Reaction Mechanisms in Massive Nuclei Collisions and Perspectives for Synthesis of Heavier Superheavy Elements Postprint

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Abstract

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Full Text

Preamble

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Reaction mechanisms in massive nuclei collisions and perspectives for synthesis of heavier superheavy elements

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Abstract

We discuss the hardship in synthesizing the heaviest superheavy elements in massive nuclei reactions due to the hindrance to complete fusion of reacting nuclei caused by the onset of the quasifission process, which strongly competes with complete fusion, and due to the strong increase of fission yields along the de-excitation cascade of the compound nucleus in comparison with evaporation residue formation. The hindrance to formation of the compound nucleus and evaporation residue is determined by the characteristics of the entrance channel.

Key words
Capture, Quasifission, Complete fusion, Fast fission, Fusion-fission, Evaporation residue

Introduction

In massive nuclei collisions, reactions evolve through various steps and different processes that determine the nature and characteristics of reaction products depending on the choice and conditions of reacting nuclei in the entrance channel. Therefore, different reactants that reach the same compound nucleus (CN)—characterized by the same mass number A, atomic number Z, and excitation energy CNE—do not necessarily lead to the same reaction products with identical characteristics [1-3]. Compound nuclei formed dynamically through very different entrance channels are characterized by different angular momentum distributions, even at the same excitation energy CNE.

In this context, a mass-asymmetric reaction in the entrance channel, for which a dinuclear system (DNS) is formed after capture of the reactants, mainly evolves toward complete fusion (CF) and reaches the stage of a compound nucleus. The subsequent de-excitation behavior of the CN is determined by competition between fission and particle evaporation processes. In contrast, the DNS formed in a more mass-symmetric reaction in the entrance channel undergoes strong hindrance in its evolution toward a CN due to competition with the quasifission process (QF), which represents the decay of the DNS into two fragments. In this case, the QF yield increases and the CF rate decreases with increasing mass and charge of the nuclei in the entrance channel. Consequently, in some cases the evaporation residue (ER) cross section σ_{ER} decreases to values lower than 1 pb.

To demonstrate these statements, we consider as examples the reactions: ^{22}Ne+^{248}Cf (highly asymmetric reaction), ^{24}Mg+^{248}Cm, ^{34}S+^{238}U (less asymmetric reaction), ^{40}Ar+^{232}Th (more mass-symmetric reaction), ^{132}Sn+^{140}Ce (almost mass-symmetric reaction), and ^{136}Xe+^{136}Xe (mass-symmetric reaction), all leading to the same ^{272}Hs CN. In the case of the ^{22}Ne-induced reaction, the capture cross section is mainly transformed into complete fusion cross section at low beam energy [3], and subsequent ER formation dominates the reaction products. At higher energies, besides the large contribution of QF, the FF formation competes with ER yields during de-excitation of the CN. In the case of the ^{34}S-induced reaction, the QF cross section is at least one order of

magnitude higher than the CN cross section because CF is strongly hindered by the dominant role of QF, and during CN decay the fission rate exceeds the ER process [4]. For the ^{40}Ar-induced reaction, ER formation is lower than 1 pb, a result jointly caused by the dominant role of QF compared to fusion and the dominant role of fission compared to evaporation.

Moreover, for the ^{132}Sn+^{140}Ce and ^{136}Xe+^{136}Xe reactions, ER formation completely disappears. The competition between QF and CF processes depends on the orbital angular momentum distribution of the DNS. Consequently, the formation of a rotating and excited CN is also characterized by the mass asymmetry of reactants in the entrance channel through a specific angular momentum distribution of the DNS. Therefore, the same CN formed by different entrance channels, even when characterized by the same CNE, has different angular momentum distributions and consequently decays differently in competition between fission (FF) or evaporation residue (ER) nuclei along the various steps of the de-excitation cascade.

Since the fission barriers (contributed by macroscopic and microscopic parts of nuclear binding energy) of the CN and intermediate excited nuclei depend on nuclear temperature T and angular momentum , the rates of fission fragments and ERs are sensitive to the specific dynamical properties of the CN and intermediate excited nuclei determined by the reactants used in the entrance channel. Therefore, ER cross sections decrease with increasing angular momentum due to its influence on the rotating CN. Finally, the CN formed at the same CNE by different entrance channels decays forming products (FFs and ERs) with different properties because of dynamic peculiarities of reacting nuclei in the entrance channel.

