Mixing of fusion-fission and quasifission products in reaction with massive nuclei

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Abstract. It is known the fusion cross section plays crucial role in the choice of the reaction to synthesize new superheavy elements. An estimation of the fusion cross section in the reactions with massive nuclei is difficult task when the mass (charge) and angular distributions of the quasifission and fusion-fission fragments strongly overlap. The measured yields of evaporation residues, fusion-fission and quasifission fragments in the \textsuperscript{48}Ca+\textsuperscript{154}Sm reactions are analyzed in the framework of the method based on the dinuclear system concept and advanced statistical model. The experimental data of the fission fragments are decomposed into contributions coming from fusion-fission, quasifission, and fast fission. Our investigations showed the synthesis of the new element \(Z=120\) (\(A=302\)) is more preferable in the \textsuperscript{54}Cr+\textsuperscript{248}Cm reaction in comparison with the \textsuperscript{58}Fe+\textsuperscript{244}Pu and \textsuperscript{64}Ni+\textsuperscript{238}U reactions because the excitation function of the evaporation residues of the former reaction is some orders of magnitude larger than that for the last two reactions.

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1. Introduction

The synthesis of the new superheavy elements is one of modern problems in nuclear physics. The correct estimation of the cross section of the compound nucleus formation in the reactions with massive nuclei is important to choose favorable reaction and optimal values of bombarding energy allowing us to observe an events corresponding to synthesis of the new expected element. The experimental methods used to estimate the fusion probability depend on the unambiguity in identifying of the complete fusion reaction products among the quasifission products. The difficulties arise when the mass (charge) and angular distributions of the quasifission and fusion-fission fragments strongly overlap depending on the reaction dynamics. As a result, the complete fusion cross sections may be overestimated. We know that quasifission fragments show anisotropic angular distributions \[1, 2\]. This is a way to separate them from the fusion-fission fragments which should have isotropic angular distributions. But fission fragments in reactions with heavy ions also show anisotropic angular distributions which is explained by the assumption that an equilibrium \(K\)-distribution is not reached (\(K\) is the projection of the total spin of the compound nucleus on its axial symmetry axis). At the same time the angular distribution of
the quasifission fragments may be isotropic when the dinuclear system decays having a large angular momentum [3].

This paper is devoted to analyze reasons for the disappearance of the quasifission feature in the experimental data for the $^{48}\text{Ca}+^{154}\text{Sm}$ reactions studied in the paper [4] by Knyazheva et al. The same method of analysis is applied to study the problem of the synthesis of the new superheavy element $Z=120$. The three reactions $^{54}\text{Cr}+^{248}\text{Cm}$, $^{58}\text{Fe}+^{244}\text{Pu}$ and $^{64}\text{Ni}+^{238}\text{U}$ are compared with the aim to answer the question which of these reactions is preferable to obtain $Z=302$.120.

2. Mixing the mass and angular distributions of the fusion-fission and quasifission products

The reaction channels with the full momentum transfer at low collision energies take place through the capture stage at which dinuclear system (DNS) is formed. The lifetime of DNS should be enough for its transformation into compound nucleus during its evolution. There is a hindrance at formation of the compound nucleus (CN) in reactions with massive nuclei: not all of DNS formed at capture of the projectile by the target-nucleus can be transformed into CN. DNS may break up into two parts after multinucleon transfer changing strongly its mass and charge asymmetry or with the masses and charges close ones of the projectile and target. The decay of the DNS into two fragments bypassing the stage of the CN formation is called a quasifission. The mass distribution of the quasifission products depends on the landscape of potential energy surface, on the initial mass and charge asymmetry, as well as on the beam energy and impact parameter of the collision. So due to quasifission of DNS the number of events corresponding to formation of CN decreases. Another process which decreases the probability of CN formation is the fast fission. It is the inevitable decay of the fast rotating mononucleus into two fragments without reaching the equilibrium compact shape of CN. Such a mononucleus is formed from DNS which survived against quasifission. At large values of the angular momentum $\ell > \ell_f$, where $\ell_f$ is a value of $\ell$ at which the fission barrier of the corresponding compound nucleus disappears, the mononucleus immediately decays into two fragments [8]. As distinct from fast fission, the quasifission can occur at all values of $\ell$ at which capture occurs. Both of processes can produce fragments which have overlap of their mass (or charge) and angular distributions with ones of fusion-fission reactions.

