Aligned breakup of heavy nuclear systems as a new type of deep inelastic collisions at small impact parameters

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An interesting process of violent reseparation of a heavy nuclear system into three or four fragments of comparable size was recently observed in ^{197}Au + ^{197}Au collisions at 15 MeV/nucleon. Combined analysis of the binary deep inelastic events and the ternary and quaternary breakup events demonstrates that the newly observed ternary and quaternary reactions belong to the same wide class of deep inelastic collisions as the conventional (binary) damped reactions. It is shown that the ternary and quaternary breakup reactions occur at extremely inelastic collisions corresponding to small impact parameters, while more peripheral collisions lead to well-known binary deep inelastic reactions.

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In a Letter [1], followed by a regular article [2], we reported on the observation of a new reaction mode in reseparation of a very heavy nuclear system in ^{197}Au + ^{197}Au collisions at 15 MeV/nucleon. In an exclusive-type experiment it was demonstrated that, in addition to the binary (deep inelastic) reaction mode, the colliding system shows a rather exotic process of violent reseparation into three or four massive fragments, nearly aligned along a common reseparation axis. From the systematic effect of the deflection of fragments from the reseparation axis, a very short time scale of the breakup process, not exceeding 100 fm/c, was estimated in Refs. [1] and [2].

In this Brief Report we focus our attention on the question of interpretation of the newly observed ternary and quaternary reactions as a new form of deep inelastic reactions (also called dissipative [3] or strongly damped [4] collisions). The experiment was carried out at the Laboratori Nazionali del Sud (LNS) in Catania. The beam of ^{197}Au ions from the LNS superconducting cyclotron, accelerated to the energy of 2900 MeV, bombarded a ^{197}Au target placed inside the Charged Heavy Ion Mass and Energy Resolving Array (CHIMERA). The CHIMERA multidetector, arranged in 4π geometry, is built of 1192 two-layer ΔE-E telescopes, each telescope consisting of a planar 300-μm silicon detector and a CsI(Tl) scintillator. By combining the energy and time-of-flight measurements, the masses of fragments stopped in the silicon detectors were determined. For more experimental details see Ref. [2].

By using the multidetector CHIMERA array, those events that were nearly completely detected could be kinematically reconstructed. It was found in the experiment that, neglecting emission of light particles (mostly nucleons and α particles, which were assumed to originate from secondary processes of de-excitation of much larger primary fragments), only binary, ternary, and quaternary partition reactions contributed significantly to the balance of the total cross section. As argued in Refs. [1] and [2], the reseparation of the colliding system essentially is binary; that is, two main fragments, a

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projectile-like fragment (PLF) and a targetlike fragment (TLF), are formed in the primary stage of the reaction. Depending on the impact parameter and total amount of excitation energy generated in a given collision, either (i) both the PLF and the TLF survive [binary reaction; Eq. (1)], or (ii) one of the primary fragments, the PLF or TLF, breaks up [ternary reaction; Eqs. (2) and (3)], or (iii) both the PLF and the TLF break up [quaternary reaction; Eq. (4)]:

$$^{197}\text{Au} + {}^{197}\text{Au} \rightarrow \text{TLF} + \text{PLF}; \quad (1)$$

$$^{197}\text{Au} + {}^{197}\text{Au} \rightarrow \text{TLF} + \text{PLF} \rightarrow \text{TLF} + \text{F1} + \text{F2}, \quad (2)$$

$$^{197}\text{Au} + {}^{197}\text{Au} \rightarrow \text{TLF} + \text{PLF} \rightarrow \text{PLF} + \text{F3} + \text{F4}; \quad (3)$$

$$^{197}\text{Au} + {}^{197}\text{Au} \rightarrow \text{TLF} + \text{PLF} \rightarrow \text{F1} + \text{F2} + \text{F3} + \text{F4}. \quad (4)$$

Detailed information on the binary reactions (1) detected exclusively, that is, under the condition of the presence of only two fragments in a given event, is given in Ref. [5]. Figure 1(a) shows the correlation between the kinetic energy of the final PLF + TLF system, $E_{\text{kin}}(\text{PLF} + \text{TLF})$, and the center-of-mass scattering angle $\Theta_{\text{c.m.}}(\text{PLF})$. This figure displays typical features of the deep-inelastic reactions, namely, a distinct peak in the cross section reflecting the dissipative scattering processes at so-called grazing trajectories, in which the nuclei collide nearly tangentially but the contact between them is close enough for the exchange of many nucleons, resulting in large inelasticity of the reaction [the peak in Fig. 1(a) is located at $E_{\text{kin}}(\text{PLF} + \text{TLF}) \approx 1350$ MeV and grazing angle $\Theta_{\text{graz}} \approx 25^\circ$]. The energy of the grazing peak corresponds to the total kinetic energy loss $E_{\text{TKEL}} \approx 100$ MeV, but events with a much larger inelasticity are shown in Fig. 1(a) distributed down to the limit of completely damped binary reseparation processes at $E_{\text{kin}}(\text{PLF} + \text{TLF}) \approx 400$ MeV (for approximately symmetric divisions). The ridge extending from the grazing peak down to the completely damped events can be interpreted as a manifestation of the trajectories for the intermediate range of semiperipheral collisions at impact parameters smaller than that for the grazing peak. This is a standard interpretation of the deep-inelastic reactions based on the energy-angle correlation plots (Wilczynski diagrams [6]) and classical dissipative trajectory calculations (see, e.g., Ref. [7]).

