

Shell effects in fission, quasifission and multinucleon transfer reaction

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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 of ions located between ^{22}Ne and ^{136}Xe 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, quasifission and multinucleon transfer reactions are discussed. The observed peculiarities of the mass and energy distributions of reaction fragments are determined by the shell structure of the formed fragments. Special attention is paid on the symmetric fragment features in order to clarify the origin of these fragments (fission or quasifission). The influence of shell effects on the fragment yield in quasifission and multinucleon transfer reactions is considered. It is noted that the major part of the asymmetric quasifission fragments peaks around the region of the $Z=82$ and $N=126$ (double magic lead) and $Z=28$ and $N=50$ shells; moreover the maximum of the yield of the quasifission component is a mixing between all these shells. Hence, shell effects are everywhere present and determine the basic characteristics of fragment mass distributions.

1. Introduction

In reactions with massive heavy ions at energies close to the Coulomb barrier the main competing processes are complete fusion, quasifission, and deep-inelastic collisions [1–4]. The relative strength of these processes strongly depends on entrance channel properties, such as mass asymmetry, deformation of the interacting nuclei, collision energy, and the Coulomb factor Z_1Z_2 , but also on the entrance channel dynamics. The renewed interest in the study of heavy-ion collisions involving massive nuclei is driven by the search for new neutron-rich heavy nuclei. This, in turn, has rejuvenated the interest in the physics of mass transfer processes ranging from few to many nucleons. In earlier experiments the emphasis was placed on the investigation of heavy-ion transfer reactions with actinide targets. The energies were well above (20–30%) the Coulomb barrier and the aim was to produce superheavy nuclei [5, 6]. In these kinds of reactions the superheavy production cross sections decrease very rapidly with the increase of the atomic numbers of the colliding partners and binary reactions fully cover the reaction cross sections. Moreover, the amount of excitation energy available at bombarding energies well above the Coulomb barrier hinders the binding role of shell closures in the formation of fragments and reduces their survival probability against neutron evaporation or fission. Most of the reactions exploited to explore the production of superheavy nuclei with hot fusion reactions are, consequently, not suited to produce new neutron-rich nuclides. This brings us to the



conclusion that one possible pathway to produce new neutron-rich nuclides is to count on the binding power of the shell closures in a condition of lowest excitation energy possible.

The aim of the present work has been experimental investigation of dynamics and properties fission, quasifission and multi-nucleon transfer reactions of heavy and superheavy composite systems formed in the reactions with heavy ions by measuring mass-energy and angular distributions of binary fragments. Velocity vectors of binary reaction products were measured using the two-arm time-of-flight spectrometer CORSET [7]. The extraction of the masses and Total Kinetic Energy (TKE) of the binary reaction products is based upon the analyses of the two-body velocity diagram. The mass resolution of the spectrometer for these measurements was about 3u (FWHM) that allows to investigate the features of mass distributions with good accuracy. Table 1 presents the reactions studied using the CORSET set-up.

Table 1. The reactions studied with Corset set-up.

Reaction	CN	E_{lab} (MeV)	$E_{c.m.}/E_B$	Ref.
$^{22}\text{Ne}+^{249}\text{Cf}$	^{271}Hs	102, 127	0.86, 1.08	Itkis [8]
$^{26}\text{Mg}+^{248}\text{Cm}$	^{274}Hs	125-160	0.90-1.15	Itkis [8]
$^{36}\text{S}+^{238}\text{U}$	^{274}Hs	168-198	0.92-1.09	Itkis [8]
$^{48}\text{Ca}+^{144}\text{Sm}$	^{192}Pb	178-245	0.95-1.31	Knyazheva [9]
$^{40}\text{Ca}+^{154}\text{Sm}$	^{194}Pb	175-210	0.98-1.18	Knyazheva [9]
$^{48}\text{Ca}+^{154}\text{Sm}$	^{202}Pb	168-260	0.92-1.43	Knyazheva [9]
$^{48}\text{Ca}+^{168,170}\text{Er}$	$^{216,218}\text{Ra}$	180-208	0.93-1.08	Chizhov [10], Sagaidak [11]
$^{44}\text{Ca}+^{206}\text{Pb}$	^{250}No	217, 227	1.00, 1.05	Knyazheva [12]
$^{48}\text{Ca}+^{208}\text{Pb}$	^{256}No	206-242	0.95-1.12	Prokhorova [13]
$^{48}\text{Ca}+^{232}\text{Th}$	^{280}Ds	244	1.06	Itkis [14]
$^{48}\text{Ca}+^{238}\text{U}$	^{286}Cn	212-258	0.91-1.11	Kozulin [15]
$^{48}\text{Ca}+^{244}\text{Pu}$	^{292}Fl	226-244	0.96-1.03	Itkis [14]
$^{48}\text{Ca}+^{248}\text{Cm}$	^{296}Lv	233-238	0.97-1.02	Itkis [14]
$^{58}\text{Fe}+^{208}\text{Pb}$	^{266}Hs	289-324	1.0-1.12	Itkis I M [8]
$^{58}\text{Fe}+^{244}\text{Pu}$	$^{302}\text{120}$	328	1.05	Itkis[14], Knyazheva [16]
$^{64}\text{Ni}+^{186}\text{W}$	^{250}No	300, 311	1.00, 1.05	Knyazheva [12]
$^{64}\text{Ni}+^{238}\text{U}$	$^{302}\text{120}$	330-382	0.98-1.13	Kozulin [15]
$^{86}\text{Kr}+^{208}\text{Pb}$	$^{294}\text{118}$	453, 466	1.06, 1.09	Itkis [17]
$^{88}\text{Sr}+^{176}\text{Yb}$	^{264}Hs	435	1.03	Kozulin [18]
$^{136}\text{Xe}+^{208}\text{Pb}$	$^{344}\text{136}$	700-1020	0.98-1.43	Kozulin [19]