To provide realistic estimations of reaction product cross sections for mass-symmetric or almost symmetric reactants as entrance channels, an adequate model must be developed that can reliably describe the complex dynamics and mechanisms the CN retains during all stages of the reaction. In the final stage of a nuclear reaction, the formed CN may de-excite by fission (producing fusion-fission fragments) or by emission of light particles. The reaction products that survive fission are ERs. While registration of an ER provides clear evidence of CN formation, for reactions with massive nuclei, knowledge of ER formation alone is generally insufficient to determine the complete fusion cross section and understand the dynamics of the CN de-excitation cascade if the true fission fragments are not correctly accounted for.

Furthermore, correct identification of an evaporation residue nucleus through observation of its decay chain does not guarantee that the target material contains only that specific isotope. For example, in the case of the ^{48}Ca+^{249}Cf reaction, identifying the ^{294118} nucleus as the evaporation residue of the ^{297118} CN after emission of 3 neutrons (as reported in Ref. [5]) cannot assure that the collected events corresponding to the ^{294118} nucleus arise solely from the mentioned reaction leading to ^{297118} CN formation. The interaction of the ^{48}Ca projectile with the ^{250}Cf isotope in the target must also be considered to ac-

count for the contribution of the ^{48}Ca+^{250}Cf reaction to ^{294118} ER formation, because target material inevitably contains the ^{250}Cf isotope as well. In this latter case, the ^{48}Ca+^{250}Cf reaction (forming the ^{298118} CN) leads to the same ^{294118} evaporation residue nucleus after emission of 4 neutrons from the CN. This effect depends on the excitation energy CNE of the CN, which is determined by the collision energy E_c.m. In addition, using assumptions about reaction mechanisms leading to observed fission-like fragments does not allow for correct determination of the fusion-fission contribution when mass fragment distributions from different processes (quasifission, fast fission) overlap [1,3,6,7]. The importance of having a multiparameter and sensitive model is strongly connected with the requirement to reach reliable results and provide reliable estimations of perspectives for the synthesis of superheavy elements (SHE).

2 Model and Formalism

Using the DNS model [8], the first stage of reaction involves the capture formation of a DNS after full momentum transfer of the relative motion of colliding nuclei into a rotating and excited nuclear system. In deep inelastic collisions, a DNS is formed but full momentum transfer does not occur; therefore, deep inelastic collisions are not capture reactions.

The partial capture cross section at a given center-of-mass energy E_c.m. and orbital angular momentum is determined by Eq. (1), where the capture probability is 1 or 0 for a given E_c.m. and orbital angular momentum depending on whether the collision path becomes trapped in the nucleus-nucleus potential well after dissipation of part of the initial relative angular momentum [1,9]. Our calculations show that, depending on the center-of-mass system energy E_c.m., there can be a "window" for orbital angular momentum capture with respect to the conditions described in Refs. [1,9].

The quasifission process competes with CN formation. This process occurs when the DNS prefers to break down into two fragments instead of transforming into a fully equilibrated CN. The fusion excitation function is determined by the product of the partial capture cross section $\sigma\{cap\}\hat{}$ *and the fusion probability* $P\{CN\}$ of the DNS at various E_c.m. values.

Figure 1 [Figure 1: see original paper] shows the calculated P_{CN} fusion probability versus orbital angular momentum for the ^{48}Ca+^{154}Sm reaction at two different CNE values of the ^{202}Pb CN: 49 MeV (dashed line) and 63 MeV (full line). It demonstrates how the P_{CN} fusion probability changes with at fixed CN excitation energy, and how the P_{CN} trend changes at different CNE values. Therefore, methods that do not account for the dependence of the P_{CN} fusion probability on collision energy E_c.m., angular momentum , and orientation angles of the axial symmetry axes of deformed reacting nuclei cannot yield reliable fusion cross section values.

The fast fission cross section is calculated by summing contributions of partial waves corresponding to the range leading to mononucleus formation where the

fission barrier B_f is zero; in this range, the system promptly decays into two fragments. The quasifission cross section is defined by the capture cross section minus the sum of fusion and fast fission cross sections [6]:

$\sigma\{capture\} = \sigma\{\text{quasifission}\} + \sigma\{fusion\} + \sigma\{\text{fastfission}\}$

For more specific details and model descriptions, see Refs. [1,7,9-11].

To demonstrate our model' s sensitivity, we present in Fig. 1 the calculated P_{CN} fusion probability as a function of orbital angular momentum. The fusion cross section includes cross sections of evaporation residues and fusion-fission products [7]. The ER cross section is calculated by an advanced statistical code [12-14] that accounts for damping of shell correction in the fission barrier as a function of nuclear temperature and orbital angular momentum, determining the survival probability P_{ER}( ).

