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Letter

Impact of nuclear structure on production and identification of new superheavy nuclei

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Abstract. Using the microscopic-macroscopic approach based on the modified two-center shell model, the low-lying quasiparticle spectra, ground-state shell corrections, mass excesses and Q_α-values for even Z superheavy nuclei with $108 \leq Z \leq 126$ are calculated and compared with available experimental data. The predicted properties of superheavy nuclei show that the next doubly magic nucleus beyond ^{208}Pb is at $Z \geq 120$. The perspective of using the actinide-based complete fusion reactions for production of nuclei with $Z = 120$ is studied for supporting future experiments.

Experiments on complete fusion reactions with ^{48}Ca beam and various actinide targets were successfully carried out at FLNR (Dubna), GSI (Darmstadt), and LBNL (Berkeley) in order to synthesize superheavy elements (SHE) with $Z = 112$–118 [1–11]. The found experimental trend of nuclear properties (Q_α-values and half-lives) and cross-sections of production of SHE reveals increasing stability of nuclei approaching the spherical closed neutron shell $N = 184$, and also indicates a relatively small effect of the proton shell at $Z = 114$ [3,4,12–15] predicted with the microscopic-macroscopic models [16–22]. This experimental observation seems to be in accordance with the predictions of relativistic and nonrelativistic mean-field models [23–26] where the island of stability corresponds to $Z = 120$–126 and $N = 184$. If there is a strong shell effect at $Z = 120$–126, then there is hope to synthesize new SHE with $Z \geq 120$ by using the present experimental set up and actinide-based reactions with neutron-rich stable projectiles heavier than ^{48}Ca.

With the predictions of the microscopic-macroscopic models [16], where the proton shell at $Z = 114$ is expected, the reactions ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm would result in $Z = 120$ nuclei with maximum cross-sections of 1.2 and 0.2 fb, respectively, in a $4n$ evaporation channel [27]. If the predictions of the phenomenological model [28–31], where the proton shell is assumed at $Z = 126$, are correct, the reactions ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm would lead to the production of $Z = 120$ nuclei with cross-sections of 550 fb ($3n$ evaporation channel) and 40 fb ($4n$ evaporation channel), respectively [27]. So, the structure of SHE crucially influences the evaporation residue cross-sections in actinide-based complete fusion reactions. Because nuclear models contain a number of parameters which are fixed for the best description of known nuclei, their predictive power could be smaller for nuclei far from the well-studied region of the nuclear chart. To improve the predictions, one can specially adjust the parameters for describing the known properties of shell-stabilized nuclei close to the region of interest.

In refs. [32,33] we proposed a microscopic-macroscopic approach based on the modified two-center shell model (TCSM) [34]. The parameters were set so to describe the spins and parities of the ground state of known heavy nuclei (rare earth nuclei, actinides, and transfermium nuclei). The aim of the present article is to apply this approach to SHE and to reveal the trends in shell corrections, binding energies and Q_α-values with Z and, finally, to find out the range of location (position) of the next proton shell closure beyond $Z = 82$. The dependence of the calculated production cross-sections and half-lives of new superheavy nuclei on the position of the proton shell closure is analyzed. The evaporation residue cross-sections and lifetimes for unknown nuclei with Z=120 are predicted for forthcoming experiments using the complete fusion reactions ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm. Isotopic trends of the production cross-section are also presented.