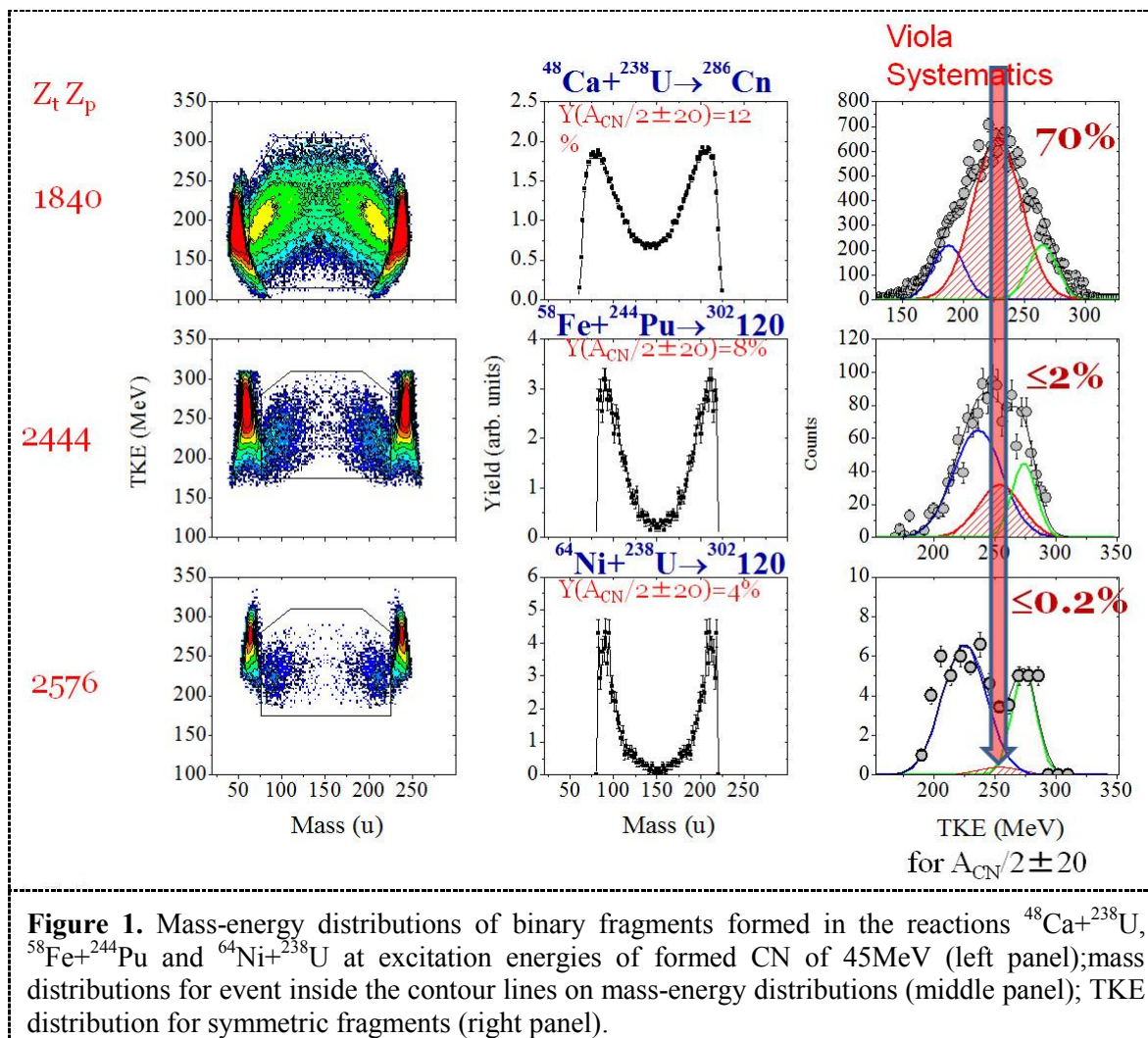
2. Fission and quasifission of superheavy systems

In reactions with heavy ions complete fusion and quasifission are competing processes. It is known that in superheavy composite systems quasifission mainly leads to the formation of asymmetric fragments with mass asymmetry ~ 0.4 [2]. This type of quasifission process, so-called asymmetric quasifission, is characterized by asymmetric angular distributions in the center-of-mass system and thus fast reaction times ($\sim 10^{-21}$ s) [9, 12]. The TKE for these fragments is observed to be higher than that for CN fission [12, 14] and hence this process is colder than fission. Due to this reason shell effects in quasifission are more pronounced [14]. Besides the asymmetric component, also the symmetric component may be affected by the presence of the quasifission process. Consequently, the question of whether the symmetric fragments originate from fission or quasifission processes arises. On the one hand, the angular distribution for all these mass-symmetric fragments is symmetric with respect to 90° in the center-of mass system and the estimated reaction time is $\sim 10^{-20}$ s, typical for CN fission processes [3, 9]. On the other hand, the calculations of potential energy surfaces for heavy-ion-induced reactions along with Langevin-type dynamic equations of motion show that one of the possible reaction channels for such systems is a process occurring without a CN stage, but with

fragment properties close to those known from fission. This process is characterized by long reaction times sufficient for mass equilibration and resulting in the formation of symmetric fragments [symmetric quasifission].

A guideline for the interpretation of the pattern following from mass-energy, angular distributions and cross sections comes from dynamical models. At present there are several theoretical approaches to describe the dynamics of the reactions with heavy ions (for example [20-24]).

Mass-energy distributions of binary fragments formed in the reactions $^{48}\text{Ca}+^{238}\text{U}$, $^{58}\text{Fe}+^{244}\text{Pu}$ and $^{64}\text{Ni}+^{238}\text{U}$ at excitation energies of formed CN of 45 MeV are shown in Fig.1. The reaction products having masses close to those of projectile and target are identified as quasielastic and deep-inelastic events in the TKE-M matrix, and we will not consider them. 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.



