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The impact of isospin dependence of pairing on fission barriers in the fission cycling regions

A. V. Afanasjev[1,*] and *A.* Taninah[1]

[1]Department of Physics and Astronomy, Mississippi State University, MS 39762

Abstract. A systematic analysis of the ground state and fission properties of actinides and superheavy nuclei important for the *r* process modeling has been performed within the framework of covariant density functional theory for the first time in Ref. [1]. A brief review of the results related to the heights of primary fission barriers and systematic uncertainties in their prediction is presented. In addition, new results on the potential impact of the isospin dependence of pairing on fission barriers in fission cycling regions is provided for the first time.

1 Introduction

The *r* process is responsible for the synthesis of approximately half of the nuclei in nature beyond Fe [2] and it is the only process which leads to the creation of nuclei heavier than Bi [3] . Fission becomes important in the *r* process simulations for the neutron-to-seed ratios which are large enough to produce fissioning nuclei [4, 5]. The *r* process can reach the region beyond neutron shell closure at $N = 184$ for these ratios exceeding 100: the fission plays a dominant role in this region. Fission leads to the termination of the hot *r* process by means of *fission cycling* which returns matter to lighter nuclei [4, 5]. It also determines the strength of fission cycling, the ratio of the actinides to light and medium mass *r* process nuclei, and thus the shape of the final element abundance pattern. In addition, it defines the possibility of the formation of neutron-rich superheavy nuclei in the *r* process [6].

The outcome of the r-process modeling sensitively depends on the quality of employed theoretical frameworks and associated theoretical uncertainties and their propagation on going to neutron-rich nuclei in the situation when experimental data are not known. So far only non-relativistic frameworks have been used in such modeling and in the analysis of fission cycling (see review in the introduction of Ref. [1]). The first attempt to produce nuclear input required for the *r* process modeling within the relativistic framework (covariant density functional theory (CDFT) [7]) has been carried out in Ref. [1]. The goal of this contribution is to briefly review the results of this study with major focus on fission properties and to analyze potential impact of isovector dependence of pairing on the fission barriers of very neutron-rich nuclei.

2 Fission barriers and related systematic uncertainties

The distributions of primary fission barrier (PFB) heights in the (Z, N) plane obtained in the axial relativistic Hartree-Bogoliubov (RHB) calculations are shown in Fig. 1. The calcu-

*e-mail: aa242@msstate.edu

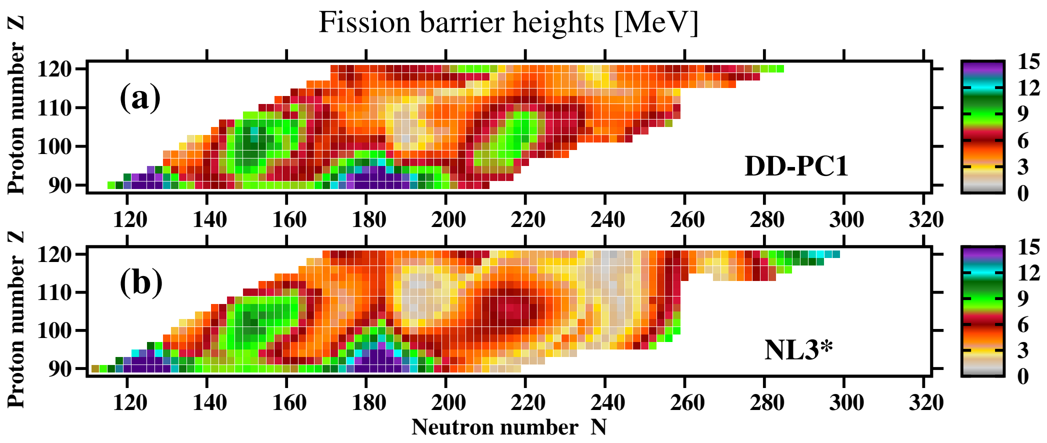

Figure 1. The heights E^B (in MeV) of PFBs obtained in axial RHB calculations as a function of proton and neutron numbers for nuclei located between two-proton and two-neutron drip lines. Based on Fig. 15 of Ref. [1].

