Symmetric and asymmetric quasifission in reactions with heavy ions

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Abstract. The main aim of the present study is to evaluate the fusion probabilities and investigate competing quasifission process in the reactions with heavy ions leading to the formation of superheavy composite systems. The mass-energy distributions of binary fragments as well as their cross sections have been measured for a wide range of composite systems with \(Z=82-122\) formed in the reactions with \(^{22}\text{Ne}, ^{26}\text{Mg}, ^{48}\text{Ca}, ^{58}\text{Fe}\) and \(^{86}\text{Kr}\) ions at energies around the Coulomb barrier. The experiments were carried out using a double-arm time-of-flight spectrometer of binary reaction products CORSET. The results of the experimental investigation of the influence of the entrance channel properties on the competition between fusion-fission and quasifission for the “warm” fusion reactions is discussed.

1. Introduction

The collision of two massive nuclei takes a special place in nuclear reaction studies due to the large number of interacting nucleons. In this type of reactions a drastic change of the reaction partners may occur that leads to different reaction mechanisms. In reactions with heavy ions complete fusion and quasifission (QF) are competing processes [1, 2, 3, 4]. The relative contribution of QF to the capture cross section becomes dominant for superheavy composite systems and compound nucleus (CN) formation is hindered by QF process. It strongly depends on the entrance channel properties, such as mass-asymmetry, deformation of interacting nuclei, collision energy and the Coulomb factor \(Z_1Z_2\).

In the context of the Liquid Drop Model (LDM) taking into account the nuclear interaction in the form of a proximity potential, calculations of the potential interaction energy were performed [5] for a large number of reactions involving heavy ions. These calculations show that the fusion barrier for the systems with \(Z_1Z_2\geq 1800\) has a double-humped shape. The internal barrier becomes predominant for the systems with \(Z_1Z_2\geq 2300\). The existence of a minimum in the potential energy after a contact of two nuclei, which is bounded by the internal barrier, is likely to be responsible for an onset of QF. These calculations, however, did not take into account the influence of the shell effects playing an important role in the interaction between two heavy nuclei.

A realistic description of the mass, energy and angular distributions of the reaction fragments formed in deep inelastic scattering, QF and compound nucleus fission (CNF) processes in low-energy heavy ion collisions was performed in [6] by using Langevin type dynamic equations of motion. It was shown that the multi-dimensional adiabatic potential energy surface (calculated within the two-centre shell model) plays the most important role in such processes. Fig. 1 shows the potential energy surface

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as a function of the mass-asymmetry and elongation for the superheavy nuclear system consisting of 116 protons and 180 neutrons. This potential energy surface is strongly modulated by shell effects and leads to the appearance of deep valleys corresponding to the formation of well bound magic nuclei. In accordance with these calculations, at least three paths leading to the formation of fission-like fragments can be distinguished: (1) asymmetric QF (QF asym in Fig. 1) caused by the influence of proton shells with \( Z = 28, 82 \) and neutron shells with \( N = 50 \) and 126; (2) symmetric QF (QF sym in Fig. 1) determined by the shells with \( Z = 50 \) and \( N = 82 \); (3) CNF (CNF path in Fig. 1) leading to the formation of symmetric fragments.

![Figure 1. Example of a driving potential energy surface as a function of elongation and mass asymmetry for a heavy ion induced reaction leading to the superheavy composite system [6].](image)

2. Asymmetric quasifission

While QF is a process occurring without a CN stage the QF fragment properties are close to CNF. The main experimental difference between asymmetric QF and asymmetric fission is connected with angular distribution of their fragments.

At comparative study of mass-energy distributions of fission-like fragments obtained in the reactions \(^{12}\text{C} + ^{208}\text{Pb}\) and \(^{48}\text{Ca} + ^{168}\text{Er}\) at excitation energy of about 40.5 MeV leading to the formation of the same CN \(^{216}\text{Ra}\) the large contribution \(\sim 30\%\) of the asymmetric fission mode in the case of the reaction \(^{48}\text{Ca} + ^{168}\text{Er}\) is immediately evident, manifesting itself in the form of wide “shoulders”. The symmetric fission component is described by a Gaussian shape for both reactions, but it is wider in the \(^{48}\text{Ca}\) induced reaction than that for the \(^{12}\text{C}\) reaction. This increase in variance is consistent with the results of Ref. [7], where it is shown that dispersion of mass distribution increases approximately linearly with angular momentum. According to [8] the critical angular momentum is \(31\hbar\) for the \(^{12}\text{C} + ^{208}\text{Pb}\) reaction and \(54\hbar\) for \(^{48}\text{Ca} + ^{168}\text{Er}\). Thus the observed increase of dispersion agrees with the expectations for normal symmetric fission of the excited CN. The shape of the curve obtained for \(\langle\text{TKE}\rangle\) in the case of \(^{48}\text{Ca} + ^{168}\text{Er}\) is far from parabolic, and is much wider than the parabola of the \(^{12}\text{C} + ^{208}\text{Pb}\).