In our microscopic-macroscopic approach the nuclear shape parametrization adopted in the modified TCSM [34] is used to minimize the potential energy surface. The single-particle spectra in the ground states are used to find the shell and pairing corrections as well as the quasiparticle spectra. For the shell-stabilized nuclei, the absolute value of the ground-state shell correction determines the height of the fission barrier. For nuclei with $Z < 112$,

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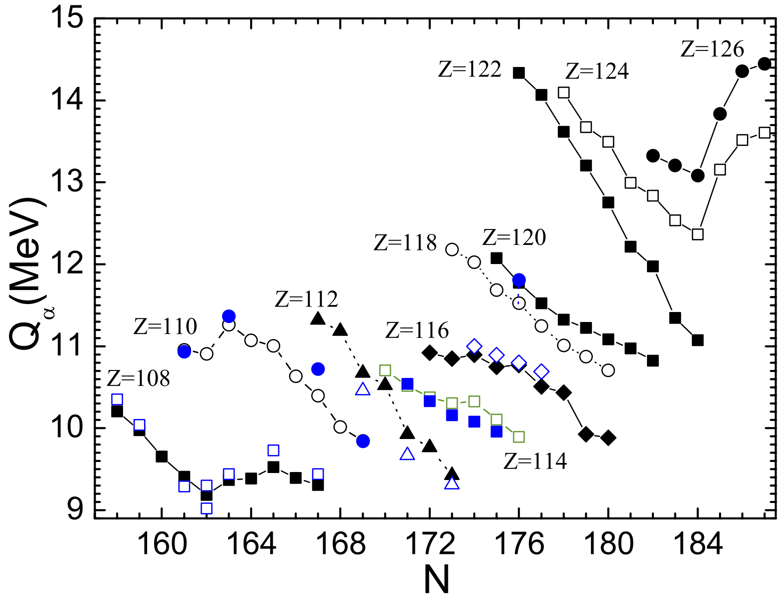

Fig. 1. Calculated α-decay energies (symbols connected by lines) are compared with available experimental data (symbols) [1–4,9] for even-Z nuclei with $108 \leq Z \leq 126$.

the absolute values of the microscopic corrections obtained in our calculations seem to be close to those obtained in refs. [16–22]. The nuclear binding energy is calculated as the sum of a smoothly varying macroscopic energy, calculated with the liquid-drop model, and the microscopic correction consisting of the shell and pairing corrections. With the obtained binding energies we calculate the values of Q_α for the ground-state-to-ground-state α-decays. In order to estimate α-decay half-lives T_α, we use the expression recently suggested in ref. [35]. Details of calculations as well as the parameters used are described in refs. [32,33,36,37].

Here, we treat only the isotopes of superheavy nuclei with even Z which can be reached in complete fusion reactions with available stable projectiles and targets. The results for odd Z nuclei are given in ref. [37]. As seen in fig. 1, the calculated values of Q_α are in good agreement, within 0.3 MeV, with the available experimental data. The shell at $N = 162$ is pronounced in our calculations as in refs. [16–22]. The shell effects at $Z = 114$ and $N = 172$–176 provide a rather weak dependence of Q_α on N. The strong role of the shell at $N = 184$ is reflected in the well-pronounced minimum of Q_α. As in our case, the dependence of Q_α on N becomes weaker at $N = 172$–176 in refs. [16–22] where smaller shell effects at $Z = 120$–126 are predicted. The phenomenological model [28–31] results in no shell effects at $N = 162$ and at $N = 172$–176. However, as in our case, there is strong evidence of a shell closure at $N = 184$.

The calculated values of Q_α for nuclei with $Z \geq 120$ are close to those given in refs. [28–31], but they are about 2 MeV smaller than in refs. [16–22]. Indeed, in refs. [28–31], the shell closure is assumed at $Z = 126$. Larger shell effects revealed in our calculations at $Z = 120$ would result in larger fission barriers and more stability with respect to α-decay and spontaneous fission. With Q_α presented in fig. 1, one can expect T_α in the interval 1.7 ms–0.2 s for $^{295-299}120$. With the predictions of refs. [16–22] T_α would be (1–20) μs. So, the experimental identification of $Z = 120$ nuclei would be extremely interesting for choosing a proper set of parameters in the microscopical calculations.

