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PRODUCTION OF NEW SUPERHEAVY NUCLEI IN COMPLETE FUSION REACTIONS*

G.G. Adamian[a,b,c], N.V. Antonenko[a,c], W. Scheid[d]

[a]Joint Institute for Nuclear Research, Dubna, Russia
[b]Institute of Nuclear Physics, Uzbekistan
[c]Gesellschaft für Schwerionenforschung mbH, Darmstadt, Germany
[d]Institut für Theoretische Physik der Justus-Liebig-Universität
Giessen, Germany

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Within the dinuclear system model we analyse the production of yet unknown superheavy nuclei in actinide-based complete fusion reactions. The yields of superheavies with $Z > 118$ are sensitive to the location of the next proton shell closure beyond ^{208}Pb.

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The study and synthesis of superheavy elements (SHE) has constituted one of the main venues in nuclear physics. The cold Pb- and Bi-based [1] and hot actinide-based [2] complete fusion reactions were carried out in order to approach "the island of stability" predicted for the SHE with charge number $Z = 114$ and neutron number $N = 184$ by the macroscopic–microscopic models [3–6]. The systematic of cross-sections and half-lives of the SHE obtained in Dubna with ^{48}Ca induced reactions reveals the increasing stability of nuclei approaching the spherical closed shell $N = 184$. No discontinuity is observed yet when the proton number 114 is crossed at the neutron numbers 172 to 176. As known, the shell at $Z = 114$ disappears in the relativistic and nonrelativistic mean field models [7]. The island of stability close to the element $Z = 120$, or 124, or 126 and $N = 184$ was predicted within these models. If these predictions are correct the survival probability of compound nucleus with $Z \geq 120$ may be much higher than the one of a compound nucleus with $Z = 114$ if the shell closure at $Z \geq 120$ has a stronger influence on the stability of the SHE than the subshell closure at $Z = 114$. Then, there is some hope to synthesize new SHE with $Z \geq 120$ by

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using the present experimental set-up and the actinide-based reactions with projectiles heavier than ^{48}Ca.

The dinuclear system (DNS) model [8] is successful in describing fusion–evaporation reactions especially related to the production of superheavy nuclei. In the DNS model the compound nucleus is reached by a series of transfers of nucleons from the light nucleus to the heavy one. The dynamics of the DNS is considered as a combined diffusion in the degrees of freedom of the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2)$ (A_1 and A_2 are the mass numbers of the DNS nuclei) and of the internuclear distance R. The evaporation residue cross-section is written as

$$\sigma_{\rm ER}(E_{\rm c.m.}) = \sum_J \sigma_{\rm c}(E_{\rm c.m.}, J) P_{\rm CN}(E_{\rm c.m.}, J) W_{\rm sur}(E_{\rm c.m.}, J)\,.$$

For the correct description of the experimental data, all three factors ($\sigma_{\rm c}$ the capture cross-section, $P_{\rm CN}$ the probability of complete fusion, $W_{\rm sur}$ the survival probability) determining $\sigma_{\rm ER}$ should be properly calculated [8]. Note that with a certain mass table the same set of parameters is used for all nuclei considered. The predictions of macroscopic–microscopic models [4, 5] based on magic number $Z = 114$ and phenomenological models [9, 10] based on magic number $Z = 126$ presently provide us all values which are necessary to calculate $\sigma_{\rm ER}$. Since the lower fission barriers and, correspondingly, the smaller values of $B_f - B_n$ are predicted in the macroscopic–microscopic models [4, 5] for $Z \geq 118$, the expected evaporation residue cross-sections of the nuclei with $Z = 118 - 126$ should be smaller than those of the isotopes of nuclei with $Z = 114$–116. However, the models [9, 10] with the closed proton shell at $Z \geq 120$ predict the growth of the values of B_f–B_n for $Z = 118$–126 nuclei which might result in larger production cross sections for the xn-evaporation channels. The expected increases of the survival probability may be negated by the decreases of the fusion probability.

The available experimental data for $Z \leq 118$ ($Z < 118$) are well described [8] with our approach to calculate $\sigma_{\rm ER}$ using the mass table [5] ([4]). The evaporation residue cross-sections at the maxima of $(2-4)n$ excitation functions and corresponding optimal excitation energies $E^*_{\rm CN}$ calculated with the mass tables of Refs. [4, 5] are presented in Fig. 1 for the reactions ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni + ^{238}U, ^{244}Pu, ^{248}Cm, ^{249}Cf. The value of $\sigma_{\rm ER}$ decreases by about two to three orders of magnitude with increasing the charge number of the target from 92 to 98. The reactions with lighter targets are more favorable. The main reason of the fall-off of $\sigma_{\rm ER}$ with Z of the compound nucleus is the strong decrease of fusion probability $P_{\rm CN}$. The quasifission channel becomes much stronger than the complete fusion with increasing $Z_1 \times Z_2$. Only the projectiles ^{50}Ti, ^{54}Cr result production cross-section of $Z = 114$, 116, 118 on the level of the present experimental possibilities.

