DECAY PROPERTIES OF HEAVIEST ATOMIC NUCLEI*

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Stability of transactinide nuclei is discussed. Theoretical results were obtained in a multidimensional deformation space on the basis of the macroscopic-microscopic model. In the large enough deformation space, shell closures at $Z = 108$ and $N = 162$ were obtained which stabilize the recently synthesized deformed superheavy nuclei. Much stronger influence of the shells at $Z = 114$ and $N = 184$ on the calculated half-lives for spherical superheavy nuclei is also demonstrated.

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1. Introduction

Nowadays, one hundred years after the discovery of radioactivity [1, 2], the Mendeleyev Table contains 112 chemical elements. All elements beyond Uranium, which is the heaviest one observed in nature, were obtained artificially in nuclear reactions. An impressive progress in the production of heaviest elements has been made during the last few years due to the discovery of α-decaying isotopes of the new elements 110 [3–5], 111 [6] and 112 [7].

Transactinide nuclei known so far decay mainly by the emission of the α-particle or by the spontaneous fission [8]. This is because these short-living nuclei are situated on the nuclear chart very close to the area of the β-stability. The aim of this contribution is to present results on the α-decay and spontaneous-fission half-lives calculated on the basis of the macroscopic-microscopic model [9, 10].

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2. The method

We calculated the potential energy and its dependence on deformation using the macroscopic–microscopic model [9, 10]. The Yukawa-plus-exponential potential [11] with the parameters from Ref. [10] was taken for the macroscopic energy. The microscopic energy was calculated by means of the Strutinsky method [12]. The single-particle levels, from which the microscopic energy was calculated, have been obtained by the diagonalization of the Woods–Saxon single-particle Hamiltonian [13] in the deformed harmonic oscillator basis. We used the Woods–Saxon potential with the universal parameters [13]. Residual pairing interaction was treated in the BCS approximation with the strength taken from Ref. [14].

Nuclear shapes were parametrized in the intrinsic frame of reference connected with a nucleus. We used the standard deformation parameters β_λ which multiply spherical harmonics $Y_{\lambda 0}(\vartheta)$ in the expression for the nuclear radius. We checked that the use of four deformation parameters β_λ, $\lambda = 2, 4, 6, 8$, describing axially and reflection symmetric nuclear shapes, is sufficient for the calculation of the ground-state energy for almost all transactinides [9, 10]. This set of deformation parameters is also sufficient for the calculation of the spontaneous-fission half-lives because of the dynamical description of this decay mode [9,10]. In the dynamical calculation [15,16], the fission trajectory is determined by the minimization of the action integral which describes penetration of the potential energy barrier by a nucleus. This quantity is dependent on both the potential energy and the tensor of inertia calculated along a trajectory. The tensor of inertia was obtained by using the cranking approximation with the inclusion of pairing [17]. The probability of tunneling of the potential energy barrier along the fission trajectory by a nucleus and, consequently, the spontaneous-fission half-life was calculated by means of the WKB approximation. The shortest trajectory (the smallest spontaneous-fission half-life) was obtained for axially and reflection symmetric nuclear shapes.

The α-decay half-life (in seconds) was calculated by the semi phenomenological Viola and Seaborg formula

$$\log_{10} T_\alpha = (aZ + b)Q_\alpha^{-1/2} + (cZ + d)\,. \tag{1}$$

The α-decay energy Q_α (in MeV) for each nucleus was obtained by subtracting from its theoretical mass the theoretical mass of the daughter nucleus and the measured mass of the α-particle. Parameters

$$a = 1.81040, \quad b = -21.7199, \quad c = -0.26488, \quad d = -28.1319\,, \tag{2}$$

were fitted to 58 even–even nuclei with $Z > 82$ and $N > 126$ for which both Q_α and T_α are experimentally known [10].

3. Discussion of the results

Transactinide nuclei are stabilized by large shell effects because very small or even no macroscopic barriers are obtained for these nuclei [18]. Such nuclei are called very often “superheavy nuclei”.