lations have been performed with four state-of-the-art covariant energy density functionals (CEDFs) DD-PC1, DD-ME2, NL3* and PC-PK1 in order to evaluate systematic theoretical uncertainties in the predictions of fission barriers (see Ref. [1] for details). There is a large similarity of the results obtained with DD-PC1 and DD-ME2 on the one hand and NL3* and PC-PK1 on the other: thus only those obtained with DD-PC1 and NL3* are shown. In general, the topologies of the fission barrier maps shown in Fig. 1 are similar. However, the fission barriers obtained with DD-PC1 are on average higher by approximately 2 MeV as compared with those calculated with NL3*. This is a consequence of different nuclear matter properties of these two functionals (see discussion in Ref. [1]). These two functionals also differ with respect of the predictions of the formation of superheavy elements with $N > 240$ in the *r* process. This is because the band of the nuclei around $N \approx 240$ has extremely low fission barriers with heights of around 2 MeV in the NL3* CEDF (see Fig. 1(b)). The nuclear flow during most of the neutron irradiation step of the *r* process follows the neutron drip line and this flow will most likely be terminated at $N \approx 240$ nuclei because of these low fission barriers in the calculations with NL3*.

Theoretical systematic uncertainties in the heights of PFBs given by the spreads ΔE^B are shown as a function of proton and neutron numbers in Fig. 2. They are relatively modest in some regions but are enhanced near the $N = 184$ and $N = 258$ shell closures, for the $Z \approx 90$ nuclei with $N = 166 - 184$ and in the wide band of nuclei parallel to the two-neutron drip line. The analysis of these spreads allows us to identify two major sources of theoretical uncertainties in the predictions of the heights of PFBs (see Ref. [1] for details). These are underlying single-particle structure (especially the one in the vicinity of shell closures) and nuclear matter properties of employed CEDFs. The former mostly affects the predictions for the ground states (and thus for the heights of PFBs) in the first two regions and the latter the predictions for PFBs of the nuclei located in the vicinity of the neutron drip line.

3 The impact of isospin dependence of pairing on fission barriers

The systematic calculations of Ref. [1], the results of which are presented in Figs. 1 and 2, have been performed with separable pairing of Ref. [9] the scaling factors f_i of which for the

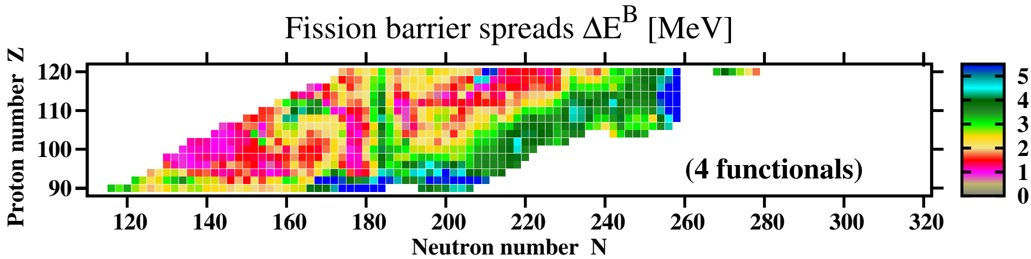

Figure 2. The spreads ΔE^B of the heights of PFBs as a function of proton and neutron numbers. $\Delta E^B(Z,N) = |E^B_{max}(Z,N) - E^B_{min}(Z,N)|$, where, for given Z and N values, $E^B_{max}(Z,N)$ and $E^B_{min}(Z,N)$ are the largest and smallest heights of PFBs obtained with the employed set of four functionals. Based on Fig. 15 of Ref. [1].

Table 1. Different versions (v1, v2 and v3) of separable pairing interaction as defined by the particle number dependencies of their scaling factors f_i ($i = \pi$ or ν). The constants C_i and α_i are taken from Table 4 of Ref. [8].

