Calculations of the cross sections for synthesis of new $^{293-296}^{118}$ isotopes in $^{249-252}$Cf($^{48}$Ca,xn) reactions

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(Dated: May 11, 2014)

A project of using a target consisting of the mixture of $^{249-252}$Cf isotopes to be bombarded with the $^{48}$Ca beam, aimed to synthesize new isotopes of the heaviest known element $Z = 118$, is under way at the FLNR in Dubna. In the present work excitation functions for all the reactions: $^{249}$Cf($^{48}$Ca,xn)$^{297-299}$118, $^{250}$Cf($^{48}$Ca,xn)$^{298-299}$118, $^{251}$Cf($^{48}$Ca,xn)$^{299-301}$118 and $^{252}$Cf($^{48}$Ca,xn)$^{300-301}$118 have been calculated in the framework of the fusion-by-diffusion model, assuming fission barriers, ground-state masses and shell effects of the superheavy nuclei predicted by Kowal et al. Energy dependence of the effective cross sections for the synthesis of selected new isotopes: $^{293}$118, $^{294}$118, $^{295}$118 and $^{296}$118 is predicted for the particular isotopic composition of the Cf target prepared for the Dubna experiment.

PACS numbers: 25.70.Jj, 25.70.Gh

Following the great success of the synthesis of new superheavy nuclei of $Z = 113-118$ in hot fusion reactions, in which various actinide targets ($^{242,244}$Pu, $^{243}$Am, $^{245,248}$Cm, $^{249}$Bk and $^{250}$Cf) were bombarded with $^{48}$Ca projectiles $^1$, a number of theoretical attempts to reproduce the observed synthesis cross sections have been made. Systematic model calculations were done for this class of hot fusion reactions with the Langevin dynamics model $^2$, fusion-by-diffusion model $^3$ and also with a phenomenological version of the di-nuclear system (DNS) model $^4$. In Ref. $^5$, calculations for the $^{48}$Ca induced reactions on $^{249-252}$Cf targets have been done with the DNS model.

The aim of this Brief Report is to give predictions for the experiment being under way at the Flerov Laboratory of Nuclear Reactions in Dubna, in which a target consisting of a mixture of $^{249-252}$Cf isotopes will be bombarded with the $^{48}$Ca beam in order to synthesize new isotopes of the element $Z = 118$. We present the energy dependence of the evaporation-residue cross sections for synthesis of $^{293}$118, $^{294}$118, $^{295}$118 and $^{296}$118 nuclides, predicted within the fusion-by-diffusion (FBD) model $^6$ $^8$. Below we give a short description of this model.

As in other theoretical models used to describe synthesis of superheavy nuclei, the partial evaporation residue cross section $\sigma_{ER}(l)$ is factorized in the FBD model as the product of the partial capture cross section $\sigma_{cap}(l) = \pi\bar{\alpha}^2(2l + 1)T(l)$, the fusion probability $P_{fus}(l)$ and the survival probability $P_{surv}(l)$:

$$\sigma_{ER} = \pi\bar{\alpha}^2 \sum_{l=0}^{\infty}(2l + 1)T(l)P_{fus}(l)P_{surv}(l).$$

(1)

Here, $\bar{\alpha}$ is the wave length, $\bar{\alpha}^2 = \hbar^2/2\mu E_{c.m.}$, and $\mu$ is the reduced mass of the colliding system. The capture transmission coefficients, $T(l)$, are calculated from the systematics of the fusion cross sections for lighter systems $^8$ $^9$.

The fusion probability $P_{fus}(l)$ is a key factor in all models aimed to describe fusion of superheavy systems. It tells us what is the probability that after reaching the capture configuration (sticking), the colliding system will eventually overcome the saddle point and fuse, avoiding reseparation. It is well known that for very heavy and less asymmetric systems, $P_{fus}(l)$ is much smaller than 1 and thus is responsible for the dramatically small cross sections for the production of superheavy nuclei. The fusion hindrance in these reactions is caused by the fact that for the heaviest compound nuclei the saddle configuration is more compact than the configuration of the two initial nuclei at sticking. It is assumed in the FBD model that after the sticking, a neck between the two nuclei grows rapidly at an approximately fixed mass asymmetry and constant length of the system $^9$ $^10$ bringing the system to the “injection point” somewhere along the bottom of the asymmetric fission valley. To overcome the saddle point and fuse, the system must climb uphill from the injection point to the saddle in the process of thermal fluctuations in shape degrees of freedom. (A similar scenario of fusion of the heaviest nuclear systems has been demonstrated analytically in a simple two-dimensional Langevin dynamics model $^10$.) The location of the injection point, $s_{inj}$, is the only adjustable parameter of the FBD model. It was shown in Ref. $^9$ that by solving the Smoluchowski diffusion equation, the probability that the system injected on the outside of the saddle point at an energy $H$ below the saddle point will achieve fusion is

