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Hyperheavy nuclei: Existence and stability

A.V. Afanasjev *, S.E. Agbemava, A. Gyawali

Department of Physics and Astronomy, Mississippi State University, MS 39762, United States of America

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ABSTRACT

What are the limits of the existence of nuclei? What are the highest proton numbers Z at which the nuclear landscape and periodic table of chemical elements cease to exist? These deceivably simple questions are difficult to answer especially in the region of hyperheavy ($Z \geq 126$) nuclei. We present the covariant density functional study of different aspects of the existence and stability of hyperheavy nuclei. For the first time, we demonstrate the existence of three regions of spherical hyperheavy nuclei centered around ($Z \sim 138$, $N \sim 230$), ($Z \sim 156$, $N \sim 310$) and ($Z \sim 174$, $N \sim 410$) which are expected to be reasonably stable against spontaneous fission. The triaxiality of the nuclei plays an extremely important role in the reduction of the stability of hyperheavy nuclei against fission. As a result, the boundaries of nuclear landscape in hyperheavy nuclei are defined by spontaneous fission and not by the particle emission as in lower Z nuclei. Moreover, the current study suggests that only localized islands of stability can exist in hyperheavy nuclei.

The investigation of superheavy elements (SHE) remains one of the most important sub-fields of low-energy nuclear physics [1]. The element Og with proton number $Z = 118$ is the highest Z element observed so far [2]. Although future observation of the elements in the vicinity of $Z \sim 120$ seems to be feasible, this is not a case for the elements with Z beyond 122. Considering also that the highest in Z spherical shell closure in SHE is predicted at $Z = 126$ in Skyrme density functional theory (DFT) [3], it is logical to name the nuclei with $Z > 126$ as hyperheavy [4,5]. The properties of such nuclei are governed by increased Coulomb repulsion and single-particle level density; these factors reduce the localization of shell effects in particle number [5].

Although hyperheavy nuclei have been studied both within DFTs [4–9] and phenomenological [10–12] approaches, the majority of these studies have been performed only for spherical shapes of the nuclei. This is a severe limitation which leads to misinterpretation of physical situation in many cases since there is no guarantee that spherical minimum in potential energy surface exist even in the nuclei with relative large spherical shell gaps (see discussion in Ref. [13]). In addition, the stability of hyperheavy nuclei against spontaneous fission could not be established in the calculations restricted to spherical shape. The effects of axial and triaxial deformations in hyperheavy nuclei are considered only in Refs. [6,14] and in Ref. [8,15], respectively. However, only few nuclei are studied in Refs. [6,14,15] and according to the present study the deformation range employed in Ref. [8] is not sufficient for $Z \geq 130$ nuclei.

The investigation of hyperheavy nuclei is also intimately connected with the establishment of the limits of both the nuclear landscape and periodic table of elements. The limits of nuclear landscape at the proton and neutron drip lines and related theoretical uncertainties have been extensively investigated in a number of theoretical frameworks but only for the $Z < 120$ nuclei [16–18]. The atomic relativistic Hartree–Fock [19] and relativistic Multi-Configuration Dirac–Fock [20,21] calculations indicate that the periodic table of elements terminates at $Z = 172$ and $Z = 173$, respectively. However, at present it is not even clear whether such nuclei are stable against fission. In addition, Refs. [19–21] employ phenomenological expression for charge radii and its validity for the $Z \sim 172$ nuclei is not clear.

To address these deficiencies in our understanding of hyperheavy nuclei the systematic investigation of even-even nuclei from $Z = 122$ up to $Z = 180$ is performed within the axial relativistic Hartree–Bogoliubov (RHB) framework employing the DD-PC1 covariant energy density functional [22]. This functional provides good description of the ground state and fission properties of known even-even nuclei [18,23]. To establish the stability of nuclei with respect to triaxial distortions a number of nuclei have been studied within the triaxial RHB [24] and relativistic mean field + BCS (RMF + BCS) [25] frameworks. The main goals of this study are (i) to understand whether the nuclei stable against fis-

* Corresponding author.
E-mail address: Anatoli.Afanasjev@gmail.com (A.V. Afanasjev).

