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Shell effects in damped collisions of ^{88}Sr with ^{176}Yb at the Coulomb barrier energy

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This work is a study of the influence of shell effects on the formation of binary fragments in damped collision. We have investigated binary reaction channels of the composite system with $Z = 108$ produced in the reaction ^{88}Sr+^{176}Yb at an energy slightly above the Bass barrier ($E_{\mathrm{c.m.}}/E_{\mathrm{Bass}} = 1.03$). Reaction products were detected by using the two-arm time-of-flight spectrometer CORSET at the K130 cyclotron of the Department of Physics, University of Jyväskylä. The mass-energy distribution of primary binary fragments has been measured. For targetlike fragments heavier than 190 u, which correspond to a mass transfer as large as twenty nucleons or more, an enhancement of the yields is observed. This striking result can be ascribed to the proton shells at $Z = 28$ and 82 and implies the persistence of the shell effects in the formation of reaction fragments even for large mass transfers.

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I. 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.

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. Our measurements [7] have shown that in the case of the reactions induced by ^{36}S and ^{58}Fe 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 [$\eta_0 = (A_{\mathbf{projectile}} - A_{\mathbf{target}})/(A_{\mathbf{projectile}} + A_{\mathbf{target}}) = 0.73$ 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 [7]. 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.

Several years ago, on the basis of a multidimensional model, it was proposed to use multinucleon transfer reactions to produce new neutron-rich heavy and superheavy nuclei at bombarding energies close to the Coulomb barrier [8,9]. In this theoretical study it is proposed that proton and neutron (independent) flows strongly depend on the shell structure of the multidimensional potential energy surface and the values of fundamental parameters which guide the nuclear dynamics, such as nuclear viscosity. One of the successes of this model is the prediction of an increased yield of targetlike fragments (TLF) in the lead region formed in the reaction ^{160}Gd+^{186}W [10]. This prediction has been confirmed experimentally [11].

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}Sr+^{176}Yb at an energy slightly above the Coulomb barrier ($E_{\mathrm{c.m.}}/E_{\mathbf{Bass}} = 1.03$). The total charge of such system is $Z = 108$, as in the case of the reactions ^{36}S+^{238}U ($Z_1Z_2 = 1472$) and ^{58}Fe+^{208}Pb ($Z_1Z_2 = 2132$). What is different in the reaction ^{88}Sr+^{176}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 main task of the present experiment is to test if shell closures are still effective on the primary fragment production even for such a large mass transfer.

In Fig. 1 the potential energy for this composite system (calculated using the proximity model with NRV code [12]) at scission point is shown as a function of the fragment mass. The arrows pointing upward indicate the projectile and the target mass used in our experiment. Similarly to the case of the W+Gd reaction, there are minima in the potential energy caused by the proton shells at $Z = 28$ and $Z = 82$ and which correspond to a fragment of a mass around 200 u and an exit channel mass asymmetry larger than the one of the entrance channel, namely, $\eta = 0.50 > \eta_0 = 0.33$. If, according to the driving potential, such minima exist we may expect an increase in the yield of the fragments with the mass of the heavy fragment of about 200 u. Table I summarizes the main reaction parameters characterizing the studied system.

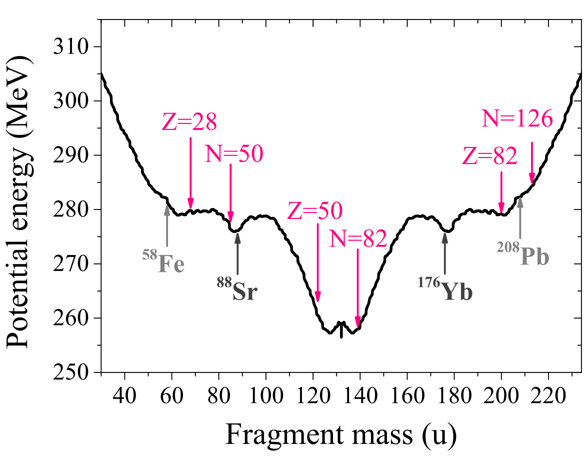

FIG. 1. (Color online) Potential energy at scission point as a function of the primary fragment mass in the reaction ^{88}Sr+^{176}Yb. The deformation of the fragments is fixed at $\beta = 0.1$. The arrows indicate the positions of neutron and proton shells.

