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Evidence of quasifission in the ^{180}Hg composite system formed in the ^{68}Zn + ^{112}Sn reaction

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ABSTRACT

For the ^{68}Zn + ^{112}Sn reaction the Coulomb parameter Z_1Z_2 is equal to 1500 that is close to the threshold value for the appearance of quasifission process. It was found that mass-energy distributions of the reaction fragments differ significantly from those obtained in the ^{36}Ar + ^{144}Sm reaction leading to the formation of the same composite system of ^{180}Hg at similar excitation energies of about 50 MeV. In the case of the reaction with ^{68}Zn ions, the mass distribution of fissionlike fragments has a wide two-humped shape with maximum yields at 70 and 110 u for the light and heavy fragments, respectively, instead of 80 and 100 u observed in the fission of ^{180}Hg formed in the ^{36}Ar + ^{144}Sm reaction. The difference is explained by an unexpectedly large contribution (more than 70%) of quasifission in the case of the ^{68}Zn + ^{112}Sn reaction.

1. Introduction

Investigation of nuclei far from the valley of stability is one of modern nuclear physics's primary goals. Heavy-ion-induced reactions are widely used to produce these nuclei. However, the formation of a fully equilibrated compound nucleus (CN) is opposed by the Coulomb repulsion between the interacting nuclei. As a result, the composite system may disintegrate into two fragments via the quasifission (QF) process [1,2] and deep inelastic collisions (DIC) [3]. QF is the main mechanism preventing the formation of heavy and superheavy elements via fusion. The ratio between QF and CN formation is determined by the entrance channel properties [4,5]. As the dynamic evolution of a perturbed quantum many-body system is challenging, current theoretical models come short of an unambiguous prediction of the reaction mechanisms.

Further studies on the origin and strength of the processes that hinder the CN formation are needed to explore the dynamics of heavy ion interactions. One of the experimental tasks is to verify the dependence of the QF and CN-formation mechanisms on the entrance channel's properties and identify the trends in cross sections which can be summarized into a systematics. Moreover, the studies of low-fissility systems would also expand a systematics of heavy ion reactions and provide the needed input to design a model having a wider universality in covered nuclei and parameters.

QF and DIC are considered as binary multinucleon transfer reactions with a full momentum transfer and characterized by sufficient mass transfer and energy dissipation. There is no clear separation between these processes. The DIC angular distributions are mainly focused near the grazing angles of collisions, DIC evolution time being a few zeptoseconds [6]. Mass distributions are peaked around the projectile and target nuclei masses, and the yield of fragments with masses heavier or lighter than interacting nuclei decreases exponentially. QF is characterized by smoother angular distributions and its evolution time can extend up to tens of zeptoseconds [2]. As a rule, shell effects strongly affect the yield of QF fragments leading to the asymmetric mass distributions with the maxima located near the closed neutron and proton shells [4].

According to the calculations within the macroscopic-microscopic model of Swiatecki [7], the Z_1Z_2 threshold value for the appearance of QF is 1600. From the analysis of a large set of experimental mass-angular distributions of fissionlike fragments formed in the reactions with heavy ions [8], it was found that for the composite systems with $Z_{CN} = 80$ the threshold value for the QF appearance is $Z_1Z_2 = 1450 \pm 100$. A key parameter used to assess QF probability is the mean fissility parameter x_m. It is expressed

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Table 1
The entrance channel properties for the reactions leading to the formation of ^{180}Hg. Z_1Z_2 is the Coulomb factor, x_m is the mean fissility parameter, α_0 is the entrance-channel mass asymmetry, E_{lab} and $E_{c.m.}$ are the interaction energies in the laboratory and the center-of-mass (c.m.) systems, $E_{c.m.}/E_{Bass}$ is the relation to the Bass barrier of the reaction, E^*_{CN} is the excitation energy of formed CN, L_{gr}, L_{crit}, and $\langle L\rangle$ are the grazing, critical [13], and mean angular momenta, θ_{lab} are the capture angles of CORSET setup, and θ_{gr} are the grazing collisions angles.

