

Fusion-fission of superheavy nuclei and clustering phenomena

M G Itkis, I M Itkis, G N Knyazheva and E M Kozulin

Joint Institute for Nuclear Research, 141980 Dubna, Russia.

E-mail: itkis@jinr.ru

Abstract. Results of the study of mass-energy distributions of binary fragments for a wide range of nuclei with $Z = 82-122$ produced in reactions with heavy ions at energies close and below the Coulomb barrier are reported. The role of the shell effects, the influence of the entrance channel asymmetry and the deformations of colliding nuclei on the mechanism of the fusion-fission and quasifission processes are discussed. The observed peculiarities of the mass and energy distributions of reaction fragments are determined by the shell structure of the formed fragments.

1. Introduction

Nowadays more than 30 nuclei around the superheavy elements (SHE) region have been synthesized in fusion reactions of heavy nuclei. The existence of these nuclei is completely determined by proton and neutron closed shells at $Z = 114-120$ and $N = 184$ (island of stability). In the collisions of two massive nuclei many different reaction mechanisms such as elastic and inelastic scatterings, deep inelastic reactions, fusion and de-excitation of a compound nucleus, fusion-, quasi- and fast fission may take place. The existence of deep valleys on potential energy surface caused by shell effects is likely to be responsible for the manifestation of clustering phenomena in different reaction channels.

In low-energy collisions of heavy ions the quasifission (QF) process caused by the shell effects dominates hindering formation of compound nucleus [1]. QF is a transitional mechanism between deep-inelastic collisions and complete fusion, in which the composite system separates in two main fragments without forming a compound nucleus (CN). QF happens to be the most important mechanism that prevents the formation of SHE in the fusion of heavy nuclei.

This paper presents the results of the study of mass-energy distributions of binary fragments for a wide range of nuclei with $Z = 82-122$ produced in reactions heavy ions at energies close and below the Coulomb barrier. Velocity vectors of binary reaction products were measured using the two-arm time-of-flight spectrometer CORSET [2].

2. Shell effects in quasifission

In the last decade a great success in the synthesis of SHE with $Z = 112-118$ was achieved bombarding actinide targets with ^{48}Ca ions (hot fusion reactions). In these reactions, in contrast to the cold fusion, neutron excess in the composite systems leads to difference in a cluster composition of the compound system (due to the neutron shell with $N = 184$) as well as in its decay products.

One can see from Figure 1 that mass-energy distributions of binary reaction products, obtained in the $^{48}\text{Ca}+^{208}\text{Pb}$, ^{232}Th , ^{238}U , ^{244}Pu , ^{248}Cm reactions change from triangular shape for the reaction with spherical target ^{208}Pb [3], where CN-fission process dominates, to the wide two-humped shape in the case of reactions with actinide targets [4] determined by the QF process. This onset of quasifission for the latter reactions might be explained by the target deformation and, consequently, the orientation



effect that favors the QF process which mainly leads to the formation of the clusters in the exit channel of the reaction.

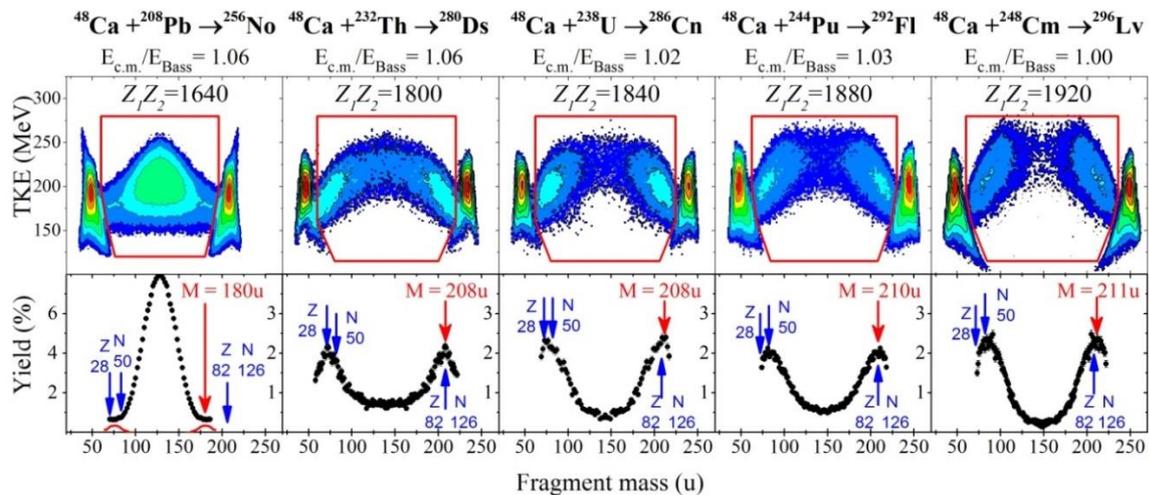


Figure 1. Top: Mass-TKE matrices for the reactions $^{48}\text{Ca} + ^{208}\text{Pb}$, ^{232}Th , ^{238}U , ^{244}Pu , ^{248}Cm at energies close to the Coulomb barrier; bottom: open circles are mass distributions for fission-like fragments inside the regions limited by red lines on mass-TKE matrices; arrows indicate the positions of neutron and proton shells.

