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FUSABILITY AND SURVIVABILITY IN REACTIONS LEADING TO HEAVY NUCLEI IN THE VICINITY OF THE $N = 126$ SHELL

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Вероятность слияния и выживаемость в реакциях, приводящих к тяжелым ядрам
в окрестности оболочки $N = 126$

Образование тяжелых ядер от Rn до Th в окрестности нейтронной оболочки $N = 126$ в реакциях полного слияния ядер рассматривается систематически в рамках обычной модели слияния с прохождением через барьер и стандартной статистической модели (ССМ). Имеющиеся данные по функциям возбуждения для деления и образования испарительных остатков, полученные в сильно асимметричных комбинациях, хорошо описываются в рамках этих моделей. При взаимодействии массивных налетающих частиц с тяжелыми ядрами мишеней появляются эффекты квазиделения во входном канале реакции. Чтобы воспроизвести функции возбуждения с параметрами ССМ (барьерами деления), полученными при анализе сильно асимметричных комбинаций, вводится эмпирически вероятность слияния ядер. Отсутствие стабилизации относительно деления в окрестности $N = 126$ для ядер Th ранее объяснялось уменьшением вклада коллективных степеней свободы в плотность уровней сферических ядер. Однако настоящий анализ показывает ощутимые запреты на слияние, т. е. падение сечений образования ядер Th в окрестности $N = 126$ обуславливается в основном эффектами входного канала. Макроскопическая компонента барьеров деления для ядер, вовлеченных в каскад девозбуждения составного ядра, извлекается и сравнивается с предсказаниями теоретических моделей и имеющимися данными.

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Fusability and Survivability in Reactions Leading to Heavy Nuclei in the Vicinity
of the $N = 126$ Shell

The production of heavy nuclei from Rn to Th around the $N = 126$ neutron shell in complete fusion reactions of nuclei has been considered in a systematic way in the framework of the conventional barrier-passing fusion model coupled with the Standard Statistical Model (SSM). Available data on the excitation functions for fission and production of evaporation residues obtained in very asymmetric combinations are described with these models rather well. In the interaction of massive projectiles with heavy target nuclei quasi-fission effects appear in the entrance reaction channel. The quantity of the fusion probability introduced empirically has been used to reproduce excitation functions with the same SSM parameters (fission barriers) as those obtained in the analysis of very asymmetric combinations. A lack of stabilization against fission around $N = 126$ for Th nuclei was earlier explained with a reduced collective contribution to the level density in spherical nuclei. However, the present analysis shows severe inhibition for fusion, i.e., the drop in production cross sections of Th nuclei in the vicinity of $N = 126$ is mainly caused by entrance channel effects. The macroscopic component of fission barriers for nuclei involved in a deexcitation cascade has been derived and compared with the theoretical model predictions and available data.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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INTRODUCTION AND MOTIVATION

Proton-rich nuclei near the 126-neutron shell are expected to have rather low macroscopic (liquid-drop) fission barriers and thus offer a unique possibility to study the survival probability of magic nuclei at different excitation energies. The measured cross sections for ERs around ^{216}Th produced in heavy-ion fusion reactions with ^{40}Ar [1] and heavier projectiles [2] do not show any noticeable enhancement due to the shell stabilization around $N = 126$, although a strong shell effect about of 5 MeV is clearly seen in the ground-state masses. This result is in a sharp contrast to expectations based on the SSM calculations using intrinsic level densities [1]. The lack of stabilization against fission around $N = 126$ nuclei was explained by the influence of collective excitations in terms of a reduced collective contribution to the level density in spherical nuclei [3].

Later, in the analysis of production cross sections for nuclei obtained in the U projectile fragmentation, the expected stabilization against fission for spherical nuclei near $N = 126$ was not again found in the experimental data [4]. With the inclusion of collective enhancement in the level density (CELD) the experimental data are well described. It is implied that CELD is essentially the same at the saddle point deformation (fission channel) for all nuclei, but it differs strongly in the ground-state deformation of an evaporation channel. For well-deformed nuclei the collective enhancement factors above the saddle point and above the ground state are almost equal and correspond to rotational excitations in both configurations. In the case of spherical nuclei, the vibrational enhancement factor in the ground state is much smaller than the rotational one applied in the deformed saddle-point configuration. It was found that the damping of the collective enhancement with excitation energy has to be treated as essentially independent of nuclear deformation. The lack of shell stabilization against fission observed for the $N = 126$ shell was expected to have consequences for the production cross sections of spherical superheavy nuclei around $N = 184$ [4].

