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ON THE POSSIBILITY TO OBSERVE NEW SHAPE ISOMERS IN THE Po–Th REGION*

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Using the macroscopic–microscopic approach with the macroscopic energy determined by the Lublin–Strasbourg Drop model and the microscopic, shell plus pairing, corrections evaluated through the Yukawa-folded mean-field potential, a certain number of yet unknown super- and hyper-deformed shape isomers in even–even Po, Ra and Th isotopes are predicted. Quadrupole moments and the energies of the lowest rotational state 2^+ in the local minima of the potential-energy surfaces are evaluated. We show that they turn out to be in good agreement with the available experimental data for the ground state.

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1. Introduction

The very broad fission barriers that are found in the actinides, in particular in the polonium–thorium region, indicate that the inclusion of shell effects will have a good chance to produce local minima in the potential energy surface of these nuclei corresponding to super- and hyper-deformed shapes. Extended calculations for long isotopic chains of even–even nuclei in that region have, therefore, been performed within the macroscopic–microscopic model. The Lublin–Strasbourg Drop formula [1] has been used for the macroscopic part of the potential energy surface, microscopic effects were evaluated with the Yukawa-folded single-particle potential [2] and the BCS theory for pairing correlations. The Modified Funny Hills shape parametrization [3] is used to describe nuclear deformations. Several shapes isomers could be identified in our calculations. Hope is that some of them can be found experimentally

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using proton beams that allow to produce compound systems with not too large angular momentum. Moments of inertia and quadrupole moments of the most pronounced minima were evaluated.

2. The model

In order to describe shape isomeric states in general, and fission isomers in particular, one needs to calculate the energy of a given nucleus as a function of its deformation. Such a calculation relies on two essential ingredients. On the one hand, one needs a description that is able to determine the energy of the studied nucleus as realistically as ever possible. It is clear that the energy that one is speaking about needs to describe the quantum-mechanical structure as well as the pairing correlations, and this for any nuclear deformation. Such a description could rely on some mean-field approach using nucleon–nucleon (NN) interaction rooted (more or less directly) in the meson fields or elementary NN diffusion cross sections. Instead, and this is the description that is used in our present investigation, one could use the macroscopic–microscopic model to obtain this nuclear energy. On the other hand, one also needs to describe the vast variety of nuclear shapes that are encountered in the course of the deformation process. In the case of the nuclear fission process, this is particularly demanding since very elongated and necked-in shapes need to be described. These essential ingredients are briefly reviewed below.

2.1. The Lublin–Strasbourg Drop

The macroscopic–microscopic model is used in the present investigation to determine the nuclear energy as a function of its deformation, where the macroscopic energy is given by the so-called Lublin–Strasbourg Drop (LSD) [1] and the microscopic energy corrections are obtained for the shell-energy part by the Strutinsky method [4] determined at any deformation from a mean-field potential generated by a Yukawa-folding procedure [2] and by the BCS theory for the pairing correlations [5].

Let us mention in this context that even though many macroscopic models exist that have been publicised in recent years and have been shown to yield sometimes a very good description of nuclear ground-state masses, some of them [6–8] badly fail to reproduce nuclear fission-barrier heights as has been shown in Ref. [9]. The LSD liquid-drop type macroscopic energy, on the contrary, has been shown not only to yield an excellent description of nuclear ground-state masses (with a r.m.s. deviation from the experiment of less than 0.7 MeV) but also to give precise fission-barrier heights throughout the periodic table. It should be noted that, contrary to other macroscopic models [10, 11], our LSD approach relies on only 9 parameters to describe the masses of more than 2700 nuclei, plus, in addition, their fission-barrier heights for the light, medium and heavy nuclei.