Thus in the \(^{48}\text{Ca}\) reaction we observe a strong increase (by a factor of \(\sim 20\)) in the contribution of asymmetric fission compared with the \(^{12}\text{C}\) reaction. This increase is also reflected in the energy distributions of the fragments. It is interesting to note that this effect is observed at all
energies around the fusion barrier in the $^{48}$Ca reaction though its importance decreases sharply with increasing excitation energy.

Angular distributions for symmetric (98-118 u) and asymmetric (68-88 u) fragment masses were derived attempting to find experimental evidence for the QF nature of the mass-asymmetric “shoulders” observed in the reaction $^{48}$Ca+$^{168}$Er (see Fig.3). A significant forward-backward asymmetry is observed in the angular distribution of fragments with masses 68-88 u (the region where asymmetric “shoulders” is observed), while symmetric fragments show a typical for CN symmetrical with respect to 90° in the centre-of-mass system angular distribution. Forward-backward asymmetry in angular distribution indicates that the composite system lives less than the time of one turn of composite system (∼10⁻²¹s) and this time is not sufficient for the formation of the fully equilibrated CN.

![Figure 2](image)

Figure 2. From top to bottom: two-dimensional matrix (TKE, Mass) of binary fragments obtained in the reactions $^{12}$C+$^{204}$Pb and $^{48}$Ca+$^{168}$Er; mass distributions and average TKE’s as functions of fragment masses.
Figure 3. Differential cross sections for fission-like fragments in the reaction $^{48}\text{Ca}+^{168}\text{Er}$ for asymmetric and symmetric fragment masses.

Figure 4. Two-dimensional matrices (TKE, Mass) for the reactions $^{48}\text{Ca}+^{144}\text{Sm}$ and $^{48}\text{Ca}+^{208}\text{Pb}$ (targets and projectile are spherical) in comparison with the $^{48}\text{Ca}+^{154}\text{Sm}$ and $^{48}\text{Ca}+^{238}\text{U}$ (targets are strong deformed) at the energy near the Coulomb barrier.
The QF process has been found for the reactions $^{48}\text{Ca}+^{168,170}\text{Er}$ [9], $^{40,48}\text{Ca}+^{154}\text{Sm}$ [10] which involve deformed targets and lead to moderately fissile compound nuclei. For these reactions along with a maximum corresponding to the symmetric mass division around $A_{CN}/2$, reveals two additional “asymmetric shoulders” corresponding to QF asym. The major part of the asymmetric component fits into the region of the $Z=28$ and $N=82$ shells, and its maximum yield is a “compromise” between them. Thus, we have an indication that the shell structure of the fragments formed in the ranges of the light $M=60-75$ u and heavy $M=130-145$ u masses, respectively, strongly favour the QF process, the shells in both light and heavy fragments playing an important role.

![Figure 5](image)

**Figure 5.** Mass-energy distributions for the reactions $^{36}\text{S}$, $^{48}\text{Ca}$, $^{64}\text{Ni}+^{238}\text{U}$ at energies close to the Coulomb barrier.

However, for the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction with spherical nuclei the QF asym is not observed, the closed shells with $N=50$ and $Z=50$ fall into the region of the symmetric mass distribution, i.e., in the region of “normal” CNF. The same trend may be expected in the reactions leading to the superheavy nuclei. In the case when both reaction partners are spherical the contribution of QF process may be expected relatively small (for example, $^{48}\text{Ca}+^{208}\text{Pb}$ [11]).

The yields of evaporation residues, fusion-fission, and quasifission fragments in the $^{48}\text{Ca}+^{144,154}\text{Sm}$ and $^{16}\text{O}+^{186}\text{W}$ reactions have been analyzed in the framework of the combined theoretical method based on the dinuclear system concept and advanced statistical model [12]. According to these calculations the decrease in the measured yield of QF fragments in $^{48}\text{Ca}+^{154}\text{Sm}$ at the large collision energies and the lack of QF fragments in the $^{48}\text{Ca}+^{144}\text{Sm}$ reaction are explained by the overlap in mass angle distributions of the QF and CNF fragments.

