NUCLEAR STRUCTURE OF SUPERHEAVY NUCLEI IN A LARGE DEFORMATION SPACE*

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The structure of SuperHeavy Nuclei (SHN) is analyzed in two microscopic approaches. First one is the Hartree–Fock–Bogolyubov method used with the Gogny force, applied to a large range of nuclei with axial and left–right symmetries. The second one breaks both of these symmetries in mean field. Potential energy surfaces of a few transactinides are studied in this framework. One observes that the fission paths can be strongly modified, leading to significant changes in lifetimes obtained from HFB-D1S.

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1. Nuclear structure of superheavy nuclei with the Gogny force

The constrained Hartree–Fock–Bogolyubov mean field approach used with the Gogny effective force D1S has been extensively employed these last years to describe the properties of even–even transactinide nuclei along the valley of β-stability up to $Z = 128$. In this framework where both the mean field and the pairing field are defined in a self-consistent way, the axial and left–right symmetries have been prescribed to nuclei. The mass quadrupole deformation

$$\widehat{Q}_{20} = \sum_{i=1}^{A} \sqrt{\frac{16\pi}{5}} r_i^2 Y_2^0$$

is the only constraint used.

Results of this study are detailed in Ref. [1–3]. Let us recall that strong spherical shell effects are found in neutron single particle levels for $N =$ 126, 184 and 228. Smaller ones also exist for $N = 138$, 164, 178 and 246. Deformed nuclei, with $\beta \approx 0.25$, have neutron shell gaps for $N = 152$ and 162. Concerning proton single particle levels, spherical shell effects are found

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for $Z = 92$, 114, 120, 126 and also for $Z = 138$ and 164. $Z = 114$ is never found magic, which is confirmed by the proton pairing energy in $^{298}114_{184}$ about 17.4 MeV.

According to N three regions of increased stability have been well put into evidence. Fig. 1 shows the pertinence of N to describe Potential Energy Surfaces (PES) and subsequently Ground State (GS) β-deformation. For $150 < N < 170$, prolate nuclear shapes with $0.18 < \beta < 0.28$ are found. When N increases, GS β-deformation becomes spherical. Nuclei with $182 < N < 192$ are all found spherical. Above $N = 202$, GS β-deformation becomes strongly oblate, with $\beta \approx -0.4$.

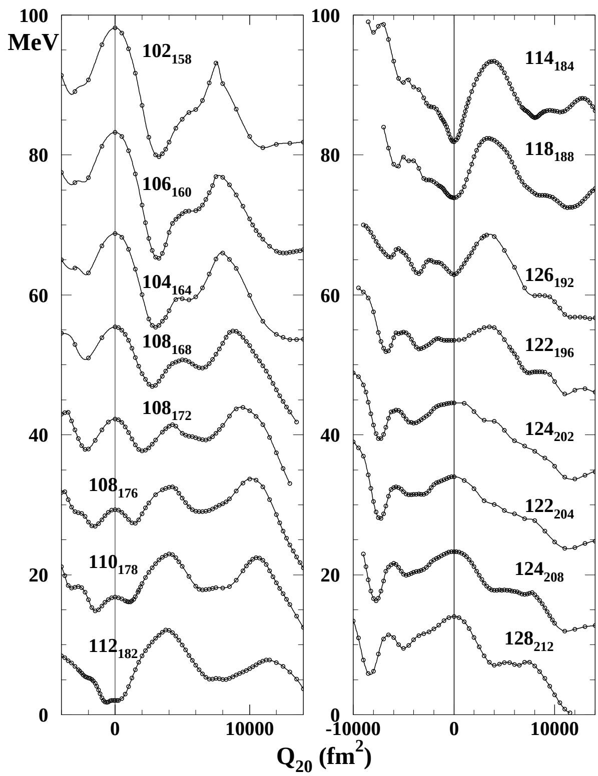


Fig. 1. Fission barriers of a few representative superheavy nuclei as functions of the mass quadrupole moment obtained from HFB-D1S. The darker squares display the bottom of the valley of β-stability.

From fission barrier heights and binding energies, first full microscopic predictions of transactinides spontaneous fission and α-decay [4] half-lives have been deduced, focusing on this N-dependence.

2. Potential energy surfaces of transactinides

As studies of fission suggest, realistic description of fission barrier heights and consequently of fission half-lives requires to examine the influence of octupolar and non-axial deformations. Because of the extremely large numerical work necessary to compute the exchange and pairing fields, breaking both the axial and left–right symmetries in HFB-D1S calculations, the PES of transactinides are analyzed below within a simplified mean-field approach.

2.1. Microscopic framework

In this approach, a new effective finite-range force called L1 is used. It is parametrized in such a way that the gross properties of nuclei can be reproduced in self-consistent calculations where only the direct part of the mean-field is taken into account. The equation to be solved follows from the variational principle:

$$\delta\langle\Psi|\widehat{H} - \lambda_N\widehat{\mathcal{N}}_N - \lambda_Z\widehat{\mathcal{N}}_Z - \lambda_{20}\widehat{Q}_{20} - \lambda_{22}\widehat{Q}_{22} - \lambda_{30}\widehat{Q}_{30}|\Psi\rangle = 0\,, \qquad (1)$$

where $\widehat{H}$ is the many-body effective Hamiltonian built with L1 and $|\Psi\rangle$ represents an independent correlated nucleon pair state of the BCS form. As usual, constraints on neutron and proton mean numbers $\widehat{\mathcal{N}}_N$ and $\widehat{\mathcal{N}}_Z$ are introduced in order to ensure the conservation of the mean number of particles. The Lagrange parameters λ_N and λ_Z are determined such as these conditions are assumed.