We can calculate mass- and angle-distributions of quasifission and fusion-fission fragments, anisotropy of fission fragment angular distribution, and the dependence of cross sections, Coulomb barrier, fusion barrier, and quasifission barrier on the orientation angle of symmetry axes of colliding nuclei (see Refs. [3,7,15]). As an example, Fig. 2 shows the mass distribution of quasifission fragments for the ^{48}Ca+^{154}Sm reaction.

In many cases, depending on entrance channel peculiarities, the mass distributions of fusion-fission, quasifission, and fast fission fragments can overlap [3,10], creating real difficulties in analyzing experimental data to identify true yields of corresponding processes in heavy-ion collisions. Figure 2 shows that at lower E_c.m. energy, the mass distribution of quasifission products populates the asymmetric mass region at any DNS lifetime value (Fig. 2a), while at higher E_c.m. energy it also populates the symmetric mass region for longer DNS lifetimes (Fig. 2b). The lifetime of an excited DNS for a given reaction depends on the initial collision energy E_c.m. and angular momentum distribution values. Therefore, during its evolution the DNS can either evolve to complete fusion or decay into two fragments (quasifission). The competition between these processes relates to the values of intrinsic fusion barrier and quasifission barrier B_{qf}, which depend on the peculiarities of reacting nuclei, beam energy, and angular momentum distribution [1,2,16].

3 Comparison Between the ^{136}Xe+^{136}Xe and ^{24}Mg+^{248}Cm Reactions Leading to ^{272}Hs

To verify whether any projectile and target combination can always lead to complete fusion of reactants (given sufficient beam energy to overcome the Coulomb barrier) and synthesis of the desired SHE, we consider the mass-symmetric ^{136}Xe+^{136}Xe reaction that would lead to the ^{272}Hs CN. Using the procedure presented in the previous section, results for this reaction are shown in Fig. 3. Figure 3a shows capture, quasifission, fusion, and fast fission cross sections versus E_c.m. energy, while Fig. 3b shows the fusion probability P_{CN} over

the same E_c.m. energy range. The capture cross section for the ^{136}Xe+^{136}Xe reaction is about 10 mb in the explored energy range, while the fusion cross section leading to the ^{272}Hs CN ranges between 10^{-4} and 10^{-1} pb (with a fusion probability of about 10^{-14}-10^{-11}) in the same E_c.m. interval. From this investigation, we can conclude that the evaporation residue cross section is much lower than 10^{-10} pb, a value that practically means no synthesis events of the SHE occur.

For comparison with these results, Fig. 4a shows our calculated results for the mass-asymmetric ^{24}Mg+^{248}Cm reaction leading to the same ^{272}Hs CN. In the lower-medium E_c.m. energy range, the fusion process dominates the reaction dynamics, while at high energy the quasifission process prevails. Figure 4b shows the ER cross sections. Comparing Figs. 3 and 4 reveals that the fusion-fission cross section for the ^{24}Mg+^{248}Cm reaction at CNE 55 MeV (E_c.m. = 192 MeV) is about 150 mb, while the corresponding fusion-fission cross section for the ^{136}Xe+^{136}Xe mass-symmetric reaction is lower than a few pb (because the reaction dynamics is completely dominated by the quasifission process). For the symmetric reaction at the same CN excitation energy of 55 MeV (E_c.m. = 355 MeV), the fusion-fission yield is at least 10^{-12} times lower than that obtained in the ^{24}Mg+^{248}Cm reaction.

Results

Study of Perspectives for Heavier Superheavy Elements

To estimate realistic possibilities for SHE synthesis via massive nuclei reactions, we performed calculations of ER cross sections for a set of reactions forming fissile compound nuclei with Z $\geq$ 100 at the same excitation energy (CNE 37 MeV). Table 1 presents this set of reactions with various entrance channels having different charge (mass) asymmetry parameters. It is interesting to observe and analyze the overall trend of fusion probability P_{CN} and evaporation residue yields for various reactions as functions of charge Z_{CN} and the parameter $z = (Z_1 \times Z_2)/(A_1^{1/3} + A_2^{1/3})$ to draw useful indications about possible reactions leading to heavy nuclei with Z_{CN} $\geq$ 100, particularly those leading to SHE with Z_{CN} $\geq$ 120.