Parameter	^{68}Zn + ^{112}Sn [this paper]	^{36}Ar + ^{144}Sm [12]
Z_1Z_2	1500	1116
x_m	0.695	0.634
α_0	0.24	0.60
E_{lab} (MeV)	300	181
$E_{c.m.}$ (MeV)	186.7	144.8
$E_{c.m.}/E_{Bass}$	1.096	1.115
E^*_{CN} (MeV)	48	53
L_{gr} ($\hbar$)	81	59
L_{crit} ($\hbar$)	70	52
$\langle L\rangle$ ($\hbar$)	47	35
θ_{lab} (deg)	45 ± 14	60 ± 19
θ_{gr} (deg)	72.8	91.2

as $x_m = 0.75x_{eff} + 0.25x_{CN}$, where x_{CN} is a fissility of CN and x_{eff} is the effective fissility parameter [9] reflecting the entrance-channel mass and charge asymmetry. QF appears for reactions with $x_m > 0.68$ and results in widening of mass distributions and forward-backward asymmetry in angular distributions. At $x_m > 0.765$, QF becomes dominant that leads to a wide two-humped shape of mass distributions and pronounced peaks near the grazing angles in angular distributions of the reaction fragments [8]. Since the lower the mass asymmetry the higher the Coulomb factor (Z_1Z_2), QF probabilities are higher for symmetric than for asymmetric reactions leading to the same composite systems. The fusion probability P_{CN} correlates with the entrance-channel mass asymmetry $\alpha_0 = (A_{target} - A_{projectile})/(A_{target} + A_{projectile})$. The criterion based on the entrance-channel mass asymmetry states that QF appears for systems with the entrance-channel mass asymmetry α_0 lower than the mass asymmetry associated with the Businaro-Gallone point α_{BG} [10]. At the α_{BG}, the contact potential energy of a composite system as a function of the entrance-channel mass asymmetry is maximal. However, this criterion is known to predict the appearance of QF process even for the systems where only CN fission was observed. Interaction energy, angular momentum, and static deformation of interacting nuclei also influence the balance between QF process and CN formation. The study of the reactions in the vicinity of the threshold for the appearance of QF process is therefore extremely important for the understanding of mechanisms of heavy-ion reactions.

The present paper investigates the ^{68}Zn + ^{112}Sn reaction leading to the formation of ^{180}Hg at the interaction energy of 300 MeV. The mass and energy distributions of fissionlike fragments were measured and compared with those formed in the ^{36}Ar + ^{144}Sm reaction [11,12] leading to the formation of the same CN. The entrance channel properties of the reactions are given in Table 1.

The values listed in Table 1 indicate that the mean fissility parameter x_m and the Coulomb factor Z_1Z_2 are close to the threshold values for the onset of QF process in the case of the ^{68}Zn + ^{112}Sn reaction, whereas for the ^{36}Ar + ^{144}Sm reaction the values are favorable for CN formation. Nevertheless, it should be stressed that although in the ^{68}Zn + ^{112}Sn reaction x_m exceeds the threshold value for QF appearance, it is essentially lower than 0.765, a starting point for QF to prevail. Therefore, in the ^{68}Zn + ^{112}Sn reaction one can expect that the CN formation and its subsequent fission is the main process whereas QF is a small part of the capture cross section.

The entrance-channel mass asymmetry is smaller than $\alpha_{BG} = 0.83$ for both reactions. However, for the ^{36}Ar + ^{144}Sm reaction, QF was not observed in the previous studies [11,12]. Further, the mass asymmetry for the ^{68}Zn + ^{112}Sn reaction is smaller than for the ^{36}Ar + ^{144}Sm reaction. This should ensure that different interaction mechanism would be involved.

