Remarks on the fission barriers of super-heavy nuclei

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Abstract. Shell-correction energies of super-heavy nuclei are approximated by using $Q_\alpha$ values of measured decay chains. Five decay chains were analyzed, which start at the isotopes $^{285}$Fl, $^{294}$Lv, $^{291}$Lv, $^{292}$Lv and $^{293}$Lv. The data are compared with predictions of macroscopic-microscopic models. Fission barriers are estimated that can be used to eliminate uncertainties in partial fission half-lives and in calculations of evaporation-residue cross-sections. In that calculations, fission probability of the compound nucleus is a major factor contributing to the total cross-section. The data also provide constraints on the cross-sections of capture and quasi-fission in the entrance channel of the fusion reaction. Arguments are presented that fusion reactions for synthesis of isotopes of elements 118 and 120 may have higher cross-sections than assumed so far.

1 Introduction

Shell-correction energies (SCE) determine the stability of super-heavy nuclei (SHN). They are also responsible for the emerging of a fission barrier (FB) which is a main cause for the survival of a compound nucleus (CN) formed in a heavy-ion fusion reaction. The extension of the region of SHN around the double shell closure being predicted at proton numbers $Z = 114, 120$ or 126 and at neutron number $N = 184$ is rather limited, so that an island of SHN occurs, which is separated from the lighter nuclei at about mass number $A = 280$ [1–4]. This original definition of SHN differs from the one introduced by nuclear chemists nowadays, who usually define the elements beyond the actinide series as super-heavy elements (SHE), beginning with rutherfordium, element 104, in the Periodic Table.

Experiments performed at the Flerov Laboratory of Nuclear Reactions (FLNR) in Dubna during the last fifteen years have confirmed the existence of the island of SHN [see review articles [5,6]]. However, the site and strength of highest stability is still uncertain. Predicted $Q_\alpha$ values as shown in fig. 1 for the decay chain through $^{291}$Lv reveal the ambiguity. The macroscopic-microscopic (MM) models [7–15] predict a closed proton shell at $Z = 114$ and thus increasing $Q_\alpha$ values beyond. Other models, as, e.g., the chiral mean-field model (CMF) [16] and the
semi-empirical model (SE) [17] predict subshells or shells at 120 and 126, respectively, resulting in less steep increasing or even decreasing $Q_\alpha$ values. Experimental data, also plotted in fig. 1 and known from seaborgium ($Z = 106$) up to livermorium (116) in the shown chain of $\alpha$ decays, do not give preference to a specific model. However, decisive information could be obtained from the $\alpha$-decays of elements 118 and 120.

One isotope of element 118, $^{294}$118, is already known [18,19]. However, in this case the predicted $Q_\alpha$ values of various models are less separated so that the measured value is not decisive (see fig. 12 in [20]). So far, attempts to synthesize element 120 using fusion reactions with targets of $^{244}$Pu [21], $^{238}$U [22] and $^{249}$Cf [23] were negative. At GSI in Darmstadt we proposed another attempt using a $^{248}$Cm target. In a preparatory experiment we successfully studied the reaction $^{48}$Ca + $^{248}$Cm $\rightarrow$ $^{296}$Lv* [20] and confirmed data measured earlier at FLNR [5]. A publication is in preparation, where we present the results of the first part of an experiment to search for element 120 using a $^{54}$Cr beam and a $^{248}$Cm target [24,25]. The choice of $^{248}$Cm as a target has the great technical advantage that its half-life of $3.4 \times 10^5$ years is very long and thus the specific activity is low. In addition, there is sufficient material available so that target wheels can be prepared.

Further experiments to search for new isotopes of element 118 and of the new element 120 are in preparation at FLNR [6,26] and at RIKEN in Japan [27,28]. At FLNR a target of $^{249,250,251}$Cf will be irradiated with beams of $^{48}$Ca and $^{50}$Ti, respectively, and at RIKEN a target of $^{248}$Cm with beams of $^{50}$Ti and $^{54}$Cr. At GSI the search for element 120 was stopped, because beam time is no longer available for this experiment.

In this work we make an attempt to deduce information on SCE and FB of SHN from known experimental data of $Q_\alpha$ energies. The results are compared with theoretical predictions of two MM models. The model developed by A. Sobiczewski et al. [7–11], in the following denoted with MM-S, used for the macroscopic part the Yukawa plus exponential model and a Strutinsky SCE [29] based on the deformed Woods-Saxon single-particle potential. The model developed by P. Möller et al. [12–15] is based on the finite-range droplet macroscopic model (FRDM) and the folded-Yukawa single-particle microscopic model, in the following denoted with MM-M.

The results of both models are frequently used in studies of decay modes ($\alpha$ and $\beta$ decay and spontaneous fission (SF)) of SHN and in calculations of reaction cross-sections. In these calculations the survival probability of the formed CN is an important factor, which is determined by the competition between fission and neutron evaporation. Due to the strong dependence of the fission probability from the FB which again is formed solely by shell effects in the region a SHN, an accurate knowledge of this quantity is essential. We hope that our study will be helpful for the preparation of forthcoming experiments and for further improvement of theoretical models.

**2 Shell-correction energies**

Nuclear masses or binding energies are determined as sum of a macroscopic liquid-drop (LD) mass and SCE in MM models. Vice versa, experimental SCE can be determined by subtracting theoretical LD masses from measured masses. However, the so determined SCE are not absolutely fixed data, because the LD masses are part of the specific model used.

In the case of SHN ($A \geq 280$), another difficulty arises from the fact that measured masses are not existing. However, relative masses can be determined in the case of $\alpha$-decay chains. Within a chain the masses are fixed by the measured $Q_\alpha$ values. Therefore, in a limited region determined by the lengths of the decay chains, experimental trends of masses and model-dependent SCE can be compared with trends predicted by the theoretical models. In order to distinguish between the so determined masses and deduced SCE from the theoretical ones, we denote them “experimental data” in the following. Instead of the correct term “mass excess” we also will use the term “mass” for simplicity.

So far, $\alpha$ decay of five decay chains was measured for even-Z elements in the region of SHN: $^{285}$Fl-$^{269}$Sg ($N=Z=57$), $^{294}$118-$^{286}$Fl (58), $^{291}$Lv-$^{271}$Sg (59), $^{292}$Lv-$^{288}$Fl (60), and $^{293}$Lv-$^{281}$Ds (61). The chains terminate by SF.