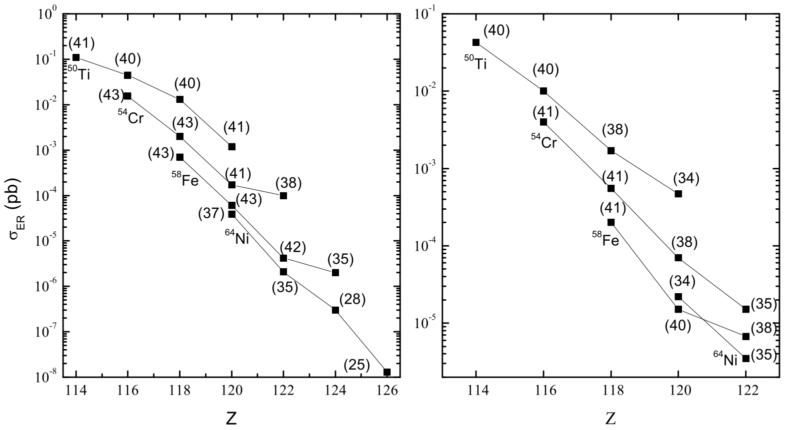

Fig. 1. Evaporation residue cross-sections calculated with the mass tables of Ref. [5] (left-hand side) and of Ref. [4] (right-hand side) at the maxima of $(2-4)n$ excitation functions of the actinide-based reactions. The projectiles and excitation energies are indicated. The $a_f/a_n = 1.07$ with Ref. [4], $a_f/a_n = 1.05$ with Ref. [5], $a_n = A/12\,\mathrm{MeV}^{-1}$ and damping parameter $E_d = 25\,\mathrm{MeV}$ are used in the calculations.

With the mass tables [9, 10] the calculated cross-sections (Fig. 2) for producing the evaporation residues with $Z \geq 114$ are larger than the cross-sections calculated with the mass tables [4] and [5] (Fig. 1). With any mass tables the value of σ_{ER} decreases with increasing Z in the interval Z = 114–120. However, the absolute values of cross-sections are different

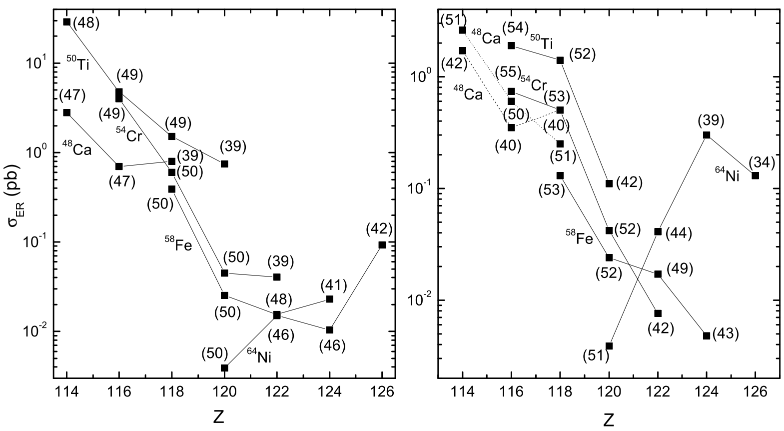

Fig. 2. The same as Fig. 1, but with the predictions of Ref. [9] ($a_n = A/21$, $a_f/a_n = 1$, left-hand side) and of Ref. [10] ($a_n = A/23$, $a_f/a_n = 1$, right-hand side). The points connected by dashed (dotted) lines correspond to $3n(4n)$ channel in the ^{48}Ca-induced reactions.

because the survival probability with the mass tables [9, 10] is larger than the one calculated with the mass tables [4, 5]. Using the mass tables [9, 10], the calculated values of $\sigma_{\rm ER}$ for $Z = 114$, 116 and 118 in the reactions with ^{50}Ti and ^{54}Cr (Fig. 2) can be even larger than those in the reactions with ^{48}Ca because of the dependence of $B_f - B_n$ on A at fixed Z. The calculated production cross-sections of element $Z = 120$ with the mass table [9] are about 100–600 times larger than those calculated with the mass table [5]. The effect of the magic number $Z = 126$ is clearly seen in Fig. 2 where we do not find the fall-off of the cross-section for the nuclei with $Z = 122$, 124 and 126. The value of $B_f - B_n$ strongly increases with A for the nuclei with $Z > 120$ and, thus, $W_{\rm sur}$ strongly increases and overcompensates the loss in fusion probability. With the mass tables [9, 10] the calculated optimal excitation energies of the maximal evaporation residue cross-sections are shifted to higher energies than with the mass tables [4, 5].

In conclusion, a series of experiments is desirable to answer the question where the next spherical proton shell after ^{208}Pb occurs. The answer can be obtained from the values of evaporation residue cross-sections. If the experimental cross-sections in reactions ^{50}Ti + ^{238}U, ^{244}Pu, ^{248}Cm $\to 114, 116, 118$ and ^{54}Cr + ^{238}U, ^{244}Pu$\to 116, 118$ are larger than 0.1 pb, one can conclude that $Z = 114$ is not a proper magic number and the next magic nucleus beyond ^{208}Pb is the nucleus with $Z \geq 120$.

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