TABLE I. The reaction parameters for the system ^{88}Sr+^{176}Yb.

Parameter	Value
Mass asymmetry of entrance channel η_0	0.33
The Coulomb factor Z_1Z_2	2660
^{88}Sr energy in laboratory system	435 MeV
Energy in c.m. system	290 MeV
Bass barrier	278.9 MeV Ref. [12]
Grazing angle for projectile ^{88}Sr:	
in laboratory system	90.2° Ref. [12]
in c.m. system	120.2° Ref. [12]
Grazing angle for target ^{176}Yb:	
in laboratory system	29.9°

II. MASS-ENERGY DISTRIBUTION OF BINARY FRAGMENTS FROM THE SYSTEM ^{88}SR+^{176}YB

The experiment was carried out at the K130 cyclotron of the Department of Physics, University of Jyväskylä. A beam of 435-MeV ^{88}Sr ions impinged a layer of 240 μg/cm^2 ^{176}Yb (99.9% enriched) deposited on a 50 μg/cm^2 carbon backing. The beam current on the target was 15 nA.

In the two-body coincidence method the two products were detected in coincidence by the two-arm time-of-flight spectrometer CORSET [7,13]. Each arm of the spectrometer consists of a compact start detector and a position-sensitive stop detector, both based on microchannel plates. The distance between the start and the stop detector was 25 cm. The start detectors were placed at a distance of 5 cm from the target. The acceptance of the spectrometer was ±8° in the reaction plane. The angular resolution of the stop detectors was 0.3°. The arms of the spectrometer were positioned in an optimal way according to the kinematics of the reaction and moved several times during the experiment. This arrangement allowed us to detect the coincident binary fragments over an angular range 23–88° in the laboratory frame that corresponds to the center-of-mass angular range 45–140°. The differential cross sections of the primary binary fragments were obtained after normalization to elastic scattering detected by CORSET and by the current integration by means of a Faraday cup.

Primary masses, velocities, energies, and angles in the center-of-mass system of the reaction products were calculated from measured velocities and angles by using the momentum and energy conservation laws with the assumption that the mass number of the composite system is equal to $A_{\mathbf{target}} + A_{\mathbf{projectile}}$. The extraction of the binary reaction channels with full momentum transfer was based on the analysis of the kinematics diagram (see Refs. [7,13] for details). The mass and energy resolutions of the present CORSET setup, which define the bin width of the experimental mass and energy yield curves, are taken as the FWHM of the mass and energy spectra constructed for the elastic scattering. In the above conditions, the mass resolution of the spectrometer is ±2 u and the energy resolution is ±3 MeV.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the mass-TKE (total kinetic energy) distribution of primary fragments measured in the reaction

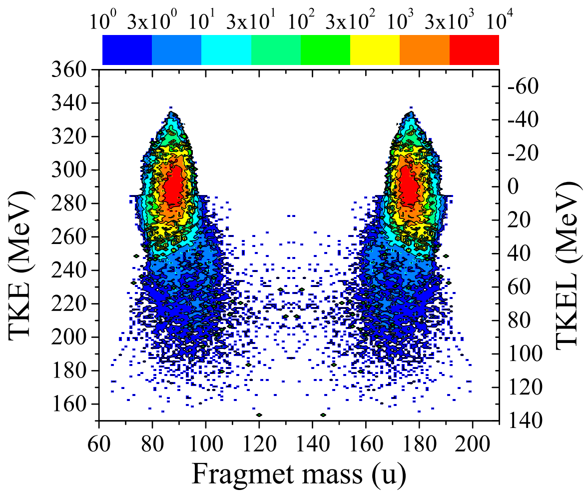

FIG. 2. (Color online) Mass-energy distribution of binary fragments obtained in the reaction ^{88}Sr+^{176}Yb at a c.m. energy of 290 MeV and integrated over the angular range of 45–140° in c.m. Only true two-body events are included (no sequential fission). On the right vertical axis the total kinetic energy lost (TKEL) scale is reported.