Two possibilities exist to adjust the mass of the final fissioning nucleus. Firstly, it can be normalized to mass...
Comparison of theoretical masses and experimental mass estimates deduced from measured \(Q_\alpha\) values of the decay chain through or starting, respectively, at \(^{291}\text{Lv}\) \((N-Z = 59)\). Also given are theoretical and model-dependent “experimental” shell-correction energies (SCE). The \(Q_\alpha\) values of \(^{295}\text{Rf}\) and \(^{299}\text{FBE}\) given in brackets in column 2 are estimates used for extrapolation of “experimental” masses and SCE, see text at the end of sect. 2. See text for an explanation of the used abbreviations.

### Table 1

| Experiment \([5,24,30,31]\) | Theory by A. Sobiczewski et al. \([7–11]\) | Theory by P. Möller et al. \([12–15]\) |
|-----------------------------|--------------------------------|--------------------------------|
| Isotope                    | \(Q_{\alpha}^{\text{exp}}\) | \(\Delta m_{\alpha}^{\text{exp}}\) |
| \(^{267}\text{Rf}\)        | \(- 113.45\)  | \(112.19 \pm 122.30 \pm 177.07\) | \(- 4.88 \pm 4.77 \pm 4.65\) |
| \(^{271}\text{Sr}\)       | \(8.66\)         | \(123.32 \pm 123.38 \pm 128.07\) | \(- 4.75 \pm 4.69 \pm 4.35\) |
| \(^{275}\text{Hs}\)       | \(9.45\)         | \(135.15 \pm 135.26 \pm 139.69\) | \(- 4.54 \pm 4.43 \pm 3.96\) |
| \(^{279}\text{Ds}\)       | \(9.85\)         | \(147.82 \pm 147.93 \pm 151.94\) | \(- 4.12 \pm 4.13 \pm 3.38\) |
| \(^{283}\text{Cn}\)       | \(9.66\)         | \(160.40 \pm 159.61 \pm 164.81\) | \(- 5.20 \pm 5.19 \pm 3.99\) |
| \(^{287}\text{Fl}\)       | \(10.17\)        | \(173.38 \pm 173.46 \pm 178.28\) | \(- 4.90 \pm 6.07 \pm 5.18\) |
| \(^{291}\text{Lv}\)       | \(10.89\)        | \(186.71 \pm 185.52 \pm 192.35\) | \(- 5.64 \pm 6.83 \pm 6.12\) |
| \(^{295}\text{Rf}\)       | \(12.20\)        | \(201.36 \pm 201.46 \pm 207.03\) | \(- 5.67 \pm 6.68 \pm 6.02\) |
| \(^{299}\text{FBE}\)      | \(13.16\)        | \(217.01 \pm 215.72 \pm 222.29\) | \(- 5.28 \pm 5.66 \pm 5.28\) |
| \(^{303}\text{Hg}\)       | \(-\)            | \(-\)                           | \(-\)                           |

- \(\Delta m_{\alpha}^{\text{LD}}\) - shell-correction energy
- \(\Delta m_{\alpha}^{\text{LD,S}}\) - shell-correction energy
- \(\Delta m_{\alpha}^{\text{LD,FBE}}\) - shell-correction energy

- \(\Delta m_{\alpha}^{\text{SCE}}\) - shell-correction energy
- \(\Delta m_{\alpha}^{\text{SCE,M}}\) - shell-correction energy
- \(\Delta m_{\alpha}^{\text{FBE}}\) - shell-correction energy

The procedure how we determined the experimental data is elucidated in table 1, showing numerical values for the decay chain through \(^{291}\text{Lv}\). As example we used this decay chain because it is the longest chain measured and, interestingly, this is the decay chain which would be populated in a three neutron evaporation channel (3n channel) of the reaction \(^{54}\text{Cr} + \^{248}\text{Cm}\) resulting in the evaporation residue (ER) \(^{295}\text{Rf}\) of the new element 120. Theoretical as well as measured \(Q_\alpha\) values of nuclei of this chain are also drawn in fig. 1.

In table 1 given are the mass excesses \((\Delta m)\), the mass excesses of the liquid-drop part \((\Delta m_{\text{LD}})\), the shell-correction energies (SCE) and the heights of the fission barriers (FBE). The three mass values in italic in column 5 and 11 were obtained by fitting the relative mass data calculated from the \(Q_\alpha\) values to the theoretical ones to their left. The mass of \(^{267}\text{Rf}\) given in italic in column 3 was taken from the AME2012 mass estimate \([30]\) for normalization. Note that the differences between masses of nuclei within an \(\alpha\)-decay chain are fixed by the connecting \(Q_\alpha\) values.

Model-dependent experimental SCE values were obtained by subtraction of the theoretical LD masses from the experimental masses.

As a result of the estimation procedure used in AME, the error bars are relatively large in the region of interest, approximately 0.4 to 0.8 MeV. Few new experimental \(\alpha\)-decay data or improved energy values were measured since the AME evaluation, which we considered in our study. The measured \(\alpha\) energies which we used here were taken from \([5,24]\) and of \(^{287}\text{Fl}\) from \([26,32]\). However, the majority of SHN data is already included in AME. The contribution of the uncertainty of the measured \(Q_\alpha\) values of approximately 15 to 70 keV to the error propagation of the mass values is small, nevertheless, it was considered.

The differences between AME masses and the masses used here are plotted at the bottom of figs. 2(f)–(j) for all even-element decay chains. The data completely agree for the masses of the even-even nuclei. In the case of even-odd nuclei the AME masses reveal a trend to higher values, which is due to the assumption made by the authors of AME that \(\alpha\) decay populates low energy Nilsson levels in the region of deformed nuclei. The effect vanishes for spherical nuclei in the region of SHN. The influence of this possible effect which is difficult to estimate precisely, on the evaluation of SCE will be discussed below.

The experimental masses are compared with the theoretical predictions of the MM-S model in figs. 2(a)–(e) and of the MM-M model in figs. 2(f)–(j). In both models the majority of masses are smaller (higher binding energy) than the experimental ones. In the region of elements \(^{86}\text{Rg}–^{88}\text{Ds}\) the difference is about 1 MeV in MM-S and 2 MeV in MM-M. However, more striking is the opposite trend into the experimental data at element 116, whereas the MM-M values reveal significantly increased binding of SHN. The deviations reach values up to 4 MeV for nuclei of elements 114 and 116.

The SCE values of all five decay chains are plotted in fig. 3. In the top row are shown the data related to the MM-S model and in the bottom row those related to the MM-M model. The data are compared with the results of the model calculations, correspondingly denoted as SCE-S and SCE-M.

The AME-based experimental SCE are given with error bars, the difference between filled and open symbols is explained in fig. 2.