Energy-angle correlation plots, analogous to Fig. 1(a) for binary reactions, are shown in Figs. 1(b) and 1(c) for the ternary and quaternary partitioning processes investigated in Refs. [1] and [2]. In the case of the ternary partitioning, Eq. (2), in which the PLF breaks up into two fragments (F1 and F2) of comparable size, the velocity vector of the PLF was reconstructed, event by event, from velocity vectors of the two fastest fragments F1 and F2. Thus, for each such ternary event the kinetic energy $E_{\text{kin}}(\text{PLF} + \text{TLF})$ of the primary PLF + TLF system was determined similarly as for the binary reactions. The Wilczynski diagram for these ternary events [Fig. 1(b)] shows that the ternary-reaction peak is located in the energy-angle space at $E_{\text{kin}}(\text{PLF} + \text{TLF}) \approx 1050$ MeV and $\Theta_{\text{c.m.}} \approx 25^\circ$, that is, exactly below the peak for binary events in Fig. 1(a), along the common ridge of the distribution of events in the energy-angle space.

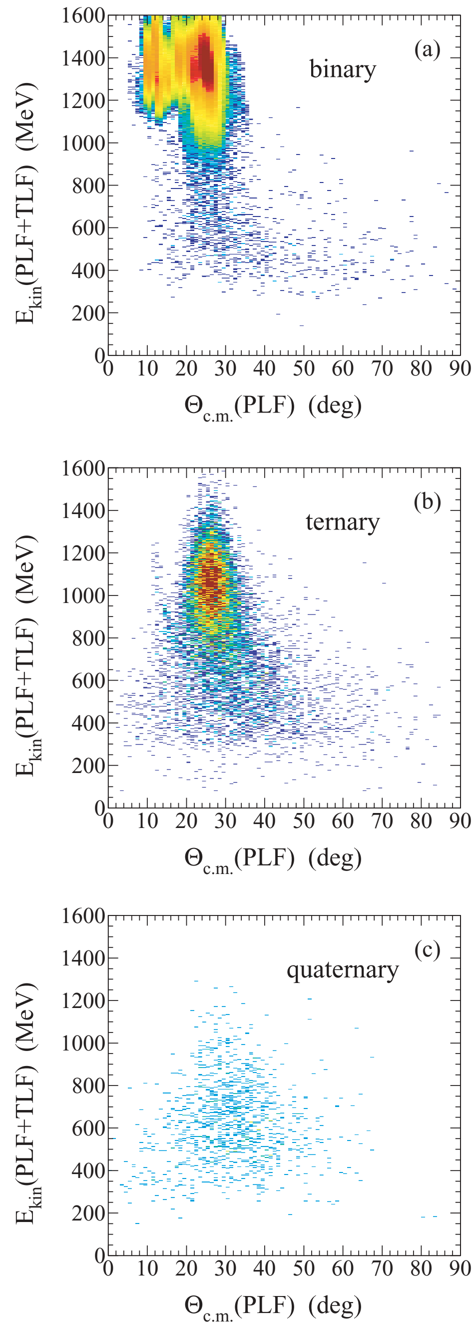

FIG. 1. (Color online) Energy-angle correlation plots for binary (a), ternary (b), and quaternary (c) reactions. The kinetic energy of the final PLF + TLF system, $E_{\text{kin}}(\text{PLF} + \text{TLF})$, was calculated for ternary and quaternary reseparation processes in a way equivalent to that for binary reseparation reactions in which the PLF and TLF do not break up: $E_{\text{kin}}(\text{PLF} + \text{TLF})$ is the kinetic energy of the relative motion of the centers of mass of the PLF and TLF.

Also, the quaternary partitioning processes, Eq. (4), in which both the PLF and the TLF undergo a similar fast breakup, seem to follow the common pattern of the energy-angle correlation. For quaternary events, the velocity vector of the primary fragment PLF was reconstructed from velocity vectors of two fastest fragments F1 and F2, while the velocity vector of the TLF was reconstructed from velocity vectors of

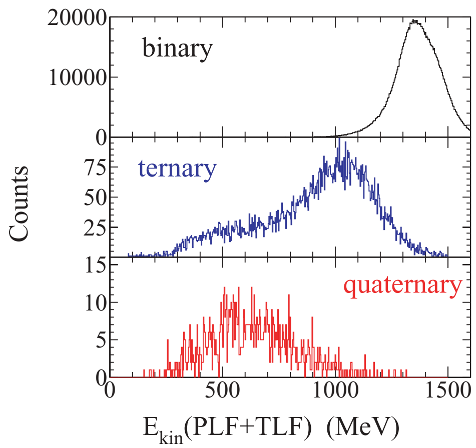

FIG. 2. (Color online) Distributions of the total kinetic energy $E_{\text{kin}}(\text{PLF} + \text{TLF})$ for the binary, ternary, and quaternary reseparation processes.

the slowest fragments F3 and F4. (For details see Ref. [2].) The kinetic energy of the primary PLF + TLF system could then be determined in the same way as for binary and ternary reactions. From Fig. 1(c) we can see that the quaternary events coincide in the energy-angle space with the most inelastic part of the binary deep-inelastic events shown in Fig. 1(a).