Mass-energy distributions for the reaction $^{64}\text{Ni}+^{238}\text{U}$ have the wide two-humped shape caused by quasifission process mainly determined by the influence of spherical closed shells with $Z = 82$ and $N = 50, 126$. The maximum yield corresponds to the fragments with masses about 215 a.m.u. and complementary light ones. Based on simple assumption on N/Z equilibration the nuclear shells with $Z=82$ and $N=126$ correspond to the heavy fragment mass 207-209 a.m.u., neutron shell at $N=50$ results in light fragment mass 82-83 a.m.u. and the complementary heavy masses for this nuclear shell is 219

a.m.u. So, the major part of the asymmetric quasifission peak fits into the region of the $Z=82$ and $N=126$ (double magic lead) and $N = 50$ shells and maximum of yield of asymmetric QF component is a compromise between all these shells. In the formation of the quasifission asymmetric component the closed shell at $N=50$ seem to be effective on a par with shells $Z=82$ and $N=126$, and it leads to the shift of asymmetric quasifission peak from mass 208 a.m.u, observed in the reaction $^{48}\text{Ca}+^{238}\text{U}$, to 215 a.m.u. at the transition from 112 to 120 superheavy nucleus.

At first sight the mass-energy distributions for the reactions $^{58}\text{Fe}+^{244}\text{Pu}$ and $^{64}\text{Ni}+^{238}\text{U}$ at the CN excitation energies about 45 MeV are similar: the wide two-humped shape with large quasifission component peaked around the mass 215 a.m.u. However, at the same CN excitation energy the mass drift to the symmetry (estimated as a width between masses corresponding to the maximum and half maximum of quasifission yields) is 22 nucleons in the case of ^{58}Fe reaction and only 11 nucleons in the case of ^{64}Ni -ions. It is significant that the mass drift to the symmetry is about 34 a.m.u. for the $^{48}\text{Ca}+^{238}\text{U}$ at the same CN excitation energy. At the symmetric mass region $A_{\text{CN}}/2 \pm 20$ the contribution of the fragments is about 12%, 8% and 4% for Ca, Fe and Ni-ions, respectively.

The TKE distributions for symmetric fragments with masses $A_{\text{CN}}/2 \pm 20$ u for all reactions are presented in figure 1. It is readily seen that both TKE distributions have a complex structure which is not consistent with only CN fission. In fact, it is known that in such a case the average TKE of the partner fragments is substantially independent on the excitation energy and shows a typical Gaussian-like shape. The TKE distributions of symmetric fragments of the $^{48}\text{Ca}+^{238}\text{U}$, $^{58}\text{Fe}+^{244}\text{Pu}$ and $^{64}\text{Ni}+^{238}\text{U}$ may be deconvoluted into three Gaussians. We use the Viola systematics as a starting point to evaluate mean and variance of the CN fission mode. After a 3-Gaussian fitting procedure we can evaluate the cross-sections due to each of the three components: CN-fission, asymmetric and symmetric quasifissions. In contrast to $^{58}\text{Fe}+^{244}\text{Pu}$, for the reaction $^{64}\text{Ni}+^{238}\text{U}$ the TKE distribution has more pronounced low and high energy components (see fig. 1 right column), 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.

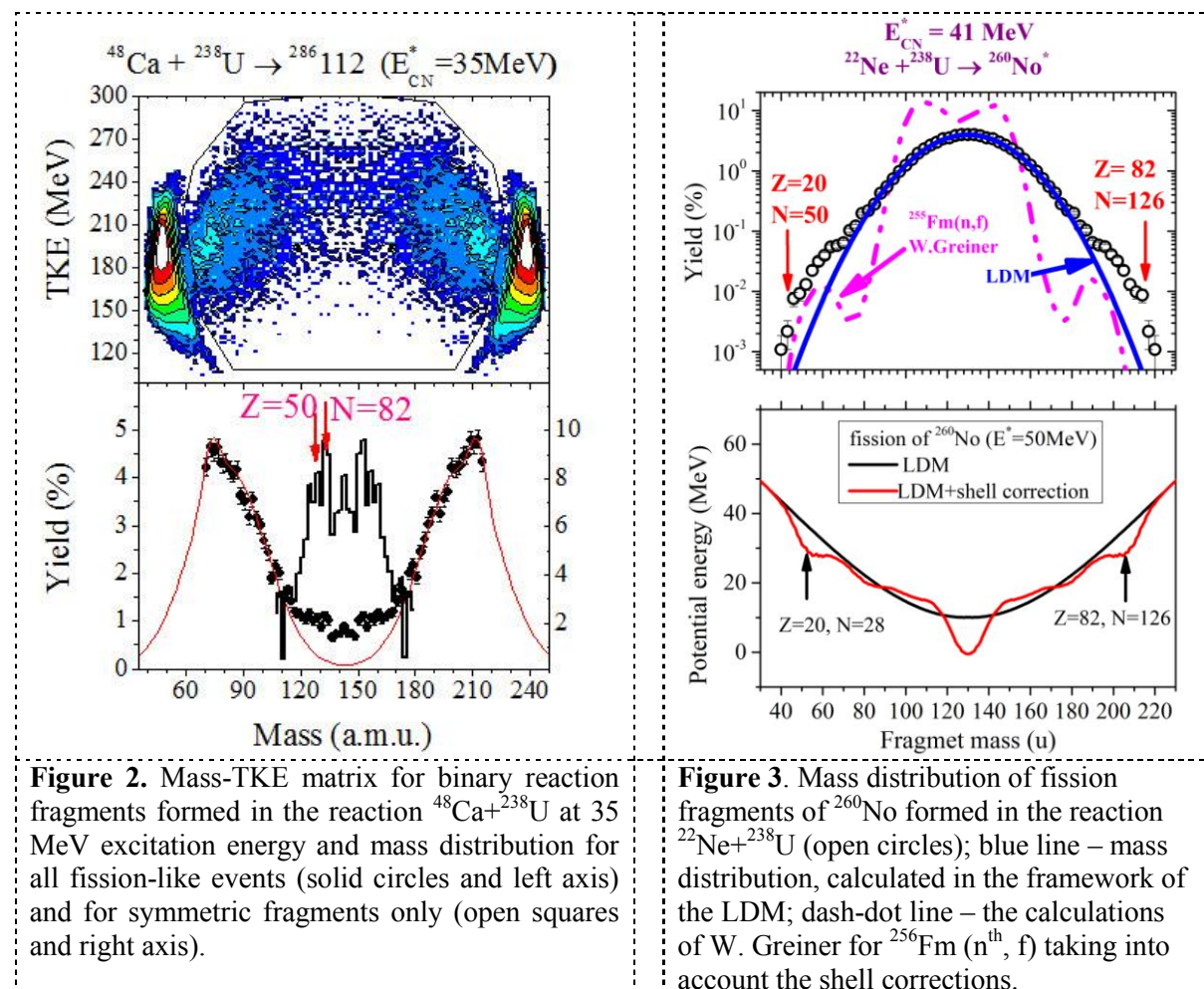
On the basis of the reasonably good success of the analysis method proposed, we can draw some main conclusion. The capture cross-sections are about a few hundred millibarns for Ca and Ni induced reactions, whereas the formation of symmetric fragments is one order of magnitude less for the reaction $^{64}\text{Ni}+^{238}\text{U}$. 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 $^{64}\text{Ni} + ^{238}\text{U}$ only a few percent of symmetric fragments have the TKE compatible with the Viola prediction for the $^{302}120$ CN fission. While the $^{64}\text{Ni} + ^{238}\text{U}$ reaction has lower excitation energy at center of mass energies close to the Bass barrier, the CN fission cross-section is suppressed by stronger symmetric and asymmetric quasifission processes and the expected gain in CN survival probability was not observed. The CN fission cross-section in the $^{64}\text{Ni} + ^{238}\text{U} \rightarrow ^{302}120$ case drops three orders of magnitude with respect to the $^{48}\text{Ca} + ^{238}\text{U} \rightarrow ^{286}112$ case. This 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 $^{58}\text{Fe} + ^{244}\text{Pu} \rightarrow ^{302}120$. Recently the experiments aimed at the synthesis of isotopes of element $Z = 120$ have been performed using the $^{244}\text{Pu}(^{58}\text{Fe}, xn)^{302-x}120$ reaction [25] and $^{238}\text{U}(^{64}\text{Ni}, xn)^{302-x}120$ reaction [26]. 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 $^{48}\text{Ca} + ^{238}\text{U}$ 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 orders of magnitude, respectively. Thus, we conclude that the reaction $^{64}\text{Ni} + ^{238}\text{U}$ is less favorable compared to $^{58}\text{Fe} + ^{244}\text{Pu}$ for production of the superheavy element with atomic number 120.