In Fig. 4 the mass-energy distributions for the reactions $^{48}\text{Ca}+^{144,154}\text{Sm}$ and $^{48}\text{Ca}+^{208}\text{Pb}$, $^{238}\text{U}$ at the energy near the Coulomb barrier are shown. Deformation of the interacting nuclei favours the QF process which mainly leads to the formation of the clusters in the exit channel of the reaction. The contribution of asymmetric QF component in the capture cross section increase with increasing the reaction Coulomb factor $Z_1Z_2$ and becomes dominant for the composite systems with $Z_1Z_2>1800$ [13]. Fig. 5 shows the mass energy distributions of binary fragments obtained in the reactions of $^{16}\text{S}$, $^{48}\text{Ca}$, $^{64}\text{Ni}$ ions with an uranium target. The Coulomb factors are 1472, 1840 and 2576 for the $^{16}\text{S}+^{238}\text{U}$, $^{48}\text{Ca}+^{238}\text{U}$ and $^{64}\text{Ni}+^{238}\text{U}$, respectively.

Some noteworthy features of QF asym component of fragment mass distributions for the studied reactions can be highlighted at this point. Generally, in heavy-ion induced reactions the formation of QF asym fragments is connected with the strong influence of the nuclear shell at $Z = 82$. 

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International Symposium on Quasifission Process in Heavy Ion Reactions

Journal of Physics: Conference Series 282 (2011) 012008

doi:10.1088/1742-6596/282/1/012008

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and \( N = 126 \) (doubly magic lead). In fact, as it was shown in Ref. [14], for the \(^{48}\text{Ca}+^{238}\text{U}\) reaction the maximum yield corresponds to fragments with masses 208 u. However, in reactions with lighter projectiles on an uranium target, the asymmetric QF peak shifts to more symmetric masses [15]. By contrast, for the heavier projectile \(^{64}\text{Ni}\) the maximum yield of QF\(_{\text{sym}}\) fragments corresponds to the heavy mass 215u [14]. This trend is illustrated in Table 1 where the positions of light and heavy QF fragments for these reactions are presented. Notice, that even in the case of the \(^{36}\text{S}+^{238}\text{U}\) and \(^{26}\text{Mg}+^{248}\text{Cm}\) leading to the formation of the same composite nucleus \(^{274}\text{Hs}\) the position of the asymmetric QF peaks changes [16] (see Fig. 6). This trend is contrary to the multimodal fission [17] where the position of each mode determined by the nuclear shells is constant for specific compound nucleus and only the relative contribution of each mode varies in dependence of excitation energy. Thus, for more asymmetric reactions the Coulomb repulsion is expected to be smaller. For lighter projectiles this may lead to longer reaction times before separation for asymmetric QF and thus to larger numbers of exchange nucleons.

### Table 1. Positions of heavy and light peaks in the mass distributions of QF\(_{\text{asym}}\) fragments.

| Reaction           | \( Z_1Z_2 \) | \( M_L \) | \( M_H \) | Exchange nucleons | Ref.               |
|--------------------|--------------|----------|----------|-------------------|--------------------|
| \(^{30}\text{Si} + ^{238}\text{U}\) | 1288        | 90       | 178      | 60                | Nishio et al. [15] |
| \(^{36}\text{S} + ^{238}\text{U}\) | 1472        | 74       | 200      | 38                | Itkis et al [16], Nishio et al. [15] |
| \(^{40}\text{Ar} + ^{238}\text{U}\) | 1656        | 74       | 204      | 34                | Nishio et al. [15] |
| \(^{48}\text{Ca} + ^{238}\text{U}\) | 1840        | 78       | 208      | 30                | Kozulin et al. [14] |
| \(^{64}\text{Ni} + ^{238}\text{U}\) | 2576        | 87       | 215      | 23                | Kozulin et al. [14] |
| \(^{26}\text{Mg} + ^{248}\text{Cm}\) | 1152        | 94       | 180      | 68                | Itkis et al [16] |

3. **Symmetric quasifission**

Besides asymmetric also symmetric component may be affected by the presence of QF process. Consequently the question of whether the symmetric fragments originate from CNF or QF processes arises. On the one hand the angular distribution for these fragments is symmetric with respect to 90° in the centre-of-mass system and the estimated reaction time is about \( 10^{-20} \) s typical for CNF processes. On the other hand mass drift is rather slow process and long reaction time is needed to reach the mass equilibration. But this condition is not enough for CN formation, in which all degrees of freedom have
to come to equilibration. Thereby, the possible reaction channel for superheavy composite systems is a process occurring without a CN stage. This process is characterized by long reaction times sufficient for mass equilibration and resulting in the formation of symmetric fragments (symmetric quasifission (QFsym)) in Fig. 1.

