COMPETITION BETWEEN DYNAMICAL AND SEQUENTIAL REACTION CHANNELS IN ^{197}Au+^{197}Au COLLISIONS AT A BOMBARDING ENERGY OF 23A MeV*

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Competition between the two reaction channels: sequential breakup and neck fragmentation has been studied in peripheral and semi-peripheral collisions of the ^{197}Au+^{197}Au system at bombarding energy of 23A MeV. It was found that the emission of heavy ($A < 50$) neck-originating fragments occurs in about 22% of ternary breakup events, making this reaction channel highly competitive with the sequential breakup of the projectile- or target-like fragment (78% of events).

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1. Introduction

The fission of the projectile- or target-like fragment observed in collisions of heavy nuclear systems in the Fermi energy range (20–40 MeV per nucleon) is one of the possible paths to obtain new nuclides located close to the neutron drip line [1]. The most exotic neutron-rich fission products are observed in collisions of the heaviest, rather symmetric systems for which the fusion channel is completely suppressed. With increasing mass and symmetry of the colliding system, new exit channels start to emerge and, in some cases, their contribution to the total cross section may be comparable to that of the sequential fission channel. Dynamical processes such as ternary aligned breakup [2] or emission of neck-originating fragments [3] are good examples of such reaction channels. Our previous studies have shown that the latter process plays an important role in collisions of the $^{197}\mathrm{Au}+^{197}\mathrm{Au}$ system at a bombarding energy of $23A$ MeV [4]. In this paper, we would like to examine the competition between the neck fragmentation reaction and the sequential breakup process in more detail.

Breakup of one or both colliding nuclei proceeds as a rule sequentially, *i.e.* in two stages. In the first stage, a large portion of the kinetic energy is dissipated and excited projectile-like (PLF*) and excited target-like (TLF*) fragments are formed as a result of the exchange of many nucleons between the target and projectile nuclei. In the second stage of the reaction, one of the fragments, or less often both, undergoes fission. In the case of an initially symmetric system, PLF* and TLF* decay modes are identical, so it is enough to study half of the events in which the PLF* breaks up into fragments FF1 and FF2

$$^{197}\mathrm{Au}+^{197}\mathrm{Au}\rightarrow \mathrm{TLF}^*+\mathrm{PLF}^*\rightarrow \mathrm{TLF}+\mathrm{FF1}+\mathrm{FF2}+\mathrm{evap.\ part.}\,, \quad (1)$$

where TLF is the *cold* (deexcited) target-like fragment.

The neck fragmentation process observed by us in ^{197}Au+^{197}Au collisions is similar to the emission of so-called intermediate mass fragments (IMFs) directly from the projectile–target interaction zone observed at higher bombarding energies [5]. The atomic masses of observed IMFs (A reaching 40–50 mass units) greatly exceed those reported for the lighter colliding systems [6]. The observation of such massive IMFs was reported for the heaviest systems only, such as ^{208}Pb+^{197}Au [3]. Neck fragmentation is a ternary reaction and proceeds as follows:

$$^{197}\mathrm{Au}+^{197}\mathrm{Au}\rightarrow \mathrm{TR}+\mathrm{PR}+\mathrm{IMF}+\mathrm{evaporated\ particles}\,, \quad (2)$$

where TR and PR are residuals of the target and projectile nuclei, respectively.

2. Experiment

The experiment was performed at the INFN Laboratori Nazionali del Sud (LNS) in Catania, Italy. A beam of ^{197}Au ions from the LNS Superconducting Cyclotron was accelerated to an energy of $23A$ MeV and bombarded a ^{197}Au target placed inside the Charged Heavy Ion Mass and Energy Resolving Array (CHIMERA) [7]. The CHIMERA multidetector is arranged in 4π geometry and is made up of 1192 two-layer ΔE–E telescopes, each consisting of a planar 275 μm-silicon detector and a CsI(Tl) scintillator. Information on the methods of mass identification and fragment energy determination may be found in [8].

3. Results

The data are analyzed in a simplified, semi-inclusive approach in which only two fragments have to be detected in coincidence: both PLF breakup products (FF1 + FF2) or the projectile-residue together with the neck-originating fragment (PR + IMF) (see Eqs. (1) and (2)). Detection of the third fragment (TLF or TR) or its decay products is not required.