Figure 5 shows the fusion probability P_{CN} for the reactions listed in Table 1 as a function of charge Z_{CN} at CNE 37 MeV. As shown in Fig. 5, P_{CN} slowly decreases with Z_{CN} but strongly decreases for more symmetric reactions in the entrance channel leading to the same Z_{CN}. The trend of P_{CN} for the investigated reactions becomes clearer when we plot calculated P_{CN} values as a function of the parameter $z = (Z_1 \times Z_2)/(A_1^{1/3} + A_2^{1/3})$, which is related to the Coulomb barrier of interacting nuclei in the entrance channel (see Fig. 7 from Ref. [19]). In this representation, the P_{CN} values at given Z_{CN} values (108, 118, 120, 122, 124, and 126) represent different fusion probabilities for various entrance channels leading to the same Z_{CN}. The fusion probability P_{CN} strongly decreases with increasing z

parameter and decreasing charge (mass) asymmetry parameter of reactions in the entrance channel. Hindrance to fusion increases for more symmetric reactions and for higher Coulomb barriers in the entrance channel. Evaporation residues after neutron emission only from the CN de-excitation cascade can be observed for reactions with z parameter lower than about 200. For reactions with z values in the range of approximately 200–235, observation of residues is at the limit (or appears very problematic) of current experimental capabilities. For reactions with z higher than 235, it is impossible to observe ERs of the CN after neutron emission only.

Table 2 presents results for investigated reactions leading to CN with Z = 120, 122, 124, and 126 at CNE 37 MeV. We estimate that only for SHE with Z_{CN} = 120 is it possible to observe evaporation residues from reactions with z parameter lower than 230. The possibility of obtaining the heaviest ^{302119} and ^{305120} SHEs using the ^{48}Ca beam in the ^{48}Ca+^{254}Es and ^{48}Ca+^{257}Fm reactions, respectively, is restricted by difficulties in obtaining sufficiently thick targets of ^{254}Es and ^{257}Fm because other Es and Fm isotopes are radioactive with shorter lifetimes. Therefore, to reach heavier SHE, reactions with beams heavier than ^{48}Ca (such as ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni, and other heavier projectiles) against actinide targets should be used. Unfortunately, evaporation residue cross sections strongly decrease with decreasing charge (mass) asymmetry of reactants in the entrance channel.

Figures 6 and 7 show, as examples, the ER excitation functions obtained for the ^{48}Ca+^{249},^{250}Cf reactions using the masses and barriers from Refs. [17,18]. We also investigated formation of the heaviest evaporation residue nuclei from the ^{299},^{300118} CNs formed in reactions induced by ^{48}Ca projectiles with the heaviest accessible ^{251},^{252}Cf actinide targets, and the results are comparable to those obtained for reactions on ^{249},^{250}Cf targets.

By analyzing the 2, 3, 4, and 5 neutron emission channels along the de-excitation cascade of ^{48}Ca+^{249},^{250}Cf compound nuclei, we studied possibilities for synthesizing the ^{292}-^{296118} ER nuclei. Considering currently available experimental conditions in laboratories, the most convenient and accessible reaction channels for observing evaporation residue nuclei are the 3- and 4-neutron emission channels in the ^{48}Ca+^{249}-^{252}Cf reactions at excitation energies CNE = 25–40 MeV. Comparing our analysis of the ^{48}Ca+^{249},^{250}Cf reactions with experimental data from Ref. [5] regarding observation of the ^{294118} evaporation residue nucleus, we conclude that the observed ^{294118} synthesis events registered at two different beam energies are contributed by the 3n channel in the ^{48}Ca+^{249}Cf reaction and the 4n channel in the ^{48}Ca+^{250}Cf reaction, due to the inevitable presence of the ^{250}Cf isotope in the ^{249}Cf-enriched target. Moreover, comparison of results for ER nuclei in the ^{48}Ca+^{252}Cf studied reaction suggests using a single target composed of all Cf isotopes with longer lifetimes, which is more convenient both for target preparation and for analysis of a single experiment. In fact, it is possible to observe and study a wide set of ER nuclei formed by 2n, 3n, 4n, and 5n emission channels simply by changing the ^{48}Ca beam energy E_{lab}

in the range of 235–260 MeV.

Reactions such as ^{132}Sn+^{249}Cf (with z = 431) to reach the ^{340132} and ^{381148} SHE, and mass-symmetric reactions like ^{139},^{149}La+^{139},^{149}La (with z = 317 and 306, respectively), cannot synthesize heavy and superheavy elements because of the absolutely dominant contribution of the quasifission process after capture and the fast fission process present at the stage of the already improbable formation of complete fusion.

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Note: Figure translations are in progress. See original paper for figures.