Experimental data without error bars are based on the theoretical masses. They better reflect different trends between experiment and theory along the measured decay chain. In figs. 3(a) and (f) these experimental masses were fitted to the masses of \(^{269}\text{Cn}, ^{273}\text{Hs}\) and \(^{277}\text{Ds}\) (filled di-
Fig. 2. Differences of experimental and theoretical masses of five neighboring decay chains of even-element SHN. The data are compared with theoretical masses of the MM-S model in (a)–(e) and with the MM-M model in (f)–(j). Filled symbols mark differences obtained with extrapolated masses of the AME2012 evaluation [30], open symbols mark those where the experimental masses were determined from the measured $Q_\alpha$ values [5, 24, 26, 32]. These data were normalized to the AME mass of the nucleus terminating the chain. Circles in (f)–(j) show the difference between AME masses and the masses used in this work. The horizontal dashed lines at 2 MeV are drawn as reference lines to guide the eye.

Amonds), in (c), (h) to $^{271}\text{Sg}$, $^{275}\text{Hs}$, and $^{279}\text{Ds}$, in (e), (j) the experimental mass was normalized to $^{277}\text{Hs}$. In (b), (g) the straight line between the known nuclei $^{284}\text{Cn}$ and $^{288}\text{Fl}$ was extrapolated to $^{278}\text{Ds}$, and in (d), (i) the straight line between $^{284}\text{Cn}$ and $^{288}\text{Fl}$ was extrapolated to $^{280}\text{Ds}$. The resulting values of the two Ds isotopes were normalized to the calculated ones. Note that within an $\alpha$-decay chain the shape of the experimental SCE curves is fixed by the measured $Q_\alpha$ values and the used theoretical LD masses.

The curves of theoretical SCE reveal some common features. Only small changes occur between rutherfordium and darmstadtium followed by a sharp decrease (higher binding energy), which ends at a pronounced minimum at livermorium, after which the curves rise steeply again. This behavior is well understood in terms of the shell model. It predicts a closed shell for the protons at $Z = 114$ and a low level density above, up to $Z = 126$, which shifts the minimum of SCE to $Z = 116-118$. Correspondingly, for the neutrons a closed shell is predicted at $N = 184$ and a low level density below, down to $N = 164$, which shifts the minimum of SCE to $N = 178-182$ (see also figs. 53 and 54 in [13]). However, the minimum of SCE is less pronounced in the MM-S calculations than in MM-M. The difference is 2.8 MeV at $^{293}\text{Lv}$.

A comparison of the theoretical SCE with the AME-based experimental SCE (values given with error bars) reveals that the experimental data are about 1.0 to 1.5 MeV weaker than SCE-S for isotopes of Rf to Ds. Beyond Ds, the difference decreases and the SCE values match within error bars for isotopes of Fl, Lv and 118. The perfect agreement there is also due to slightly steeper slopes of experimental SCE as function of $Z$. The effect is better visualized in a comparison of SCE-S with the m-S–based experimental data (diamonds in figs. 3(a)–(e)).

The scenario is significantly different in a comparison of data within the MM-M model, figs. 3(f)–(j). For isotopes of Rf to Ds the difference between AME-based experimental data and SCE-M is about 2.0 MeV. Beyond Ds the difference increases up to about 4.0 MeV for isotopes of Fl, Lv and 118. Responsible for the deviation is primarily the strong theoretically predicted shell effect at Fl and Lv. The different trend is even better visualized in a comparison of SCE-M with the m-M–based experimental SCE (diamonds in figs. 3(f)–(j)). In addition, we observe a flatter drop of experimental SCE than in the case of the MM-S model. The reason for this is that the LDE-M values increase less than the LDE-S values. As given in table 1, columns 6 and 12, LDE-M is 0.3 MeV smaller than LDE-S at $^{267}\text{Rf}$ but 1.9 MeV smaller at $^{303}\text{Rf}$.
Fig. 3. Experimental shell-correction energies of five neighboring decay chains are compared with theoretical values of the MM-S model in (a)–(e) and of the MM-M model in (f)–(j). Experimental data with error bars are based on the AME masses, see also fig. 2, from which the theoretical LD masses, LD-S and LD-M, were subtracted. Experimental data without error bars are based on the theoretical masses of isotopes at the end of the decay chains (see text for a detailed explanation). They better reflect different trends between experiment and theory along the measured decay chains. Curves without symbols show the negative values of the heights of the fission barriers, \(-FBE-S\) and \(-FBE-M\), obtained in models MM-S and MM-M. The horizontal dashed lines at \(-4\) MeV are drawn as reference lines to guide the eye.

It is necessary to note that the AME-based experimental SCE values of odd-\(N\) isotopes of the same \(N - Z\) value of elements from Rf to Ds are almost equal in MM-S and MM-M (the absolute values in MM-M are systematically only about 0.5 MeV smaller than in MM-S). However, in the same range of elements but for even-\(N\) isotopes, the absolute values in MM-M are 1.4 MeV smaller than in MM-S. This difference of about 0.9 MeV is due to the fact that part of the pairing energy which separates the LD mass surface of even-even from even-odd nuclei is included in the LD mass of MM-M, whereas all parts of the pairing energy are included in the microscopic part in MM-S. For the different definitions of the macroscopic and microscopic energies in MM-M and MM-S see [12] and [33], respectively. However, this difference of the models has no influence on the shape of the curves plotted for constant \(N - Z\), and it does not change the conclusions drawn in this work.

The systematic difference between even-even and even-odd nuclei due to the different treatment of part of the pairing energy continues up to the heaviest elements for which \(\alpha\) decay was measured. Mean values of AME-based experimental SCE of five even-odd isotopes of Fl and of five of Lv are 1.0 MeV more negative in the MM-S model than in MM-M, whereas the mean difference of two even-even isotopes of Fl and two of Lv result in 1.9 MeV more negative values in MM-S than in MM-M.

Finally, we mention that irregularities at the lower end of the more neutron deficient decay chains are due to structure effects arising from large gaps between single-particle energies at \(Z = 108\) and \(N = 162\) for deformed nuclei. However, the discussion of these effects is beyond the scope of this work.

So far, experimental data for the heaviest nuclei do not indicate a bending upwards of SCE values as predicted by the MM models. Site and depth of an SCE minimum is not yet allocatable experimentally. On the contrary, in the only one case measured up to element 118, \(^{284}\)118, the experimental SCE value decreases further whereas MM-M predicts already a slight increase (fig. 3(g)). Especially here we see the importance of accurately measured \(\alpha\)-decay data of more isotopes of element 118 and of the new element 120. The \(Q_\alpha\) values and deduced SCE of these nuclei will provide us with the information of further decreasing or increasing SCE and, thus, with a possible existence and strength of a shell or sub-shell closure at \(Z = 120\).
The influence of the different theoretical LD masses on the model-dependent experimental SCE is largely removed, when we normalize the masses of the nuclei at the end of the chains to the theoretical masses itself. These data are closer related to the theoretical models, so that a comparison reveals locally appearing differences more convincingly. The data points are shown as diamonds without error bars also in fig. 3. The normalizing procedure was explained before. Naturally, the shape of the curves is the same as for the data normalized to the AME masses, for which error bars are given. Therefore, the arguments related to the slope of the data remain. For the binding of SHN of elements from Ds to Lv we deduce that experimental SCE based on the model masses m-S are slightly stronger (lower negative SCE) than calculated in MM-S, but those based on m-M are significantly weaker than in MM-M.