In the middle of 1980s significant limitations on fusion in heavy systems were revealed in studies of fission-like processes proceeding in reactions with massive nuclei [5]. These limitations are caused by quasi-fission (QF), the process of reseparation of two fission-like fragments in dinuclear system, which proceeds besides the CN formation. Afterwards quasi-fission was observed in extensive fission studies of reactions leading to very heavy [6] and less-heavy [7] composite systems. Notice that the quasi-fission effect reducing a complete fusion cross section was observed in rather asymmetric $^{32}\mathrm{S}+^{182}\mathrm{W}$ combination leading to the $^{214}\mathrm{Th}^*$ CN [8]. Not long ago a visible entrance channel effect of fusion suppression was observed in quite asymmetric combinations with $^{19}\mathrm{F}$ and $^{30}\mathrm{Si}$ leading to the $^{216}\mathrm{Ra}^*$ CN in studies of the ER production. It follows from the comparison of the ER cross sections with those obtained in the $^{12}\mathrm{C}+^{204}\mathrm{Pb}$ reaction leading to the same CN [9]. Such a fusion suppression is quite unexpected, especially for the reaction induced by $^{19}\mathrm{F}$, since according to the fission studies [6, 7] QF appears in reactions with Mg and heavier projectiles.

Thus the question arises of whether a drop in the cross sections measured for nuclei produced in asymmetric combinations is mainly connected with entrance channel effects or it is caused by the decay properties of compound nuclei formed in the vicinity of the $N = 126$ shell. It is important to divide these processes in order to obtain any systematic ideas on the fusion probability and survivability of nuclei in this region.

1. METHOD

The analysis of the measured ER and fission excitation functions is performed within the framework of the conventional barrier-passing (BP) model describing an experimental capture cross section as the barrier-passing one. The calculated BP cross section can be associated with the fusion cross section implying that the fusion probability $P_{\mathrm{fus}} = 1$. The deexcitation of a CN resulting from the complete fusion of the projectile and target nuclei is described with SSM. Both models are incorporated into the HIVAP code [10]. The fluctuating barrier is used in the potential BP model that allows reproducing the effect of coupling the entrance channel to other reaction channels. In the analysis, all the BP model parameters are fixed with the exception of the strength V_0 and the barrier fluctuation (determined by the radius-parameter fluctuation $\sigma(r_0)/r_0$) in the nuclear exponential potential [11]. Variations of these parameters allow one to reproduce the experimental cross-section data for fission and ER production at sub-barrier energies in calculations. For strongly fissile compound nuclei the ER cross sections at energies well above the Coulomb (Bass [12]) barrier are weakly sensitive to the form of the nuclear potential and are mainly determined by SSM parameters. In the use of SSM, only intrinsic level densities are considered. The expression of W. Reisdorf [10] for the calculations of the macroscopic level density parameters $\widetilde{a}_f$ and $\widetilde{a}_\nu$ in fission and evaporation channels, respectively, is used. The scaling factor k_f at the rotating liquid drop (LD) fission barriers [13] in the expression for the fission barrier heights $B_f(L) = k_f B_f^{\mathrm{LD}}(L) - \Delta W_{gs}$ is used as a main fitted parameter in the analysis of the ER and fission cross sections. Empirical masses [14] are used to calculate shell corrections ΔW_{gs} (a difference between empirical and LD masses), as well as the excitation and separation energies. In the analysis of the most asymmetric combinations such as C, O + Pb, excitation functions at high energies are fitted with the variation of k_f mainly. The lack of any fusion suppression ($P_{\rm fus} = 1$) in these cases is implied and the fusion probability values for less asymmetric combinations can be derived using the same scaling for fission barriers and other parameters of SSM. For the ^{19}F- and ^{30}Si-induced reactions $P_{\rm fus} = 0.65$ and 0.55, respectively, are obtained with this approach, i.e., the same values as in [9] whereas lower values ($P_{\rm fus} \sim 0.3$) are derived in the cases of ^{48}Ca + ^{168,170}Er [15], where some additional details of the analysis are considered.