Both reaction mechanisms will be studied together using the same methods. For the sake of clarity, regardless of the reaction mechanism, we will denote the two fragments in question by F1 and F2, where F1 is the *heavier* fragment of mass number A_{F1} and F2 is the *lighter* one of mass number A_{F2}. The analysis has been restricted to fragments with positive longitudinal velocities in the centre-of-mass system to exclude the contribution from TLF breakup events. Only pairs of fragments for which both A_{F1} and A_{F2} are greater than 7 (to exclude evaporated light particles) and $160 \leq A_{\mathrm{F1}}+A_{\mathrm{F2}} \leq 197$ (to minimize the number of events where the PLF* breaks into more than two fragments, of which only 2 are detected) are analyzed.

All selected events are presented in Fig. 1 (a) showing the correlation between the total kinetic energy (TKE) and the fragment mass number (two points for each event). TKE is the energy of the *cold* (deexcited) binary system and is calculated as the sum of the kinetic energies of the center-of-mass of the F1+F2 subsystem and the complementary heavy fragment (TLF or TR) calculated from momentum balance (momenta of evaporated neutrons and light charged particles are neglected). The center-of-mass of the F1+F2 subsystem can be associated with the reconstructed *cold* PLF or with the short-lived projectile-like composite system (PR+IMF). The assumption that both processes under study proceed sequentially gives a reasonable estimation of the energy dissipation and enables us to localize a given reaction channel in impact parameter space, but it is limited to TKEs greater than the kinetic energy of relative motion of the completely damped binary system. Therefore, in the later analysis, we will study events with TKE $>$ 500 MeV only.

It is clearly seen in Fig. 1 (a) that events from both processes are well-separated. The PLF breakup products are located in the most intense region around $A \approx 90$. The *light* and *heavy* fragments from the neck fragmentation process are located in two less intense regions of $A \leq 35$ and $A \approx 150$, respectively. Both processes take place in the same wide range of TKE between 700 and 2000 MeV (corresponding to peripheral and semi-peripheral collisions [4]).

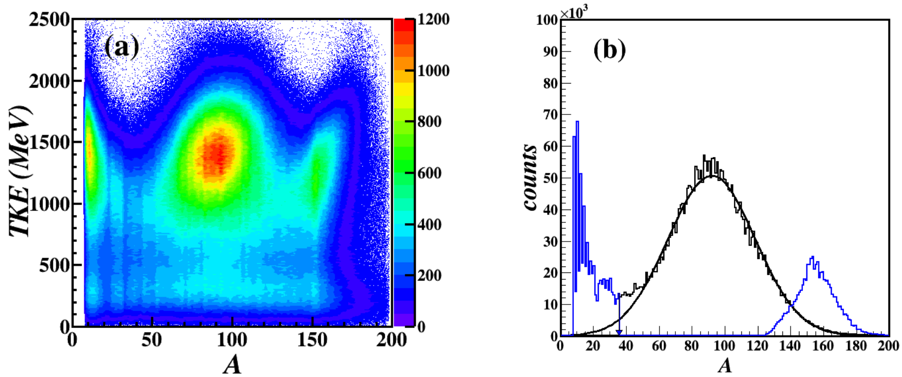

Fig. 1. (Color online) Panel (a): The correlation between the total kinetic energy (TKE) and the fragment mass number (two points for each event). The intensity scale is arbitrary. Panel (b): Mass distributions of the PLF breakup products (in black), IMFs and their complementary fragments (both in gray/blue) obtained for TKE > 500 MeV. Data presented in both figures are not corrected for the detection efficiency. See the text for details.

Our previous studies (see Ref. [9]) have shown that fragments with $A \leq 30$ are almost exclusively emitted in the neck fragmentation process. In the inclusive analyses it was shown that the parallel velocity in the center-of-mass of the ^{197}Au+^{197}Au system for fragments with $A \leq 30$ is localized around 0 cm/ns. Moreover, the emission yield of the neck-originating IMFs decreases rapidly with increasing mass and vanishes for $A \approx 40$–50. To estimate the contribution from each of the reaction channels, we will assume (for simplicity) that all fragments with $A \leq 35$ are emitted in the process of neck fragmentation. Consequently, all events in which the *lighter* of the two fragments has a mass number greater than 35 will be considered to be PLF breakup. No other conditions are applied, setting the mass limit for the *lighter* fragment only is enough to assign the *heavier* fragment to the proper class of events.