In figs. 2 and 3 the energies of two-quasiparticle states are presented for the nuclei of α-decay chains of $^{296,298}120$. While for nuclei with $Z \leq 118$ the first two-quasiproton states have energies smaller than 1.2 MeV, in $^{296,298}120$ the energies of the first two-quasiproton states are at about 1.9 MeV. This indicates a larger gap in the proton single-particle spectrum. So, the shell effects become stronger beyond $Z = 114$. The α-decay chain starting from $^{298}120$ likely terminates at ^{282}Cn by spontaneous fission [1]. The α-decay chain starting from $^{296}120$ probably terminates at $^{284}114$ by spontaneous fission. Indeed, $^{284}114$ is predicted to decay by spontaneous fission in 0.012 s [38] whereas α-decay is expected to have a longer half-life of 0.045 s.

The two-quasiparticle isomeric states are predicted in our calculations. The states $8^-_\nu\{15/2^-[707] \otimes 1/2^+[600]\}$ and $11^-_\nu\{15/2^-[707] \otimes 7/2^+[604]\}$ in $^{298}120$, the state $13^-_\nu\{11/2^+[606] \otimes 15/2^-[707]\}$ in $^{294}118$, and the state $8^+_\pi\{7/2^-[503] \otimes 9/2^-[505]\}$ in $^{290}116$ (fig. 2) can be treated as isomers in the region of the heaviest nuclei. If they survive long enough (> 0.05 s) with respect to the γ-decay, one can expect α-decays from these states which will be distinguished from the ground-state-to-ground-state α-decays by other T_α and energies. The spontaneous fission from these isomeric states seems to be delayed with respect to the spontaneous fission from the ground state. The lowest two-quasiparticle isomeric states in $^{296}120$, $^{292}118$, $^{288}116$, and $^{284}114$ are $13^-_\nu\{11/2^+[606]\otimes 15/2^-[707]\}$, $8^+_\nu\{5/2^+[602]\otimes 11/2^+[6076]\}$, $8^-_\pi\{7/2^-[503]\otimes$

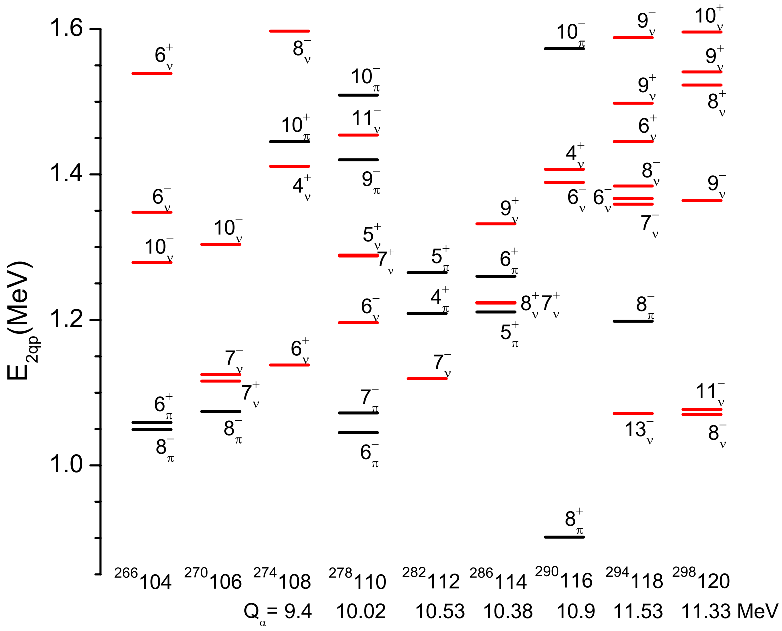

Fig. 2. (Colour on-line) Calculated energies of low-lying two-quasiproton (black signs) and two-quasineutron (red signs) states in the indicated nuclei of the α-decay chain of $^{298}120$. The resulting K values are indicated.