2.2. The Modified Funny Hills shape parametrization

For the description of nuclear shapes along the fission path, we use a slightly improved version of the famous Funny Hills (FH) parametrization [12] that is now known as the "*Modified Funny Hills*" (MFH) shapes [3]

$$\rho_s^2(z,\varphi) = \mathcal{N}\,\left(1-u^2\right)\left[1 - Be^{-(3-B)(u-\alpha)^2}\right]\,F(\varphi) \tag{1}$$

and which has proven to yield even slightly lower fission barriers [13]. In the above equation $\rho_s(z)$ is the distance of the nuclear surface to the symmetry axis z and $u = (z - z_{sh})/z_0$ where the elongation of the shape in z-direction is given by $2z_0$ and one defines a dimensionless elongation parameter $c = z_0/R_0$. R_0 is the radius of the corresponding spherical nucleus. The coordinate z_{sh} is defined in such a way that the centre-of-mass of the distribution is located at $z = 0$. The normalization coefficient $\mathcal{N}$ ensures that the volume of the deformed nucleus is the same as of the spherical one. The parameters c, B and α describe the elongation, neck and reflection asymmetry of the nucleus. Note that the deformation $c = 1$ with $B = 0$ represents the spherical shape, while the neck parameter $B = 1$ corresponds to a scission configuration. Non-axial shapes are obtained through a function $F(\varphi)$ containing a non-axiality parameter η as explained in detail in Ref. [3]. Instead of the neck parameter B, we will also use, as done for the FH shapes, a parameter h that is chosen such that the liquid-drop path to scission evolves approximately along $h = 0$, which is obtained by choosing $h = B/2 - (c-1)/4$.

In Fig. 1 we show, as a typical example, the deformation-energy landscape (relative to the LSD energy of the spherical shape) of the nucleus ^{232}Th on the $(c,\,h)$ plane. This deformation-energy landscape is evaluated

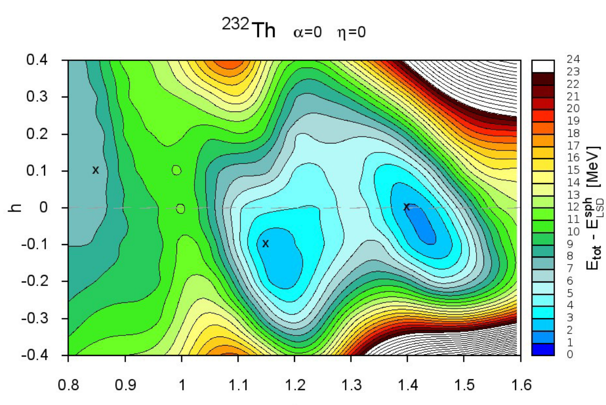

Fig. 1. Deformation-energy landscape for the nucleus ^{232}Th as a function of the elongation c and the neck parameter h.

in the above introduced 4-dimensional $\{c, h, \alpha, \eta\}$ space to determine the nuclear ground state and all possible shape isomeric states, but since we are only able, in such a figure, to represent the energy as a function of two parameters, in this case c and h, we mark these local minima by crosses. In Fig. 1 for ^{232}Th, one obtains the ground state at $\{c = 1.15, h = -0.1\}$ and a prolate isomeric state at $\{c = 1.40, h = 0.02\}$. In addition, a local oblate minimum is found at $\{c = 0.85, h = 0.1\}$. One observes that the ground state is slightly left–right asymmetric ($\alpha \neq 0$), while the first fission isomer is axial and left–right symmetric.

A problem that arises with the above shape parametrization lies in the fact that the scission configuration is not clearly defined as a function of the elongation parameter c, *i.e.* scission is obtained, in various regions of the nuclear chart, for different values of c. That is why we have introduced in Ref. [9], instead of c and B, some new deformation parameters ψ and κ that are related to the former ones through

$$c = 1 + e^{\kappa} \sin\psi \qquad \text{and} \qquad B = 1 - e^{\kappa} \cos\psi \tag{2}$$

so that the scission configuration is always obtained for $\psi = \pi/2$. To exhibit the large variety of MFH shapes that can be described, we show schematically some of them in Fig. 2. Even though one can conclude from the below figure that a vast family of shapes can, indeed, be described by our MFH parametrization, the question arises how close these shapes are to the physical reality. To be able to answer this question, we have compared our shapes with the so-called *Strutinsky optimal shapes* that are obtained from a variational calculation [14, 15] and we found an excellent agreement [16].