It remains to discuss the consequences of $\alpha$ decays into excited levels of the daughter nucleus, which may occur in the region of deformed nuclei which are populated at the end of the decay chains. Assuming higher $Q_\alpha$ values from ground-state–to–ground-state transitions would result in a higher mass of the decaying nucleus. Subtracting the same theoretical LD mass as before would result in less negative SCE. Therefore, this effect would diminish for the odd-N isotopes the already small deviations between m-S–based experimental data (diamonds) and SCE-S, but would further increase the differences between m-M–based data and SCE-M. However, for two reasons we expect only a small modification of the data from this effect. Firstly, suitable Nilsson levels coming in question for being populated are located at energies of a few hundred keV maximum [34], which is within the error estimates attributed to the masses in the AME table. Secondly, the very similar trend of masses and SCE of nuclei of neighboring even-even and even-odd chains justifies to neglect this effect.

We conclude that AME-based experimental SCE of nuclei of the elements 114 and 116 and with neutron numbers from 171 to 175 and 174 to 177, respectively, are in good agreement with the MM-S model. Deviations are less than 1 MeV. For the same nuclei deviations up to 4 MeV were observed in comparison with MM-M. The study clearly reveals that too strong shell effects are predicted by the MM-M model, which are not observed in the experimental data. Systematic differences exist of about 0.9 MeV of experimental SCE between even-even and even-odd nuclei deduced with LDS and LDM masses, which are due to a different consideration of pairing energies as pointed out before.

At this point we want to add that differences between experimental data and theoretical values observed in this work could be used for local corrections to theoretical models. They became visible due to accurately measured $\alpha$ energies. Such local deviations do not allow for evaluating the quality of the models which are developed to explain properties of nuclei in a much wider region (MM-S) or even globally (MM-M). Nevertheless, such corrections of a few MeV are essential, in particular for the calculation of reaction cross-sections in which FB deduced from SCE are used.

![Fig. 4. Experimental shell-correction energies (filled symbols) of isotopes of elements flerovium, livermorium and 118 taken from fig. 3 are compared with theoretical predictions of the MM-S model in (a) and of the MM-M model in (b) calculated across a wider range of neutron numbers. In (a) theoretical values of only the even-even nuclei are plotted. Also shown are estimates of SCE values of $^{295}$118 and $^{299}$120 (open symbols, crosses for $Z = 120$). These nuclei belong to the decay chain through $^{291}$Lv, also shown in fig. 1, which could be produced in a 3n channel of the reaction $^{54}$Cr + $^{248}$Cm. The difference between experimental data shown with and without error bars is explained in the text and in the caption to fig. 3. Note that the experimental SCE of Fl and Lv based on AME are shifted upward by 2 MeV for clarity in (a).](image-url)
Of particular interest for the synthesis of the new element 120 is the variation of SCE of nuclei at and beyond flerovium. In fig. 4 we show the results of the MM models of the even elements from 114 to 120 as function of a wider range of neutron numbers, in (a) of the MM-S and in (b) of the MM-M model. The experimental data deduced from five individual decay chains as discussed before and presented in fig. 3 are included.

As pointed out before, pairing energies are not included in the LD part of MM-S whereas they are in MM-M. The different odd-even staggering as function of the neutron number of AME-based SCE in the two models is due the different treatment of pairing in the models. Note that in fig. 4(a) the theoretical SCE are plotted only for even-even nuclei and that the experimental SCE of Fl and Lv based on AME are shifted upward by 2 MeV for clarity.

Despite the different treatment of pairing in the two models, which results in a systematically lower negative SCE of even-even nuclei of about 0.5–1.0 MeV relative to a calculation with pairing included in the LD part, we notice good agreement between SCE-S and AME-based experimental values, fig. 4(a), whereas large deviations exist in the case of MM-M, fig. 4(b).

Another difference between the models becomes visible in this representation. It is the rapidity how SCE changes from 114 to 120 in the region of interest. The gradient is about 2 MeV per six elements in MM-M and only 1 MeV in MM-S. That means, stability of element 120 isotopes relative to that of Fl is lost faster in MM-M than in MM-S. To be highlighted is also the order of decreasing or increasing SCE as function of $N$. As far as experimental data are known, we always observe an increase of stability from Fl via Lv to 118. This is not the case for SCE-M at $N = 175$ to 117, where the theoretical values reveal loss of stability from Fl via Lv to 118.

For the already highlighted decay chain through the isotope $^{291}$Lv we estimated SCE of $^{295}$118 and $^{299}$120 starting from AME-based masses. As $Q_\alpha$ values of these two nuclei we used the mean values of the MM-S and MM-M model, which are very close in energy, see fig. 1. These values and the obtained masses are given in columns 2 and 3 in brackets in table 1. The deduced AME-based SCE are $-5.74$ and $-5.41$ MeV for $^{295}$118 and $^{299}$120, respectively, using LDS and, correspondingly, $-4.39$ and $-3.80$ using LDM. Values of SCE based on m-S and m-M are given in brackets in table 1. The SCE data are plotted as open symbols in fig. 4.

Also for these two nuclei we observe good agreement of the AME-based estimates of SCE with MM-S and significantly less binding than predicted in MM-M. In this latter model the decrease of stability from the heaviest known isotope of livermorium, $^{283}$Lv, to $^{299}$120 is 1.26 MeV whereas the difference between AME-based SCE is less than half, 0.54 MeV.

We also estimated SCE of $^{295}$118 and $^{299}$120 assuming stronger bound nuclei than predicted in MM models. E.g. the $Q_\alpha$ values of the SE model, which are in good agreement with those of the MM-S model up to $^{291}$Lv, see fig. 1, are about 1 and 2 MeV less for $^{295}$118 and $^{299}$120, respectively. This decrease is due to the assumption of a closed shell at $Z = 126$. In that case the AME-based masses of $^{295}$118 and $^{299}$120 would be 1 and 3 MeV less than the values given in column 3 of table 1, and, correspondingly, the negative SCE would decrease further by 1 and 3 MeV, respectively, giving increased stability to isotopes of these elements. At this point we see again the need for more experimental data, especially of the decays of more isotopes of element 118 and the new element 120, which will determine the trend of SCE into the region of heavier elements.