2. PRODUCTION OF Th NUCLEI

ER and fission excitation functions obtained recently for the ^{16}O + ^{204}Pb reaction [16] allow one to determine $P_{\rm fus}$ in a number of less asymmetric and near symmetric combinations leading to the ^{220}Th* CN. In Fig. 1 the results of the present analysis of the data [16] together with the same ones for similar but less asymmetric data [1, 2] are shown. As one can see, the latter (^{40}Ar + ^{180}Hf) can be described either independently using $k_f = 0.62$ obtained with the data

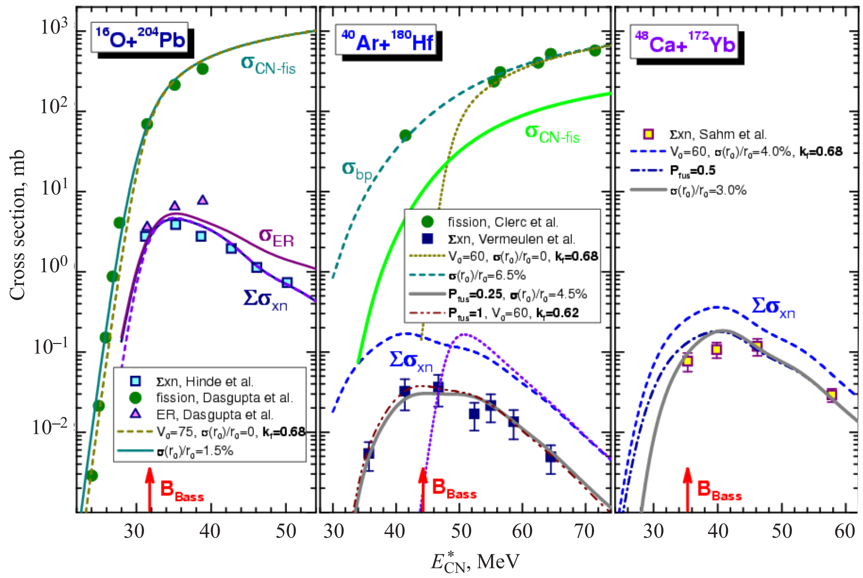

Fig. 1. Results of analysis of excitation functions obtained in reactions leading to the ^{220}Th* CN

fit or using the same fission barriers as obtained for $^{16}\mathrm{O}+^{204}\mathrm{Pb}$, i.e., using $k_f = 0.68$ and introducing $P_{\mathrm{fus}} = 0.25$. The analysis of ER and fission excitation functions obtained in very asymmetric combinations leading to the more neutron rich $^{224,226}\mathrm{Th}^*$ compound nuclei gives substantially higher LD fission barriers, corresponding to $k_f = 0.78{-}0.82$ (see [17] and references therein). The $^{4}\mathrm{He}+^{226}\mathrm{Ra}$ data [18] corresponding to the $^{230}\mathrm{Th}^*$ CN formation show $k_f = 0.84$. The transition from LD fission barrier heights for nuclei of evaporation chains of the $^{224,226,230}\mathrm{Th}^*$ compound nuclei to the ones of $^{220}\mathrm{Th}^*$ seems to be very sharp, whereas the LD (macroscopic) fission barriers are implied to be a smooth function of N. A sharp decrease in fission barriers can be associated with the manifestation of the CELD effect for spherical nuclei around the $N = 126$ shell, as proposed earlier [3, 4]. To estimate the strength of the effect, the calculation with the fission barriers extrapolated from the ones corresponding to deformed Th nuclei (resulting from the $^{224,226,230}\mathrm{Th}^*$ compound nuclei deexcitation) can be performed using $k_f = 0.75$. It shows that a decrease in the production cross section for spherical Th nuclei, which is caused by the CELD effect, corresponds to the factor of 3–5 that is much smaller than one could expect this according to the prediction of the schematic model proposed in [4].