Figure 7 displays the obtained distributions of binary fragments obtained in the reaction $^{48}$Ca+$^{238}$U at different excitation energies, namely (from top to bottom): the two-dimensional matrix of events as a function of the mass and total kinetic energy; the mass distribution for fission events framed into the contour line drawn on the two-dimensional mass-energy plot. Reaction products lying between elastic peaks can be identified as totally relaxed events, i.e., as fission (or fission-like) fragments. We have outlined them by solid lines in the panels. Henceforth we consider the properties of these events only.

![Figure 7](image)

**Figure 7.** The two-dimensional TKE–M matrices (upper panels) and yields of fragments inside the contour lines on TKE-M matrices (bottom panels) in the $^{48}$Ca+112 reaction at projectile energies 212, 222, 232, 244 and 258 MeV corresponding to excitation energies of the CN of 18, 26, 35, 45 and 56 MeV, respectively.

Mass-energy distributions for the reaction $^{48}$Ca+$^{238}$U have the wide two-humped shape caused by QFsym process. In spite of domination of asymmetric QF fragments at energies below the Coulomb barrier, especially, the yield of symmetric fragments increases with increasing excitation energy. Figure 8 presents the TKE distribution of fragments with masses $A_{CN}/2\pm20$ u for the reaction $^{48}$Ca+$^{238}$U at energy 232 MeV. It is readily seen that TKE distribution has a complex structure which is not consistent with only CNF process. In fact, it is known that in CNF process the average TKE of the partner fragments is substantially independent on the excitation energy and shows a typical Gaussian-like shape. The TKE distribution was described by the sum of the three Gaussians with the next values of mean energies and dispersions: $188\pm3.0$ MeV and $213\pm5$ MeV; $228.5\pm1.5$ MeV and $420\pm5$ MeV; $265.9\pm1.9$ MeV and $74\pm4$ MeV.

From the Viola systematics [18] we infer that the average TKE is in a first approximation a linear function of the Coulomb barrier $Z^2/A^{1/3}$ whereas from the systematics in Ref. [7] we can estimate the variance of the TKE distribution. For the $^{286}$112 CN the variance of the TKE distribution is about $\sim 450$ MeV$^2$ and the TKE is 226 MeV. Given the considerable good agreement with the systematics, we associate the middle component of the TKE distribution with the CNF process. Since the asymmetric fragments have lower TKE that the symmetric ones, the low energy component of the experimental TKE distribution may be associated with fragments originating from the asymmetric QF process. The high energy part may arise instead from the symmetric mode of the QF. Furthermore, we
note that the mean TKE from this mode is about 40 MeV higher than the mean TKE for the CNF process. Considering that both processes give rise to symmetric mass fragments, the difference in mean TKE can be taken as an evidence that in the QF process a complete dissipation of the entrance channel energy does not occur. As a consequence, the symmetric fragments with high TKE do not originate from complete fusion because the final fragments retain part of the entrance channel total kinetic energy.

Figure 8. TKE distribution of fragments with masses $\frac{\text{ACN}}{2} \pm 20$ u for the reaction $^{48}\text{Ca}+^{238}\text{U}$ at energy 232 MeV. The open circles are the experimental points, the hatched region corresponds to CN fission with energy taken from the Viola systematic, dashed and dotted curves represent high and low energy components of the TKE distribution.

Figure 9. The two-dimensional TKE–M matrices (upper panels) and yields of fission-like fragments (bottom panels) in the $^{48}\text{Ca}+^{238}\text{U}$, $^{244}\text{Pu}$, $^{248}\text{Cm}$ reactions at the CN excitation energies around 33 MeV. At the transition from $^{238}\text{U}$ to the heavier $^{244}\text{Pu}$ and $^{248}\text{Cm}$ targets the mass-energy distributions of binary reaction products do not change practically. Figure 9 displays the TKE-M matrices for these reactions at CN excitation energy of about 33 MeV. The typical wide two-humped shape with small contribution to the symmetric mass region is observed for these reactions. It is important to note that the relative contribution of the symmetric fragments into the capture cross section does not drop dramatically with increasing of charge of composite system and equal 5-10% at CN excitation of 33 MeV. The evaporation residues cross sections are of the picobarn level for these
Consequently, the reaction mechanism is practically the same for the reactions with the $^{48}\text{Ca}$ ions with actinide targets.