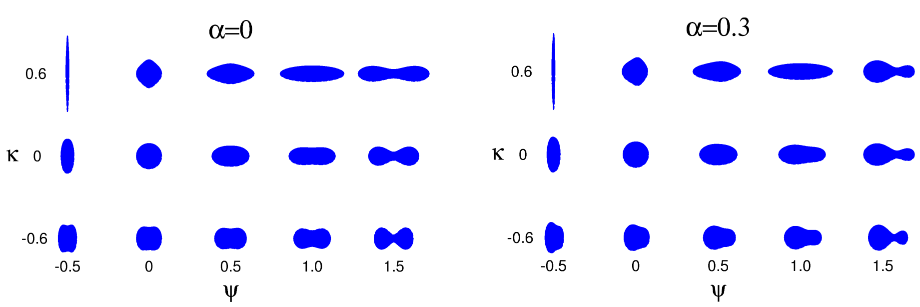

Fig. 2. Variety of shapes that are obtained for different (ψ, κ) values in the left–right symmetric ($\alpha = 0$, left) and asymmetric ($\alpha = 0.3$, right) case.

3. Deformation energies of fissioning nuclei

A first deformation energy has already been presented in Fig. 1. One notices, as discussed above, several local minima that represent respectively the nuclear ground state and fission isomeric states that we will refer to as *super deformed* (SD, $c \approx 1.25$) and *hyper deformed* (HD, $c \approx 1.45$). For the polonium isotopic chain the deformation energies of ^{188}Po up to ^{220}Po are shown in Fig. 3 [9]. Local minima are indicated by letters "s" or "a" for

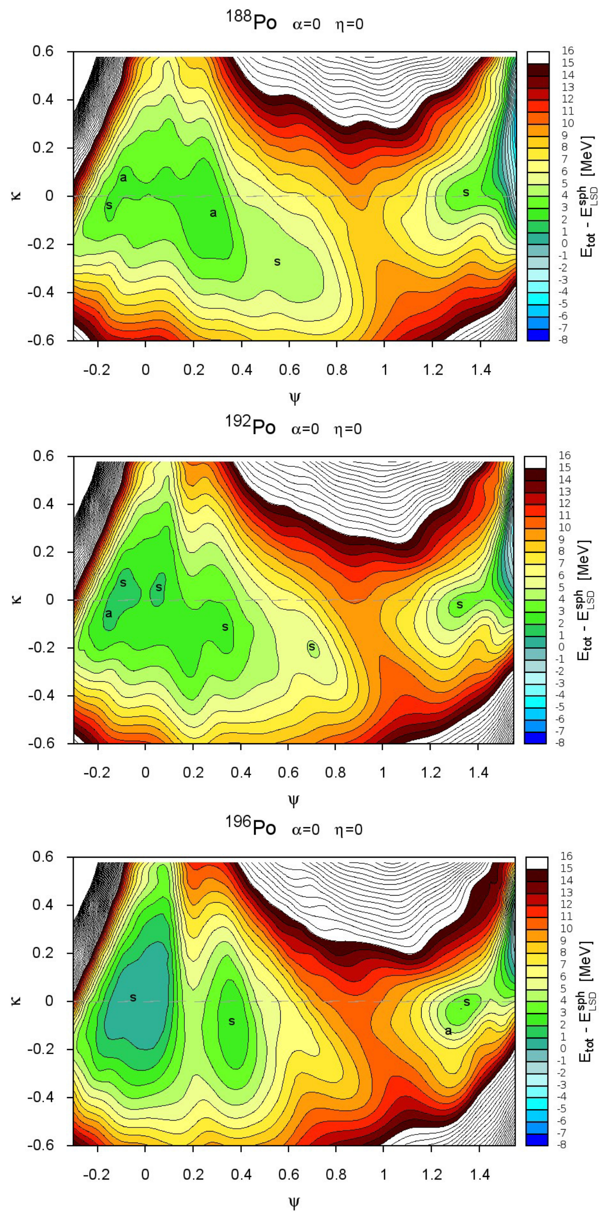

Fig. 3. Deformation-energy landscapes for the even–even nuclei of the polonium isotopic chain ^{188}Po–^{220}Po as functions of the $\{\psi, \kappa\}$ parameters.

