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SURVIVAL PROBABILITY OF EXCITED HEAVY NUCLEI*

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Using the statistical model, we analyse the survival probabilities of excited heavy and superheavy nuclei. The calculated production cross sections of heavy neutron-deficient isotopes are in a good agreement with the experimental data for different de-excitation channels, especially near the maxima of excitation functions. The dependence of obtained values for superheavy nuclei produced in cold fusion reactions on different theoretical predictions of nuclear properties are discussed.

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1. Introduction

The synthesis of heavy and superheavy nuclei is an interesting field of nuclear physics research during the last decade. The analysis of experimental yields of different neutron-deficient evaporation residues allows us to conclude whether magic numbers are changed in the nuclei far from the line of stability. There is experimental evidence that in the de-excitation of these nuclei the charged particles emission successfully competes with neutron emission which is the most probable process in the nuclei near the line of stability. Since the stability of superheavy nuclei is mainly determined by shell effects, it is important to find the regions in (Z, N)-plane where the shell effects are strongest and supply the largest survival of excited superheavy nuclei.

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Among various models the dinuclear system (DNS) model seems to be more successful in the consideration of production of heavy and superheavy nuclei [1–4]. The DNS model assumes that the compound nucleus is reached by a series of transfers of nucleons or small clusters from the light nucleus to the heavier one in a touching configuration. So, the dynamics of fusion is considered as a diffusion of the DNS in the mass asymmetry, defined by $\eta = (A_1 - A_2)/(A_1 + A_2)$ (A_1 and A_2 are the mass numbers of the DNS nuclei). In fusion reactions the evaporation residue cross section [1–4]

$$\sigma_{\rm ER}(E_{\rm c.m.}, J) \approx \sigma_{\rm c}(E_{\rm c.m.}, J) P_{\rm CN}(E_{\rm c.m.}) W_{\rm sur}(E_{\rm c.m.}) , \tag{1}$$

depends on the partial capture cross section $\sigma_{\rm c}$ for the transition of the colliding nuclei over the entrance (Coulomb) barrier, on the probability $P_{\rm CN}$ of the compound nucleus formation after the capture and on the survival probability $W_{\rm sur}$ of the excited nucleus against fission. $P_{\rm CN}$ and $W_{\rm sur}$ are considered as the most crucial factors for production of heavy and superheavy nuclei. Reducing the survival probability to that of zero angular momentum, we include the dependence on angular momentum in the effective capture cross section [4].

In the present paper the survival probabilities of different neutron-deficient isotopes and superheavy nuclei are analysed by using statistical model. The dependence of obtained values for superheavy nuclei produced in cold fusion reactions on different theoretical predictions [5–8] of nuclear properties is discussed.

2. Survival probability

The survival probability under the evaporation of a certain sequence s of x particles is considered as

$$W_{\rm sur}^{s}(E^*_{\rm CN}, J) = P_s(E^*_{\rm CN}, J) \prod_{i_s=1}^{x} \frac{\Gamma_i(E^*_{i_s}, J_{i_s})}{\Gamma_{\rm t}(E^*_{i_s}, J_{i_s})} . \tag{2}$$

Here, i_s, P_s, $E^*_{i_s}$ and J_{i_s} are the indices of the evaporation step, the probability of realization of the channel s at the initial excitation energy $E^*_{\rm CN}$ of the compound nucleus, the mean values of excitation energy and, angular momentum quantum number, respectively. The total width $\Gamma_{\rm t}$ for compound nucleus decay is the sum of partial widths of particle evaporation Γ_i, γ-emission and fission $\Gamma_{\rm f}$. At the first step $i_s = 1_s$, $E^*_{1_s} = E^*_{\rm CN}$ and $J_{1_s} = J$ [9, 10]. Since $\sigma_{\rm ER}$ can be factorised into three factors in (1) with $W_{\rm sur}(E_{\rm c.m.}, J = 0)$ the calculations of the survival probability were done for $J = 0$ only. The probability of realization of considered evaporation sequence $P_s(E^*_{\rm CN})$ [11,12] is a function of particles separation energies and their

Coulomb energies in the case of charged particles emission. This function has a bell-like shape with a maximum near the maximum of corresponding excitation function.