### 3 Fission barrier and half-life

The existence of an island of SHN is determined by sufficiently low SF probabilities of the nuclei in the ground-states or in isomeric states. Properties which determine the fission probability are the FB and the inertia of the fissioning system. FB itself depends from the shape of the barrier which is formed in the region of SHN by nuclear-structure effects and at larger deformation by the rapid drop of the macroscopic potential energy. In addition, FB is modified by angular momentum and excitation energy.

In a rough manner the characteristics of FB are described by a barrier height, FBE, and a width. The largest contribution to FBE of SHN comes from the ground-state SCE. This is due to the circumstance that, firstly, macroscopic liquid-drop barriers vanish for $Z = 104$ and above, and, secondly, the shell-correction energy at the saddle point is expected to be small [35]. The mutual dependence becomes obvious in a comparison of SCE with the negative values of FBE. On this condition we compare in fig. 3 calculated FBE in the MM-S and MM-M model with experimental and theoretical SCE values. In both FB calculations, a specialization energy which increases FB due to energy shifts of the odd neutron at deformation during the fission process, is not considered.

However, even at similar FBE, the width of the barrier can significantly modify the SF half-life ($T_{SF}$), see e.g. fig. 1 in [6]. Calculated $T_{SF}$ values change from $10^3$ s for well deformed nuclei at $^{270}$Hs [36] to $10^{12}$ s for spherical SHN at $^{288}$Fl [37], although in both cases FBE values of about 7 MeV were used. Therefore, without sufficient knowledge of the degree of deformation, it is not possible to establish a relation between FBE and $T_{SF}$. Nevertheless, for completeness we present fission data of the only four even-even SHN in table 2, for which such data were measured and compare them with calculated results.

The two decay chains of even-even nuclei studied here terminate by SF of $^{282}$Cn ($T_{SF} = 0.96$ ms) and $^{284}$Cn (118 ms). For the $\alpha$-decay parent of $^{282}$Cn, $^{286}$Fl, an SF branching of 48% was measured, which results in a $T_{SF}$ value of 346 ms [5, 24]. One more even-even nucleus, $^{284}$Fl, was produced recently [26]. It decayed directly as ER by SF with $T_{SF} = 2.5$ ms.

SF half-lives of these nuclei were calculated within the MM-S model in [36]. The statical and slightly higher dynamical FB which was used in these calculations are also
Experimental and theoretical partial spontaneous fission half-lives $T_{SF}$ of the only four known fissioning even-even SHN. The table is completed with values of fission barriers and shell-correction energies discussed in this work. Also given are the calculated ground-state deformation parameters $\beta_2$ of the four nuclei. Half-lives are given in ms, energies in MeV. A mass estimate for $^{284}$Fl is not available in AME2012 [30].

| Isotope | $^{282}$Cn | $^{284}$Cn | $^{284}$Fl | $^{286}$Fl | Ref. |
|---------|-----------|-----------|-----------|-----------|-----|
| $T_{SF}$    | 0.96      | 118       | 2.5       | 346       | [5,24] |
| $T_{th}$    | 71        | 4000      | 12        | 1500      | [36] |
| $T_{th}$ / $T_{SF}$ | 74 | 34 | 4.8 | 4.3 | |
| FBE$_{stat}$ | 3.4       | 3.4       | 3.1       | 3.3       | [36] |
| FBE$_{dyn}$  | 3.5       | 3.5       | 3.3       | 3.8       | [36] |
| FBE-S        | 3.7       | 4.3       | 4.2       | 4.8       | [10] |
| FBE-M        | 6.5       | 7.4       | 8.1       | 9.0       | [15] |
| SCE-S        | $-4.8$    | $-5.1$    | $-4.9$    | $-5.2$    | [10,11] |
| SCE$_{rel.m}$-AME | $-4.4$ | $-4.3$    | $-5.2$    | t.w.      |     |
| SCE-M        | $-5.7$    | $-6.2$    | $-7.0$    | $-7.4$    | [12] |
| SCE$_{rel.m}$-AME | $-2.7$ | $-2.8$    | $-3.4$    | t.w.      |     |
| $\beta_2$    | 0.144     | 0.123     | 0.145     | 0.121     | [36] |
| $\beta_2$    | 0.089     | 0.089     | 0.062     | $-0.096$  | [12] |

4 Fission barrier and cross-section

In models commonly used in calculations of heavy-ion fusion cross-sections it is assumed that after capture of the reacting nuclei a CN nucleus is formed at a certain excitation energy, which cools down by evaporation of neutrons. In fusion of SHN, the total cross-section is highly reduced, firstly, due to re-separation of the nuclei by the so called quasi-fission in the entrance channel and, secondly, by the high probability of fission of the CN. In reactions with actinide targets, the CN has excitation energies $E^*$ of 35–50 MeV, for which reason these reactions were named “hot fusion” in contrast to “cold-fusion” reactions based on targets of lead or bismuth. There, $E^*$ is in the range of 12 to 20 MeV.

Refined cross-section calculations as described e.g. in [41–46] take these processes into account, which depend from charge, size, and deformation of projectile and target nuclei, damping of shell effects, which reduces FBE [47–49] as function of the excitation energy, level densities, angular momenta, and neutron binding energies.

Although the calculations describe rather well the measured cross-sections for synthesis of Fl and Lv, the predictions for synthesis of element 120 cover a wide range from 0.07 to 8000 fb depending on the model and FB used. Reactions with beams of $^{50}$Ti, $^{54}$Cr and $^{58}$Fe and targets of $^{249}$Cf, $^{248}$Cn and $^{244}$Pu, respectively, were investigated in the calculations.

Theoretical estimates reveal how sensitively the cross-sections depend from FBE. In [41], a change by a factor of 200 was obtained for the reaction $^{48}$Ca + $^{239}$U if FBE of $\approx 5.5$ MeV [8] was changed by $\pm 1$ MeV. In [50, 51], the 3n cross-section of the reaction $^{48}$Ca + $^{238}$U was calculated for FBE of 4.5, 5.5, and 6.5 MeV resulting in cross-sections of 0.23, 5.0, and 30 pb, respectively. That calculation reveals that a decrease of FBE is more sensitive than an increase, which is a result of the exponential dependence of the cross-section from FBE.

From an adjustments of quasi-fission, fusion-fission, and ER cross-sections of hot-fusion reactions, lower limits of FBE were determined in [50,51]. Values of 6.7 and 6.4 MeV were deduced for the nuclei $^{288-292}$F1 and $^{292-296}$Lv, respectively. However, in the calculations of cross-sections and excitation functions [42,51] not the lower limits but the higher FBE-M of [12] were used.