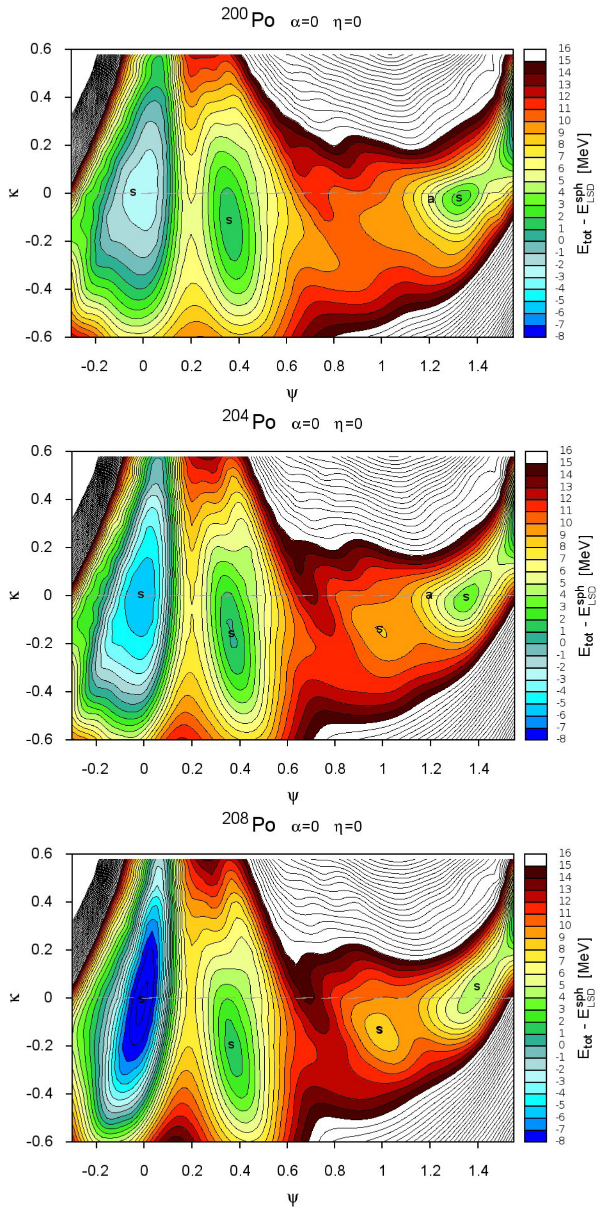

Fig. 3. (continued).