In the excited superheavy nuclei the Coulomb barrier for the emission of charged particles is high and the widths for the emission of a proton or an α-particle are much smaller than the width Γ_n for the neutron emission in these nuclei. Under these circumstances we set $\Gamma_{\rm t} \approx \Gamma_n + \Gamma_{\rm f}$. So, the survival probability under the evaporation of x neutrons in this case is considered according to as

$$W_{\rm sur}(E^*_{\rm CN}, J) \approx P_{xn}(E^*_{\rm CN}, J) \prod_{i=1}^{x} \frac{\Gamma_n(E^*_i, J_i)}{\Gamma_n(E^*_i, J_i) + \Gamma_{\rm f}(E^*_i, J_i)} \,. \quad (3)$$

The width of the decay of channel i is defined through the probability $R_{{\rm CN}_i}$ of this process as [9, 10, 13–15]

$$\Gamma_i = \frac{R_{{\rm CN}_i}}{2\pi\rho(E^*_{\rm CN}, J)} \,. \quad (4)$$

The probability of evaporation of particle j (neutron, proton, α-particle)

$$R_{{\rm CN}_j}(E^*_{\rm CN}, J) = \sum\nolimits_{J_{\rm d}} \int\limits_0^{E^*_{\rm CN} - B_j} d\varepsilon \rho_{\rm d}(E^*_{\rm CN} - B_j - \varepsilon, J_{\rm d}) \sum_{S=|J_{\rm d}-s|}^{J_{\rm d}+s} \sum_{l=|J-S|}^{J+S} T_{jl}(\varepsilon) \quad (5)$$

can be calculated by using the separation energy B_j of particle j with spin s, the level density $\rho_{\rm d}(E^*_{\rm CN} - B_j - \varepsilon, J_{\rm d})$ of the daughter nucleus, and the transmission coefficient $T_{jl}(\varepsilon)$ through the barrier. The value of $T_{jl}(\varepsilon)$ is calculated using an optical model potential [13].

The fission probability in the case of an one-hump barrier of height $B_{\rm f}(E^*_{\rm CN})$ and curvature determined by $\hbar\omega$ is defined as

$$R_{{\rm CN}_{\rm f}}(E^*_{\rm CN}, J) = \int\limits_0^{E^*_{\rm CN} - B_{\rm f}} \frac{\rho_{\rm f}(E^*_{\rm CN} - B_{\rm f} - \varepsilon, J)\, d\varepsilon}{1 + \exp\left[\frac{2\pi(\varepsilon + B_{\rm f} - E^*_{\rm CN})}{\hbar\omega}\right]} \,, \quad (6)$$

where $\rho_{\rm f}(E^*_{\rm CN} - B_{\rm f} - \varepsilon, J)$ is the level density at the saddle point. For all the nuclei considered, we take $\hbar\omega = 2$ MeV. We calculated the level density using the Fermi-gas model [15].

The value of fission barrier $B_{\rm f}$ consists of the liquid drop $B_{\rm f}^{\rm LD}$ and microscopical $B_{\rm f}^{\rm M}$ parts. The liquid drop part is calculated as in Ref. [16]. The value $B_{\rm f}^{\rm M} = \delta W^A_{\rm sd} - \delta W^A_{\rm gr}$ is related to the shell correction $\delta W^A_{\rm gr}$ of the nucleus with mass number A at the ground state and the shell correction $\delta W^A_{\rm sd}$ at the saddle point. Usually, one neglects the shell correction at the saddle point, $\delta W^A_{\rm sd} \approx 0$. Due to the dependence of the shell effects on the nuclear excitation, the microscopical part and $B_{\rm f}$ depend on $E^*_{\rm CN}$ as

$$B_{\rm f}(E^*_{\rm CN}) = B^{\rm LD}_{\rm f} + B^{\rm M}_{\rm f}(E^*_{\rm CN} = 0)\exp\left[\frac{-E^*_{\rm CN}}{E_{\rm D}}\right]. \tag{7}$$

With (7) the level density parameter is taken as a constant. The other way to take into account the shell effects is using excitation energy dependent level density parameter in the calculations of level density [15] (without damping of the shell effects in $B_{\rm f}$). However, as was shown in Ref. [17] these two possible ways are equivalent and lead to the same results at the proper choice of parameters.