A comparison of SCE and $-FBE$ in fig. 3 reveals that for isotopes of elements beyond Ds both values are almost identical in MM-S. However, the difference between SCE-S and $-FBE$-S of even-even nuclei of elements from Rf to Ds plotted in figs. 3(b) and (c) of about 1 MeV shows again that pairing is not included in the LD part of the model.
On the contrary SCE-S and \( -\)FBE-S are almost identical for even-odd nuclei.

In the case of MM-M, a saddle point SCE of about +1 MeV increases FBE for isotopes of elements Ds, Fl and Lv. The difference vanishes for 118 and 120. FBE-M values were published in 2009 and 2015 [14,15]. Therefore, in earlier cross-section calculations, the negative of SCE-M published in 1995 [12] has been commonly used to estimate FBE.

It is beyond the scope of this work to perform accurate cross-section calculations, which consider all details of the reaction mechanism. However, we can estimate the modifications which occur when the here estimated lower “experimental” FBE, respectively, \(-\)SCE values are used instead of the rather high FBE-M, respectively \(-\)SCE-M values. In particular, we are interested if and how much the predicted cross-section for synthesis of element 120 will change. As a main argument, we make use of the estimate that cross-sections will decrease by one order of magnitude if FBE decreases by 1 MeV.

As an example, where \(-\)SCE-M was used in calculations of cross-sections, we discuss the results obtained in [42,51]. Calculated were excitation functions for synthesis of isotopes of Fl and Lv using a \(^{48}\)Ca beam and targets of \(^{242}\)Pu, \(^{244}\)Pu, \(^{245}\)Cm, and \(^{248}\)Cm. The calculated predictions are compared with measured cross-sections in [5].

In most cases, agreement within the experimental error bars is found.

Isotopes intermediated produced during the evaporation of neutrons from the CN \(^{299}\)Fl in the reaction \(^{242}\)Pu \((^{48}\)Ca, 4n)\(^{296}\)Fl overlap with those for which experimental SCE values were obtained, see fig. 4. For that reaction a cross-section of \((4.5 \pm 1.3)\) pb was measured in [52]. The predicted cross-section was 3.1 pb [42,51]. In the cross-section calculations, values of \(-\)SCE-M were used as FBE. The mean \(-\)SCE-M of the isotopes involved in the 4n channel is 8 MeV. The negative of the mean experimental value of \("\)SCE-M rel. m-M" is lower by 1.9 MeV, that of \("\)SCE-M rel. AME" lower by 4.2 MeV and that of \("\)SCE-S rel. AME" lower by 3.3 MeV. The latter value being well in agreement with the predictions of the MM-S model.

In fig. 5, we show a similar plot for a target of \(^{248}\)Cm, and \(^{299}\)Fl overlap with those for which experimental values of the SCE values of \(^{299}\)Fl to 120 based on experimental estimates is significantly less, about 1 MeV at \(N = 174\)–179, than in the calculations of MM-M, where it is about 2 MeV at \(N = 176\)–182. However, the change is similar as in the predictions of the MM-S model.

It has to be added that the requested higher probability for formation a CN due to lower quasi-fission probability as consequence of lower FB could, partially, be also obtained by less damping of SCE at high excitation energies. However, if this is valid but the ratio between both effects, lower quasi-fission and less damping, stays fixed, the conclusions regarding higher cross-sections for element 120 remain unchanged.

We also estimated model-dependent experimental neutron binding energies \((B_{1n})\). The values were calculated from the masses of isotopes of Fl and Lv, which were determined as sum of the experimental “SCE-M rel. to m-M” shown in fig. 4(b) and the FRDM liquid-drop masses LD-M of [12]. For the isotopes \(^{286}–^{299}\)Fl we obtained values of \(B_{1n} = -7.81, -5.62, -7.44, \) and \(-5.54\) MeV and for \(^{291}–^{293}\)Lv values of \(B_{1n} = -5.74, -7.52, \) and \(-5.64\) MeV, respectively. Compared to the theoretical values given in [13], we obtain less bound neutrons, the differences being 0.14 and 0.25 MeV on the average for the ER cross-sections of Fl and Lv, respectively. Concerning the ER cross-section, less bound neutrons increase the probability of neutron emission. At an \(exp(B_{1n})\)-dependence, we obtain an increase of 15% and 29% on the average for the ER cross-sections of Fl and Lv, respectively, in each step of the neutron evaporation compared to calculations using the higher neutron binding energies of [13].

5 Excitation energy at the fusion barrier

The excitation energy of the fused system produced in reactions with a \(^{208}\)Pb target and various beam particles at beam energies which were just high enough to reach a contact configuration according to the fusion model described in [53] were calculated in [55]. For these cold-fusion reactions the cross-section maxima were always measured at excitation energies several MeV below the calculated values. In fig. 5, we show a similar plot for a target of \(^{248}\)Cm as an example for a hot-fusion reaction. The data were calculated with the assumption of spherical projectile and...
target nuclei. In this case the maxima of measured cross-sections for synthesis of isotopes of nobelium up to hassium are about 3 MeV above the calculation for beams of neutron-rich isotopes of carbon, oxygen, neon, magnesium and 7 MeV for \( ^{48}\text{Ca} \) for synthesis of livermorium. In this latter reaction, a local minimum of the excitation energy occurs due to the strong binding of the double magic \( ^{48}\text{Ca} \).

The observation that the measured cross-section maxima are at higher excitation energies than the ones calculated with the fusion model of [53] is due to the deformation of the \( ^{248}\text{Cm} \) target. More kinetic energy is needed to reach a compact configuration [56]. When one considers the hexadecapole deformation of the target, a compact configuration is achieved only when the projectile collides with the target nucleus at an angle of about 45 degrees relative to the symmetry axis. It is such a configuration which eventually leads to fusion.

It is interesting to note that for heavier systems the excitation energy at contact decreases rapidly. For the reaction \( ^{54}\text{Cr} + ^{236}\text{Cm} \) it is already 2.1 MeV smaller than for \( ^{48}\text{Ca} + ^{248}\text{Cm} \), and the excitation energies approach the \( 1n \) binding energy for synthesis of element 126. This means that hot fusion will change into cold fusion for the heaviest systems, an effect which strongly reduces the fission probability of the CN, because only two or even only one neutron have to be and can be evaporated during the cooling process. The question remains open, to which degree this effect can compensate for the increasing quasi-fission due to higher Coulomb repulsion in the entrance channel of the reaction.