2. Experiment

The experiment was carried out at the Physics Department of the Jyväskylä University, Finland, with 300-MeV ^{68}Zn ions from the K-130 cyclotron. The energy resolution of the beam was 1%. The target was prepared by sputtering ^{112}Sn (200 μg/cm^2) on a 30-μg/cm^2 carbon backing. The enrichment of the target was 99.9%. The experimental setup was identical to the one used for the ^{36}Ar + ^{144}Sm reaction [12]. The binary reaction fragments were detected by the double-arm time-of-flight spectrometer CORSET [14]. Each arm of the spectrometer consists of a compact start detector and a position-sensitive stop detector. Both detectors are based on microchannel plates. The arms of the spectrometer were set symmetrically with respect to the beam axes, at the angle of 45°. For symmetric reaction products, that configuration corresponds to the 90° angle in the c.m. system. The position resolution of the stop detectors was 0.3°. The full width at half maximum (FWHM) time of flight resolution was about 150 ps. The mass and energy resolutions of the CORSET setup were calculated from the FWHM of the mass and energy spectra of the elastically scattered particles. The resulting mass- and total kinetic energy (TKE) resolutions were ±2 u and ±6 MeV, respectively. The extraction of the binary reaction channels, exhibiting full momentum transfer, was based on the analysis of the kinematical diagram (see [15,16] for details).

3. Results and discussion

The mass-total kinetic energy (M-TKE) distribution of the primary binary fragments, obtained in the ^{68}Zn + ^{112}Sn reaction at the interaction energy of 300 MeV, are shown in the top panel of Fig. 1. The two maxima at TKE close to the interaction energy in the c.m. system and masses close to those of the projectile and the target are associated with elastic and quasielastic scattering. The rest of the reaction products formed in the reaction show significant energy dissipation (TKE < $E_{c.m.}$) and nucleon transfer (fragment mass different from that of the target and the projectile). These are characteristic features of CN-fission and QF processes (fissionlike events) [1,2,4]. Because of the overlap in the M-TKE distributions for the fissionlike and quasielastic scattering events, their separation is difficult. In the mid-panel of Fig. 1, the energy loss ($E_{c.m.}$ − TKE) distribution of the reaction products is shown. The distribution consists of quasielastic component which could be well reproduced by the Gaussian distribution with mean energy equal to $E_{c.m}$, and a wide distribution spreading up to the energy losses of about 100 MeV. At the energy loss of about 26 MeV and above, corresponding to TKE ≤ 160 MeV, the contribution of the quasielastic component becomes insignificant.

The bottom panel of Fig. 1 shows the energy of all binary reaction products obtained in the ^{68}Zn + ^{112}Sn reaction plotted as a function of the registration angle in the c.m. system. The shaded region corresponds to the events with energy losses of more than 26 MeV. Since the fissionlike reaction products are lying lower than the elastic and quasielastic events, they can be separated. Even though a small part of the fissionlike fragments, overlapping with elastic and quasielastic events, are cut off, it does not significantly affect the mass-energy distribution of fissionlike fragments. Fig. 2 shows the mass-energy distributions of these fissionlike fragments obtained in the reaction ^{68}Zn + ^{112}Sn and the ^{36}Ar + ^{144}Sm reaction [12]. Both lead to the same CN, ^{180}Hg, at similar excitation energy listed in Table 1. In the case of ^{36}Ar + ^{144}Sm