Figure 1 (b) shows the mass distributions of PLF breakup products (in black), IMFs and their complementary fragments (in gray/blue) for TKE > 500 MeV. The mass number $A = 35$ is indicated by a vertical arrow. The solid black line shows the overall shape of the PLF breakup product mass distribution, which was obtained by fitting a Gaussian distribution to points with $A \geq 50$. The extrapolation of the fitted distribution to the region below 50 mass units shows that setting a sharp limit for IMF mass number should give a reasonable estimation of the total number of events in a given reaction channel (the area below the Gaussian distribution for $A \leq 35$ and the area between the experimental and Gaussian distributions for $35 < A < 50$ are approximately the same). The ratio of one process to the other can thus be simply calculated as $N_{\mathrm{FF}}/N_{\mathrm{IMF}}$, where N_{FF} is the number of PLF breakup events and N_{IMF} is the number of neck fragmentation events. The data presented in Fig. 1 are not corrected for detection efficiency.

After taking into account the efficiency corrections (detection of fragments F1 and F2 in coincidence) estimated using the Monte Carlo method described in detail in Ref. [9], the ratio $N_{\mathrm{FF}}/N_{\mathrm{IMF}} \approx 3.6$ (for the data presented in the Fig. 1 (b)). This result is, in fact, more general. Our analysis included only half of the events. However, due to the symmetry of the colliding system, the same result is expected for the TLF breakup. Therefore, about 78% of the ternary events correspond to sequential breakup (of PLF* or TLF*, see Eq. (1)) and the remaining 22% to the neck fragmentation process (Eq. (2)). The contribution from the neck fragmentation process is a factor of two larger than that reported for ^{208}Pb+^{197}Au collisions at a bombarding energy of 29A MeV [3].

To study how the contribution from each process varies with the energy dissipation, we have divided the data presented in Fig. 1 (a) for 500 MeV $\leq$ TKE $<$ 2200 MeV into 17 equal bins, each 100 MeV wide. The data in each bin were analyzed in the same manner as the data shown in Fig. 1 (b). Figure 2 (a) shows the number of events of a given type as a function of

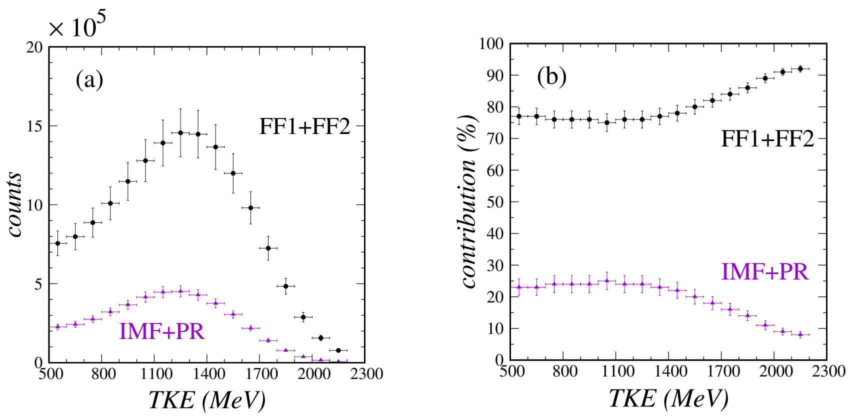

Fig. 2. (Color online) Panel (a): Yields of the PLF breakup and neck fragmentation processes as a function of TKE. Panel (b): Relative contributions of both processes. Data in both panels are corrected for detection efficiency. The vertical errors also include uncertainties in the efficiency estimations that are of the order of 10%.

TKE. Both curves in Fig. 2 (a) are very similar in shape. In the TKE region between 500 MeV and 1300 MeV, values of the respective ratios are increased by the same factor reaching a maximum for approximately the same TKE, and then both decrease to zero. The relative contributions of the two reaction channels are basically constant up to a TKE of around 1300 MeV (see Fig. 2 (b)). Above this energy, the contribution of the neck fragmentation process decreases as a result of the increasing impact parameter.

4. Summary

Our analysis confirms that the emission of heavy ($A > 7$) neck-originating fragments plays an important role in collisions of very heavy nuclear systems. The large contribution of this reaction channel shows that neck fragmentation can successfully compete with sequential processes and has to be taken into consideration in planning experiments aimed at production of new nuclides in projectile fission reactions.

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