Contour map of the total shell correction energy defined as the difference between the total potential energy calculated for the equilibrium shape and the macroscopic part of the potential for the spherical shape is given in Fig. 1. Since the spherical shape is the equilibrium point in the macroscopic

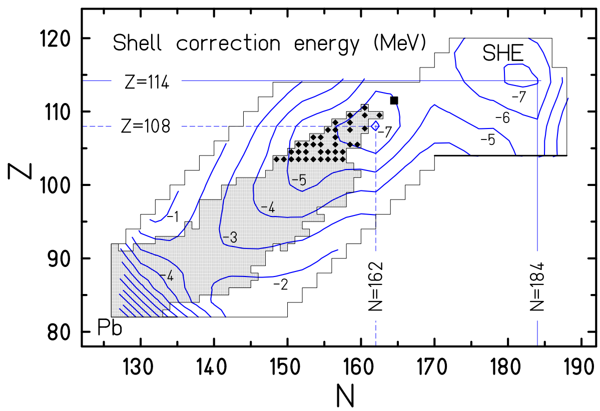

Fig. 1. Contour map of the total shell correction energy $E_{\rm sh}$ for even-even nuclei with Z=82–120 [10]. Numbers at contour lines give energy in MeV. The energy difference between neighboring contour lines is equal to 1 MeV. Squares denote deformed transactinide nuclei synthesized so far. The region of known nuclei is also shown. Deformed magic numbers, Z=108, N=162, as well as spherical ones, Z=114, N=184, are indicated. Traditional superheavy elements (SHE), which are not observed so far, are expected to be stabilized by the large spherical shells.

(*i.e.*, without shell structure) model, the total shell correction $E_{\rm sh}$ is the gain in energy of a nucleus due to its shell structure, including the effect of pairing. In the region of superheavy nuclei, two minima of $E_{\rm sh}$, exceeding slightly 7 MeV, were obtained [10]. They appear at the well deformed nucleus $^{270}{\rm Hs}_{162}$ ($^{270}108_{162}$) and for nuclei close to the spherical nucleus $^{298}114_{184}$. The minima indicate the creation of large gaps at the Fermi level in the single-particle spectra of these nuclei. The energy gaps equal to 2.1 MeV were obtained between $Z = 114$ and 115 in the proton spectrum and between $N = 184$ and 185 in the neutron spectrum of the spherical nucleus $^{298}114_{184}$. In case of the deformed nucleus $^{270}{\rm Hs}_{162}$, nuclear shells are created by energy gaps equal to 1.4 MeV which appear between $Z = 108$ and 109 in the proton spectrum and between N=162 and 163 in the neutron spectrum. These nuclear shells are filled out by outer nucleons for the nuclei $^{298}114_{184}$ [19] and $^{270}\mathrm{Hs}_{162}$ [20,21] what leads to the increased stability of these heavy systems against α decay and especially against spontaneous fission. Therefore, we call these nuclei "spherical doubly magic superheavy nucleus" and "deformed doubly magic superheavy nucleus", respectively.

Fig. 2 shows the spontaneous-fission half-life T_{sf} and the α-decay half-life T_α calculated for even-even deformed superheavy nuclei [9]. These quantities are plotted as functions of neutron number N. The effect of the deformed neutron shell is seen as maxima of T_{sf} and T_α at N=162 for particular elements. Measured spontaneous-fission and α-decay half-lives for even-even deformed superheavy nuclei [22–27] are also shown in Fig. 2 together with the experimental α-decay half-lives for odd-N isotopes of the elements Hs-112 [3–5,7,28]. Experimental half-lives obtained for odd-N iso-