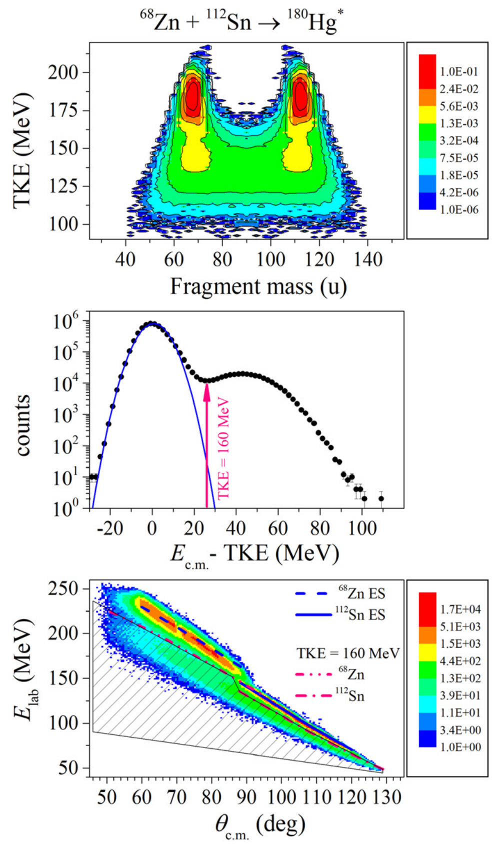

Fig. 1. The mass-TKE (top panel), energy loss (middle panel) and angular-energy (bottom panel) distributions of all binary fragments formed in the ^{68}Zn + ^{112}Sn reaction at $E_{lab} = 300$ MeV.

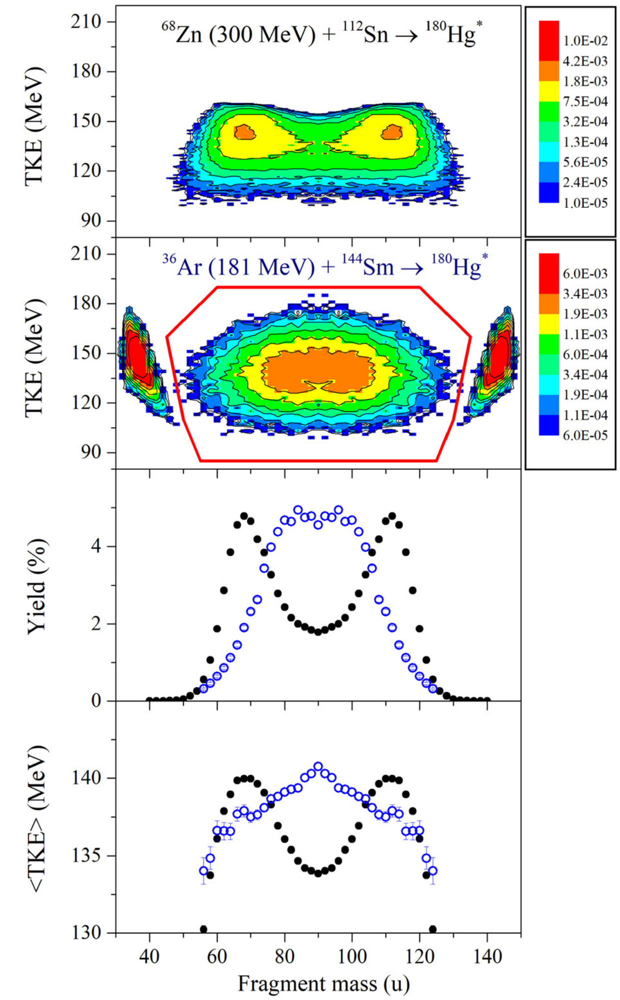

Fig. 2. From top to bottom: the mass-energy distribution of fissionlike fragments formed in the ^{68}Zn + ^{112}Sn reaction at $E_{lab} = 300$ MeV; the mass-energy distribution of fragments formed in the ^{36}Ar + ^{144}Sm reaction at $E_{lab} = 181$ MeV; the comparison of mass yields and mean total kinetic energies as a function of mass for the reactions ^{68}Zn + ^{112}Sn (solid circles) and ^{36}Ar + ^{144}Sm (open circles).

the fissionlike reaction products (inside the polygon in M-TKE matrix in Fig. 2) are well separated from the elastic and quasielastic scattering events. These fissionlike fragments have characteristics expected for the fission of the excited ^{180}Hg compound nucleus. As it was mentioned above the properties of the reaction entrance channel are favorable for CN formation. Moreover, in the mass, energy, and angular distributions of fragments obtained in a similar reaction (^{48}Ca + ^{144}Sm) [17], no evidence of QF process was observed.