For calculation of the Coulomb barrier, we used the expression

$$U_{\rm C} = \frac{Z_{\rm CN} - jZ_j e^2}{r_{0j}\left(A^{1/3}_{{\rm CN}-j} + A^{1/3}_j\right)}\,, \tag{8}$$

where r_{0j} is the constant and $Z_{{\rm CN}-j}$ and $A_{{\rm CN}-j}$ are the charge and mass numbers of the daughter nucleus after the evaporation of particle j (proton or alpha) with charge Z_j and mass number A_j. The variations of parameter r_{0j} are not crucial for our calculations of $\sigma_{\rm ER}$ near the maxima of excitation functions for all neutron-deficient isotopes considered [12].

3. Results and discussion

While considering the heavy neutron-deficient isotopes yields we use the existing experimental values of microscopic corrections and particle separation energies, and their theoretical values from Ref. [5] when the experimental data are not available. For superheavy nuclei we used a set of different theoretical predictions [5–8] and analysed their influence on the results obtained.

3.1. De-excitation of ^{230}U

Production cross sections and excitation functions of neutron deficient isotopes of U, Pa and Th have been measured in the ^{22}Ne+^{208}Pb reaction [18]. Since the initial configuration is very asymmetric, the quasifission probability can be neglected and the probability of complete fusion $P_{\rm CN}$ is close to 1. The calculated values of $\sigma_{\rm ER}$ in Fig. 1 are in a good agreement with the experimental data especially near the maxima of excitation functions both for neutron and charged particles evaporation channels [12].

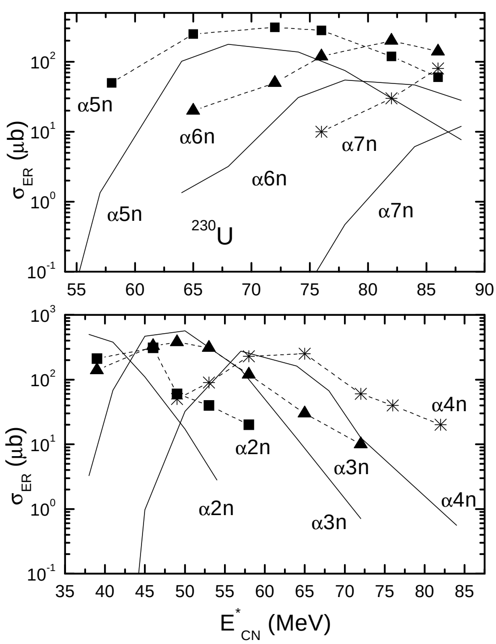

Fig. 1. Measured [18] and calculated excitation functions and evaporation residue cross sections for αxn evaporation channels in the reaction ^{22}Ne+^{208}Pb.

3.2. De-excitation of ^{220}Th

In Fig. 2 and Fig. 3 evaporation residue cross sections and excitation functions for the reactions ^{40}Ar+^{180}Hf [19] and ^{124}Sn+^{96}Zr [20] are shown, respectively. Due to the different fusion probabilities, the same isotopes are finally produced in these two reactions at the same excitation energy with the cross sections differing approximately by one order of magnitude. One can conclude, that the fusion probability $P_{\rm CN}$, which is calculated with the dinuclear system model in Ref. [12], is important ingredient of the description of excitation function. Note that the excitation functions for these reactions were calculated in [20]. Here, we obtain a better agreement with the experiment, especially for the channels with evaporation of charged particles, without special adjustment of the theoretical data to one of the evaporation channel as was done in Ref. [20]. The results of measurements and our calculations are in quite good agreement almost for all evaporation channels except some points on the low energy tails of excitation functions. These tails are related to the influence of contamination of the target used in the experiment [12].

