^{208}Pb. The second one ($E_{\rm sh}$=–7.2 MeV) appears at the nucleus $^{270}108_{162}$, which is predicted to be a doubly magic deformed nucleus. The third minimum, with the same depth ($E_{\rm sh}$=–7.2 MeV) as that of the second minimum, is obtained for the nucleus $^{296}114_{182}$, which is close to the nucleus $^{298}114_{184}$ predicted [23, 24] to be a doubly magic spherical nucleus, the next one to the last experimentally known ^{208}Pb.

One can see in Fig. 1 that some of the already synthesized nuclei profit by 6–7 MeV in their binding energy from the shell correction. Without this profit they could not exist, as already mentioned in Section 2.

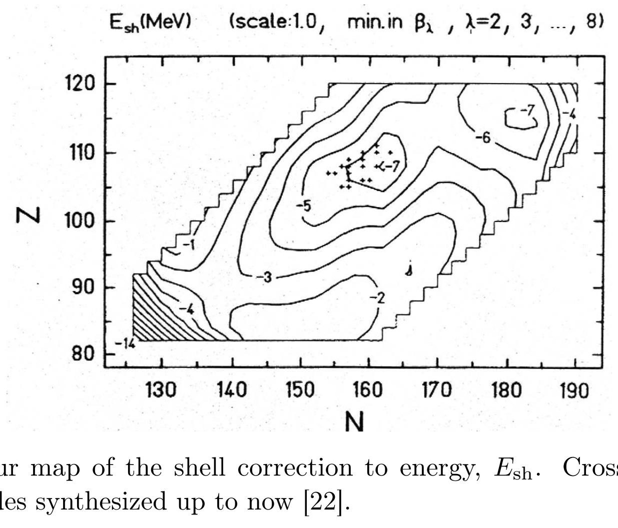

Fig. 1. Contour map of the shell correction to energy, $E_{\rm sh}$. Crosses denote the heaviest nuclides synthesized up to now [22].

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.

4.2. Single-particle structure (spectra)

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 $E_{\rm sh}$ have been obtained in Fig. 1. The spectra are shown in Fig. 2, for neutrons.

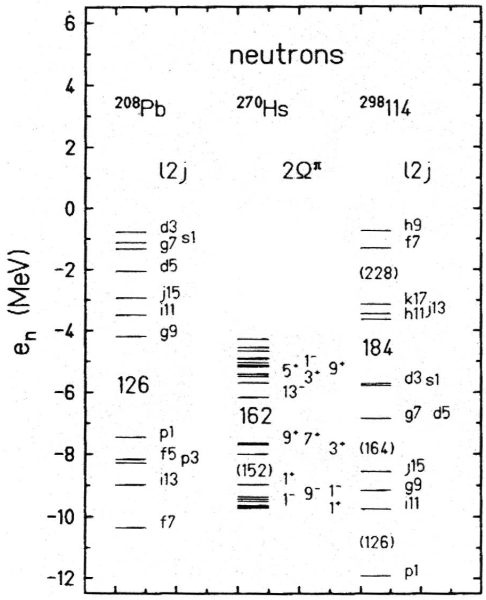

Fig. 2. Neutron single-particle levels calculated for the doubly magic nuclei: ^{208}Pb, ^{270}Hs and ^{298}114. Spectroscopic symbol for the orbital angular momentum l and total spin (multiplied by two) $2j$ are given at each level of the spherical nuclei ^{208}Pb and ^{298}114. Projection of spin (multiplied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

4.3. Half-lives of deformed superheavy nuclei

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. 1, have been given and extensively discussed in [2, 3, 22]. Here, we only illustrate a comparison of these results with the experimental values obtained for the element 110. This is shown in Fig. 3. The experimental values are taken from [12] for ^{257}110, from [11] for ^{259,261}110 and from [15] 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 $T_{\rm sf}$ is larger than T_α for respective nuclei, as only α-decay has been observed for them.

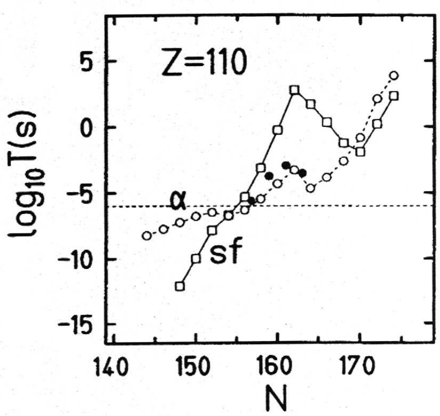

Fig. 3. Comparison between predicted theoretically (open cirles) and measured (full circles) α-decay half-lives, for isotopes of the element 110.