Generally, in heavy-ion-induced reactions the formation of asymmetric QF fragments is connected with the strong influence of the nuclear shell at $Z = 82$ and $N = 126$ (double magic lead). In fact for the $^{48}\text{Ca} + ^{232}\text{Th}$ and $^{48}\text{Ca} + ^{238}\text{U}$ reaction the maximum yield corresponds to fragments with masses around 208 u. However, in reactions with heavier targets the maximum is shifted up to 211 u for the reaction $^{48}\text{Ca} + ^{248}\text{Cm}$. Notice, for the reaction $^{64}\text{Ni} + ^{238}\text{U}$, the maximum yield of asymmetric QF fragments corresponds to the heavy mass 215 u. As it was shown in [5] the shells in light fragment at $Z = 28$ and $N = 50$ could be effective, together with the shell $Z = 82$ and $N = 126$, and could lead to the shift of the asymmetric QF peak.

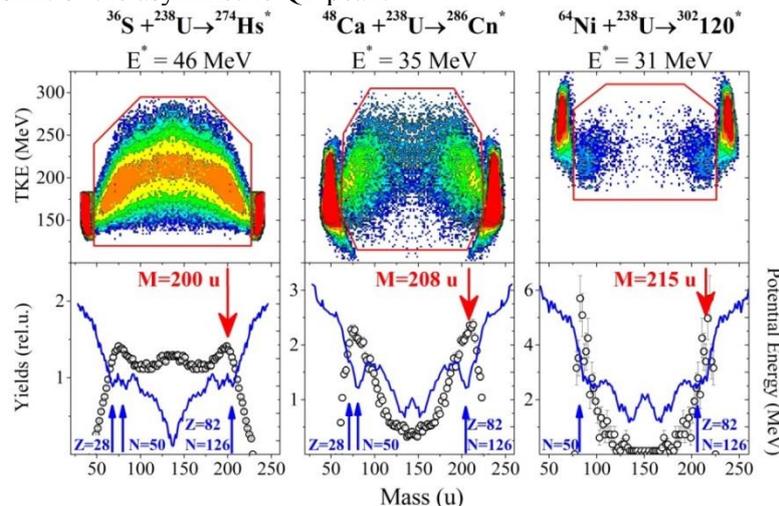


Figure 2. Top: Mass-TKE matrices for the reactions ^{36}S , ^{48}Ca , $^{64}\text{Ni} + ^{238}\text{U}$ at energies close to the Coulomb barrier; bottom: open circles are mass distributions for fission-like fragments inside the regions limited by red lines on mass-TKE matrices; solid lines are the potential energies as a function of mass.

Figure 2 shows the mass-energy distributions of binary fragments obtained in the reactions of ^{36}S , ^{48}Ca , ^{64}Ni ions with uranium target at energies close to the Coulomb barrier. The Coulomb factors are very different for these systems: $Z_1Z_2 = 1472$, 1840 and 2576 for the reactions $^{16}\text{S} + ^{238}\text{U}$, $^{48}\text{Ca} + ^{238}\text{U}$ and $^{64}\text{Ni} + ^{238}\text{U}$, respectively. In the bottom panel of Fig. 2 the potential energy at scission point

calculated with NRV code [6] using the proximity model along with the experimental mass distributions are shown. A strong correlation between the maxima in mass distributions and the minima of the potential energy is likely to be responsible for the shift of the heavier mass asymmetric peaks. These effects on the fragments formation due to the nuclear shells are evidences of clustering phenomena. Another noticeable case of the importance of shell closures in driving the mass flow is reported in [7] for the system $^{88}\text{Sr} + ^{176}\text{Yb}$.

3. Fission of heavy and superheavy nuclei

3.1. Bimodal fission

The question about symmetric and asymmetric modes in low-energy nuclear fission arose immediately after the discovery of nuclear fission. The numerous theoretical works [8, 9, 10] showed that multimodality is caused by the valley structure of the deformation potential energy surface of a fissioning nucleus.