6 Conclusion

In this paper we used existing experimental \( Q_\alpha \) values measured from the decay of super-heavy nuclei for an estimate of shell-correction energies which in turn are used to estimate fission barriers. The results were compared with two different macroscopic-microscopic models, both reproducing measured \( Q_\alpha \) values of SHN well. The model dependence of the experimental SCE is governed by the theoretical macroscopic liquid-drop mass which is noticeably smaller in the MM-M model by P. Möller et al. [12–15] than in the MM-S model by A. Sobieczweski et al. [7–11].

Experimental SCE values based on the LD mass of the MM-S model and theoretical SCE of the MM-S model are in good agreement. However, a pronounced shell strength for isotopes of Fl and Lv as predicted in the MM-M model is not observed. The strong shell effects of that model for isotopes of Fl and Lv result, on the other hand, in a rapid loss of shell strength beyond these elements. Consequently, reaction calculations which use fission barriers of the MM-M model and reproduce well the cross-sections for synthesis of isotopes of Fl and Lv, will predict too low cross-sections for synthesis of element 120.

The use of lower fission barriers for isotopes of Fl and Lv requests a higher probability for the formation of a compound nucleus and/or less damping of shell-correction energies of the heated system during neutron evaporation. Together with a more moderate change of shell strength from Fl to element 120 as predicted by the MM-S model, higher cross-sections for elements beyond Lv are expected. Based on simple arguments, a change of the predicted cross-section of 28 fb calculated with fission barriers of the MM-M model for the reaction \( ^{248}\text{Cm}(^{54}\text{Cr},4n)^{298}\text{Lv} \) [42] by factors of 4 to 20 was estimated.

We also revealed the significance of experimental data of more isotopes of element 118 and of the new element 120. Measured \( \alpha \) energies of such isotopes will eventually decide about the extension of the island of SHN into the direction of new elements. Also important are measurements of masses of nuclei at the end of the \( \alpha \)-decay chains. Their half-lives are long so that ion traps or multi-reflection time-of-flight mass spectrometers can be used. These neutron-rich nuclei located in the region of elements from Rf to Sg are presently produced at low cross-section as decay products of SHN. However, in future experiments with radioactive beams these nuclei will be directly produced with higher cross-sections.

Important for determination of masses of more nuclei along \( \alpha \)-decay chains is the detection of small \( \alpha \)-decay branchings, in particular of neutron-rich even-even isotopes of Ds, which decay dominantly by spontaneous fission, and \( \alpha \) decay was not yet observed.
A comparison of experimental and theoretical SF half-lives of the known even-even isotopes of Ds and Fl is difficult, because these nuclei are located in a transitional region between spherical SHN and deformed heavy nuclei and the degree of deformation is not known. The measurement of small SF branchings of more neutron-rich even isotopes of Fl, which are located closer to the center of the island of spherical SHN, will allow for a solid comparison of experimental and theoretical SF half-lives. Expected are significant data on fission barriers of spherical SHN, which are needed for better estimates of production cross-sections in various reactions as e.g. fusion with radioactive neutron-rich beams, multi-nucleon transfer reactions as discussed in [57] and rapid neutron capture in a stellar environment. The latter aspect is closely related to the question if SHN could be produced in Nature and how long they could survive.

Experiments in preparation for the synthesis of isotopes of elements 118 and 120 are the irradiations of californium targets with beams of $^{48}\text{Ca}$ and $^{50}\text{Ti}$ at FLNR [6, 26] and irradiations of a $^{248}\text{Cm}$ target with beams of $^{50}\text{Ti}$ and $^{54}\text{Cr}$ at RIKEN [27,28].

We dedicate this paper to our colleague and friend Valeriy Zagrebaev who unexpectedly passed away on January 17, 2015 at the age of 64. Valeriy was a physicist with great knowledge and experience. His theoretical description of nuclei and nuclear reactions helped us to understand our experimental results and to plan new experiments. We always admired his enthusiasm, how he took part in discussions on the interpretation of experimental results and on the planning of new experiments. We will keep him in good memories.

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References
1. A. Sobiczewski, F.A. Gareev, B.N. Kalinkin, Phys. Lett. 22, 500 (1966).
2. W.D. Myers, W.J. Światecki, Nucl. Phys. 81, 1 (1966).
3. S.G. Nilsson, S.G. Thompson, C.F. Tsang, Phys. Lett. B 28, 458 (1969).
4. U. Mosel, W. Greiner, Z. Phys. 222, 261 (1969).
5. Yu.Ts. Oganessian, J. Phys: G: Nucl. Part. Phys. 34, R165 (2007).
6. J.H. Hamilton, S. Hofmann, Y.T. Oganessian, Annu. Rev. Nucl. Part. Sci. 63, 383 (2013).
7. I. Muntian, Z. Patyk, A. Sobiczewski, Phys. At. Nucl. 66, 1015 (2003).
8. I. Muntian, Z. Patyk, A. Sobiczewski, Acta Phys. Pol. B 34, 2141 (2003).
9. I. Muntian, S. Hofmann, Z. Patyk, A. Sobiczewski, Acta Phys. Pol. B 34, 2073 (2003) and A. Sobiczewski, private communication (2014).
10. M. Kowal, P. Jachimowicz, A. Sobiczewski, Phys. Rev. C 82, 014303 (2010) and A. Sobiczewski, private communication (2014).
11. M. Kowal, P. Jachimowicz, J. Skalski, arXiv:1203.5013v1 [nucl-th] (2012).
12. P. Möller, J.R. Nix, W.D. Myers, W.J. Światecki, At. Data Nucl. Data Tables 59, 185 (1995).
13. P. Möller, J.R. Nix, K.L. Kratz, At. Data Nucl. Data Tables 66, 131 (1997).
14. P. Möller, A.J. Sierk, T. Ichikawa, A. Iwamoto, R. Bengtsson, H. Uhrenholt, S. Åberg, Phys. Rev. C 79, 064304 (2009).
15. P. Möller, A.J. Sierk, T. Ichikawa, A. Iwamoto, M. Mumpower, Phys. Rev. C 91, 024310 (2015).
16. S. Schramm, Phys. Rev. C 66, 064310 (2002) and private communication (2014).
17. S. Liran, A. Marinov, N. Zeldes, Phys. Rev. C 63, 017302 (2000) arXiv:nucl-th/0102055.
18. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, R.N. Sagaidak, I.V. Shirokovsky, Yu.S. Tsyganov, A.A. Voinov, G.G. Gilbektan et al., Phys. Rev. C 74, 044602 (2006).
19. Yu.Ts. Oganessian, F.Sh. Abdullin, C. Alexander, J. Binder, R.A. Boll, S.N. Dmitriev, J. Ezold, K. Felker, J.M. Gostic, R.K. Grzywacz et al., Phys. Rev. Lett. 109, 162501 (2012).
20. S. Hofmann, S. Heinz, R. Mann, J. Maurer, J. Khuyagbaatar, D. Ackermann, S. Antalic, W. Barth, M. Block, H.G. Burkhard et al., Eur. Phys. J. A 48, 62 (2012).
21. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, R.N. Sagaidak, I.V. Shirokovsky, Yu.S. Tsyganov, A.A. Voinov, A.N. Mezentsev et al., Phys. Rev. C 79, 024603 (2009).
22. S. Hofmann, D. Ackermann, S. Antalic, V.F. Comas, S. Heinz, J.A. Heredia, F.P. Helberger, J. Khuyagbaatar, B. Kindler, I. Kojocharov et al., GSI Scientific Report 2008, GSI Report 2009-1, 131 (2009).
23. J. Khuyagbaatar, A. Yakushev, Ch.E. Düllmann, H. Nitsche, J. Roberto, D. Ackermann, L-L. Andersson, M. Assai, H. Brand, M. Block et al., GSI Scientific Report 2012, GSI Report 2013-1, 131 (2013).
24. S. Hofmann, S. Heinz, R. Mann, J. Maurer, G. Münzenberg, S. Antalic, W. Barth, H.G. Burkhard, L. Dahl, K. Eberhardt et al., to be published in Eur. Phys. J. A.
25. S. Hofmann, Super-heavy nuclei: current status and future developments, in International Symposium on Super Heavy Nuclei, College Station, TX, USA (2015), http://cyclotron.tamu.edu/she2015/assets/pdfs/presentations/Hofmann_SHE_2015_TAMU.pdf.
26. V.K. Utyonkov, N.T. Brewer, Yu.Ts. Oganessian, K.P. Rykaczewski, F.Sh. Abdullin, S.N. Dmitriev, R.K. Grzywacz, M.G. Itkis, K. Miernik, A.N. Polyakov et al., Phys. Rev. C 92, 034609 (2015).
27. K. Morita, K. Morimoto, D. Kaji, H. Haba, Y. Wakahayashi, M. Takeyama, S. Yamaki, K. Tanaka, H. Hasche, M. Huang, et al., RIKEN Accelerator Progress Report (APR), to be published (2015).
28. K. Morita, SHE research at RIKEN/GARIS, in International Symposium on Super Heavy Nuclei, College
Station, TX, USA (2015), http://cyclotron.tamu.edu/she2015/assets/pdfs/presentations/Morita_SHE2015_TAMU.pdf.