As usual in Bruyères-le-Châtel linear constraints are used in this work [5]. The Lagrange parameters λ_{lm} are readjusted so that the mean values of $\widehat{Q}_{lm}$ prescribed to nucleus are obtained. With variations of these values the PES of the nucleus is generated. In addition of $\widehat{Q}_{20}$ one uses:

$$\left\{\begin{array}{ll} \widehat{Q}_{22} & = \displaystyle\sum_{i=1}^{A}\sqrt{\frac{8\pi}{15}}r_i^2\left[Y_2^2(\widehat{r}_i) + Y_2^{-2}(\widehat{r}_i)\right]\,, \\ \widehat{Q}_{30} & = \displaystyle\sum_{i=1}^{A}\sqrt{\frac{4\pi}{7}}r_i^3 Y_3^0(\widehat{r}_i)\,, \end{array}\right. \qquad (2)$$

where the Y_l^m are the spherical harmonic. In our study, we impose up to 4 simultaneously constraints. Indeed the constraints on $\widehat{Q}_{10}$ is also necessary when octupolar deformation on nuclei is imposed to avoid oscillations of the center of mass. The mass multipole moments which are not constraints move towards values that minimize binding energy according to variational principle.

The effective interaction we used takes the form:

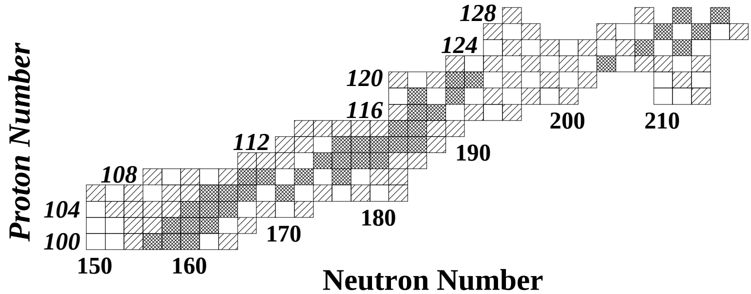
$$\begin{aligned}\widehat{v}_{12} \; = \; & \frac{\exp\left(-\frac{r}{a}\right)}{r}(W_1 - H_1 P_\tau) \\ & + t_3(1 + x_0 P_\tau)\delta(\vec{r})\left(\rho\left(\frac{\vec{r_1} + \vec{r_2}}{2}\right)\right)^\alpha + \frac{e^2}{r}\,,\end{aligned} \tag{3}$$

where we put $r = |\vec{r_1} - \vec{r_2}|$. The first term is the finite range central component that only depends on isospin in order to satisfy the charge symmetry of the nuclear interaction. The second term is, as in D1S effective force, function of the density so that usual saturation properties of symmetric infinite nuclear matter are found and the last term represents the usual Coulomb component. Let us mention that for numerical reasons we calculate the spin–orbit mean field from the usual expression used in the single particle models but with the central part of the mean field derived from the L1 force.

In the same spirit, pairing correlations are included by simply adding to the Hamiltonian a BCS residual interaction as in calculations with the Skyrme force. The pairing strengths are determined in order to reproduce the pairing energies given by HFB-D1S in one point of the axial symmetric fission barrier. With these simplifications self-consistent calculations in which both the axial and left–right symmetries are released can be performed to SHN.

2.2. Triaxial and asymmetric fission barriers: first results

To confirm HFB-D1S results on SHN fission barriers heights, one has to check that they are not modified when new free degrees related to triaxial and left–right asymmetric nuclear shapes are introduced. In this aim, investigations have been performed on nuclei representative of the three stability region as functions of N previously mentioned. First results show that the fission barrier of $^{298}114_{184}$ and of $^{332}124_{208}$ are not modified. Nonetheless, with the inclusion of more general symmetries figure 2 shows that the fission barrier of $^{266}106_{160}$ is unstable against both non-axial and left–right asymmetric deformations. The top of the axial symmetric fission barrier is reduced by about 4 MeV. Taking these into account the fission half-life decreases from 14 y. to 71 s. As T_α is about 270 s with the 9-parameter empirical model in Ref. [4], total half-life appears in good agreement with experimental results.



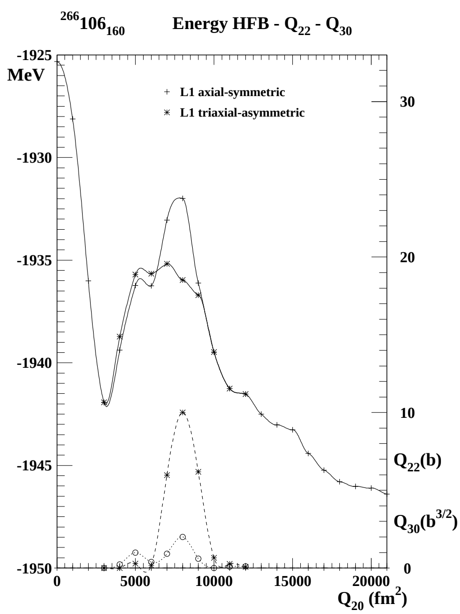


Fig. 2. Axial symmetric (plus) and triaxial asymmetric (star) fission barriers of $^{266}106_{160}$ obtained from HF+BCS-L1. The two curves in the lower part, related to the right y-axis, show the evolution of triaxial (star) and octupolar deformations (circle) in each point of the triaxial asymmetric barrier.

3. Conclusion and outlook

The simplified mean field approach HF+BCS-L1 is a very useful and reliable tool to describe well deformed nuclei and in particular to have the more realistic fission barriers of SHN. Extensive calculations applied to SHN are envisaged with this method.

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