The phenomenon of bimodal fission, discovered in the 1980's for the case of spontaneous and low-energy fission of nuclei in the Fm-Rf region [11], means the co-existence of two fission modes with different total kinetic energies for the same symmetric mass division. Bimodality is connected with a possibility for these nuclei to have in both fragments the number of neutrons and protons close to magic numbers $Z = 50$ and $N = 82$ (Super-Short (SS) mode). This possibility will sharply disappear when moving from Fm to more heavy nuclei. However, calculations show that the SS-valley should exist up to $^{270, 272}\text{Hs}$ and even $^{278, 290}\text{Ds}$ nuclei.

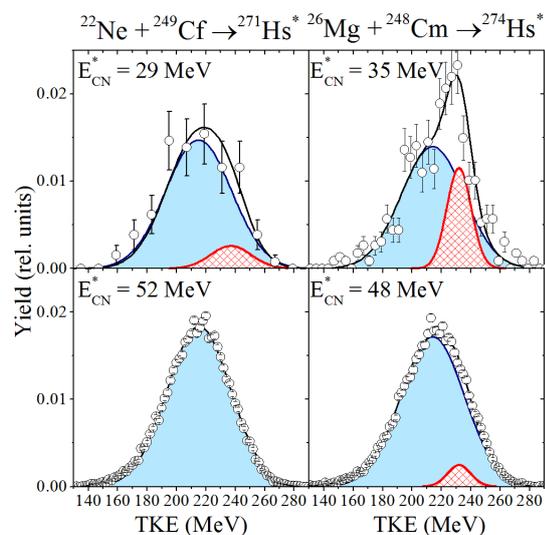


Figure 3. TKE distributions of fragments with masses $A_{\text{CN}}/2 \pm 20$ u obtained in the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$ (left panels) and $^{26}\text{Mg} + ^{248}\text{Cm}$ (right panels). High and low kinetic energy components are given as hatched and filled regions, respectively.

The TKE distributions of symmetric fragments with masses $A_{\text{CN}}/2 \pm 20$ u for the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$ and $^{26}\text{Mg} + ^{248}\text{Cm}$ are presented in Fig. 3. At sub-barrier energies the TKE distributions of symmetric fragments have a complex structure with mean TKEs and its dispersions higher than predicted by the liquid drop model (LDM). At the same time the mass distributions for both nuclei are symmetric. 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 behavior could be observed when both fission fragments are close to the spherical proton shell $Z = 50$. Thus the properties of mass and TKE distributions show the characteristic features for bimodal fission.

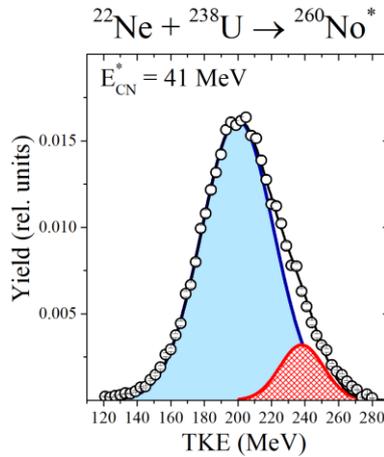


Figure 4. The TKE distribution of fission fragments obtained in the reaction $^{22}\text{Ne} + ^{238}\text{U}$ and its' decomposition into high and low energy components.

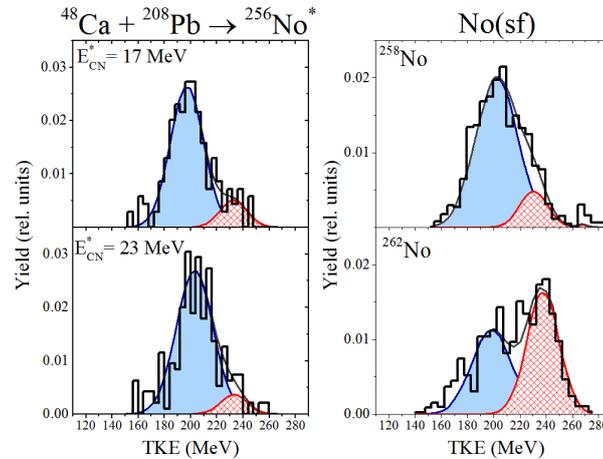


Figure 5. The TKE distributions of fragments The TKE distributions of fission fragments obtained in the reaction $^{48}\text{Ca} + ^{208}\text{Pb}$ [3] and in spontaneous fission of ^{258}No and ^{262}No taken from [12].

The TKE distribution of symmetric fragments obtained in the $^{22}\text{Ne} + ^{238}\text{U}$ reaction at an excitation energy of $^{260}\text{No}^*$ of 41 MeV is shown in Fig. 4. For this reaction the contribution of high energy component is about 7%. The presence of SS-mode in energy distributions of fragments of the $^{256}\text{No}^*$ induced fission at low excitation energies was observed in [3], although the contribution high energy component in this case is rather small: about 2.5% at an excitation energy of 17 MeV and about 1.7% at 23 MeV (see Fig. 5 left panel). In the case of spontaneous fission of ^{258}No and ^{262}No [12] the contributions of high energy component are about 14% and 54%, respectively (see Fig. 5 right panel).