subsystem	v1	v2	v3
proton	$f_\pi = 1.0$	$f_\pi = C_\pi * (N+Z)^{\alpha_\pi}$	$f_\pi = C_\pi * e^{\alpha_\pi \lvert N-Z \rvert}$
neutron	$f_\nu = 1.0$	$f_\nu = C_\nu e^{\alpha_\nu \frac{\lvert N-Z \rvert}{N+Z}}$	$f_\nu = C_\nu * \lvert N-Z \rvert^{\alpha_\nu}$
		$C_\pi = 1.877$, $\alpha_\pi = -0.1072$	$C_\pi = 1.178$, $\alpha_\pi = -0.0026$
		$C_\nu = 1.208$, $\alpha_\nu = -0.674$	$C_\nu = 1.264$, $\alpha_\nu = -0.0495$

nuclei with $Z > 88$ are set to $f_\pi = f_\nu = 1.0$ (see Ref. [10] for definition of pairing strength). This pairing is labeled as "v1" below, see Table 1. However, in general more complicated particle number dependencies of scaling factors f_i are allowed (see Refs. [8, 10]). Indeed, recent systematic analysis of Ref. [8] clearly reveals isospin dependence of scaling factors f_ν of neutron pairing. However, the situation is less certain in the proton subsystem since similar accuracy of the description of pairing indicators can be achieved both with isospin-dependent and mass-dependent scaling factors f_π.

The fission barrier heights sensitively depends on the strength of pairing interaction (see Ref. [11]). Thus, it is important to understand by how much and in which direction the fission barriers can be affected by these particle number dependencies of pairing interaction. For that the primary fission barriers of very neutron-rich ^{316}Fm and ^{324}Rf nuclei have been calculated with three versions (v1, v2 and v3) of scaling factors for separable pairing (see Table 1). These nuclei are located at the neutron-rich side of expected fission cycling region (see Fig. 1 in Ref. [1]). The versions v2 and v3 are the combinations of proton and neutron scaling factors favored by the analysis of Sec. IV of Ref. [8]. One can see in Table 2 that in all cases the inclusion of isospin dependence of pairing increases the heights of primary fission barriers but the magnitude of the increase depends both on the CEDF and nucleus. The latter feature is mostly due to the differences between the functionals in underlying single-particle structure. The magnitude of the increase varies from $E^B_{v2} - E^B_{v1} = 0.25$ MeV to $E^B_{v3} - E^B_{v1} = 1.57$ MeV (see DD-ME2 results in ^{324}Rf). This large difference in ^{324}Rf is caused by substantially weakened proton pairing in the calculations with the v3 version of separable pairing which according to Ref. [11] leads to a significant increase of fission barrier height. However, in most of the cases the difference between $E^B_{v2} - E^B_{v1}$ and $E^B_{v3} - E^B_{v1}$ is relatively small being typically around 0.2 MeV and the magnitude of these two quantities is around 1 MeV. Another observation is that the v3 version of separable pairing leads to somewhat

Table 2. Fission barriers heights E^B [in MeV] for the indicated nuclei, functionals and versions of separable pairing. The columns 6 and 7 show the increases of fission barrier heights for two isospin dependent pairing interactions (v2 and v3) as compared to the one obtained with pairing of constant strength (v1).

Nucleus	CEDF	E^B_{v1}	E^B_{v2}	E^B_{v3}	$E^B_{v2} - E^B_{v1}$	$E^B_{v3} - E^B_{v1}$
1	2	3	4	5	6	7
^{316}Fm	NL3*	5.71	6.49	6.38	0.78	0.756
	DD-PC1	8.83	9.11	9.45	0.28	0.62
	DD-ME2	9.77	10.36	10.53	0.59	0.76
^{324}Rf	NL3*	6.39	7.06	7.23	0.67	0.84
	DD-PC1	9.08	10.44	10.58	1.36	1.50
	DD-ME2	10.44	10.69	12.01	0.25	1.57

higher fission barriers as compared with the ones obtained with v2 version. Note that these nuclei are extremely neutron-rich with N/Z ratio exceeding 2.0. Thus, it is reasonable to expect that the magnitude of the increase of fission barriers due to isospin dependence of pairing will be lower in the nuclei located closer to the β-stability line.

4 Conclusions

The detailed analysis of the ground state and fission properties of actinides and superheavy nuclei important for the r process modeling has been performed within the framework of CDFT for the first time (see Ref. [1]). In particular, it allowed to establish the systematic uncertainties in the heights of primary fission barriers and their sources. In addition, the present investigation reveals isospin dependence of pairing as an additional factor affecting fission barriers in fission cycling regions. Its inclusion leads to a substantial increase of fission barriers in very neutron rich nuclei. Available covariant [8] and non-relativistic Skyrme [12, 13] DFT investigations strongly point to the existence of isospin dependence of effective pairing interaction. However, its details and accurate form are still under debate.

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