In the symmetric region of fragment masses with $A_{\text{CN}}/2 \pm 20$ the fusion-fission process may coexists with quasifission and nuclear shells with $Z=50$ and $N=82$ are now involved. In Fig 2 the mass-energy distribution for the reaction $^{48}\text{Ca}+^{238}\text{U}$ at an excitation energy of 35MeV for the compound nucleus $^{286}112$ is presented. On the bottom panel of this figure the mass distribution (normalized to 200%) for

fragments inside the contour line on the M-TKE matrix is shown as solid circles. The solid curve is a description of the mass distribution by the sum of Gaussians with average masses corresponding to nuclear shells $Z = 28$ and 82 , and $N = 50$ and 126 . Open squares depict the symmetric component (normalized to 200 %) obtained as the difference between the experimental mass distribution and the fit to the quasi-fission contribution. One can see that the mass distribution for symmetric fragments is asymmetric in shape with the light fragments mass at about 132-134 a.m.u.

The same trends were observed for mass distributions of reaction fragments measured in the reactions $^{48}\text{Ca} + ^{244}\text{Pu}$ and $^{48}\text{Ca} + ^{248}\text{Cm}$ [14]. With the assumption that the fusion-fission process prevails in the symmetric mass region, the induced fission reactions for the compound nuclei $^{286}112$, $^{292}114$ and $^{296}116$ have asymmetric mass distribution like in the familiar cases of fission of actinide nuclei.

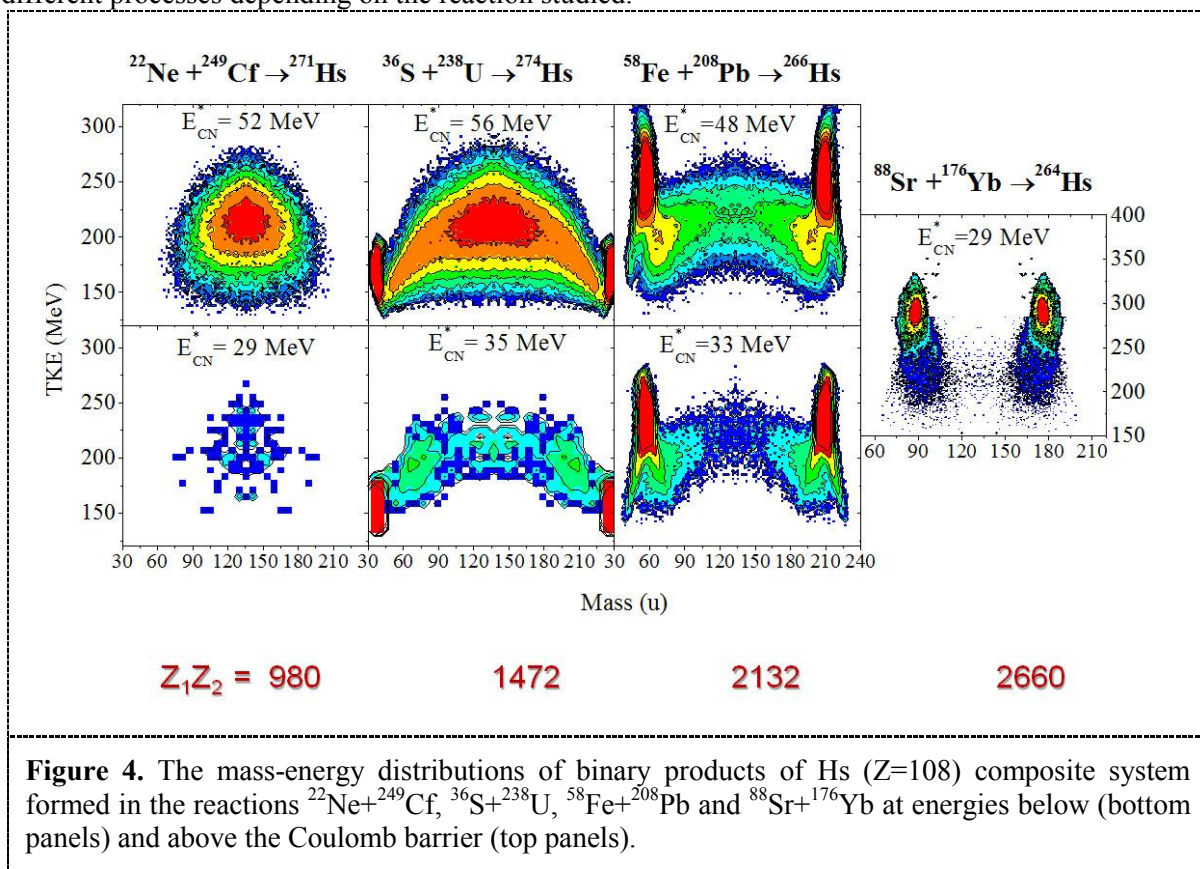
The question about the possibility of the formation of supersymmetric fragments in fusion-fission, quasifission and multinucleon transfer reactions when both fission fragments are close to the double magic nuclei arises. The mass distribution of fission fragments of ^{260}No formed in the reaction of $^{22}\text{Ne} + ^{238}\text{U}$ is presented in fig. 3. The increase of fragment yields in the mass region around 52/208 u that corresponds to the formation of fissioning pair of two magic nuclei Ca/Pb was observed.