Simple k_f-scaling is applied in estimates of P_{fus} and k_f for the $^{40}\mathrm{Ar}+\mathrm{Hf}$ reactions leading to neutron-deficient Th compound nuclei with $A_{\mathrm{CN}} < 220$ [1]:

$$k_f(A_{\mathrm{CN}} < 220) = k_f(^{16}\mathrm{O} + {}^{204}\mathrm{Pb})/k_f(^{40}\mathrm{Ar} + {}^{180}\mathrm{Hf}, P_{\mathrm{fus}} = 1)\times \\ \times\, k_f(^{40}\mathrm{Ar} + \mathrm{Hf}, A_{\mathrm{CN}} < 220, P_{\mathrm{fus}} = 1).$$

With this scaling $P_{\mathrm{fus}} = 0.25 - 0.35$ and $k_f = 0.658 - 0.614$ for the $^{40}\mathrm{Ar}+ {}^{179-176}\mathrm{Hf}$ reactions have been obtained. The same scaling applied to the analysis of the $^{32}\mathrm{S}+^{182}\mathrm{W}$ data [8, 19] shows the same values of P_{fus} and k_f as obtained for $^{40}\mathrm{Ar}+^{176}\mathrm{Hf}$. One has to note that P_{fus} corresponding to the analysis of ER data [19] is less than the value derived with the fission data [8] as seen in Fig. 2. The results of the ER data analysis of reactions with deformed target nuclei also demonstrate essentially smaller values of $\sigma(r_0)/r_0$ than those obtained in the fission data analysis for the same reaction (see Fig. 2). It implies that preferably side-collisions at sub-barrier energies lead to the complete fusion following with the ER production, whereas tip-collisions give a main contribution of QF events to the measured fission cross section. Much more severe limitations on fusion are observed in near symmetric reactions. Besides smaller values of the fusion probability, characterizing fusion at energies well above the nominal fusion barrier [12], some additive ΔB to the potential barrier has to be applied in calculations to reproduce strong suppression of the ER production at sub-barrier and barrier energies, as seen in Fig. 2 for the $^{124}\mathrm{Sn}+^{96}\mathrm{Zr}$ data [2, 20]. This extra-energy can be associated with the well-known «extra–extra-push» [21] as well as the effect of a deformation of fusioning nuclei.

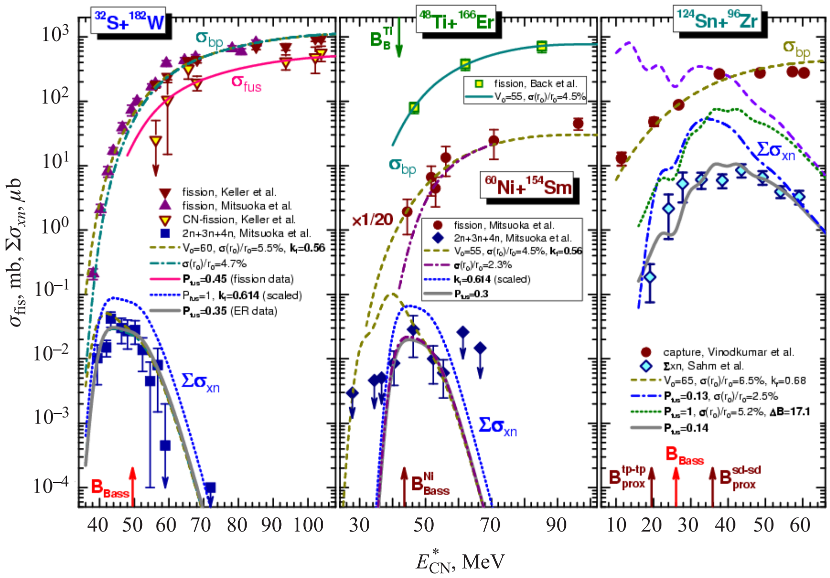

Fig. 2. Examples of fusion suppression in reactions leading to the ^{214}Th* and ^{220}Th* compound nuclei