To explore the relative contributions of CNF and QF to symmetric splitting we have investigated binary reaction channels of the composite systems with $Z = 108$ produced in reactions with $^{22}\text{Ne}$, $^{26}\text{Mg}$, $^{36}\text{S}$ and $^{58}\text{Fe}$ ions at energies below and above the Bass barrier. The entrance channel properties of these systems vary strongly: for the reaction $^{58}\text{Fe} + ^{208}\text{Pb}$ entrance channel mass-asymmetry $\eta = 0.571$, for $^{36}\text{S} + ^{238}\text{U}$ - 0.737, for $^{26}\text{Mg} + ^{248}\text{Cm}$ - 0.810, and for $^{22}\text{Ne} + ^{249}\text{Cf}$ - 0.838. It is important to note that all reaction partners, except $^{208}\text{Pb}$, are well deformed nuclei. In the reactions with deformed nuclei the potential energy surface strongly depends on the relative orientation of the reaction partners. Except for reactions with strong mass-asymmetry in the entrance channel the dominance of tip configurations at energies below the barrier leads to the increase of QF contributions. As demonstrated in Fig. 10 the mass-energy distributions change with decreasing asymmetry $\eta$ in the entrance channel from symmetric for incoming $^{22}\text{Ne}$-ions to strongly asymmetric for incoming $^{58}\text{Fe}$-ions. These changes are understood as reflecting the relative contributions from FF and QF to the fission process of Hs depending on the reaction studied.

![Figure 10. Mass-energy distributions of binary reaction fragments for the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$, $^{26}\text{Mg} + ^{248}\text{Cm}$, $^{36}\text{S} + ^{238}\text{U}$, $^{58}\text{Fe} + ^{208}\text{Pb}$ leading to the formation of elements with $Z = 108$ at energies above (top panel) and below (bottom panel) the Coulomb barrier.](image)

It is clearly seen that even at similar CN excitation energies the mass-energy distributions are vastly different for these reactions. In the case of the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$ and $^{26}\text{Mg} + ^{248}\text{Cm}$ the mass distributions have a near Gaussian shape with no evidence for asymmetric fission. The reactions are considered to be mainly CNF process. For the $^{36}\text{S} + ^{238}\text{U}$ reaction the mass distributions of the fission-like fragments change markedly. This difference in mass distributions for the $^{26}\text{Mg} + ^{248}\text{Cm}$ and $^{36}\text{S} + ^{238}\text{U}$ reactions is connected with an increasing contribution of the QF process for the $^{36}\text{S}$-induced reaction. At low excitation energies QF is the dominant process for the reaction $^{36}\text{S} + ^{238}\text{U}$. At higher excitation energies the mass distribution becomes symmetric and similar to the reaction $^{26}\text{Mg} + ^{248}\text{Cm}$ though - due to a remaining trace of QF - slightly wider.

In the case of the $^{58}\text{Fe} + ^{208}\text{Pb}$ reaction the mass-energy distribution has a wide two-humped shape even at 48 MeV excitation energy. For this reaction the QF process dominates at energies below and above the Bass barrier. The strong overlap between QF fragments, quasi-elastic and deep-inelastic events is observed due to the fact that one of the partners is doubly magic lead.
The TKE of symmetric fragments is also higher than predicted. In Fig. 11 the TKE distributions are shown for symmetric fragments with masses $A_{CN}/2 \pm 20\text{u}$ obtained in the $^{22}\text{Ne} + ^{249}\text{Cf}$ and $^{26}\text{Mg} + ^{248}\text{Cm}$ reactions at two excitation energies of the compound nuclei (below and above the Bass barrier). It is readily seen that the TKE distributions have a complex structure at low excitation energy, while at high excitation energy the TKE distributions are well described by single Gaussians with parameters coming from the LDM.

At low excitation shell effects show up in the CNF process giving rise to a structure in the mass-energy distributions of fission fragments. The structural features of the TKE distributions at low excitation may arise due to the fact that in symmetric fission both fragments are close to the spherical neutron shells with $N = 82$. A similar behaviour could be observed when both fission fragments are close to the spherical proton shell $Z = 50$. In fact, the phenomenon of bimodality has been disclosed in the case of spontaneous and low energy fission of nuclei in the Fm-Rf ($Z = 100-104$) region [20]. One can see in Fig. 11 that they may be deconvoluted into two Gaussians, the constituent peaks lying near ~214 MeV and ~230 MeV. Only the lower energy corresponds to the established linear dependency of the TKE on the Coulomb parameter $Z^2/A^{1/3}$ in the LDM. Hence, in this case bimodal fission is observed.