3. Transition from fission to multinucleon transfer reactions

In order to investigate on the role of shell effects on the fragment productions in colliding systems with total charge $Z = 108$ we have used reactions of ^{22}Ne , ^{26}Mg , ^{36}S , and ^{58}Fe beams on ^{249}Cf , ^{248}Cm , ^{238}U , and ^{208}Pb targets at energies below and above the Coulomb barrier [8,18]. The mass and energy

distributions of binary fragments formed in these reactions at energies below and above the Coulomb barrier are shown in figure 2. The entrance channel properties of these systems vary strongly: the entrance channel mass asymmetry is $\eta = 0.571$ for the reaction $^{58}\text{Fe} + ^{208}\text{Pb}$, 0.737 for $^{36}\text{S} + ^{238}\text{U}$, 0.810 for $^{26}\text{Mg} + ^{248}\text{Cm}$, and 0.838 for $^{22}\text{Ne} + ^{249}\text{Cf}$. It is important to note that all reaction partners, except ^{208}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 quasifission contributions. As demonstrated in Fig. 4 the mass-energy distributions change with decreasing the asymmetry η in the entrance channel from typical for fusion – fission triangular shape for incoming ^{22}Ne -ions to strongly two humped asymmetric shapes for incoming ^{58}Fe and ^{88}Sr ions. These changes are understood as reflecting the relative contributions of different processes depending on the reaction studied.



Previously to distinguish between quasifission and CN-fission the angular and mass distributions of fission-like fragments were used. The present analysis of the TKE distributions of fragments with masses $A_{\text{CN}}/2 \pm 20$ u for different reactions studied shows that the variance of the TKE distribution is sensitive to the presence of the quasifission process. At an excitation of CN larger than 40 MeV (when the shell in CN-fission is practically disappeared) the broadening of the TKE distribution points out to the presence of the both quasifission and CN-fission processes. The narrowing of the TKE distributions indicates that quasifission is a dominant process. This tendency is illustrated in Fig.5 for the case of Hs-composite systems formed in the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$, $^{36}\text{S} + ^{238}\text{U}$ and $^{58}\text{Fe} + ^{208}\text{Pb}$.

Our measurements [8] have shown that in the case of the reactions induced by ^{36}S (at energy below the Coulomb barrier) and ^{58}Fe (for energies below and above the Coulomb barrier) asymmetric quasifission is the dominant process. This is caused by the influence of the closed shells at $Z = 28, 82$ and $N = 50, 126$. The fragments formed in such asymmetric quasifission processes have masses around

200 u. However, the entrance channel asymmetry for both projectiles [$\eta = (A_{\text{projectile}} - A_{\text{target}})/(A_{\text{projectile}} + A_{\text{target}}) = 0.73$ in the case of ^{36}S and 0.56 for ^{58}Fe] is larger than the mass asymmetry of asymmetric quasifission fragments (0.45–0.50). This means that nucleons flow mainly from target to projectile in the above mass range as a consequence of the entrance channel asymmetry and the shape of the potential energy surface for heavy nuclei [8]. These results pave the way toward the search for entrance channel conditions which favor the flow of nucleons in the opposite direction, which is a necessary condition for the neutron-rich nuclei to be produced.