3. PRODUCTION OF Ra AND Fr NUCLEI

Studies of Ra nuclei production in very asymmetric $^{12}\mathrm{C}+^{204,206,208}\mathrm{Pb}$ combinations [9, 15] show a gradual k_f-value reduction from 0.85 to 0.78 in going from ^{208}Pb to ^{204}Pb [15]. Using this finding in the analysis of the ER data obtained in the $^{22}\mathrm{Ne}+^{194,196,198}\mathrm{Pt}$ reactions [22], leading to the same Ra compound nuclei, shows that $P_{\rm fus} = 0.3 - 0.4$ should be introduced to describe the data in a wide region of the excitation energy, otherwise essentially smaller fission barriers had to be implied (see Fig. 3). These fusion probability values are about the same as obtained in the more symmetric $^{48}\mathrm{Ca}+^{168,170}\mathrm{Er}$ combinations [15] and are less than those deduced for the more asymmetric ones [9, 15]. In Fig. 3 the reduced cross sections for the corresponding sums of *xn*-evaporation channels are used for the ^{12}C and ^{22}Ne data presentation. It implies that the ER cross section can be written as

$$\Sigma\sigma_{xn} = \pi/k^2 \Sigma(2L+1) T_L P_{\rm fus}(E^*_{\rm CN}, L) W^{srv}_{xn}(E^*_{\rm CN}, L),$$

where k is the wave number, T_L are transmission coefficients for the L partial wave, $P_{\rm fus}$ and W^{srv}_{xn} are fusion probability and survivability, correspondingly. Bearing in mind the same set of angular momenta corresponding to the ER production in reactions leading to fissile nuclei ($L \leqslant 15\ \hbar$), the reduced cross section $k^2/\pi\Sigma\sigma_{xn}$ has to be independent of the way of the ER production at the same excitation energies well above the fusion barrier (where $T_L = 1$), if $P_{\rm fus} = 1$, as seen in Fig. 3.

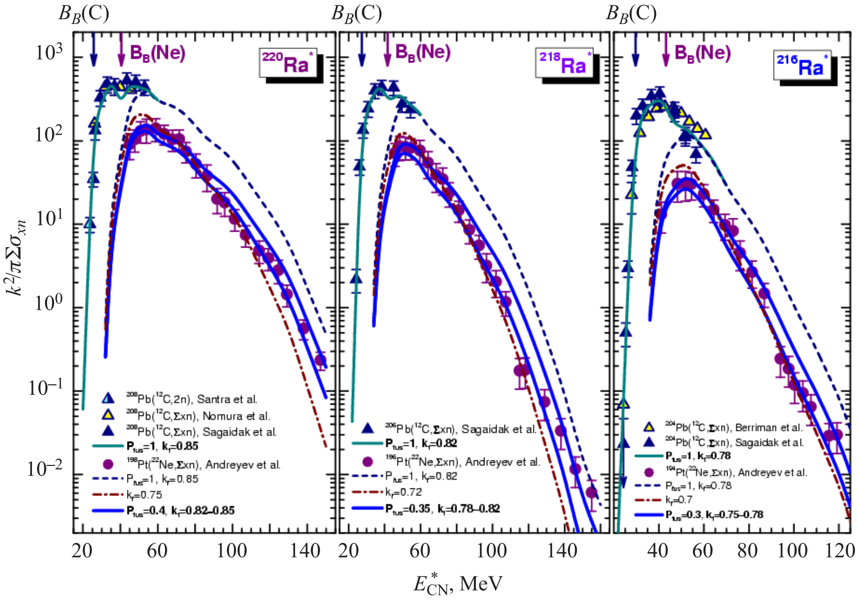

Fig. 3. The comparison of reduced cross sections for Ra nuclei produced in the ^{12}C + Pb and ^{22}Ne + Pt reactions

The production of Fr nuclei in the very asymmetric ^{9}Be + ^{209}Bi and ^{16,18}O + ^{197}Au reactions is well described with about the same scaling parameter at the LD fission barriers that correspond to rather wide range of neutron numbers for intermediate nuclei and ERs (see [23] and references therein).

4. PRODUCTION OF Rn NUCLEI

ER and fission excitation functions obtained in reactions with weakly bound light projectiles, which lead to the $^{217-215}$Rn* compound nuclei [24], are well described with $k_f = 0.85$. The analysis of reactions leading to more neutron-deficient ^{212,211,207,206}Rn* [25, 26] shows $k_f = 0.76$, as one can see in Fig. 4. It should be mentioned that transition from the ^{14}N-induced (very asymmetric) reaction to the ^{22}Ne-one (less asymmetric) [25] does not reveal any fusion suppression in contrast to the similar analysis of reactions leading to Ra compound nuclei (see Sec. 3). At the same time, in going from ^{28}Si to ^{31}P [26], some fusion suppression appears, as shown in Fig. 4.

