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Nuclear Physics A ••• (••••) •••–•••

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Sensitivity of the nuclear deformability and fission barriers to the equation of state

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Received 12 February 2018; received in revised form 28 March 2018; accepted 13 April 2018

Abstract

The model-dependent analysis of the fission data impacts the extracted fission-related quantities, which are not directly observables, such as the super- and hyperdeformed isomeric states and their energies. We investigated the model dependence of the deformability of a nucleus and its fission barriers on the nuclear equation of state. Within the microscopic–macroscopic model based on a large number of Skyrme nucleon–nucleon interactions, the total energy surfaces and the double-humped fission barrier of ^{230}Th are calculated in a multidimensional deformation space. In addition to the ground-state (GS) and the superdeformed (SD) minima, all the investigated forces yielded a hyperdeformed (HD) minimum. The contour map of the shell-plus-pairing energy clearly displayed the three minima. We found that the GS binding energy and the deformation energy of the different deformation modes along the fission path increase with the incompressibility coefficient K_0, while the fission barrier heights and the excitation energies of the SD and HD modes decrease with it. Conversely, the surface-energy coefficient a_{surf}, the symmetry-energy, and its density-slope parameter decrease the GS energy and the deformation energies, but increase the fission barrier heights and the excitation energies. The obtained deformation parameters of the different deformation modes exhibit almost independence on K_0, and on the symmetry-energy and its density-slope. The principle deformation parameters of the SD and HD isomeric states tend to decrease with a_{surf}.

Keywords: Fission barrier; Deformation; Equation of state; Binding energy

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https://doi.org/10.1016/j.nuclphysa.2018.04.005
0375-9474/

1. Introduction

The long-standing interest in the nuclear fission studies and nuclear deformations has been renewed in the last two decades because of the continuing progress in the synthesis of new super-heavy elements and neutron-rich isotopes. This huge progress accompanies the recent development of radioactive beam facilities in the world-leading laboratories. Using the modern techniques, high-resolution data can be obtained for the fission resonances [1]. Extreme super- and hyper-deformations in the nuclear shapes corresponding to 2:1 and 3:1 axis ratios, respectively [2], were expected to take places during the fission process of actinides. Nuclear deformability significantly influences the formation of superheavy nuclei via the energy-deformation surfaces along the fission and fusion trajectories [3,4]. This also affects neutron stars structure where nucleosynthesis of strongly deformed superheavy nuclei in their inner crust can takes place, within the final stages of the astrophysical r process [5]. Generally, nuclear deformations impact the rotational properties of neutron-rich nuclei and the border of their existence at the edge of the neutron drip line [4], in addition to their decays and reactions [6,7]. Moreover, the competition between Coulomb repulsion, shell effect, and surface tension might give rise to synthesis new superheavy nuclei of atomic numbers $Z > 126$ with exotic types of topology, such as toroidal [8], bubble, and semi-bubble nuclei [9].

Earlier, the first saddles of the fission barriers for most actinides, as indicated by the calculations of potential energy surfaces, were a few MeV above the experimental values. On the contrary, the theoretically estimated first saddle and second minima of light thorium actinides were approximately 3 MeV below the experimentally extracted values [10,11]. This was reported in the literature as thorium anomaly. Based on mass-asymmetric deformation, Möller and Nix [12] have resolved this anomaly in terms of indicated splitting of the asymmetric second saddle point, for $N < 146$, into two distinct saddle points separated by an asymmetric shallow third minimum. A similar third well for fissioning nucleus with octupole deformations had been a posterior obtained using the microscopic–macroscopic method of Strutinsky [13,14]. Subsequently, many experimental evidences have also indicated a shallow third minimum of asymmetric deformation in the fission barrier of the ^{231}Th [15], ^{232}Th [16], ^{233}Th [17], ^{228}Ra and ^{227}Ac [18] light actinides. In a more recent work [2,14], third minima were also indicated in the potential energy surfaces (PES) of ^{230,231,233}Th through fission probability measurements with high energy resolution, and neutron-induced fission [19] and electrofission cross sections [20]. For these nuclei, the experimental observables of the fission barrier parameters, the depth as a function of the neutron number, and the hyperdeformation related to the third minimum are in agreement with the theoretical estimates in different studies. For instance, self-consistent Hartree–Fock–Bogoliubov (HFB) [21,22] and macroscopic–microscopic [23–25] calculations consistently displayed the shallow third minimum in the fission potential of ^{230,232}Th. These experimental results and calculations of Th isotopes indicated a shallow third minimum in the fission barrier at large quadrupole deformations, with a depth in the range of 0.3–1.5 MeV. The indicated third barrier mostly lie above the second one. The triple-humped features of ^{232}Th fission barrier were manifested as well by the relativistic mean field [26], shell-correction [27], and Generalized Liquid Drop (GLD) [28] calculations, but with a hyperdeformed third barrier deeper than 3 MeV. On the contrary, the calculations based on finite-temperature nuclear density-functional (FT-DF) [29] indicated very shallow or no hyperdeformed third minimum in the PES of ^{232}Th, supporting shallow ones for ^{226,228}Th. On the other hand, the measured fission probability and the photofission cross section indicated the existence of deep third potential well and related fission resonances in ^{232,234,236,238}U isotopes [30–33]. The observed fission resonances

Please cite this article in press as: W.M. Seif, H. Anwer, Sensitivity of the nuclear deformability and fission barriers to the equation of state, Nucl. Phys. A (2018), https://doi.org/10.1016/j.nuclphysa.2018.04.005