4.4. Half-lives for "spherical" superheavy nuclei

Figure 4 gives half-lives [25, 26] of nuclei situated around the third minimum in Fig. 1, 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 subsection into quotation marks. 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.

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.

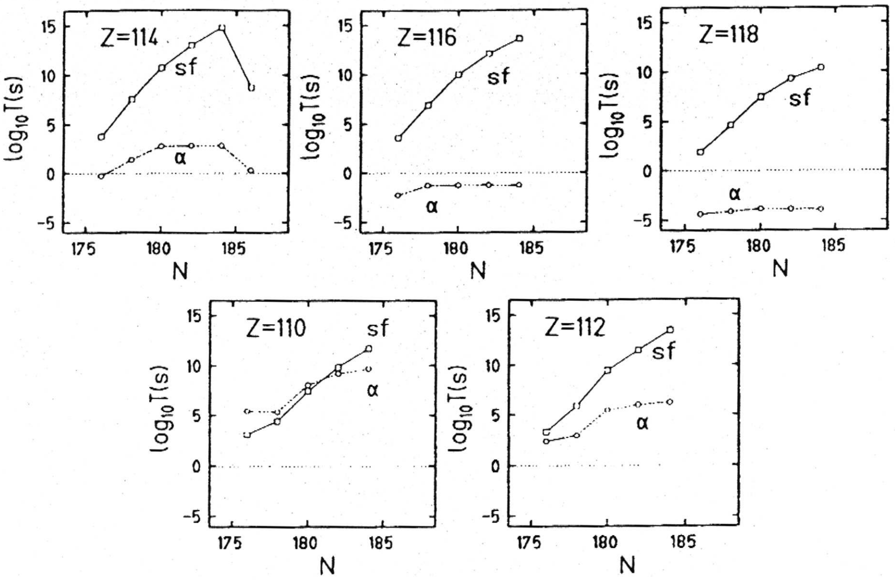

Fig. 4. Logarithms of the calculated spontaneous-fission (sf) and α-decay (α) half-lives (given in seconds), as functions of the neutron number N, for the elements: 110–118. The horizontal dashed line indicates about the lowest half-life (1 μs) of a nucleus, which can be detected in a present-day set-up, after its synthesis [26].

One can also see in Fig. 4 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.* [27]), 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 $^{270}108$, 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.

Fission half-lives of "spherical" superheavy nuclei have been also considered recently in [28] applying the approach used in [3], *i.e.* the dynamics in two-dimensional deformation space. They have been also studied in [29].

5. Present state of experimental studies and perspectives

The heaviest nucleus synthesized up to now is $^{277}112$ [14]. It has been obtained at GSI-Darmstadt in a cold fusion reaction

$$ {}^{70}_{30}\mathrm{Zn} + {}^{208}_{82}\mathrm{Pb} \;\rightarrow\; {}^{278}112^{*}_{166} \;\rightarrow\; {}^{277}112_{165} + 1n, \tag{1}$$

in which the excitation energy of the compound nucleus is small and only one neutron is emitted.

In a near future, synthesis of the elements 113 and 114 is planned. The element 113 is projected to be synthesized at GSI-Darmstadt in the cold fusion reaction

$$ {}^{70}_{30}\mathrm{Zn} + {}^{209}_{83}\mathrm{Bi} \;\rightarrow\; {}^{279}113^{*}_{166} \;\rightarrow\; {}^{278}113_{165} + 1n. \tag{2}$$

The element 114 is planned to be obtained at JINR-Dubna in a hot fusion reaction, with the use of the ^{48}Ca projectile. One of the proposed reactions is

$$ {}^{48}_{20}\mathrm{Ca} + {}^{244}_{94}\mathrm{Pu} \;\rightarrow\; {}^{292}114^{*}_{178} \;\rightarrow\; {}^{289,288}114_{175,174} + (3,4)n \tag{3}$$

Here, the excitation energy of the compound nucleus is higher than in Eq.(2), and 3 or 4 neutrons are expected to be emitted. The use of the neutron-rich projectile ^{48}Ca in the latter reaction, together with the use of a heavier target, lead to heavier isotopes of 114 than those which could be obtained in a cold fusion reaction.

Theoretically, all three evaporation residues: $^{278}113$ and $^{289,288}114$ are expected to decay by α emission, with half-lives in the microseconds region for $^{278}113$ and milliseconds region for $^{289,288}114$. Thus, they are expected to live long enough to be observed, if synthesized (1 μs half-life is considered to be about the lower limit for such an observation). The cross-section for their production, however, is an open problem.

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