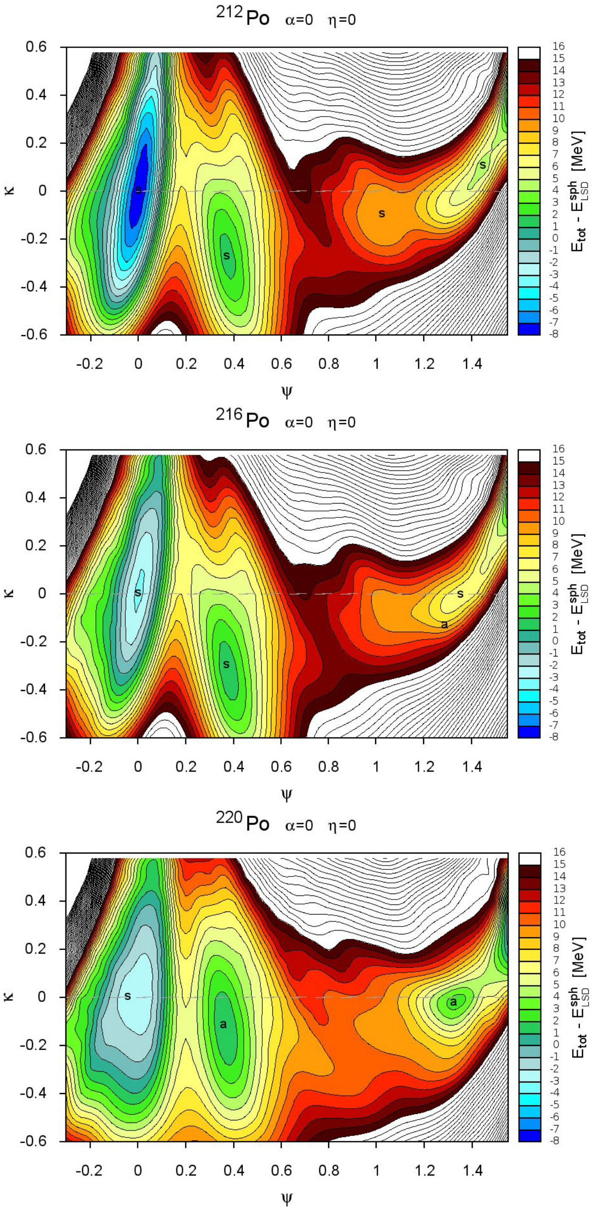

Fig. 3. (continued).

respectively axial left–right symmetric or asymmetric minima. It appears interesting to follow the evolution (appearance and disappearance) of the different *super deformed* ($\psi \approx 0.4$), *hyper deformed* ($\psi \approx 1.0$) and *ultra deformed* ($\psi \approx 1.4$) local minima. Whereas the deformation-energy landscape is rather soft for the lighter Po isotopes, very pronounced minima appear in the vicinity of the $N = 126$ neutron closed-shell nucleus ^{210}Po. Let us mention at this point that the microscopic corrections that we have determined are obtained in the same way as those given by Moeller [10] since the same single-particle potential is used here and there, but the macroscopic part (and this is the crucial point) is different which can, of course, lead to different predictions for the location and depth of fission isomeric states.

To test the quality of our description of deformation energies and fission isomeric states in particular, we present, in the l.h.s. of Figs. 4 and 5, a comparison of the charge quadrupole moments in the ground state and in the super-deformed fission isomeric state obtained in our calculation with the available experimental data [17]. The energy of the 2^+ rotational state for Th, Ra and Po chains of isotopes is shown in the r.h.s. of Figs. 4, 5 and 6, respectively. One notices a quite nice agreement between theory and experiment in the ground state of Th and Ra isotopes, where the data are available, what shows that our model yields a description that seems to be quite realistic.

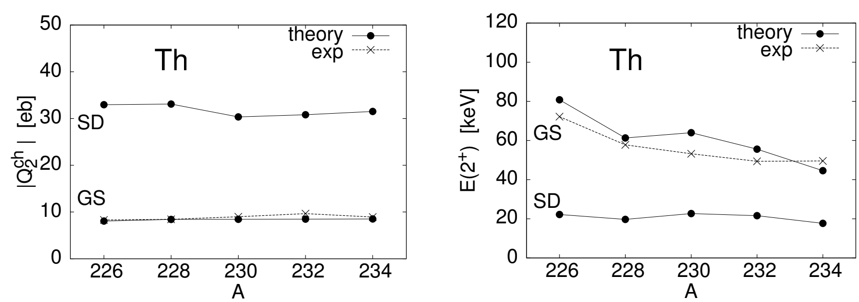

Fig. 4. Comparison, where available, of the experimental charge quadrupole moments in the ground state (GS) and the super-deformed (SD) minimum (left) and the energy of the 2^+ rotational state (right) along the Th isotopic chain.