![Figure 11. TKE distributions of fragments with masses $A_{CN}/2 \pm 20\text{u}$ for the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$ (left panel) and $^{26}\text{Mg} + ^{248}\text{Cm}$ (right panel). Mean values and standard deviations of the experimental TKE distributions are indicated in the top right corner of each plot. High and low kinetic energy components are given as densely and sparsely hatched regions, respectively.](image)

In the case of the $^{22}\text{Ne} + ^{240}\text{Cf}$ reaction we have some evidence for bimodal fission at an excitation energy of 29 MeV. The standard deviation of the experimental distribution is higher for the lower energy. It is important to note the enhanced relative contribution of the high energy component
in the case of $^{274}$Hs$^*$-fission ($^{26}$Mg + $^{248}$Cm reaction) compared to $^{271}$Hs$^*$-fission ($^{22}$Ne + $^{249}$Cf reaction), while the excitation energy is higher for the former reaction. At symmetric fission of $^{274}$Hs both fragments have $N = 83$, while in the case of $^{271}$Hs the neutron number $N$ is 81.5. According to the systematics for pre- and post-scission neutron emission accompanying fission [21], the values of 1.1 and 0.6 pre-scission neutrons are expected for $^{274}$Hs ($E^* = 35$ MeV) and $^{271}$Hs ($E^* = 29$ MeV), respectively. Thus the formation of two spherical fragments with neutron number $N = 82$ is more favourable in the case of $^{274}$Hs compared to $^{271}$Hs.

As it was mentioned above the reaction $^{36}$S + $^{238}$U leads to the formation of a similar CN as in the reaction $^{26}$Mg + $^{248}$Cm. But, the TKE distributions for these reactions are different, in particular, at the lowest excitation energy of 35 MeV studied. In the case of the S induced reaction the TKE distribution is narrower and shifted to lower energies, the mean value of the TKE being 210 MeV instead of 218 MeV for the Mg induced reaction. Since in CNF the properties of the same CN formed in different reactions at the same excitation energy do not change, this shift of the TKE is due to a large contribution of QF to the fragment region with masses $A_{CN}/2 \pm 20$ u. Thus, this points to the fact that the main part of fission-like fragments originates from the asymmetric QF process and the contribution of other processes is relatively small.

The mean value and dispersion of TKE increase with increasing energy of $^{36}$S ions and exceed the LDM predictions at the highest energy. The TKE distributions of fragments formed in the
reaction with $^{36}\text{S}$ ions at energies above and below the Coulomb barrier for symmetric mass splits are shown in the left panel of Fig. 12. As just mentioned, at the excitation energy of 35 MeV the main component of the TKE distribution is connected with QF\textsubscript{sym}. For the higher energies each TKE distribution is decomposed as a sum of three Gaussians. One of them is associated with the CNF process. We fix the mean value and variance of this component to the values predicted from the systematics \cite{18} and \cite{7}, respectively. The low energy component in Fig. 12 is attributed to QF\textsubscript{asym} while the high energy one is connected with QF\textsubscript{sym}.

Thus we can estimate the fusion probability using the measured mass-energy distributions as the ratio between the number of events attributed to CNF in the frame of the present analysis and all fission-like fragments. The fusion probabilities as a function of the energy above the barrier are presented as open symbols in Fig. 13 for these reactions. As it follows from the present experimental data, the properties of entrance channels strongly affect the reaction dynamics. At the excitation energy near the barrier the estimated values of $P_{\text{CN}}$ are about 70\% in the case of the Mg-induced reaction and $\sim 25\%$ in the S-induced reaction.

Unfortunately, the transition to heavier projectile results in the large increase in the Coulomb factors $Z_1Z_2$ that is crucial in the competition between CNF and QF. The mass-energy distributions for the reactions $^{58}\text{Fe} + ^{244}\text{Pu}$ and $^{64}\text{Ni} + ^{238}\text{U}$ (leading to the formation of the same composite system with $Z=120$ and $N=182$) at the CN excitation energies about 45 MeV are presented in the figure 14. At first glance the distributions are similar for the both reactions: the wide two-humped shape with large QF component. However, at the same CN excitation energy the mass drift to the symmetry (estimated as a distance between masses corresponding to the maximum and half maximum of QF yields) is 22 nucleons in the case of the $^{58}\text{Fe}$ reaction and only 11 nucleons in the case of the $^{64}\text{Ni}$ ions. It is significant that the mass drift to the symmetry is about 34 nucleons for the $^{48}\text{Ca} + ^{238}\text{U}$ at the same CN excitation energy. The contribution of the symmetric fragments with masses $A_{\text{CN}}/2\pm 20$ u to all fission-like events is about 8\% and 4\% for Fe and Ni-ions, respectively. The average TKE’s are similar for asymmetric QF fragments for the both reactions, while in the symmetric mass region the TKE for the Fe+Pu reaction is higher than for the Ni+U. The solid line corresponds to the parabolic dependence following from the Liquid Drop Model and the Viola systematics for TKE. The dispersions of the TKE are different for the reactions: it is bigger in the case of Fe-ion induced reaction. In the reaction $^{64}\text{Ni} + ^{238}\text{U}$ the dispersion does not depend on a fragment mass practically and its mean value is about
350 MeV², while for the reaction $^{58}\text{Fe}+^{244}\text{Pu}$ dispersion increases for symmetric fragments and its mean value is about 610 MeV². The extrapolation of the experimental dependence on dispersion of TKE distributions from [7] gives the value of about 550 MeV² for the fission of $^{208}\text{Pb}$. Hence, for the reaction with Ni-ions TKE dispersion is lower than this value, whereas it is higher in the case of Fe-ions.