In the case of the ^{36}Ar + ^{144}Sm reaction, the mass distribution demonstrates nearly Gaussian shape but has a slight asymmetry at mass numbers 80 and 100 u. Also, experiments investigating β-decay of ^{180}Tl nucleus leading to the fission of the daughter nucleus ^{180}Hg with excitation energy $E^* < 10.8$ MeV [18] observed asymmetric mass distribution of fission products with the maxima at mass numbers around 80 and 100 u. The excitation energy of the ^{180}Hg nucleus, formed in the ^{36}Ar + ^{144}Sm reaction, was about 53 MeV. At such excitation energy, the structure peculiarities specific for low-energy fission are still observable, but the main fission component is defined by macroscopic properties of the nucleus that are well-described by the liquid drop model. Hence, the mass-energy distribution of ^{180}Hg fission fragments formed in the ^{36}Ar + ^{144}Sm reaction at the interaction energy of 181 MeV can be represented as a superposition of the symmetric “liquid-drop” distribution and the asymmetric one with the peaks at 80 and 100 u.

As it is visible in Fig. 2, the mass-energy distributions of fissionlike products formed in the ^{68}Zn + ^{112}Sn reaction differ significantly from those obtained in the ^{36}Ar + ^{144}Sm reaction. The maxima in the fragments yields for the ^{68}Zn-ions-induced reaction are observed at 68 and 112 u. Although the average kinetic energy of fragments is similar for both reactions, the dependences of the mean TKE on fragment mass varies strongly. In the case of the ^{36}Ar + ^{144}Sm reaction, the maximum kinetic energy is observed for symmetric fragments, whereas for the ^{68}Zn + ^{112}Sn reaction the maxima correspond to asymmetric fragments with masses near 68 and 112 u.

The systematic study of fission of exited nuclei has shown that the excitation energy and angular momentum influence the properties of fission fragments [19]. These properties do not depend on the reaction in which they were formed. The excitation energy of ^{180}Hg formed in both reactions is about 50 MeV. Mean angular momentum $\langle L \rangle$ is higher in the reaction with ^{68}Zn ions. However, the $\langle L \rangle$ values are significantly lower than the critical angular momentum, a limiting value of the angular momentum over which the possibility of formation of a compound nucleus would disappear, for both reactions (see Table 1). According to the experimental systematics for fission of excited nuclei [19], these changes in angular momenta lead only to a minor increase in the width of the fission fragment mass distribution for the reaction with ^{68}Zn ions as compared to the ^{36}Ar-ions-induced reaction. Therefore, the fission fragment characteristics for both reactions should be similar.

The maxima in the mass yields of fission fragments formed in the ^{68}Zn + ^{112}Sn reaction are centered at the masses of the interacting nuclei: 68 and 112 u. The kinetic energy is, on average, 50 MeV lower than $E_{c.m.}$. In the present work, the measurements of fission fragments were carried out at the angles ∼30° below the grazing angle for both reactions. Consequently, the contribution of DIC to the measured mass distribution is supposed to be insignificant. Therefore, the difference in the mass-energy distributions observed for these reactions could be explained neither by the influence of angular momentum nor by the large contribution of DIC. QF is the dominant process in the ^{68}Zn + ^{112}Sn reaction. Assuming that the registration angles of the CORSET spectrometer cover the mean emission angle for QF fragments, we have estimated the rotation angle and the reaction time, as described in Ref. [2]. The estimated time for the formation of the fragment pair with masses near 68 and 112 u is about 7 zs. This time is typical for asymmetric QF process [20]. Moreover, fragments formed in QF process have masses close to the proton and neutron shells [3]. For example, in the reactions with heavy ions leading to the formation of superheavy systems, the maxima in the QF fragments mass yields are located near the closed shells $Z = 82$ and $N = 126$ [4]. Just like for superheavy systems, the QF fragment formation in the ^{68}Zn + ^{112}Sn reaction is possibly driven by the closed proton shells at $Z = 28$ and $Z = 50$.

