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APPEARANCE OF NUCLEAR SHELL EFFECTS AND INITIAL CHARGE (MASS) ASYMMETRY IN THE FORMATION OF PRODUCTS OF HEAVY ION COLLISIONS

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The role of the entrance channel in the formation of the reaction products is discussed. The excitation functions of evaporation residues for the ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm reactions are compared.

1. Introduction

The comparison of the yield of reaction products (evaporation residues (ER), fusion-fission and quasifission products) in different reactions leading to the formation of the same compound nucleus (CN) is a promising method for an experimental study of the role of an entrance channel in fusion-fission reactions. The experimental data of such a studies, presented in Refs.[1,2,3,4], indicate that the yield of reaction products depends on the mass and charge asymmetry of the colliding nuclei. The authors observed that a hindrance to complete fusion was observed in more mass symmetric reactions. It is difficult to explain the nature of this hindrance and its dependence on the nuclear shell structure of the colliding nuclei and the dynamics of the collision.

The initial mass (charge) asymmetry and nuclear shell structure of the colliding nuclei play a decisive role in the dynamics of heavy ion collision and the formation of reaction products at energies near the Coulomb barrier in reactions with massive nuclei. Theoretical methods allow us to find connections between the peculiarities of the entrance channel and mass-angular distributions of the reaction products.[5]

For light or medium-heavy systems, capture inside the Coulomb barrier leads invariably to fusion. Consequently, the role of the entrance channel may be not seen clearly in the experimental data.[6] Therefore, the capture (or barrier-passing) cross section coincides with the complete fusion cross section. In nuclear reactions with light nuclei leading to the CN formation with high fission barrier, the ER measurements allow us to find directly the fusion cross section because in these reactions the complete fusion cross section is determined by the ER cross section ($\sigma_{\rm ER}$). Therefore, for a light system the capture cross section can be found very easily because capture and fusion cross sections are nearly equal.

However, for heavy systems capture inside the barrier, i.e. the formation of a dinuclear system (DNS) is not a sufficient condition for fusion. The DNS may re-separate into two fragments before reaching a full equilibrated CN. Consequently, a considerable part of the capture events goes to the quasifission channel. This phenomenon is experimentally observed as a hindrance to fusion. In the reactions with massive nuclei, capture events can lead to quasifission, fusion-fission, fast fission and ER channels. The branching ratio of these channels in reactions with massive nuclei depends on peculiarities of the initial channel: mass (charge) asymmetry of the interacting nuclei, their shell structure, the orientation angle of the axial symmetry axis, as well as the values of the bombarding beam energy and orbital angular momentum. Unfortunately, there is an ambiguity in the experimental identification of quasifission and fusion-fission products due to a mixing of their mass and angular distributions.[5] Therefore, the dynamics of the capture, complete fusion and fission should be studied in a continuous way in the framework of the same model but taking nuclear shell structure into account. The need for more experimental data to disentangle various concurrent effects is clearly felt. A full understanding of all stages of the reaction dynamics is very important for the challenging issue of the production of superheavy element and new isotopes far from the valley of stability.

2. Dinuclear system stage of the reaction mechanism

The capture event leads to the formation of a DNS and its behaviour is sensitive to the peculiarities of the entrance channel. The stage of reaction mechanism connected with the evolution of the DNS may be prolonged due to the presence of shell effects in nucleus as the quantum states of the neutron and proton subsystems.[7] The models based on the DNS concept are useful tools to study the reaction mechanism in heavy ion collisions[5] and (spontaneous and induced) fission processes.[8]