**Figure 14.** From top to bottom: the two-dimensional TKE–M matrices, yields, average TKEs and TKE dispersions of fragments inside the contour lines on TKE–M matrices (bottom panels) in the $^{58}\text{Fe}+^{244}\text{Pu}$ and $^{64}\text{Ni}+^{238}\text{U}$ reactions at the CN excitation energies about 45 MeV.
In the figure 15 the TKE distributions of fission-like fragments in the mass region $A_{CN}/2\pm 20$ u for the reactions $^{58}\text{Fe}+^{244}\text{Pu}$ and $^{64}\text{Ni}+^{238}\text{U}$ are presented. It is seen that both TKE distributions have a complex structure as in the case of the $^{48}\text{Ca}+^{238}\text{U}$ reaction (see Fig. 8).

In contrast to the $^{58}\text{Fe}+^{244}\text{Pu}$, for the reaction $^{64}\text{Ni}+^{238}\text{U}$ the TKE distribution has more pronounced low and high energy components (see fig. 14b), while the component with average value of 252 MeV (corresponding to the Viola systematics) is highly hindered. Because of the low statistics, only an upper value for the relative yield of the CN-fission component can be reasonably given. Table 2 gives the relative contribution of the all symmetric fragments in the mass range $A_{CN}/2\pm 20$ u and symmetric fragments with TKE corresponding to the Viola systematics.

The obtained captures cross sections as well as cross section for formation of symmetric fragments with mass $A_{CN}/2\pm 20$ u are presented in the figure 16 for the reaction $^{64}\text{Ni}+^{238}\text{U}$. The capture cross sections are about a few hundred millibarns for Ca and Ni induced reactions, whereas the formation of symmetric fragments is one order of magnitude less for the reaction $^{64}\text{Ni}+^{238}\text{U}$. Yet, in the case of the Ca+U at the highest energy, approximately 70% of the events have the TKE expected for the CN fission process, whereas in the case of the Ni reaction only a few percent of symmetric fragments have the TKE compatible with the Viola prediction for the $^{302}120$ CNF. The CNF cross-section in the $^{64}\text{Ni}+^{238}\text{U}\to^{302}120$ case drops three orders of magnitude with respect to the $^{58}\text{Fe}+^{244}\text{Pu}$, which is unfortunately a limiting factor. Furthermore, the relative contribution of the CNF from $^{64}\text{Ni}+^{238}\text{U}$ is much lower than in the case of $^{58}\text{Fe}+^{244}\text{Pu}$. Recently the experiments aimed at the synthesis of isotopes of element $Z=120$ have been performed using the $^{244}\text{Pu}(^{58}\text{Fe},\text{xn})^{302}\text{A}$ reaction [22] and $^{238}\text{U}(^{64}\text{Ni},\text{xn})^{302}\text{A}$ reaction [23]. A cross-section limit of
0.4 pb at $E^* = 44.7$ MeV for the former reaction and 0.09 pb at $E^* = 36.4$ MeV for the latter reaction were obtained. In the case of $^{26}Ca + ^{238}U$ reaction the evaporation residue cross-section for 3n, 4n channels is about a few pb. Thereby in the transition from Ca to Fe and Ni ions, the evaporation residue cross-section drops down at least one and two order of magnitude, respectively.

According to the calculations performed in the frame of dinuclear system concept [12] the estimated evaporation residue cross sections are $10^{-3}$ pb in the case of the $^{244}Pu(^{58}Fe,xn)^{302-x}_{120}$ and $10^{-6}$ pb in the case of the $^{238}U(^{64}Ni,xn)^{302-x}_{120}$.

Table 2. The relative contributions of all symmetric fragments ($\sigma_{ACN/2\pm20}$) and symmetric fragments with TKE corresponding to the older Viola systematics ($\sigma_{CNF}$) to the capture cross section ($\sigma_{cap}$) for the reactions $^{48}Ca + ^{238}U$, $^{58}Fe + ^{244}Pu$ and $^{64}Ni + ^{238}U$ at CN excitation energy of around 45 MeV.

| Reaction       | $\sigma_{ACN/2\pm20}/\sigma_{cap}$ (%) | $\sigma_{CNF}/\sigma_{ACN/2\pm20}$ (%) | $\sigma_{CNF}/\sigma_{cap}$ (%) |
|----------------|----------------------------------------|--------------------------------------|----------------------------------|
| $^{48}Ca + ^{238}U$ | 12±2                                   | 68±3                                 | 8±4                             |
| $^{58}Fe + ^{244}Pu$ | 8±3                                     | ≤25                                  | ≤2                               |
| $^{64}Ni + ^{238}U$ | 4±1                                     | ≤5                                   | ≤0.2                             |

**Figure 16.** Capture cross section (squares), cross section for the formation of fragments with masses $A_{CN/2\pm20}$ (circles) and the fragments, but with TKE corresponding to the Viola systematic (open triangles) for the $^{64}Ni + ^{238}U$ reaction. Rhomb is the capture cross section from [2].