29. V.M. Strutinsky, Nucl. Phys. A 95, 420 (1967).
30. M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. Cormick, X. Xu, B. Pfeiffer, Chin. Phys. 36, 1603 (2012).
31. G. Audi, M. Wang, A.H. Wapstra, F.G. Kondev, M. Cormick, X. Xu, B. Pfeiffer, Chin. Phys. 36, 1287 (2012).
32. P.A. Ellison, K.E. Gregorich, J.S. Berryman, D.L. Bleuel, R.M. Clark, I. Dragojevic, J. Dvorak, P. Fallon, C. Fineman-Sotomayor, J.M. Gates et al., Phys. Rev. Lett. 105, 182701 (2010).
33. A. Sobiczewski, K. Pomorski, Prog. Part. Nucl. Phys. 58, 292 (2007).
34. S. Cwiok, W. Nazarewicz, P.H. Heenen, Phys. Rev. Lett. 83, 1108 (1999).
35. W.J. Świątecki, K. Siwek-Wilczyńska, J. Wilczyński, Acta Phys. Pol. B 38, 1565 (2007).
36. R. Smolanczuk, J. Skalski, A. Sobiczewski, Phys. Rev. C 52, 1871 (1995).
37. R. Smolanczuk, Phys. Rev. C 56, 812 (1997).
38. G. Henning, T.L. Khoo, A. Lopez-Martens, D. Seweryniak, M. Alcorta, M. Asai, B.B. Back, P.F. Bertone, D. Boilley, M.P. Carpenter et al., Phys. Rev. Lett. 113, 262505 (2014).
39. Z. Patyk, J. Skalski, A. Sobiczewski, S. Cwiok, Nucl. Phys. A 502, 591c (1989).
40. A. Sobiczewski, Phys. Part. Nucl. 25, 295 (1994).
41. K. Siwek-Wilczyńska, T. Cap, J. Wilczyński, Int. J. Mod. Phys. E 19, 500 (2010).
42. V.I. Zagrebaev, W. Greiner, Phys. Rev. C 78, 034610 (2008) and private communication (2011).
43. A.K. Nasirov, G. Giardina, G. Mandaglio, M. Manganaro, F. Hanappe, S. Heinz, S. Hofmann, A.I. Muminov, W. Scheid, Phys. Rev. C 79, 024606 (2009).
44. G.G. Adamian, N.V. Antonenko, W. Scheid, Eur. Phys. J. A 41, 235 (2009).
45. K. Siwek-Wilczyńska, T. Cap, M. Kowal, A. Sobiczewski, J. Wilczyński, Phys. Rev. C 86, 014611 (2012).
46. T. Cap, K. Siwek-Wilczyńska, M. Kowal, J. Wilczyński, Phys. Rev. C 88, 037603 (2013).
47. J.C. Pei, W. Nazarewicz, J.A. Sheikh, A.K. Kerman, Phys. Rev. Lett. 102, 192501 (2009).
48. J.A. Sheikh, W. Nazarewicz, J.C. Pei, Phys. Rev. C 80, 011302 (2009).
49. A.N. Bezbakh, T.M. Shneidman, G.G. Adamian, N.V. Antonenko, J. Phys.: Conf. Ser. 580, 012026 (2015).
50. M.G. Itkis, Yu.Ts. Oganessian, V.I. Zagrebaev, Phys. Rev. C 65, 044602 (2002).
51. V.I. Zagrebaev, M.G. Itkis, Yu.Ts. Oganessian, Phys. At. Nucl. 66, 1033 (2003).
52. Yu.Ts. Oganessian, V.K. Utyonkov, Yu.V. Lobanov, F.Sh. Abdullin, A.N. Polyakov, I.V. Shirakovskiy, Yu.S. Tsyganov, G.G. Gulbekian, S.L. Bogomolov, B.N. Gikal et al., Phys. Rev. C 70, 064609 (2004).
53. R. Bass, Nucl. Phys. A 231, 45 (1974).
54. W.D. Myers, W.J. Świątecki, Nucl. Phys. A 601, 141 (1996).
55. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. 72, 733 (2000).
56. P. Möller, A. Iwamoto, Nucl. Phys. A 575, 381 (1994).
57. V.I. Zagrebaev, W. Greiner, Nucl. Phys. A 944, 257 (2015).