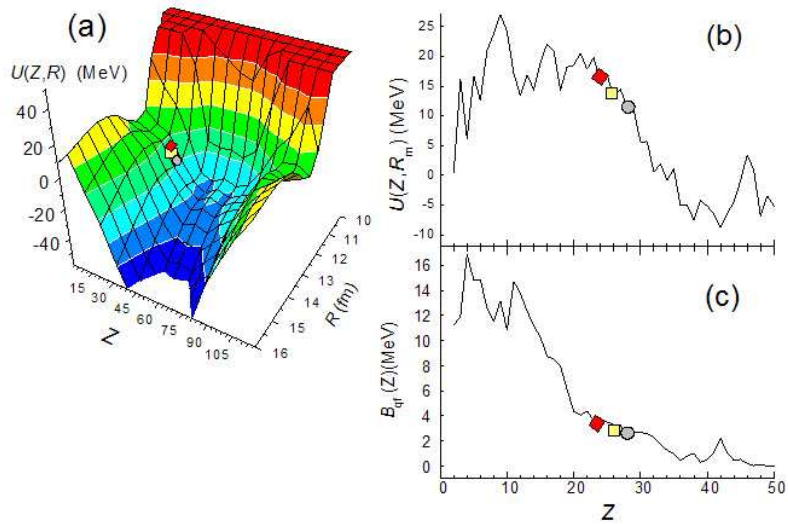

Fig. 1. Potential energy surface U(Z,R) calculated for the DNS configurations leading to the formation of the CN Z=120 and A=302 as a function of the fragment charge number Z and relative distance between the centers of fragments R (a), driving potential $U(Z, R_m)$ (b), and quasifission barriers $B_{\rm qf}$ as a function of Z (c). The initial points for the dinuclear systems formed in the ^{54}Cr + ^{248}Cm, ^{58}Fe + ^{244}Pu, and ^{64}Ni + ^{238}U reactions are shown by a diamond, a rectangle, and a circle, respectively.

Dynamical calculations of the capture cross section allow us to establish the angular momentum distribution of the DNS being in the transition stage to complete fusion, quasifission and fast fission events. In Ref.[9] we demonstrated the role of the angular momentum of the CN to explain the large difference between the $\sigma_{\rm ER}$ values of the ^{16}O+^{204}Pb and ^{96}Zr+^{124}Sn reactions leading to the same CN ^{214}Th. The angular momentum distribution of the DNS is determined by the size of the potential well in the nucleus-nucleus interaction $V(R)$ and the friction coefficients (γ_R and γ_θ) for the relative motion.[10] We take into account the dependence of the capture and fusion processes on the orientation angles (α_1 and α_2) of the axial symmetry axis of the colliding nuclei. It is well known that $V(R)$ and the driving potential $U(Z, A, R)$ are strongly changed by changing the orientation angles of the projectile and target nuclei.[10,11]

The shell effects are included in $U(Z, A, R)$ by using the experimental values of the nuclear binding energies (B_1 and B_2) or the values obtained by the macroscopic-microscopic model for superheavy elements ($B_{\rm CN}$):

$$U(R, Z, A, L, \alpha_1, \alpha_2) = B_1 + B_2 - B_{\rm CN} + V(Z, A, R, L, \alpha_1, \alpha_2) - V_{\rm rot}^{(CN)}(L), \quad (1)$$

where $B_{\rm CN}$ and $V_{\rm rot}^{(CN)}$ are the binding energy[12] and rotational energy of the CN, respectively. The shell effects in nuclei forming the DNS are included in coefficients

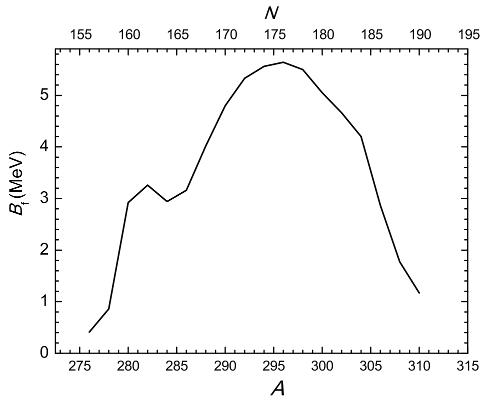

Fig. 2. The fission barrier of the CN in ground state as a function of the mass number A calculated by the macroscopic-microscopic approach.[13]

of the transport-master equation:

$$\frac{dP_Z(t)}{dt} = \Delta^{(+)}_{Z,Z-1} P_{Z-1} + \Delta^{(-)}_{Z,Z+1} P_{Z+1} - (\Delta^{(-)}_{Z-1,Z} + \Delta^{(+)}_{Z+1,Z} + \Lambda_Z) P_Z, \qquad (2)$$

where $\Delta^{(\pm)}_{Z,Z\mp1} \sim n_{T(P)}(t)(1 - n_{P(T)}(t))/(\varepsilon_P - \varepsilon_T)^2)$; n_P and n_T (ε_P and ε_T) are the nucleon occupation numbers (energies) of the single-particle states in the projectile-like and target-like nuclei of the DNS.[10] The evolution of the charge and mass distributions in DNS nuclei is used to calculate the competition between complete fusion and quasifission processes: $P_{\rm CN} = \Sigma_Z P_Z P^{(Z)}_{\rm CN}$, where $P^{(Z)}_{\rm CN}$ is the fusion probability from the DNS configuration with charge asymmetry Z and $Z_{tot} - Z$; Z_{tot} is the total charge number of the DNS.