3.2. Supersymmetric fission

For the first time the supersymmetric mode was observed in the compound nuclei fission in Pb region [13]. The enhancement of the mass yield in the region 65-75 u for the light fragment in the fission of ^{213}At and ^{210}Po compound nuclei is connected with the influence of double magic Ni ($Z = 28$, $N = 50$) and double magic Sn ($Z = 50$, $N = 82$). Notice that in this case the ratio $A_H/A_L \approx 2$, and the yield is around 0.01%. The supersymmetric fission mode with mass ratio of $A_H/A_L \approx 2.5$, caused by the closed shells $Z = 28$ and $N = 50$, was also found in thermal-neutron-induced fission of actinides nuclei [14]. In this case only the light fragment is close to the double magic Ni and the yield of supersymmetric mode does not exceed $10^{-4}\%$.

The mass and energy distributions of fragments obtained in the reaction $^{22}\text{Ne} + ^{238}\text{U}$ are shown in figures 6 and 7. The mass distribution of the symmetric fragments has a nearly Gaussian shape and the average TKE shows a parabolic dependence on fragment mass typical for fission of excited compound nuclei as established by the LDM, whereas in the mass region around 52/208 u ($A_H/A_L \approx 4.3$), that corresponds to the formation of fissioning pair of two magic nuclei Ca/Pb, an increase of fragment yields was observed. Moreover the total kinetic energy for these fragments is found to be about ~ 30 MeV higher than predicted by the LDM. The higher TKE indicates that the asymmetric fragments originate from more compact scission configuration as compared to normal fission. In the low panel of figure 6 the experimental mass distribution together with the prediction of W. Greiner for thermal neutrons induced fission of ^{255}Fm is presented. According to this calculation the yield of about 0.01% is expected due to the influence of the closed shells, while for spontaneous fission of ^{255}Fm the yield of $10^{-4}\%$ is expected for this supersymmetric mode [15].

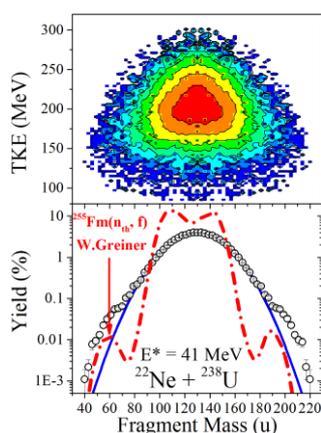


Figure 6. Double differential cross section and mass yield for the $^{22}\text{Ne} + ^{238}\text{U}$ reaction. Thick line represents the LDM calculation, dash-dot line is W. Greiner calculations for $^{255}\text{Fm}(n_{\text{th}}, f)$

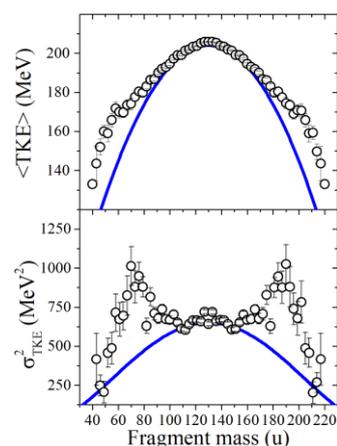


Figure 7. The mean TKE and its' dispersion as a function of fragment mass. The thick lines represent the LDM calculations.

In present work the superasymmetric mode with ratio $A_H/A_L \approx 4.3$ caused by the influence of double magic Ca and double magic Pb has been observed in fission of excited $^{260}\text{No}^*$ compound nucleus. At an excitation energy of 41 MeV the yield of these fragments is about $5 \times 10^{-2}\%$.

4. Conclusion

The clustering phenomena have a great impact on the heavy-ion reaction products. In the case of the quasifission process at least one of the fragment mass is determined mainly by nuclear shells with $Z = 28, 82$ and $N = 50, 126$; whereas in the case of the fusion-fission the nuclear shells with $Z = 50$ and $N = 82$ play an important role in the fragment formation.

The static deformation of the reaction partners is responsible for the evolution of the composite system and the appearing of the clusters in the exit channel for quasifission process.

The bimodal fission caused by clustering phenomena was observed for fission of superheavy nuclei $^{271, 274}\text{Hs}^*$ and $^{256}\text{No}^*$. For the compound nucleus $^{260}\text{No}^*$ formed in the reaction $^{22}\text{Ne} + ^{238}\text{U}$ at the initial excitation energy $E^* = 41$ MeV the bimodal fission as well as superasymmetric fission with mass ratio $A_H/A_L \approx 4.3$ were observed.

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