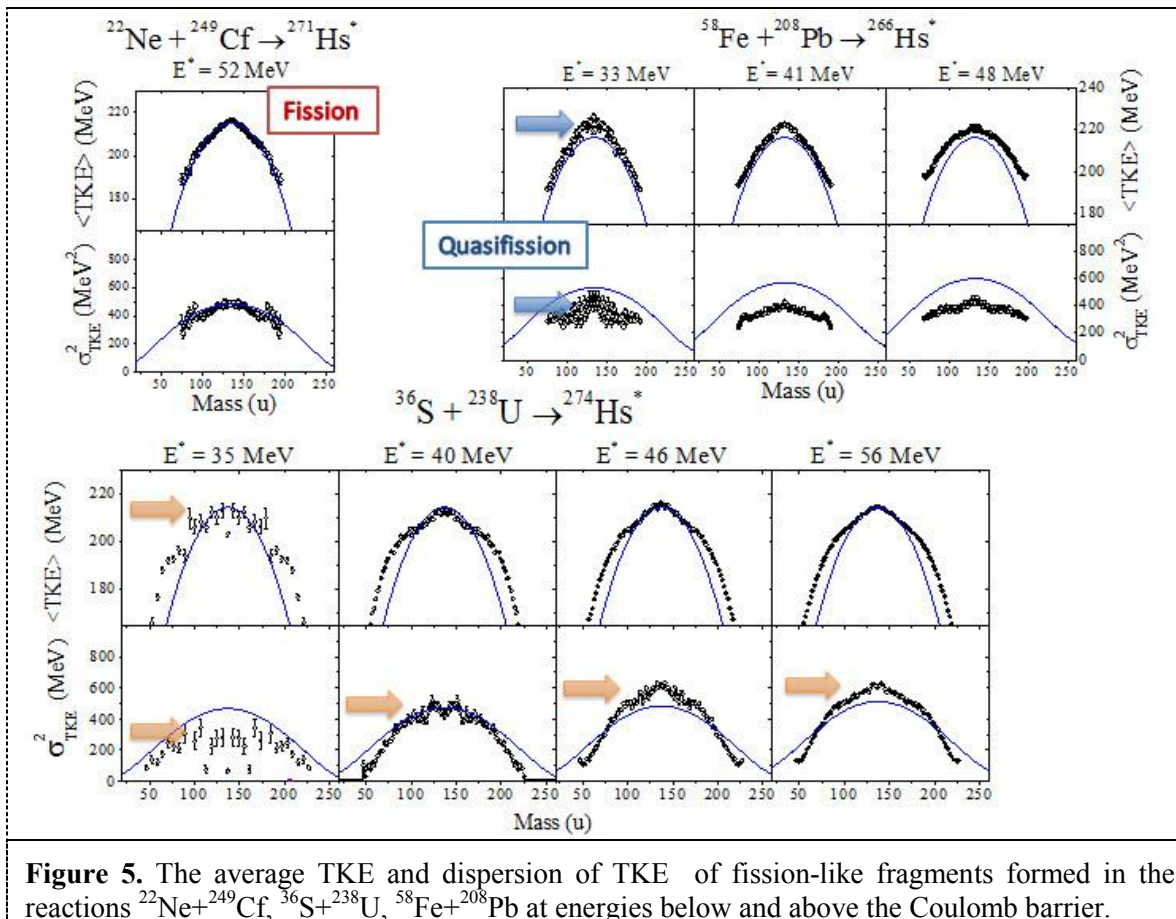


Figure 5. The average TKE and dispersion of TKE of fission-like fragments formed in the reactions $^{22}\text{Ne} + ^{249}\text{Cf}$, $^{36}\text{S} + ^{238}\text{U}$, $^{58}\text{Fe} + ^{208}\text{Pb}$ at energies below and above the Coulomb barrier.

To explore the influence of shell effects on the formation of neutron-rich binary fragments in damped collision, even in the case of a large mass transfer, we have investigated binary reaction channels in the reaction $^{88}\text{Sr} + ^{176}\text{Yb}$ at an energy slightly above the Coulomb barrier ($E_{\text{c.m.}}/E_{\text{Bass}} = 1.03$). The total charge of such system is $Z = 108$, as in the case of the reactions $^{36}\text{S} + ^{238}\text{U}$ ($Z_1 Z_2 = 1472$) and $^{58}\text{Fe} + ^{208}\text{Pb}$ ($Z_1 Z_2 = 2132$). What is different in the reaction $^{88}\text{Sr} + ^{176}\text{Yb}$ is that, in contrast to the reactions with ^{36}S and ^{58}Fe ions, the projectile nucleus has to transfer about 25 nucleons to the target to form fragments with mass of about 200 u. The mass-energy distribution of binary fragments formed in the reaction $^{88}\text{Sr} + ^{176}\text{Yb}$ (Fig 4 last column) suggests that besides the elastic and quasielastic components, a significant part of the events has a large dissipation of the entrance channel kinetic energy $E_{\text{c.m.}}$, which indicates the occurrence of strongly damped collisions. The fragments with TKE dissipation larger than 20 MeV are located mainly in the region 85–115 u for projectile-like fragments and 150–180 u for target-like fragments. The contribution of symmetric fragments with masses $(A_{\text{target}} + A_{\text{projectile}})/2 \pm 20$ u to all damped collision events with TKE losses > 20 MeV is about 1.6%. It is very unlikely that these fragments were formed in fusion-fission processes due to the large value of the Coulomb factor $Z_1 Z_2$ for this reaction. Even in the case of the more asymmetric reaction $^{58}\text{Fe} + ^{208}\text{Pb}$ the

contribution of the fusion-fission component to the symmetric fragments is less than a few percent [8]. As was shown in Ref. [16], the contribution of fusion-fission rapidly decreases with the increasing of the Coulomb factor of a reaction. The presence of symmetric fragments in damped collisions is caused by the driving potential of the system. The minimum of the potential energy of the system favors the creation of symmetric fragments. In particular, the minimum at symmetric masses is strengthened by the nuclear shells at $Z = 50$ and $N = 82$. Furthermore, the yield of the symmetric component strongly depends on the reaction time and the nucleon transfer rate. The yield of target-like fragments with mass larger than 170 u at laboratory angles from 25° up to 35° is shown in Fig. 6. This laboratory angles correspond to the angle of grazing collisions for the recoil nucleus and we may expect the maximum yield for the production of target-like fragments at this condition. We observe heavy fragments with mass up to 200 u. Considering the mass resolution of the CORSET spectrometer, this remarkably means that a net mass transfer from projectile to target of about 20–25 nucleons occurs in this reaction. Such a large net mass transfer has also been observed in the reaction $^{136}\text{Xe}+^{208}\text{Pb}$ (up to 16 nucleons from Xe to Pb) at the energy of $1.23E_{\text{Bass}}$ with a cross section of the order of 200 μb , for the lower mass transfer, and a few μb for the larger mass transfer [19].

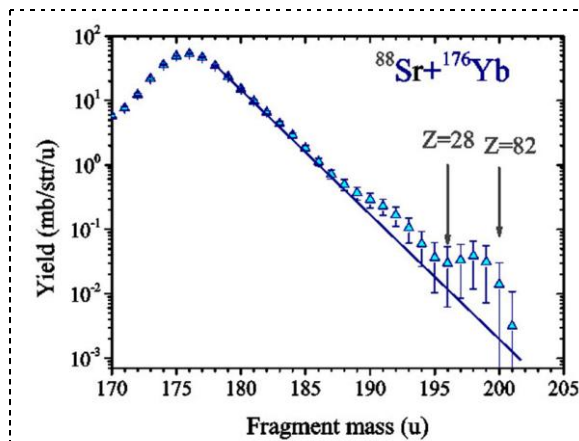


Figure 6. Double differential cross sections of heavy fragments formed in the reaction $^{88}\text{Sr}+^{176}\text{Yb}$ at $E_{\text{c.m.}} = 290$ MeV and detected at laboratory angles from 25° up to 35° .