3. Comparison reactions leading to synthesis of superheavy element Z=120

To establish a favorable reaction to synthesize the next new superheavy element $Z = 120$ we compared three reactions: ^{54}Cr+^{248}Cm, ^{58}Fe+^{244}Pu and ^{64}Ni+^{238}U.[5] Our calculations showed that the $\sigma_{\rm ER}$ values for the ^{54}Cr+^{248}Cm reaction is substantially larger than the other two more mass-symmetric reactions. This result was expected because it is a more mass asymmetric reaction. As seen from Fig. 1a the entrance channel for this reaction is located closer to the maximum in direction to complete fusion ($Z \to 0$). According to the DNS model complete fusion occurs by nucleon transfer from the light to the heavy nucleus. When the DNS approaches the $Z \to 0$ configuration, there is no barrier, and complete fusion occurs without hindrance ($P_{\rm CN}$=1). This occurs for light nuclear systems. The height of the intrinsic fusion barrier ($B^*_{\rm fus}$) for the given charge asymmetry Z_{DNS} of the DNS is determined as the difference of the values of the driving potential at $Z = Z_{DNS}$ and its maximum value in the direction to complete fusion: $B^*_{\rm fus} = U(Z_{\rm max}) - U(Z_{\rm DNS})$. In Fig. 1b, the maximum of $U(Z)$ is at $Z_{\rm max} = 9$ and $B^*_{\rm fus}$=10, 13.5 and 16 MeV for the ^{54}Cr+^{248}Cm, ^{58}Fe+^{244}Pu and ^{64}Ni+^{238}U reactions, respectively. The quasifission barriers $B_{\rm qf}$ for these reactions are shown in Fig. 1c. The life time of the DNS depends on the value of $B_{\rm qf}$ corresponding to the considered charge asymmetry Z. The larger value of $B_{\rm qf}$ leads to an increase of the fusion probability for the ^{54}Cr+^{248}Cm reaction.

The results obtained by the group of A. Sobiczewski[13] showing a monotonic increas of the fission barriers for decreasing mass numbers from $A = 310$ (B_f=1.3 MeV) up to $A = 296$ (B_f=5.7 MeV) (see Fig. 2) stimulated us to calculate the cross section $\sigma_{\rm ER}$ for the ^{54}Cr+^{244}Cm and the ^{50}Ti+^{249}Cf reactions using the nuclear masses and fission barriers presented in Refs.[13,14].

The results of the calculation of the evaporation residues at the neutron evaporation cascade is very sensitive to the shell corrections in the compound nucleus and its excitation energy which depends on the reaction Q_{gg}-value. The difference between the nuclear masses presented in Ref.[14] for $Z = 120$ and the ones of Ref.[12] is about 3 MeV. In calculations of the de-excitation cascade of neutron emission in competition with the fission of the heated and rotating $Z = 120$ CN, the use of the masses from Ref.[14] instead of those of Ref.[12] leads to a decrease of the $\sigma_{\rm ER}$ cross section by a factor of 30. The main reason that led to the decrease of $\sigma_{\rm ER}$ is the decrease of the survival probability of the heated and rotating CN.