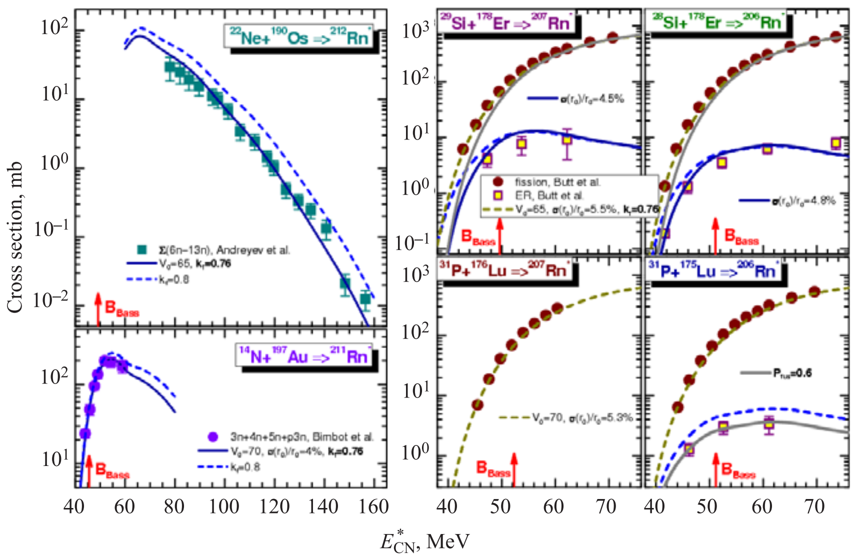

Fig. 4. Results of the analysis of the excitation functions obtained in reactions leading to Rn compound nuclei

5. MACROSCOPIC FISSION BARRIERS FOR Rn TO Th NUCLEI

The reduced LD (macroscopic) fission barriers resulting from the analysis are shown in Fig. 5 for Rn and Fr nuclei and in Fig. 6 for Ra and Th nuclei together with the ones compiled earlier for more neutron-rich nuclei [27], and the barriers calculated in various theoretical models [13, 28, 29]. In upper panels of the figures ground-state shell corrections used in the present analysis (see Sec. 1) are compared with the ones calculated in the finite-range droplet and liquid-drop models [30]. According to any theory, macroscopic fission barriers should be a smooth function of N, as observed for Fr and Ra nuclei bearing in mind that k_f-scaling is the same for all nuclei involved in a CN deexcitation cascade. For Rn nuclei a step-wise discontinuity of the barriers, which is observed at $N = 126$, has no reasonable explanation and needs experimental confirmations. At the same time, according to the prediction [30], Rn nuclei with $N < 116$ should be strongly oblate-deformed ($\beta_2 \leqslant -0.2$) and the rotational CELD in an evaporation channel has to be compensated by the similar one in a fission channel for these nuclei, as predicts the schematic model [4]. Effectively it should be manifested in a relative increase in the k_f-value (ER production cross sections). It is not observed even for short evaporation chains corresponding to the $^{28,29}Si + ^{178}Er$ data [26] (see Fig. 4). In general, the barriers derived in the analysis have 0.5–2 MeV less than the values predicted by the most sophisticated theories [28, 29].