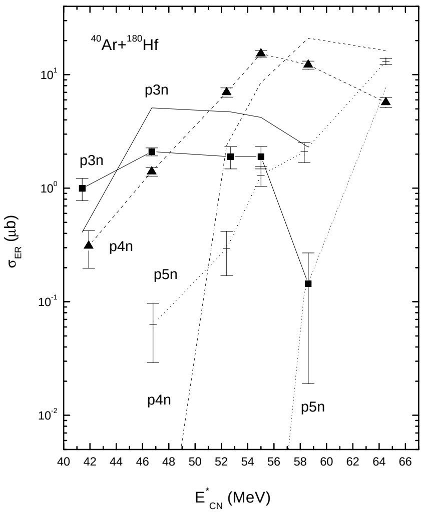

Fig. 2. Measured [19] and calculated excitation functions and evaporation residue cross sections for *pxn* evaporation channels in the reaction ^{40}Ar+^{180}Hf.

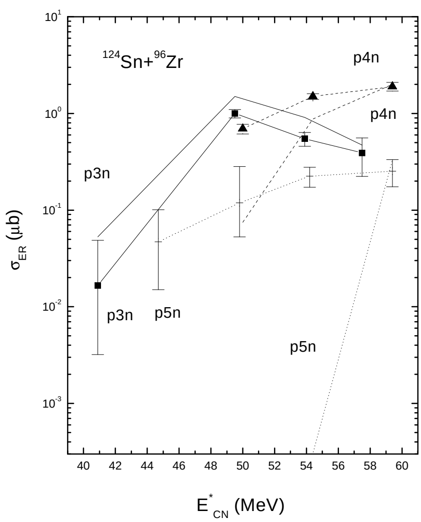

Fig. 3. Measured [20] and calculated excitation functions and evaporation residue cross sections for *pxn* evaporation channels in the reaction ^{124}Sn+^{96}Zr.

3.3. The superheavy nuclei

The survival probability of superheavy nuclei [17] (with charge numbers $Z \geq 102$) produced in cold fusion reactions is analysed using different theoretical predictions of the nuclear properties of these nuclei [5–8], which predict practically the same neutron binding energies but different fission barriers. In $1n$ evaporation channel $W_{\rm sur}$ differs from $\Gamma_n/\Gamma_{\rm f}$ by the factor of P_{1n} ($P_{1n} \approx 1$ at the maximum of excitation function). For $104 < Z < 112$, the calculated $\Gamma_n/\Gamma_{\rm f}$ weakly depend on the choice of predicted properties of superheavies. With the predictions of Ref. [7, 8] the values of $\Gamma_n/\Gamma_{\rm f}$ are much smaller than the ones obtained with Refs. [5, 6] for $Z \geq 114$. So, the calculated evaporation residue cross section for $Z \geq 114$ would be larger with the predictions of Refs. [5, 6] (Fig. 4).

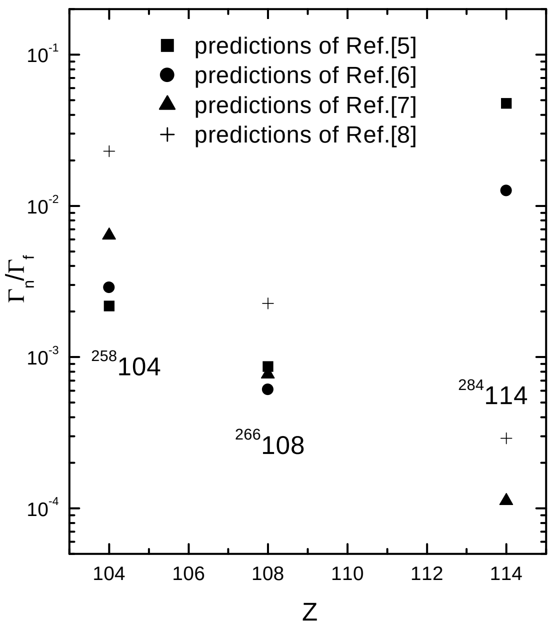

Fig. 4. The dependences of $\Gamma_n/\Gamma_{\rm f}$ calculated with the Fermi-gas model and damping of the shell effects in $B_{\rm f}$ for the indicated nuclei at the excitation energies shown in [17]. The predictions of Refs. [5–8] are used.

4. Summary

Near the maxima of excitation functions the calculated values are close to the experimental ones. The low energy tails of the excitation functions in pxn and αxn evaporation channel are sensitive to the contaminations of the targets by other isotopes. The calculated evaporation residue cross sections for the nuclei with $Z > 114$ are very crucial to the choice of the predicted properties of superheavies.

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