In Ref. [4] the authors established the fusion suppression and the presence of quasifission for the $^{48}\text{Ca}+^{154}\text{Sm}$ reaction at energies near and below the Coulomb barrier. They consider the mass and angular distribution of the fission-like products with masses in the range $55 < A < 145$. The authors did not analyze the products of the quasifission with masses outside of the range $55 < A < 145$ where the quasifission fragments yield presents (see Fig. 2). Authors accepted for quasifission products only yields corresponding to the “shoulders” peaked around the masses 65 and 140 in the mass distribution of fission fragments appearing as an “asymmetric fission mode” at $E_{\text{CN}}^* = 49$ and 57 MeV. Quasifission cross sections of this reaction have been extracted from the total fission-like events by the analysis of their mass and angular distributions. The anisotropy of the angular distribution of the products corresponding to the “asymmetric shoulders” points to the quasifission nature of this component. The contribution of the quasifission components to the total mass distribution of fission fragments increases, with respect to the one of the symmetric compound nucleus-fission, as the $^{48}\text{Ca}$ projectile energy decreases (see Fig. 3 in [4]). This phenomenon is seen in Fig. 1 where the theoretical results obtained in the framework of the DNS model [see Refs. [5, 6]] are compared with the experimental results for the quasifission and fusion-fission excitation functions from Ref. [4]. The contribution of the fast fission channel increases by increasing the bombarding energy due to the increase in the angular momentum of the mononucleus.

We can discuss three reasons leading to the overestimation of the experimental quasifission
Figure 1. Comparison of the theoretical results obtained in the DNS model (curves) [5, 6] and experimental (symbols) [4] excitation functions for the quasifission (solid line and solid triangles), fusion-fission (dot-dashed line and inverted open triangles) and fast fission (dashed line) for the $^{48}\text{Ca}^{154}\text{Sm}$ reaction. The theoretical values of the fusion-fission cross section calculated by the advanced statistical model [7] (solid triangles) cross section by our calculation (solid line) in Fig. 1. The first reason is the excluding the reaction products having mass numbers outside the mass range $55 < A < 145$ from their analysis by the authors of Ref. [4]. Consequently they lost a part of the capture cross sections related to the contributions of the quasifission fragments with $A_{qf} < 55$. Because our studies showed that capture events, i.e. events of the full momentum transfer, can lead to yields of fragments with masses $A_{qf} < 55$. It is seen in the left panel of Fig. 2 where we present the evolution of mass distribution of the quasifission product yields which were calculated by our method presented in Ref. [9]. The observed quasifission feature at low energies is connected with the peculiarities of the shell structure of the interacting nuclei.

The second reason is that at low energies the contribution of the fusion-fission to the yield of binary fragments is small in comparison with the quasifission contribution because the complete fusion is small in competition with quasifission. Third reason causing the smallness of the theoretical fusion-fission cross section is the large fission barrier ($B_f=12.33$ MeV) for the $^{202}\text{Pb}$ nucleus according to the rotating finite range model by A. J. Sierk [10] and by the additional barrier $B_{f}^{(microscopic)} = -\delta W = -(\delta W_{saddle-point} - \delta W_{gs}) \approx 8.22$ MeV due to the nuclear shell structure.

At the large bombarding energies the contribution of fusion-fission (dash-double dotted line) and fast fission (dash-dotted line) components increases and become comparable with the components of the quasifission (short dashed line) in Fig. 1. The increase in the beam energy leads to a decrease of the shell effects and the yield of the quasifission fragments near the
Figure 2. The mass distribution of the quasifission products yield in the $^{48}\text{Ca}+^{154}\text{Sm}$ reaction at $E_{\text{c.m.}}=140$ MeV as a function of the lifetime of the dinuclear system formed at capture stage (a). The mass distribution of the quasifission product yields in the $^{48}\text{Ca}+^{154}\text{Sm}$ reaction at $E_{\text{c.m.}}=160$ MeV as a function of the lifetime of the dinuclear system (b).