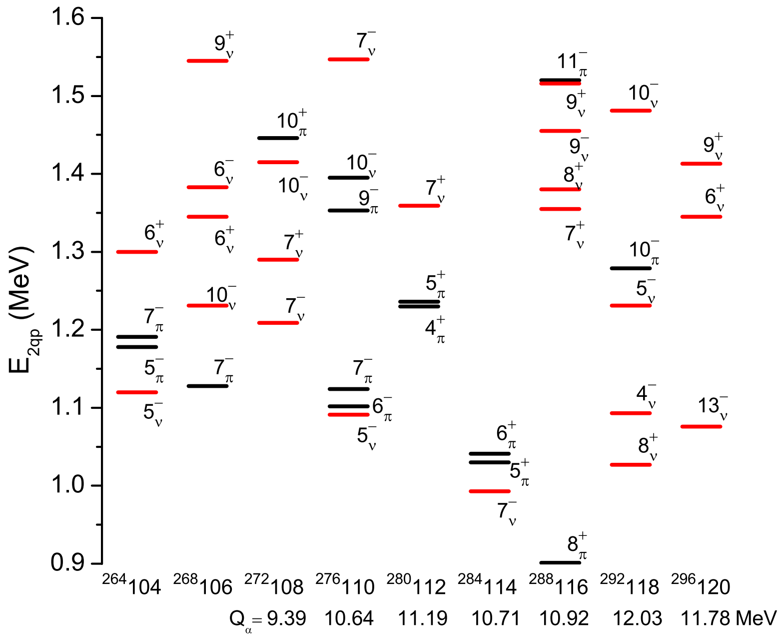

Fig. 3. (Colour on-line) The same as in fig. 2, but for the nuclei of the α-decay chain of $^{296}120$.

$9/2^-[505]\}$, and $7^-_\nu\{1/2^+[611]\otimes 13/2^-[716]\}$, respectively (fig. 3).

The α-decay chains of $^{295,297,299}120$ are expected to be long, at least up to Rf, because the spontaneous fission of odd nuclei is hindered and α-decays occur faster [1]. In figs. 4–6 we show the calculated one-quasiparticle spectra of nuclei of α-decay chains of $^{295,297,299}120$. The possible α-decays are marked. As can be seen in fig. 6, the α-decay of $^{291}116$ is hindered, because the corresponding levels have high energies in the daughter nucleus.

Since in figs. 4–6 the nuclei with $Z > 108$ are only slightly deformed, the quasiparticle spectra are rather dense near the ground states and the appearance of isomeric states is likely. Alpha decays can occur from these isomeric states if they live longer with respect to γ-decay. The α-decays from the isomeric states of $^{295,297,299}120$