^{88}Sr+^{176}Yb. At first glance, Fig. 2 suggests that besides the elastic and quasielastic components, a significant part of the events has a large dissipation of the entrance channel kinetic energy $E_{\mathrm{c.m.}}$, which indicates the occurrence of strongly damped collisions. The distribution of the total kinetic energy lost TKEL ($=E_{\mathrm{c.m.}}-$TKE) for all detected events is shown in Fig. 3. Lower TKEL values correspond to quasielastic processes whereas higher TKEL values correspond to more damped events. If we use a Gaussian fit to reasonably take into account the quasielastic component, we observe that most of the damped events are located at TKEL values above 20 MeV.

The fragments with TKEL larger than 20 MeV are located mainly in the region 85–115 u for PLF and 150–180 u for TLF. The contribution of symmetric fragments with masses $(A_{\mathrm{target}} + A_{\mathrm{projectile}})/2 \pm 20$ u to all damped collision events with TKEL >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}Fe+^{208}Pb ($Z_1 Z_2 = 2132$) the contribution of the fusion-fission component to the symmetric fragments is less than a few percent [7]. As was shown in Ref. [14], 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 (see Fig. 1). The minimum of the potential energy of the system favors the creation of symmetric fragments. In particular, the minimum at symmetric masses (Fig. 1) 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 [15].

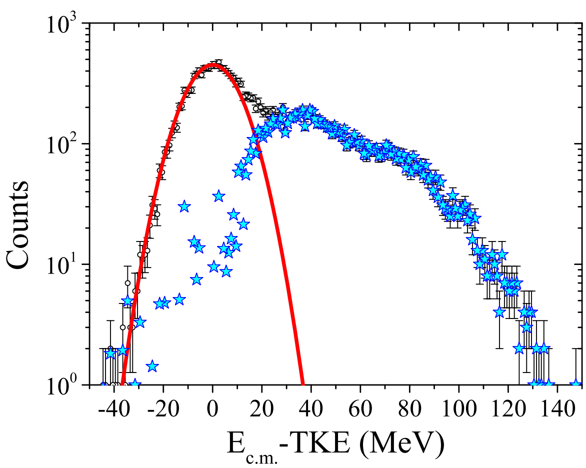

FIG. 3. (Color online) TKEL distribution for reaction products from collisions of ^{88}Sr+^{176}Yb at $E_{\mathrm{c.m.}} = 290$ MeV. The thick line represents the elastic and quasielastic contributions (Gaussian-like); stars are the difference between experimental and Gaussian distribution.

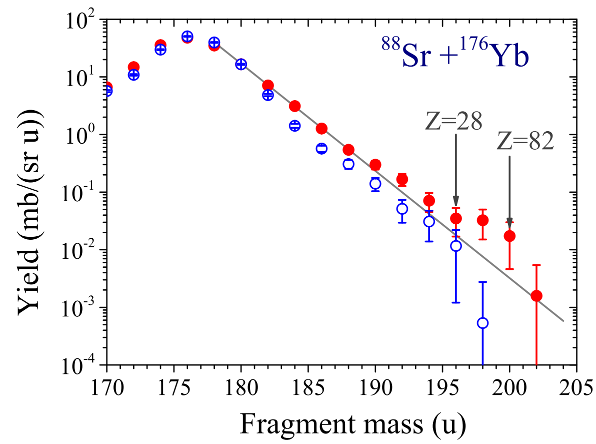

FIG. 4. (Color online) Double differential cross sections of heavy fragments formed in the reaction^{88}Sr+^{176}Yb at $E_{\mathrm{c.m.}} = 290$ MeV and detected at laboratory angles from 25° up to 35°. Filled circles indicate the primary mass distribution, and open circles indicate the mass distribution corrected for neutron emission.

The yield of TLFs with mass larger than 170 u at laboratory angles from 25° up to 35° is shown in Fig. 4. 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 TLFs 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}Xe+^{208}Pb (up to 16 nucleons from Xe to Pb) at the energy of $1.23E_{\mathrm{Bass}}$ with a cross section of the order of 200 μb, for the lower mass transfer, and a few μb for the larger mass transfer [16].