$$P_{fus} = \frac{1}{2}(1 - \text{erf}\sqrt{H/T}),$$

(2)
where $T$ is the temperature of the fusing system. The energy threshold $H$ opposing fusion in the diffusion process is thus the difference between the energy of the saddle point and the energy of the combined system at the injection point, calculated using the algebraic approximate expressions given in Ref. 3. The corresponding values of the rotational energy at the injection point and at the saddle point are calculated assuming the rigid-body moments of inertia at these configurations.

The last factor in Eq. (1), $P_{\text{surv}}(l)$, is the probability for the compound nucleus to decay to the ground state of the residual nucleus via evaporation of light particles (neutrons) and thus avoid fission (survive). To calculate the survival probability $P_{\text{surv}}$, the standard statistical model was used by applying the Weisskopf formula for the neutron emission width $\Gamma_n$ and the standard expression of the transition-state theory for the fission width $\Gamma_f$. The level density parameters $a_n$ and $a_f$ for neutron evaporation and fission channels were calculated as proposed by Reisdorf [11] with shell effects accounted for by the Ignatyuk formula [12]. All details can be found in Ref. 8. In case of calculating multiple evaporation (xn) channels a simplified algorithm avoiding the necessity of using the Monte Carlo method was used [13].

As it follows from the above description, the cross section calculations require to know individual characteristics of the synthesized compound nuclei and their decay products, first of all, the fission barriers, ground-state masses and shell effects as well as deformations of the compound nuclei in the ground state and the saddle-point configuration. It was demonstrated in Ref. 3 that the fission barriers and other characteristics of superheavy nuclei calculated according to the Warsaw macroscopic-microscopic model [14, 15] have proved to well reproduce cross sections of hot (xn) fusion reactions leading to the synthesis of $Z = 114$–118 superheavy nuclei. The recent Warsaw group calculations have been done in multidimensional deformation space including nonaxial and reflection-asymmetric shapes. As tables in Refs. [14, 15] are limited to even-even nuclei, the fission barrier heights for the odd-$A$ nuclei have been calculated separately [16, 17] by adding the energy of the odd particle occupying a single-particle state.

As mentioned above, the heaviest new element with atomic number 118 was synthesized in the $^{249}$Cf($^{48}$Ca,xn)$^{294}$118 reaction [1, 18]. This particular experiment was carried out by using a nearly mono-isotopic $^{249}$Cf target of $>98\%$ purity [18]. Recently, a project to produce a target consisting of the mixture of $^{249}$–$^{252}$Cf isotopes for experiments with the $^{48}$Ca beam was proposed [19]. By using this target, there will be a chance to synthesize more isotopes of element 118, in addition to the $^{294}$118 nuclide that was produced in the earlier experiment [18]. The synthesis efficiency in this experiment is expected to be widened to a larger number of isotopes of element 118 as a result of simultaneous production of different isotopes in several xn channels on different Cf isotopes present in the target mixture. The isotopic content of the prepared target material is $^{249}$Cf ($42.31\%$), $^{250}$Cf ($21.76\%$), $^{251}$Cf ($35.64\%$) and $^{252}$Cf ($0.29\%$) [19].

In the present work we calculated excitation functions for the reactions with all four Cf isotopes present in the target: $^{249}$Cf($^{48}$Ca,xn)$^{297}$–$^{300}$118, $^{250}$Cf($^{48}$Ca,xn)$^{298}$–$^{301}$118, $^{251}$Cf($^{48}$Ca,xn)$^{299}$–$^{302}$118 and $^{252}$Cf($^{48}$Ca,xn)$^{300}$–$^{303}$118. The calculations have been done exactly according to the scheme [3] used for analysis of the whole set of hot fusion reactions leading to the synthesis of elements $Z = 114$–118, with fission barriers and other theoretical characteristics of the superheavy compound nuclei [14, 17], and systematics of the injection point distance determined in Ref. 3.