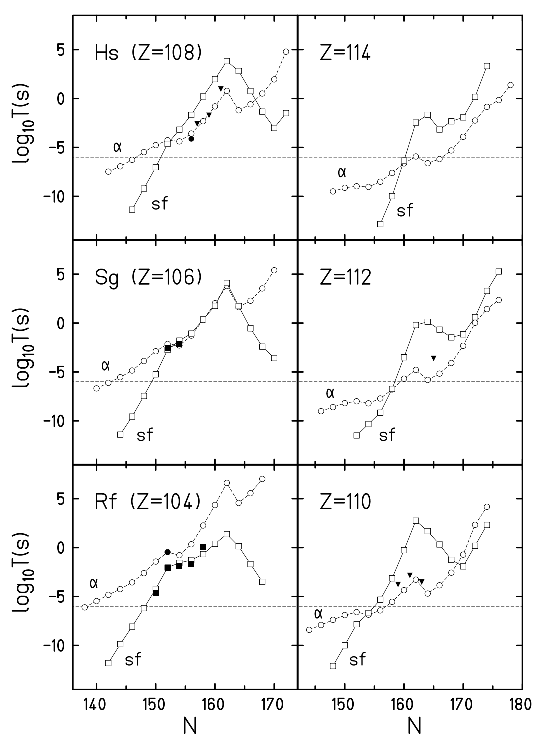

Fig. 2. Logarithm of the spontaneous-fission (squares) and α-decay (circles) half-lives [9], given in seconds, versus neutron number N, for even-even deformed isotopes of the elements Rf$-$114. Open symbols indicate calculated half-lives. Experimental data [22–27] are marked by full symbols. Triangles indicate experimental α-decay half-lives for odd-N isotopes of the elements Hs-112 [3–5,7,28].

topes of the element 110 [3–5] manifest the same behavior around N=162 as the calculated α-decay half-lives for even-even isotopes of this element. This seems to mean that the deformed neutron shell appears exactly at N=162. The influence of the spherical shell at N=184 is seen as the increase of T_{sf} for $N \gtrsim 170$.

Total half-lives calculated for β-stable even-even superheavy nuclei are shown in Fig. 3. Effect of the spherical shell at N=184, which is stronger than the one at N=162, is demonstrated. It is also clearly seen in this figure that the region of traditional superheavy nuclei (SHE), *i.e.* spherical nuclei stabilized by the shells at Z=114 and N=184, is not separated from the known nuclei by the area of deep instability. The total half-lives calculated for isotopes with $N \approx 170$ are still larger than 1 μs which is nowadays the smallest half-life possible to measure after the synthesis of a superheavy nucleus. Very recently, an attempt at the synthesis of the nuclei $^{282}112_{170}$ and $^{283}112_{171}$ has been made in Dubna. The results of this experiment are discussed in Ref. [29].

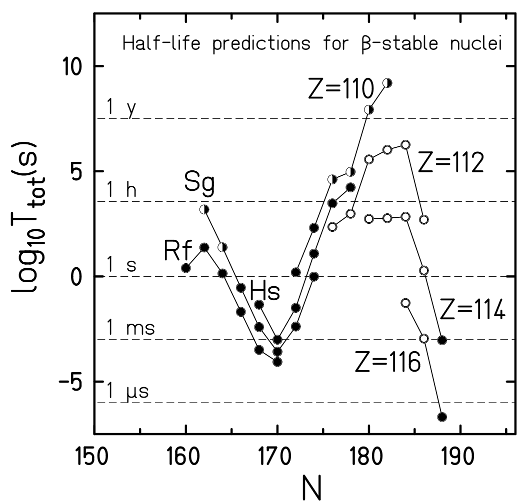

Fig. 3. Total half-life predictions for both deformed and spherical β-stable isotopes of the elements Rf−116. The total half-life was obtained from α-decay and spontaneous-fission half-lives taken from Ref. [10]. Full circles denote spontaneously fissioning nuclei, open circles mark α-decaying ones and mixed symbols indicate very heavy systems for which both decay modes are expected with the probability not differing more then about 10 times.

Many spherical superheavy nuclei (SHE) are expected to live long enough [10] to accumulate them and investigate their chemical properties [30]. The largest half-life of the order of 50 years was obtained for $^{292}110_{182}$. Due to the large half-lives predicted for many superheavy nuclei, one plans experiments in which new elements are expected to be discovered [31–34]. In case of the success of such experiments unique possibilities for atomic physics and chemistry would be opened.

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