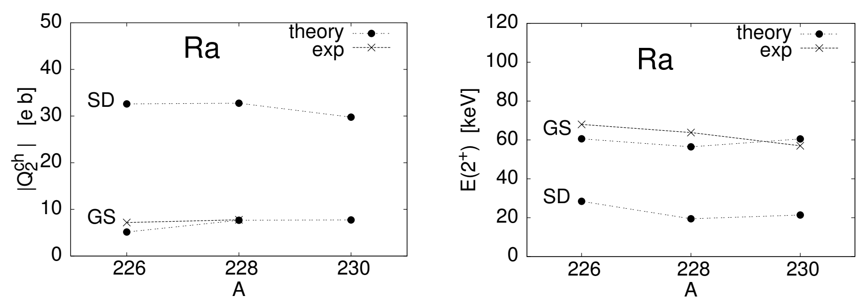

Fig. 5. The same as Fig. 4 for the radium isotopic chain.

Experimental data on $E(2^+)$ energies in fission isomeric states are very scarce. In Ref. [18] on γ spectroscopy in the superdeformed minimum of ^{240}Pu, a value of $E(2^+) = 20.1$ keV is found which is consistent with the values of our investigation. We also found in Ref. [19] a value of 12 keV for the $E(2^+)$ energy in the third minimum of ^{231}Th. Considering the fact that the odd neutron decreases the pairing gap, which implies that the cranking moment of inertia increases and the $E(2^+)$ energy is therefore lower than for the neighbouring even N nuclei, such a value is in agreement with our results.

In Fig. 6 made for the polonium chain of isotopes, the predicted charge quadrupole moments $Q_2^{\rm ch}$ and energies of the rotational 2^+ states are presented for the super-, hyper- and ultra-deformed shape isomers visible in the potential energy surfaces shown in Fig. 3.

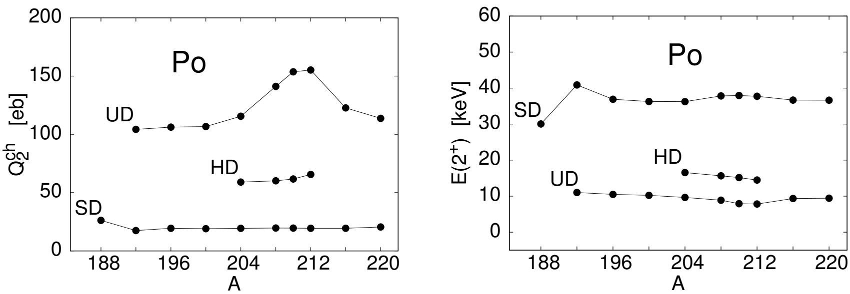

Fig. 6. Charge quadrupole moments (l.h.s.) and rotational $E(2^+)$ energies for the super- (SD), hyper- (HD) and ultra-deformed (UD) shape-isomers of the polonium isotopes.

4. Summary

Our investigations of the liquid-drop fission barriers heights and their shapes performed in Ref. [16] in a variational calculation have shown that the fission barriers of medium-heavy nuclei are very broad and do not decrease rapidly when going from the saddle to the scission point. This property of the macroscopic energy offers a chance that in this region of nuclei, shell effects may produce local minima corresponding to a large nuclear elongation. As first candidates, we have chosen the chains of polonium, radium and thorium isotopes, and we have shown that the microscopic energy corrections can, indeed, produce pronounced minima in the rather flat macroscopic potential-energy surfaces corresponding to these isotopes. The predicted energy of the lowest rotational 2^+ state in the most deformed (ultra-deformed) shape isomers can even reach 10 keV. Such a small $E(2^+)$ energy with a very large B(E2) transition probability corresponding to an electric quadrupole moment of $Q_2^{\rm ch} \sim 100\ e\,{\rm b}$ could be a fingerprint for ultra-deformed isomers. We hope that in the near future this new island of super-, hyper- and ultra-deformed shape isomers will be discovered in the experimental analysis.

The above presented results should be understood as a pilot investigation. More extended calculations, with a denser grid in the four dimensional deformation space are under way. We are also going to investigate several other isotopic chains from mercury to thorium.

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