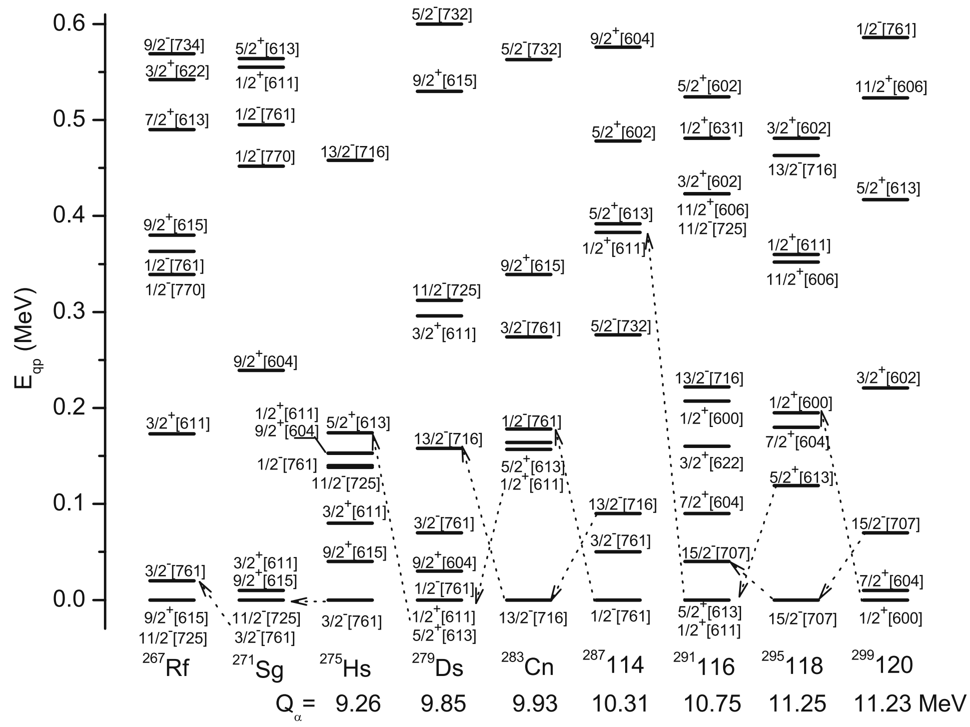

Fig. 4. Calculated energies of low-lying one-quasineutron states in the indicated nuclei of the α-decay chain of ^{299}120. The states are marked by the Nilsson asymptotic quantum numbers. The possible α-decays are shown by arrows.

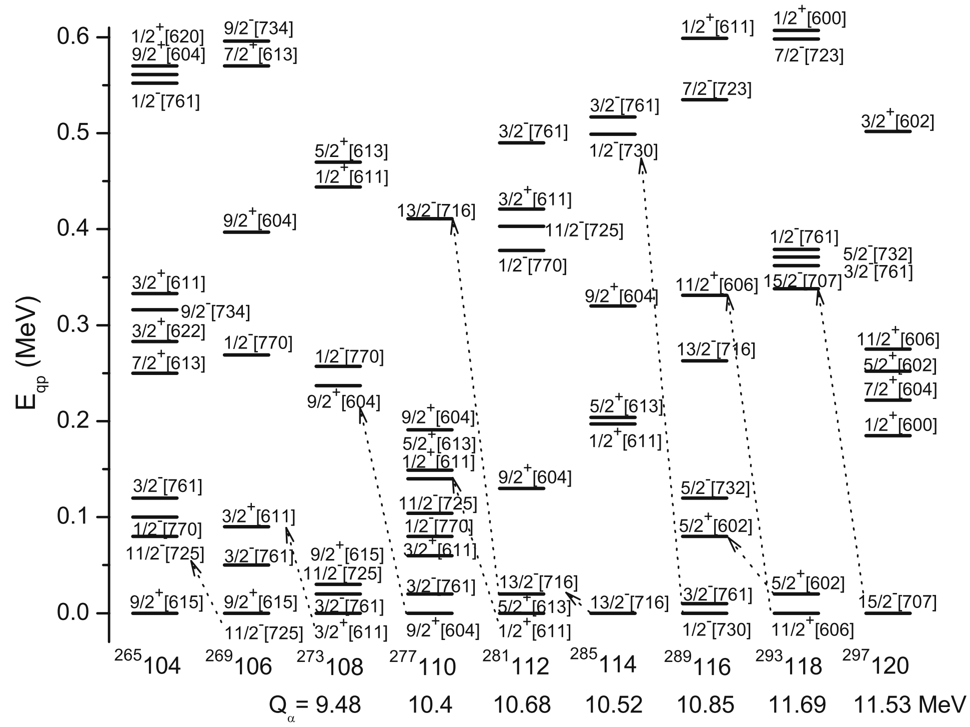

Fig. 5. The same as in fig. 4, but for the nuclei of the α-decay chain of ^{297}120.