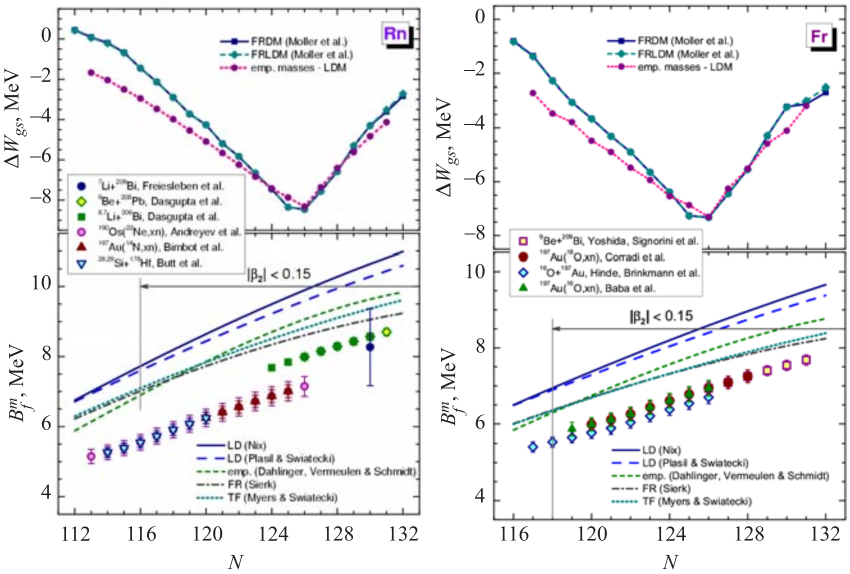

Fig. 5. Macroscopic fission barriers, resulting from the analysis of reactions leading to Rn and Fr nuclei in comparison with theoretical model predictions; the region of (near-) spherical nuclei ($|\beta_2| < 0.15$) are designated (bottom panels). Ground-state shell corrections are shown in upper panels

Macroscopic fission barriers, resulting from the analysis of Ra nuclei production, have 0.5–1.5 MeV less than the predicted ones [28, 29]. The obtained data relate to (near-) spherical nuclei ($|\beta_2| < 0.15$) [30]. The available data on the prolate-deformed Ra nuclei [27] demonstrate good agreement with the predictions [28, 29] (see Fig. 6), whereas the barrier data of the transition region are missing. The behavior of the barrier heights for more neutron-deficient nuclei is of interest from the point of view of manifestation of the CELD effect in going to the oblate-deformed nuclei with $N < 118$. The relatively low barrier heights for spherical Th nuclei can be explained by the CELD effect, as mentioned in Sec. 1. It should be noted that the data derived in the analysis of the transitional region of Th nuclei are in rather poor agreement with each other. So, more precise and consistent cross-section data are required for this region. At the same time, notice that macroscopic fission barriers for the deformed Th nuclei, which are obtained in the present analysis of the $^{4}\mathrm{He} + ^{226}\mathrm{Ra}$ data [18], are in good agreement with the data obtained in the $(n,\ f)$ and $(\gamma,\ f)$ reactions [27] for the same nuclei, as one can see in Fig. 6.

From the results obtained it may be deduced that the analysis of fusion-evaporation and fusion-fission data with the standard statistical model approxi-

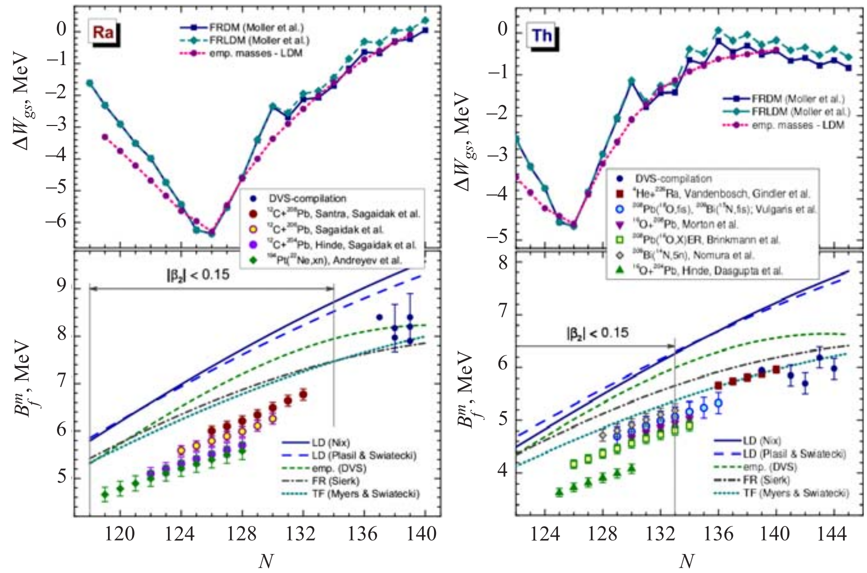

Fig. 6. The same as in Fig. 5, but for Ra and Th nuclei

mations allows one to derive reliable information on macroscopic fission barrier heights. This in turn gives a possibility to improve theoretical models for the description of isotopic dependences of macroscopic characteristics of nuclei in a wide region of their atomic and neutron numbers.

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