4. Summary

Mass-energy distributions of binary fragments obtained in the reactions $^{20}Ne + ^{240}Cf$, $^{26}Mg + ^{248}Cm$, $^{36}S + ^{238}U$, $^{48}Ca + ^{144,154}Sm, ^{168}Er$, $^{208}Pb + ^{238}U$, $^{241}Pu + ^{248}Cm$, $^{58}Fe + ^{244}Pu$, $^{64}Ni + ^{238}U$ are analysed in the terms of symmetric and asymmetric quasifission and CN-fission. The asymmetric QF shows up even in the case of the $^{26}Mg + ^{248}Cm$ reaction (Z$_1Z_2$=1152) at energy below the Coulomb barrier. The contribution of asymmetric QF component in the capture cross section increase with increasing the reaction Coulomb factor Z$_1Z_2$ and becomes dominant for the composite systems with Z$_1Z_2$>1800 formed in the reactions with deformed nuclei. Generally, in heavy-ion induced reactions the formation of QFasym fragments is mainly connected with the strong influence of the nuclear shell at Z = 82 and N = 126 (doubly magic lead). But present analysis shows that the position of asymmetric QF peak shifts to more symmetric masses for the reactions with lighter projectiles (with smaller value of Z$_1Z_2$). Even in the case of the $^{36}S + ^{238}U$ and $^{26}Mg + ^{238}Cm$ leading to the formation of the same composite nucleus $^{274}Hs$ the position of the asymmetric QF peaks changes from ~200 u to ~180 u, respectively. This trend is contrary to the multimodal fission where the position of each mode determined by the nuclear
shells is constant for specific compound nucleus and only the relative contribution of each mode varies in dependence of excitation energy. Thus, for more asymmetric reactions the Coulomb repulsion is expected to be smaller. For lighter projectiles this may lead to longer reaction times before separation for asymmetric QF and thus to larger numbers of exchange nucleons.

For the symmetric mass splitting the presence of all there processes, namely, QF asym, QF sym and CNF was found from the analysis of the TKE distributions for these events. In the case of the $^{48}$Ca+$^{238}$U the contribution of the CNF process in TKE distribution for fragment masses $A_{\text{CN}}/2\pm 20u$ was estimated as $\sim 65\%$, while for the case of the more symmetric reaction $^{64}$Ni+$^{238}$U this ratio drop to $\sim 5\%$.

At the low excitation energy of 35 MeV, when shell effects should become more effective in fission, the TKE distribution of symmetric fragments obtained in the reaction $^{26}$Mg + $^{248}$Cm differs strongly from a Gaussian shape. Besides a low energy, a high energy component not foreseen in the LDM arises. This is attributed to the fact that both fission fragments are close to the spherical neutron shell $N = 82$. It means that for the compound nucleus Hassium formed in the reaction $^{26}$Mg + $^{248}$Cm the phenomenon of bimodal fission was discovered. In contrast to the $^{38}$Mg + $^{260}$Cm reaction where both fission fragments are close to the spherical neutron shell, in the case of the $^{56}$Fe + $^{208}$Pb reaction only one fragment is spherical (at symmetric mass split both fragments have only about 79 neutrons) and consequently bimodal fission is not expected for the latter reaction. But for the reaction $^{58}$Fe + $^{208}$Pb a high energy component was also observed in the TKE distribution of symmetric fragments. Its contribution increases with increasing excitation energy. Since shell effects fade away when the excitation energy is increasing, this component should be associated with the symmetric QF process because, quite generally, the QF process is colder than CNF. Therefore shell effects still play a dominant role in QF even at relatively high excitation energies.

Acknowledgments

The authors are grateful to Prof. G. Giardina, Prof. B.B. Back and Prof. E. Vardaci for the interesting and fruitful discussions. The authors are grateful to the Organizing Committee International Symposium "Quasifission Process in Heavy Ion Reactions" and Prof. Giorgio Gardina for the support and warm hospitality during stay at the University of Messina. The work has been also supported by the Alexander von Humboldt-foundation.

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