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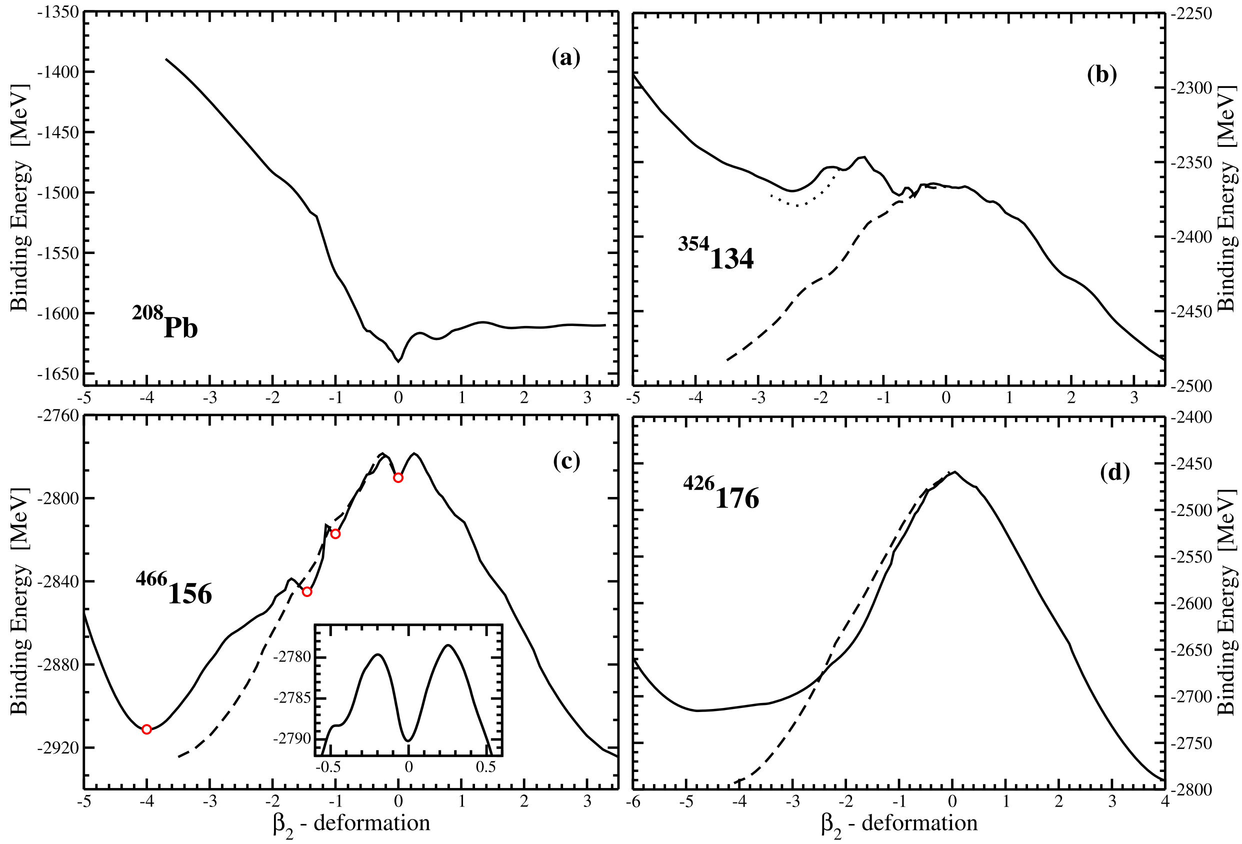

Fig. 1. Deformation energy curves of ^{208}Pb and selected even-even hyperheavy nuclei obtained in axial RHB calculations with DD-PC1 functional and the $N_F = 30$ basis. The insert in panel (c) shows the fission barriers around spherical state in details. Open circles in panel (c) indicate the deformations at which the density distributions are plotted in Fig. 2. Dashed lines show mirror reflection of the $\beta_2 > 0$ part of deformation energy curve onto negative β_2 values.

sion could be present in the $Z \geq 126$ region and (ii) to define the most important features of such nuclei.

The CDFT calculations are performed within the relativistic Hartree–Bogoliubov framework [26] employing the state-of-the-art covariant energy density functionals the global performance of which with respect to the description of the ground state [13,18,27] and fission [23–25,28] properties is well established. These functionals (DD-PC1 [22], DD-ME2 [29], PC-PK1 [30] and NL3* [31]) represent the major classes of covariant density functional models [18]. The absolute majority of the calculations employ the DD-PC1 functional which is considered to be the best relativistic functional today based on systematic and global studies of different physical observables [13,18,24,27,28,32]. Other functionals are used to assess the systematic theoretical uncertainties in the predictions of the heights of fission barriers around spherical minima. To avoid the uncertainties connected with the definition of the size of the pairing window [33], we use the separable form of the finite-range Gogny pairing interaction introduced in Ref. [34].

The truncation of the basis is performed in such a way that all states belonging to the major shells up to N_F fermionic shells for the Dirac spinors (and up to $N_B = 20$ bosonic shells for the meson fields in meson exchange functionals) are taken into account. The comparison of the axial RHB calculations with $N_F = 20$ and $N_F = 30$ shows that in ^{208}Pb the truncation of basis at $N_F = 20$ provides sufficient accuracy for all deformations of interest. However, in hyperheavy nuclei the required size of the basis depends both on the nucleus and deformation range of interest. The $N_F = 20$ basis is sufficient for the description of deformation energy curves in the region of $-1.8 < \beta_2 < 1.8$. The deformation ranges $-3.0 < \beta_2 < -1.8$ and $1.8 < \beta_2 < 3.0$ typically require $N_F = 24$ (low-Z and low-N hyperheavy nuclei) or $N_F = 26$ (high-Z and high-N hyperheavy nuclei). Even more deformed ground states with $\beta_2 \sim -4.0$ are seen in high-Z/high-N hyperheavy nuclei (see Figs. 1c and d for the ^{466}156 and ^{426}176 results); their description requires $N_F = 30$. Thus, the truncation of basis is made dependent on the nucleus and typical profile of deformation energy curves or potential energy surfaces.

The deformation parameters β_2 and γ are extracted from respective quadrupole moments:

$$Q_{20} = \int d^3r \rho(\vec{r})\,(2z^2 - x^2 - y^2), \tag{1}$$

$$Q_{22} = \int d^3r \rho(\vec{r})\,(x^2 - y^2), \tag{2}$$

via

$$\beta_2 = \sqrt{\frac{5}{16\pi}}\frac{4\pi}{3AR_0^2}\sqrt{Q_{20}^2 + 2Q_{22}^2} \tag{3}$$

$$\gamma = \arctan \sqrt{2}\frac{Q_{22}}{Q_{20}} \tag{4}$$

where $R_0 = 1.2A^{1/3}$. Note that $Q_{22} = 0$ and $\gamma = 0$ in axially symmetric RHB calculations. The β_2 and γ values have a standard meaning of the deformations of the ellipsoid-like density distributions only for $|\beta_2| \lesssim 1.0$ values. At higher β_2 values they should be treated as dimensionless and particle normalized measures of the Q_{20} and Q_{22} moments. This is because of the presence of toroidal shapes at large negative β_2 values and of necking degree of freedom at large positive β_2 values. Note that physical observables are frequently shown as a function of the Q_{20} and Q_{22}