To estimate the contribution of CN-fission fragments into all fissionlike events for the ^{68}Zn + ^{112}Sn reaction, the *M*-TKE distribution of fission fragments formed in the ^{36}Ar + ^{144}Sm reaction was used. The distribution was normalized to reach the same yield of the most probable TKE at $A_{CN}/2$ as in the ^{68}Zn + ^{112}Sn reaction. The contribution of CN-fission process in the formation of all fissionlike events was calculated as a ratio between the number of events in the normalized ^{36}Ar + ^{144}Sm *M*-TKE matrix and all fissionlike events formed in the ^{68}Zn + ^{112}Sn reaction. Thus, for the ^{68}Zn + ^{112}Sn reaction at the incident energy of 300 MeV, the CN-fission process contribution in the capture cross section was found to be less than 30%. The absolute differential cross section for all fissionlike events observed in the ^{68}Zn + ^{112}Sn reaction was measured at the angle $\theta_{c.m.} \approx 90°$. For the lack of a model (theory) to describe QF angular distributions it is impossible to integrate the measured differential cross section for all fissionlike events, therefore, the CN-fission cross section was estimated. Since the angular coverage of the spectrometer is about 30°, the CN-fission cross section was estimated assuming that the angular distribution is proportional to $1/\sin\theta_{c.m}$. The upper limit for the CN-fission cross section of about 60 mb was obtained.

According to the channel-coupling model calculations within the NRV project [21], the capture cross section for the ^{68}Zn + ^{112}Sn reaction at $E_{lab} = 300$ MeV should be about 300 mb. The NRV code predicts the CN-fission probability of about 93% (7% of evaporation residue). Therefore, the experimentally estimated upper limit for the fusion cross section amounts to 65 mb. Consequently, since the capture cross section is a sum of the fusion and QF cross sections, a significant suppression of the CN formation was observed for the reaction.

The outcome of our measurements is puzzling. Such a large contribution of QF in the ^{68}Zn + ^{112}Sn reaction was not expected since though the mean fissility parameter for the reaction $x_m = 0.695$ is just over the threshold value for QF appearance, but it is much lower than $x_m = 0.765$, when according to the systematics [8] QF becomes a dominating process. It is to be noted that in the ^{68}Zn + ^{112}Sn reaction QF fragments peak around the masses corresponding to closed proton shells at $Z = 28$ and $Z = 50$. The changes in the entrance channel properties, compared to the ^{36}Ar + ^{144}Sm reaction, are not so drastic as to cause such significant changes in the interaction mechanism. The main difference between the two cases is the mass ratio of the interacting nuclei leading to the same CN. As shown in Table 1, the entrance-channel mass asymmetry parameter α_0 drops from 0.60 to 0.24 for the ^{68}Zn + ^{112}Sn reaction. In other words, moving towards a more symmetric system increases the QF contribution. If this is indeed the case, classification of heavy-ion-induced reaction mechanisms should include both the mean fissility parameter and the entrance-channel mass asymmetry. In fact, the mean fissility parameter indirectly accounts for the mass asymmetry via the effective fissility parameter. However, the result of this study shows that the influence of the entrance-channel mass asymmetry is much stronger than previously assumed. Additional experiments with reactions leading to the formation of the ^{180}Hg composite system are needed to confirm this finding. Especially relevant are measurements of the reactions with higher (e.g. ^{56}Fe + ^{124}Xe) and lower (e.g. ^{90}Zr + ^{90}Zr) mass asymmetry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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