The calculated excitation functions are displayed in Fig. 1. Figure 1a shows the results for the $^{48}$Ca + $^{249}$Cf reaction, in which the $^{294}$118 isotope of element 118 was observed [18] in the 3n reaction channel. Along with the calculated excitation functions, the experimental value of the cross section evaluated at $E_{c.m.} \approx 210$ MeV and the upper limit of the 3n cross section at $E_{c.m.} \approx 205$ MeV are shown. For easier comparisons, dashed lines in all figures show the 1 pb level of the cross section that is a typical limit of sensitivity in modern experiments aimed to synthesize superheavy elements. It should be noted that in addition to the 3n reaction, our calculations for the $^{48}$Ca + $^{249}$Cf reaction predict a sizable cross section of the 4n reaction leading to the synthesis of the $^{293}$118 nuclide. The maximum of the theoretical 4n excitation function is located at $E_{c.m.} \approx 217$ MeV, that is well above the range of energies covered in the experiment [18].

As seen from Fig. 1b, the reaction on the $^{250}$Cf isotope gives a chance to observe the new nuclide $^{295}$118 expected to be produced with relatively large cross section of about 3 pb in the 3n reaction at $E_{c.m.} \approx 208$ MeV. Also the $^{294}$118 isotope is expected to be produced in the $^{48}$Ca + $^{250}$Cf reaction with a measurable cross section of about 1 pb in the 4n channel. The maximum of the 4n excitation function is predicted at $E_{c.m.} \approx 216$ MeV.

Our predictions show, unfortunately, that the use of the most neutron rich isotopes, $^{251}$Cf and $^{252}$Cf, is not a perspective way for synthesis of new isotopes of the element 118. As seen from Figs. 1c and 1d, the expected cross sections become extremely small, of the order of 0.1 pb, due to the decreasing theoretical values of the fission barrier with the increasing neutron number for the heaviest $Z = 118$ isotopes.

Figure 2 displays the excitation functions for the synthesis of separate isotopes $^{293}$118, $^{294}$118, $^{295}$118 and $^{296}$118, calculated for the mixture $^{249}$–$^{252}$Cf target, taking the actual content of each isotope in the mixture. The “weighted cross section” displayed in the diagrams is the sum of the synthesis cross section for a given final isotope of element 118 produced on all four Cf isotopes in the corresponding xn reaction channels, reduced by the factor of relative content of the target isotope in the mixture. For example, the weighted cross section for synthesis of the
The calculations have been done within the fusion-by-diffusion model, with fission barriers and other synthesized in hot fusion reactions. Theoretical calculations [17] predict that the life-times of the α\(^{285}\)\(^{118}\) nucleus and \(\alpha\)^{295}\(^{118}\) nucleus should follow the decay of the already discovered \(\alpha\)^{293}\(^{118}\). Its decay chain should follow the decay of the already discovered \(\alpha\)^{291}\(^{118}\) nuclei. Possible measurable cross section of few hundreds fb is expected for the unknown yet isotope \(\alpha\)^{293}\(^{118}\) (see Fig. 2a). In this case the maximum cross section is predicted around \(E_{c.m.} = 218\) MeV. Therefore an attempt to synthesize the \(\alpha\)^{293}\(^{118}\) isotope would probably require to carry out a separate run at an energy \(E_{c.m.} = 216–218\) MeV, in addition to the main experiment at \(E_{c.m.} = 208–210\) MeV focused on the synthesis of the \(\alpha\)^{293}\(^{118}\) and \(\alpha\)^{295}\(^{118}\) nuclei. Possible discovery of the \(\alpha\)^{293}\(^{118}\) isotope would be extremely valuable because its α decay product, \(289\)LV, is also unknown and further decay products, \(285\)Ft and \(281\)Cn, would be important cross checks of the present boundary of nuclides synthesized in hot fusion reactions. Theoretical calculations [17] predict that the life-times of the \(\alpha\)^{293}\(^{118}\) nucleus and of its α decay products are long enough to be detected in the experiment.