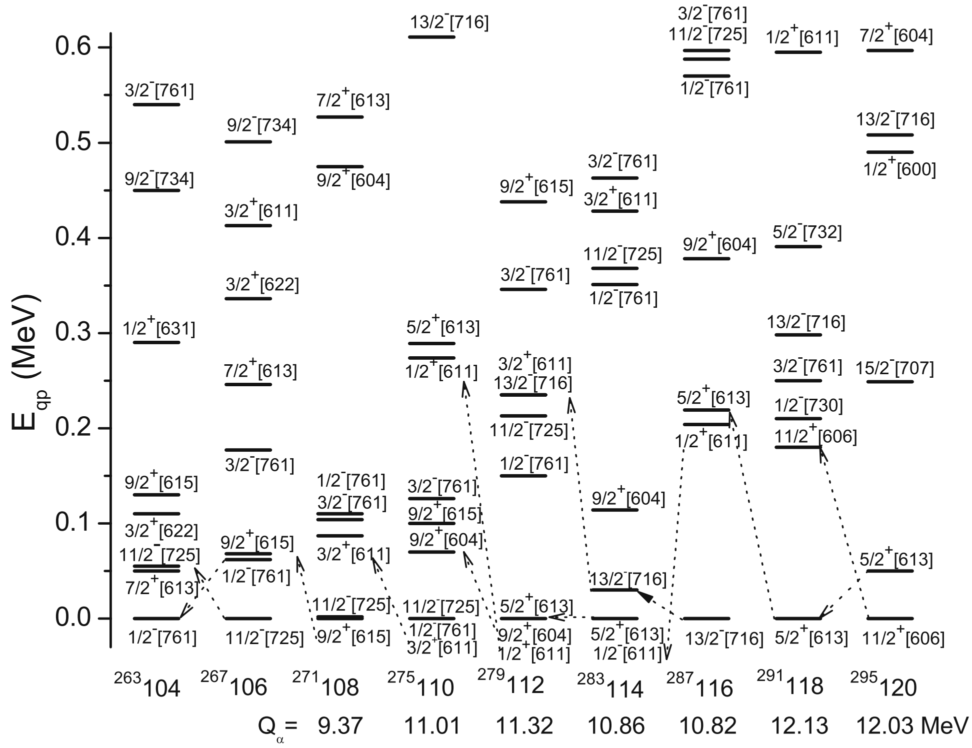

Fig. 6. The same as in fig. 4, but for the nuclei of the α-decay chain of $^{295}120$.

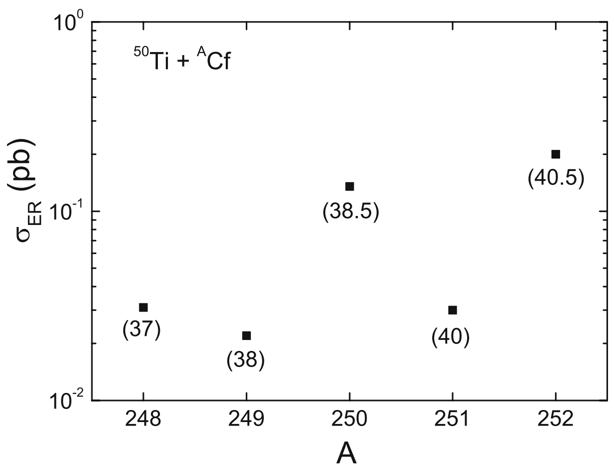

Fig. 7. Evaporation residue cross-sections of the maxima of excitation functions of the reactions ^{50}Ti+^{A}Cf *versus* A. The excitation energies of compound nuclei are given in brackets. Ground-state mass excesses $M_{\rm th}$=211.8, 213.05, 213.76, 215.15, and 216.05 MeV for the nuclei $^{298}120$, $^{299}120$, $^{300}120$, $^{301}120$, and $^{302}120$, respectively, were used in the calculations.