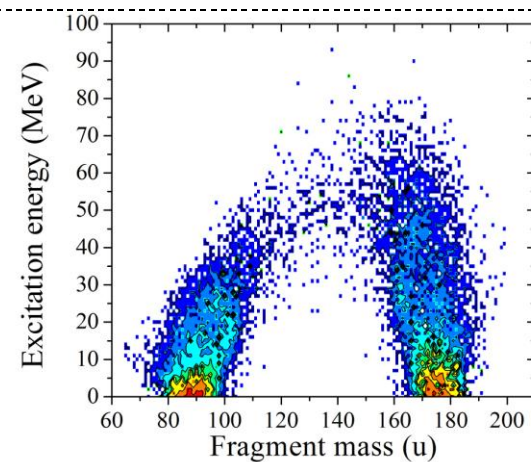


Figure 7. Excitation energy of primary fragments formed in the reaction $^{88}\text{Sr}+^{176}\text{Yb}$ at $E_{\text{c.m.}} = 290$ MeV.

For target-like fragments heavier than the target nucleus, the production cross section of the primary fragments, starting from the region of no-shell closures (maximum at mass around 176), is compatible with an exponential decrease, which is outlined by the solid line in Fig. 6. Because of the absence of shell closures in the mass degree of freedom. For target-like fragments heavier than 190 u, namely, in the mass region progressively closer to shell closures, an enhancement of the yields, with respect to the extrapolation of the exponential decrease to the shell closure region, is quite evident. This trend makes us to suspect that the proton shells at $Z = 28$ and 82 play an important role and ignite the increase by half an order of magnitude of the yield of the reaction products even for the transfer of twenty nucleons. As was mentioned above, in the previous study of the mass-energy distributions of binary fragments obtained in the reactions of $^{36}\text{S}+^{238}\text{U}$ and $^{58}\text{Fe}+^{208}\text{Pb}$ leading to composite systems with the same $Z = 108$ it was found that the maximum yield of asymmetric quasifission fragments corresponds to the heavy mass of about 200 u, but the transfer of nucleons occurs from the target to projectile. The difference with the present case here is in the entrance channel mass asymmetry, which translates in a different entry point in the potential surface. This difference plays a role on deciding where the main flow of nucleons might be directed. Additional characteristic features of the reaction under study come from the following considerations about the survival probability of the primary

fragments. All fragments formed in damped collisions are excited, and de-excited by neutron evaporation mainly. Since the interest to study this type of reactions is connected first of all with the possibility to produce new heavy isotopes, the cross sections of the fragments after the de-excitation process are important. In the present case, the bombarding energy was chosen, using the potential energy surface as a guideline, to maximize the production cross section for large mass transfers (persistence of shell closure) and the survival probability of the primary fragments with respect to neutron evaporation or fission. We estimate the available excitation energy of both fragments as $E_f^* = E_{c.m.} - TKE + Q_{gg}$ and assume that this excitation is divided between the two primary fragments according to their mass ratio. The obtained excitation energy for each fragment is shown in Fig. 7. The particular shape of the distribution in Fig. 7 is due to the (hypothetical) method used to split the excitation energy between the two primary fragments and to the distribution of Q_{gg} values. The excitation energy is largest for symmetric fragments and reaches values up to 90 MeV. For target-like fragment heavier than the target the excitation is about 30–50 MeV. Each neutron takes away on the average 10 MeV (sum of binding energy of one neutron and its kinetic energy). Hence, fragments with mass around 200 u evaporate 3–5 neutrons on average during their de-excitation.

The enhancement found in the yield of products with masses heavier than the target mass confirms that low-energy multinucleon transfer reactions are a possible pathway for producing new neutron-rich isotopes. This result is particularly promising because such mechanism was proposed in Ref. [27] for the synthesis of neutron-rich superheavy elements (SHE), which are not reachable in fusion reactions.

4. Production of heavy neutron-rich nuclei in multi-nucleon transfer reactions

The transfer of many nucleons has been pointed out in several works as a feasible route to synthesize heavy nuclei on the neutron-rich side of the stability line. The choice of the reaction $^{136}\text{Xe} + ^{208}\text{Pb}$ is based on two qualifying points: 1) the stabilizing effects of the neutron closed shell $N = 82$ for ^{136}Xe and $N = 126$ for ^{208}Pb ; 2) the specific trend of the Q_{gg} values of all possible mass transfer channels: Q_{gg} values are close to zero for mass transfers that push the primary target-like fragments toward symmetry and become more and more negative for target-like fragments heavier than ^{208}Pb . The two points above mentioned offer three important advantages. First, protons may experience a higher mobility because of the neutron closed shell in the projectile and target, and the transfer of several protons from Xe to Pb may lead to very neutron-rich nuclides, i.e., in the region of osmium and platinum. Second, for the transfers that produce target-like fragments with masses around 200 u or lower, the Q_{gg} are about zero, and windows of total kinetic energy lost select in turn windows of available excitation energy to the primary fragments. In this way, it is possible to gate on target-like fragments that experience lower excitation energy.

Mass-energy matrices of binary fragments for the reaction $^{136}\text{Xe} + ^{208}\text{Pb}$ at c.m. energies of 526 MeV that were measured by the CORSET setup are presented in Fig. 8. Figure shows the measured TKE-mass distributions integrated over the center-of mass angle 40° - 140° of the primary fragments in the reaction $^{136}\text{Xe} + ^{208}\text{Pb}$. Projectile-like and target-like fragments can be identify as elastic and quasi-elastic events at mass-energy matrices. Besides the elastic and quasi-elastic components, a significant part of events has a large dissipation of the initial kinetic energy which indicates the presence of strongly damped collisions. The primary mass distributions of fragments with energy lost greater than 40 MeV are shown in Fig. 8 (bottom panel). Due to such selection of TKEL, most of the quasi-elastic events have been removed. The mass distribution has a two-humped shape. The yield of the fragments in the mass region 136 ± 8 u is more than 60% of all damped events at all measured energies. Furthermore, we observe fragments with mass up to 238 with cross section of the order of 0.1 mb in the reaction at $E_{c.m.} = 526$ MeV. Considering the mass resolution of the CORSET spectrometer, this remarkably means that a net mass transfer from projectile to target of about 20 nucleons occurs in this reaction.