For TLF heavier than the target nucleus, the production cross section of the primary fragments, starting from the region of no-shell closures (maximun at mass around 176), is compatible with an exponential decrease, which is outlined by the solid line in Fig. 4. Because of the absence of shell closures in that mass region, such a trend recalls a phase-space effect in the mass degree of freedom. For TLF 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}S+^{238}U and ^{58}Fe+^{208}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 $E_f^* = E_{\mathrm{c.m.}} - \mathrm{TKE} + Q_{\mathrm{gg}}$ and assume that this excitation is divided between the two primary fragments according to their mass ratio [17]. The obtained excitation energy for each fragment is shown in Fig. 5. The particular shape of the

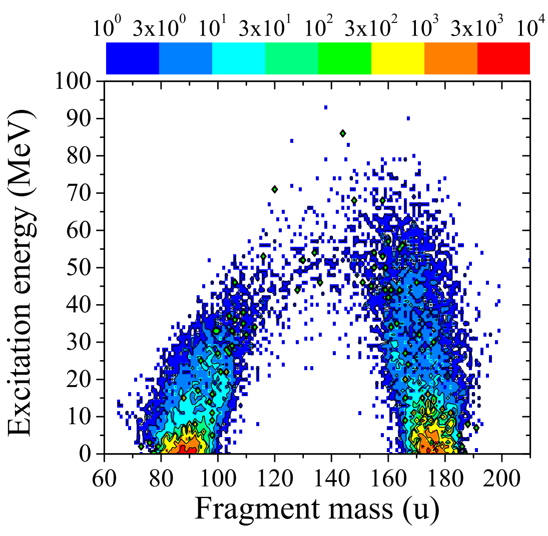

FIG. 5. (Color online) Excitation energy of primary fragments formed in the reaction ^{88}Sr+^{176}Yb at $E_{\mathrm{c.m.}} = 290$ MeV.

distribution in Fig. 5 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 reach values up to 90 MeV. For TLF 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 mass distribution of the final fragments obtained from the primary one by taking into account the neutron emission evaluated as mentioned above is presented in Fig. 4 as well.

IV. SUMMARY

In this study we question if the shell closures can favor a large net mass transfer, from projectile to target, in damped reactions between massive colliding nuclei. This approach may open the possibility to produce new heavy neutron-rich nuclei.

The mass-energy distribution of binary fragments formed in the reaction ^{88}Sr+^{176}Yb at $E_{\mathbf{lab}} = 435$ MeV at c.m. angles 30–140° has been measured. A significant part of binary fragments is correlated with a large dissipation of the initial kinetic energy, which indicates the presence of strongly damped collisions. The fragments with TKEL larger than 20 MeV are located mainly in the region 85–115 u for PLF and 150–180 u for TLF. We observe heavy fragments with mass up to 200 u, which means that a net mass transfer from projectile to target of about 20–25 nucleons occurs in this reaction.

The yield of TLFs with masses heavier than 190 u is half an order of magnitude larger than may be expected from the extrapolation of an exponential-like behavior of the fragment yields from the region of no-shell closures (mass around 176) to the region of shell closures. The enhancement of the yield of fragments with masses around 190–200 u is caused by the proton shells at $Z = 28$ and $Z = 82$. In the quasifission reactions ^{36}S+^{238}U and ^{58}Fe+^{208}Pb [7], the masses of the fragments also peak around 200 u but the transfer of nucleons occurs in the opposite direction. This is because in the case of reactions with Sr, the mass asymmetry of these produced fragments is larger than the entrance channel asymmetry, while in the reactions with S and Fe the case is reversed. Therefore, the relative contribution of multinucleon transfer reactions to the capture cross section mainly depends on the reaction entrance channel properties. The characteristics of asymmetric fragment yield are determined essentially by the driving potential of the composite system.

The estimate of the available excitation energies of the formed fragments has been done from measured TKE. For TLF heavier than the target the excitation energy is about 30–50 MeV and may give rise to the evaporation of 3–5 neutrons.

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. [9] for the synthesis of neutron-rich superheavy elements (SHE), which are not reachable in fusion reactions.

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