Figure 3. The rotational angle of the dinuclear system as a function of the orbital angular momentum (a) and (b), and angular distribution of the yield of quasifission fragments (c) and (d).
Figure 4. Calculated excitation functions for the capture, fusion and formation of the evaporation residues in the 2n, 3n, 4n, and 5n channels in the 54\textsuperscript{Cr}+248\textsuperscript{Cm} (left panel), 58\textsuperscript{Fe}+244\textsuperscript{Pu} (middle panel), and 64\textsuperscript{Ni}+238\textsuperscript{U} (right panel) reactions.

asymmetric shoulders decreases. The main contribution to quasifission moves to the symmetric mass distribution (see the right panel of Fig. 2). The decay of the DNS formed with large angular momentum can lead to yield of products with isotropic angular distribution (see Fig. 3a). Therefore, these fragments are considered as fusion-fission fragments. This result was obtained by calculation of the lifetime of the rotating DNS as a function of its excitation function and depth of the potential well in the nucleus-nucleus potential \cite{3}. This is one of mechanisms which are responsible for the disappearance of the “asymmetric shoulders” in the mass distribution of the fission fragments from the 48\textsuperscript{Ca}+154\textsuperscript{Sm} reactions at collision energies $E_{c.m.} > 154$ ($E_{CN}^* > 63$ MeV). The experimental data, which were identified as fusion-fission fragments by the authors of Ref. \cite{4}, increase strongly starting from the energies $E_{c.m.} > 147$ ($E_{CN}^* > 57$) MeV. According to our results, a large part of this increase belongs to the quasifission fragments (see Fig. 1). So we stress that, in the 48\textsuperscript{Ca}+154\textsuperscript{Sm} reaction, the quasifission (solid line in Fig.1) is the dominant channel in comparison with the fusion-fission (dot-dashed line) and fast fission (dashed line in Fig. 1) channels. The presented results in Fig. 1 are obtained by averaging over all orientation angles of the symmetry axis of 154\textsuperscript{Sm} which is a well deformed nucleus ($\beta_2 = 0.341$). The role of the target orientation angle relative to the beam direction during the formation of the fusion-fission and ER products in the 48\textsuperscript{Ca}+154\textsuperscript{Sm} reaction was analyzed in Ref. \cite{11}. Indeed the fusion probability increases by increasing the beam energy due to the inclusion of the contributions from collisions with large orientation angles of the target-nucleus symmetry axis with respect to the beam direction. The favourableness of the large orientation angles for the formation of the compound nuclei was analyzed in Refs. \cite{6,11}. The fission probability increases because fission barrier $B_f$ decreases at higher excitation energies and large values of angular momentum. We conclude that the experimental fusion-fission data obtained at the high energy collisions contain the contribution of quasifission fragments with masses $A > 93$ which show an isotropic distribution as presented in Ref. \cite{4}. The products of quasifission should have less excitation energy than the ones of fusion-fission reaction because former products come from the decay of the fast rotating DNS. Therefore, the multiplicity of neutron emission accompanying quasifission products should be smaller than that accompanying fusion-fission products.
Calculation of angular distribution of the quasifission products as a function of the angular momentum and excitation energy of DNS shows that the angles corresponding to the peak of yields concentrate near forward and backward directions as shown in Figs. 3b and 3d. As a result sufficient part of them were not registered by detector placed at angles larger than 15°. This circumstance can be considered as the technical reason of disappearance of the yield of quasifission products at $E_{c.m.} > 153$ MeV.

The experimental results confirming the large contribution of quasifission products into mass symmetric region appeared recently in Ref. [12, 13]. At the large energy $E_{c.m.}=154$ MeV ($E_{\text{CN}}^* = 63$ MeV) the experimental values of the quasifission cross section are much lower than that of the fusion-fission cross section.

So, we have explained the large difference between the calculated and experimental capture cross sections at low collision energies and the decrease in this difference at high collision energies. The experimental data of fission-like fragments seem to include some part of the quasifission and fast fission fragments which overlaps with the mass and angular distributions of the fusion-fission fragments.

In the framework of our model [5, 6] we estimate the most preferable reaction for the synthesis of the superheavy element $Z = 120$. Among the three studied reactions, $^{54}\text{Cr} + ^{248}\text{Cm}$, $^{58}\text{Fe} + ^{244}\text{Pu}$, and $^{64}\text{Ni} + ^{238}\text{U}$, the first one is most preferable for the synthesis of the element $Z=120$. Because a more asymmetric reaction it has a smaller intrinsic fusion barrier and a larger quasifission barrier that lead to a larger fusion cross section (see [14]). The expected cross section for the synthesis of superheavy element $Z=120$ in the $^{54}\text{Cr} + ^{248}\text{Cm}$ reaction is more than 1 pb for the 2n and 3n evaporation channels at $E_{c.m.}=233–245$ MeV.

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