The theoretical primary mass distribution is given. Also in this case, the calculated yield curve has been convoluted with the experimental mass resolution. One can see a good agreement between theoretical and experimental yields only in the nearly symmetric region. Indeed, the artificial normalization of the calculated yield curve, by a factor of about 0.4, reveals that the shape of the experimental curve can be very well reproduced in the full mass range except for the supersymmetric region, where the underestimation will increase even more. This kind of normalization problem is quite frequent and this result constitutes a feedback for the present model. This allows us to conclude that the model is, roughly within a factor two, in good agreement with the experimental data in the region where Q_{gg} is nearly zero (the region of major interest for this work) but it underestimates by a large extent the primary mass distribution in the supersymmetric fragment mass region. Clearly, the lack of knowledge of the atomic number distribution in this mass region is an unwanted drawback, but this result may give impulse for a more detailed experimental work with respect to the present exploration of the features of the reaction products.

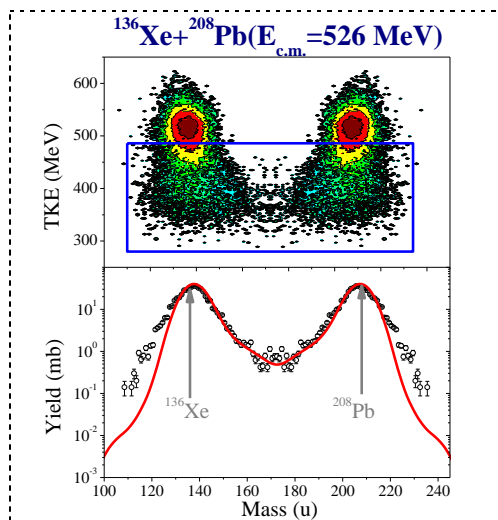


Figure 8. Mass distribution for the fragments with large energy losses (blue contour on matrix); Red line is the calculation in the framework of dynamical Langevin equations by V.Zagrebaev.

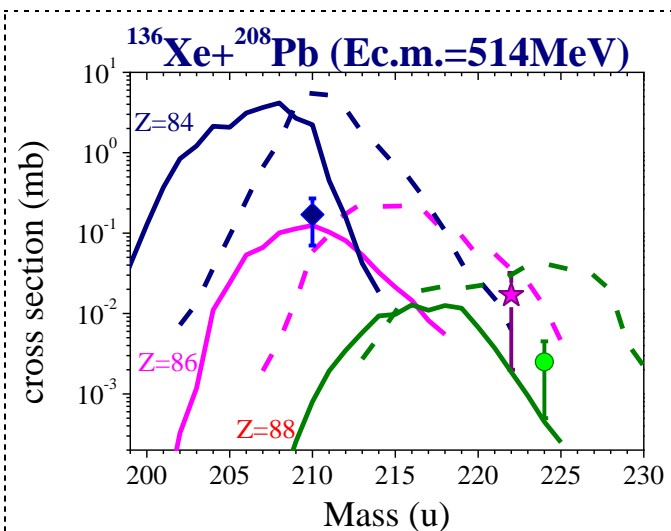


Figure 9. The calculated cross sections for the primary (dash line) and survived (solid line) fragments compared with the values obtained by activation analysis for ^{210}Po , ^{222}Rn and ^{224}Ra .

To provide a firm identification of some target-like fragments with mass greater than 210 u and also to reject any artifact due to the limited resolution of the CORSET setup, we performed a second experiment on the same system at the bombarding energy of 850 MeV by using a catcher-foil activity analysis. Since the major part of nuclides with masses larger than 210 u undergoes α -decay, a careful analysis of the α -decay spectra from nuclides implanted in a catcher-foil can indeed allow us to reconstruct the cross section of the α -emitter isotopes produced in the reaction. This method also calls for a more direct comparison of the cross sections with the expectations of the model.

The cross-section of $200 \pm 100 \mu\text{b}$, $17 \pm 14 \mu\text{b}$, and $2.5 \pm 2 \mu\text{b}$ were obtained, respectively, for ^{210}Po , ^{222}Rn , and ^{224}Ra nuclides. In Fig. 9 these values are compared to the new calculation of the model in Ref. [28]. For ^{210}Po the experimental cross-section is overestimated by one order of magnitude; contrarily, the cross section of ^{222}Rn and ^{224}Ra are underestimated by about one order of magnitude, even though at the limit of the experimental error. Both results are quite unexpected because the model is known to well reproduce cross section for transfer of few nucleons; the same trend as for ^{222}Rn and

^{224}Ra in Fig. 9 was indeed recently observed in the reaction $^{160}\text{Gd} + ^{186}\text{W}$ at $E_{\text{c.m.}} = 461.9\text{MeV}$ [29] for the transtarget reaction products near $Z = 79$.

Yet, the direct measurement of reaction product through their α activity confirms that a mass transfer up to 16 nucleons can occur with a cross section of the order of $200\text{ }\mu\text{b}$ for the lower mass transfer and few μb for the larger mass transfers. These cross sections are certainly of the order of magnitude that make a more detailed search for neutron-rich nuclei accessible with this reaction.

5. Conclusion

From these series of the experiments it was shown that the quasifission process leads not only to formation of asymmetric fragments, but also contributes to the symmetric mass region of fragments.

It was established that in the case of the quasi-fission process the influence of the shell effects on the observed characteristics is much stronger than in the case of classical fission of heavy compound nuclei.

In the reactions of inverse quasifission and multinucleon transfer it has been found that the yield of nuclei with masses heavier than target mass is relatively large. This makes even more promising the production of new neutron-rich heavy and superheavy nuclei in such kind of reactions.

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