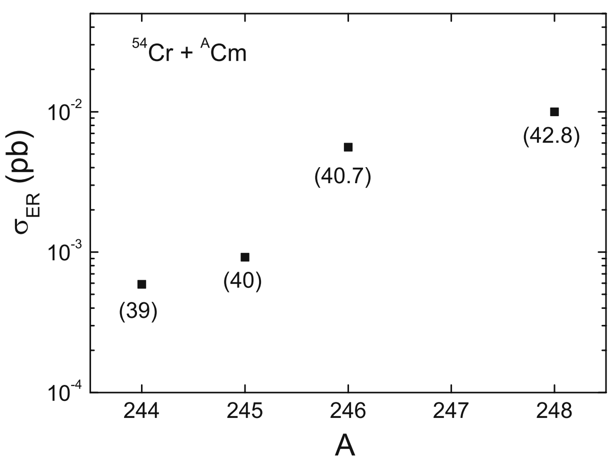

Fig. 8. The same as in fig. 7, but for the reactions ^{54}Cr+^{A}Cm.

and $^{295}118$ are calculated to be faster than from the ground states.

The dinuclear system model [39–49] is successful in describing fusion-evaporation reactions especially related to the production of superheavy nuclei. We use this model to calculate the evaporation residue cross-sections σ_{ER}^{xn}. As estimated, the uncertainty of calculated cross-sections is within a factor of 2–4 using our model applied also for predicting the properties of superheavy nuclei. Because of differences in fission barriers of about 2 MeV, the cross-sections calculated for $Z = 120$ nuclei with the predictions of refs. [28–31] are more than 100 times larger [27,46–48] than those calculated with the predictions of ref. [16].

Using our predictions of nuclear properties, we calculated the evaporation residue cross-sections of the reactions ^{50}Ti+^{A}Cf and ^{54}Cr+^{A}Cm (figs. 7 and 8). At zero excitation energy, the predicted values of fission barriers used in the calculations are in the energy interval 8.1–10.1 MeV. Note that for the reactions ^{48}Ca+^{238}U,

^{244}Pu, ^{248}Cm, ^{249}Cf the calculated and experimental values of evaporation residue cross-sections are quite close [37]. A good description of existing data allows us to be confident in the predictions for the reactions with heavier projectiles. In the ^{50}Ti+^{249}Cf ($Q = -194.75$ MeV) reaction the nucleus ^{295}120 is predicted to be produced in a $3n$ evaporation channel with a cross-section of 23 fb. In the ^{54}Cr+^{248}Cm ($Q = -205.59$ MeV) reaction the compound nucleus would have 3 neutrons more than in the ^{50}Ti+^{249}Cf reaction. Therefore, the decrease of P_{CN} is partly negated by the increase of W_{sur}, and the nucleus ^{298}120 is predicted to be produced with a cross-section of 10 fb ($4n$ evaporation channel). As in refs. [46–48], the isotopic dependence of σ_{ER} is rather weak in the treated interval of mass numbers A. Indeed, the values of σ_{ER} are almost the same in the cases of ^{246}Cm ($Q = -208.07$ MeV) and ^{248}Cm as target. There is a certain interval of mass numbers of target nuclei where the product $P_{CN}W_{sur}$ changes only weakly [46–48].

In conclusion, the calculations performed with the modified TCSM reveal quite strong shell effects at $Z =$ 120–126. The obtained properties of superheavy nuclei clearly demonstrate that the next doubly magic nucleus beyond ^{208}Pb is probably at $Z \geq 120$. Thus, our microscopic-macroscopic treatment qualitatively leads to results close to those of the self-consistent microscopic treatments. However, it should be stressed that this conclusion is model dependent. If our prediction of the structure of heaviest nuclei is correct, than one can expect the production of evaporation residues $Z = 120$ in the complete fusion reactions ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm with cross-sections of 23 and 10 fb, respectively. Nuclei with $Z = 120$ and $N =$ 178–182 are expected to have Q_α of about 11.3 MeV and lifetimes of more than 90 ms according to our predictions. The experimental determination of Q_α of at least one isotope of a $Z = 120$ nucleus would help us to fix proper shell-model parameters for $Z > 118$. The measurement of excitation functions provides a good test for the predictions of the models as well.

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