In summary, we calculated excitation functions of the synthesis of isotopes of the element 118 in \(^{249–252}\)Cf\(^{148}\)Ca\(^{xn}\) reactions. The calculations have been done within the fusion-by-diffusion model, with fission barriers and other theoretical characteristics of the superheavy compound nuclei calculated with the Warsaw macroscopic-microscopic model. Anticipating implementation of the Dubna experiment with the target consisting of the mixture of the \(^{249–252}\)Cf isotopes [19], calculations of the excitation functions for the synthesis of separate isotopes \(^{293}\)\(^{118}\), \(^{294}\)\(^{118}\), \(^{295}\)\(^{118}\), \(^{296}\)\(^{118}\), and \(^{297}\)\(^{118}\) are drawn the same color.

As one can see from Fig. 2, the largest weighted cross section, close to 1 pb, is expected for the production of the \(^{295}\)\(^{118}\) nucleus at \(E_{c.m.} \approx 208\) MeV (see Fig. 2c). The half life of \(^{295}\)\(^{118}\) is expected [17] to be longer than that of the already detected isotope \(^{294}\)\(^{118}\), enabling experimental identification of the new isotope of element 118. Its decay chain should follow the decay of the already discovered \(^{291}\)Lv nucleus.

A possibly measurable cross section of few hundreds fb is expected for the unknown yet isotope \(^{293}\)\(^{118}\) (see Fig. 2a). In this case the maximum cross section is predicted around \(E_{c.m.} = 218\) MeV. Therefore an attempt to synthesize the \(^{293}\)\(^{118}\) isotope would probably require to carry out a separate run at an energy \(E_{c.m.} = 216–218\) MeV, in addition to the main experiment at \(E_{c.m.} = 208–210\) MeV focused on the synthesis of the \(^{293}\)\(^{118}\) and \(^{295}\)\(^{118}\) nuclei. Possible discovery of the \(^{293}\)\(^{118}\) isotope would be extremely valuable because its α decay product, \(^{289}\)Lv, is also unknown and further decay products, \(^{285}\)Ft and \(^{281}\)Cn, would be important cross checks of the present boundary of nuclides synthesized in hot fusion reactions. Theoretical calculations [17] predict that the life-times of the \(^{293}\)\(^{118}\) nucleus and of its α decay products are long enough to be detected in the experiment.

In summary, we calculated excitation functions of the synthesis of isotopes of the element 118 in \(^{249–252}\)Cf\(^{148}\)Ca\(^{xn}\) reactions. The calculations have been done within the fusion-by-diffusion model, with fission barriers and other theoretical characteristics of the superheavy compound nuclei calculated with the Warsaw macroscopic-microscopic model. Anticipating implementation of the Dubna experiment with the target consisting of the mixture of the \(^{249–252}\)Cf isotopes [19], calculations of the excitation functions for the synthesis of separate isotopes \(^{293}\)\(^{118}\), \(^{294}\)\(^{118}\), \(^{295}\)\(^{118}\), \(^{296}\)\(^{118}\), and \(^{297}\)\(^{118}\) are drawn the same color.
FIG. 2: (Color online) Energy dependence of the weighted cross sections for the synthesis of separate isotopes ²⁹³₁₁₈, ²⁹⁴₁₁₈, ²⁹⁵₁₁₈ and ²⁹⁶₁₁₈ in various channels of the ²⁴⁹⁻²⁵₂Cf(⁴⁸Ca,xn) reactions, predicted for the isotopic composition of the Cf target as planned to be used in the experiment at FLNR in Dubna: 42.31% of ²⁴⁹Cf, 21.76% of ²⁵⁰Cf, 35.64% of ²⁵¹Cf and 0.29% of ²⁵²Cf [19]. The data points in Fig. 2(b) refer to the ²⁴⁹Cf(⁴⁸Ca,3n) reaction [see Fig. 1(a)]. They are rescaled accordingly with the definition of the “weighted cross section”.

²⁹⁵₁₁₈ and ²⁹⁶₁₁₈ have been done for the particular isotopic composition of the Cf target prepared for this experiment. The calculations predict observation of the already known nuclide ²⁹⁴₁₁₈ with the weighted synthesis cross section of about 0.2–0.3 pb at $E_{c.m.} = 208–216$ MeV, and also the new nuclide ²⁹⁶₁₁₈ with a larger weighted cross section of about 1 pb at the bombarding energy $E_{c.m.} \approx 208$ MeV. There is also a chance to synthesize another new nuclide ²⁹³₁₁₈ (and its unknown decay product ²⁸⁹Lv) with the weighted cross section of about 0.2 pb at $E_{c.m.} = 216–218$ MeV.

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