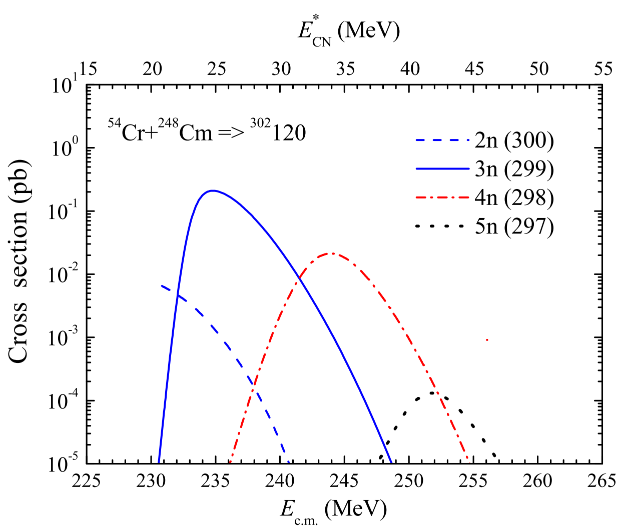

Fig. 3. The excitation function of evaporation residues for xn channels for the ^{54}Cr+^{248}Cm reaction calculated combining the DNS model and advanced statistical model.

The dependence of the CN formation probability on the variation of values of the superheavy element masses and their shapes in the region with $Z > 109$ is

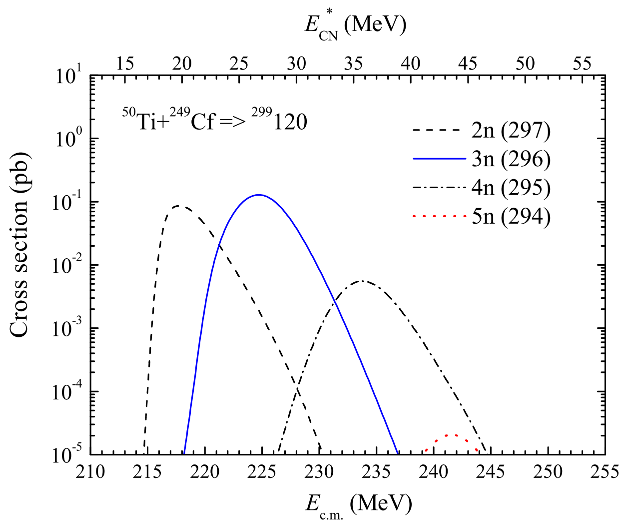

Fig. 4. The same of Fig. 3 but for the ^{50}Ti+^{249}Cf reaction.

connected with the change of the potential energy surface and driving potential in the corresponding charge and mass region. The value of the intrinsic fusion barrier $B^*_{\text{fus}} = U(Z_{\text{max}}) - U(Z_{\text{DNS}})$ is important in the calculation of the fusion probability P_{CN} (competition between complete fusion and quasifission). For the above quoted reactions the maximal values of $U(Z_{\text{max}})$ are obtained at the charge values $Z_{\text{max}} = 9$ and $Z_{\text{max}} = 111$ of the fragments of the DNS. Our calculations showed that P_{CN} is sensitive to the value of $U(Z_{\text{max}})$. But P_{CN} does not change so strongly as the survival probability changes when using the nuclear masses of Ref.[14] instead of those of P. Möller *et al.*,[12] since the mass differences are about 1 MeV or smaller for the considered isotopes of Z=110, 111. The fusion probabilities for the ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm reactions have been determined by using the masses from the paper by I. Muntian *et al.*[14] Since the capture stage depends on the entrance channel properties, no effect from the difference in the mass values obtained from the different data tables is observed.

A comparison of our results for the ER cross sections for the ^{54}Cr+^{248}Cm (Fig. 3) and ^{50}Ti+^{249}Cf (Fig. 4) reactions shows that although the latter reaction is more asymmetric and the CN ^{299}120 formed in this reaction has a larger fission barrier (see Fig. 2), the σ_{ER} for the ^{54}Cr+^{248}Cm reaction is a little bit larger than that for the ^{50}Ti+^{249}Cf reaction at excitation energies E^*_{CN} higher than 23 MeV (see Figs. 3 and 4). This is caused by the different partial fusion cross sections for the two reactions at the same value of E^*_{CN}. We should stress that the compound nucleus formed in a complete fusion is excited with excitation energy E^*_{CN} and rotating with angular momentum L. In this context, we calculate the fission barrier B_f according

Table 1. Comparison of the predicted maximum values of the evaporation residues cross section ($\sigma_{\rm ER}$) in the ^{54}Cr+^{248}Cm and ^{50}Ti+^{249}Cf reactions obtained in Refs.[17,18,19] with our results for the 3 and 4 neutrons emission channels as a function of the beam energy.

Reactions	^{50}Ti+^{249}Cf			^{54}Cr+^{248}Cm				
$E_{\rm c.m.}$ MeV	$\sigma^{(3n)}_{\rm ER}$ pb	$E_{\rm c.m.}$ MeV	$\sigma^{(4n)}_{\rm ER}$ pb	$E_{\rm c.m.}$ MeV	$\sigma^{(3n)}_{\rm ER}$ pb	$E_{\rm c.m.}$ MeV	$\sigma^{(4n)}_{\rm ER}$ pb	Reference
236.0	0.04	241.0	0.046	246.7	0.014	249.6	0.028	17
227.5	0.76	239.0	0.028	241.5	0.176	252.0	0.012	18
231.5	0.06	232.5	0.04	–	–	–	–	19
225.0	0.14	234.0	0.005	234.7	0.235	244.0	0.023	This work

Note: The data about maximum values from Refs.[17,18,19] were extracted from the figures of the ER excitation functions.

to

$$B_f(L,T) = B_f^m(L) - h(T)q(L)\delta W \tag{3}$$

where $B_f^m(L)$ is the parametrized macroscopic fission barrier[15] depending on the angular momentum L, and $\delta W = \delta W_{sad} - \delta W_{gs} \simeq -\delta W_{gs}$ is the shell correction. The damping functions $h(T)$ and $q(L)$ (depending on the temperature and angular momentum, respectively) of the shell corrections to the fission barrier are given by the following Fermi type relations:

$$h(T) = \{1 + \exp[(T - T_0)/d]\}^{-1}, \tag{4}$$

and

$$q(L) = \{1 + \exp[(L - L_{1/2})/\Delta L]\}^{-1} \tag{5}$$

where, in Eq. (4), d= 0.2 MeV is the rate of washing out the shell corrections with the temperature and T_0=1.15 MeV is the value[16] at which the damping factor $h(T)$ is reduced by 1/2. Analogously, in Eq. (5), ΔL =3$\hbar$ and $L_{1/2}$ =20$\hbar$ is the value at which $q(L)$ is reduced by 1/2. Since the macroscopic fission barrier is certainly absent for superheavy nuclei, only the microscopic part (shell correction) can give a contribution to $B_f(L,T)$. In the present paper the damping functions were applied to the fission barrier values given by M. Kowal *et al.*[13]

The masses of superheavy elements obtained in Ref.[14] are larger by approximately 3 MeV than the ones presented in Ref.[12]. Consequently, the ER excitation functions are moved to lower excitation energies: $E^*_{\rm CN} = E_{\rm c.m.} + B_1 + B_2 - B_{\rm CN}$.

In Table 1, the maximum values of $\sigma_{\rm ER}$, which were obtained in this work for the 3n and 4n-evaporation channels of the ^{54}Cr+^{248}Cm and ^{50}Ti+^{249}Cf reactions are compared with the corresponding data presented in Refs.[17,18,19]. The difference between compared results in Table 1 may be essentially explained by two facts: 1) the authors used different methods to estimate the probability of formation of the heated and rotating compound nuclei ^{299}120 and ^{302}120 in the ^{54}Cr+^{248}Cm and

^{50}Ti+^{249}Cf reactions (details of the calculations can be found in the corresponding references); 2) the authors used different theoretical mass tables for the region of superheavy elements $Z > 109$; the authors of Refs.[17,19] used the data obtained by P. Möller *et al.*[12] while the authors of Ref.[18] and we used for the reactions under discussion the data calculated by I. Muntian *et al.*[14] Using the same mass values in the calculations of the formation of the compound nucleus and its cooling by the evaporation of neutrons does not provide any closer maximum values of $\sigma_{\rm ER}$ and the corresponding beam energies since, due to the above mentioned procedure, we calculate $\sigma_{\rm ER}$ through the effective fission barriers which differ from the initial values of Ref.[13].

We can conclude that the competition between different theoretical models devoted to analyze and predict the synthesis of new superheavy elements is useful to develop these models by including a large enough number of degrees of freedom and to extract more realistic information about different stages of the reaction, starting with the capture process of nuclei up to the competition between fission and neutron evaporation.

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