Comparison of the Wilczynski diagrams for the binary, ternary, and quaternary reactions shows that all these partitioning processes are located in adjacent regions of a common deep-inelastic area in the energy-angle space. This may suggest that they originate from the adjacent portions of the classical dissipative deflection function. Therefore we can attribute the binary, ternary, and quaternary reactions to a common class of the deep-inelastic reactions taking place at successively decreasing impact parameters.

Figure 2 shows one-dimensional projections of the distributions in Fig. 1 representing the total kinetic energy spectra for all three reseparation modes. It is shown that the maxima are located at $E_{\text{kin}}(\text{PLF} + \text{TLF}) \approx 1350$, 1050, and 650 MeV for binary, ternary, and quaternary reactions, respectively. The corresponding values of the total kinetic energy loss, E_{TKEL}, are equal to about 100, 400, and 800 MeV, respectively. To link the observed energy losses to the impact parameters, we carried out calculations using the classical dynamical model HICOL of Feldmeier [7] based on one-body dissipation dynamics. This code has been widely used for analysis of deep-inelastic reactions at low energies and was found to satisfactorily reproduce the kinetic energy losses and rotational energies generated in these reactions.

The calculated relation between the impact parameter b and the final kinetic energy $E_{\text{kin}}(\text{PLF} + \text{TLF})$ of the PLF + TLF system is shown in Fig. 3. According to this theoretical "calibration curve" the maxima of the cross section for the binary, ternary, and quaternary reactions [located at $E_{\text{kin}}(\text{PLF} + \text{TLF}) = 1350$, 1050, and 650 MeV, respectively] can be attributed to the collisions at impact parameter b equal to about 10.5, 9.4, and 7.3 fm, respectively.

The information obtained from the HICOL code is limited to the binary stage of the reaction. In Refs. [1] and [2] we

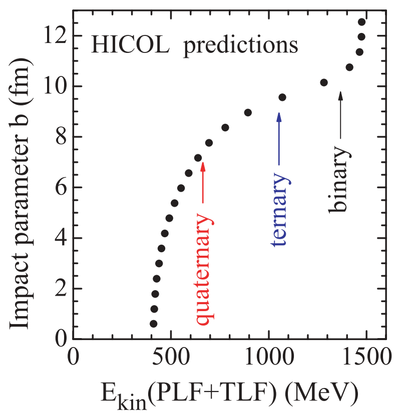

FIG. 3. (Color online) Correlation between the impact parameter and the total kinetic energy $E_{\text{kin}}(\text{PLF} + \text{TLF})$ calculated with the classical one-body dissipation model HICOL of Feldmeier [7]. Filled circles correspond to consecutive values of the angular momentum L taken in the range from $L = 50\,\hbar$ to $L = 1050\,\hbar$, at 50-$\hbar$ steps. Positions of maxima of the experimental energy spectra for binary, ternary, and quaternary reactions (see Fig. 2) are indicated by arrows.

presented comparisons of the observed ternary and quaternary reactions with predictions of the quantum molecular dynamics (QMD) model of Łukasik [8], which predicts the phenomenon of the dynamical breakup of the PLF and/or TLF into fragments of comparable masses, although it fails to reproduce the very short time scale of the breakup processes. The QMD simulation gives its own calibration of the relation between the total kinetic energy loss and the impact parameter, and additionally, it directly predicts the theoretical localization of the binary, ternary, and quaternary reactions in the energy-impact parameter space.

In Fig. 4 we show the correlation between the impact parameter b and the total kinetic energy $E_{\text{kin}}(\text{PLF} + \text{TLF})$ obtained for the set of theoretical events generated with the QMD code [8] for the binary, ternary, and quaternary reactions

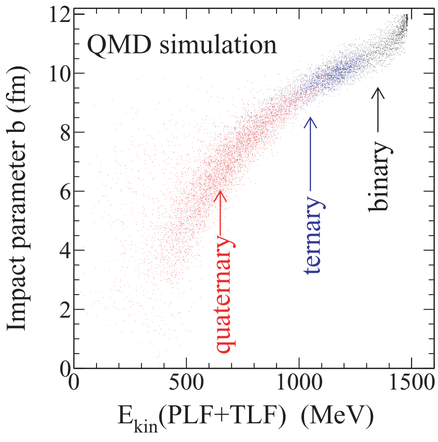

FIG. 4. (Color online) Correlation between the impact parameter and the total kinetic energy $E_{\text{kin}}(\text{PLF} + \text{TLF})$ simulated with the QMD model of Łukasik [8]. Positions of maxima of the experimental energy spectra for binary, ternary, and quaternary reactions (see Fig. 2) are indicated by arrows.

in the studied ^{197}Au + ^{197}Au collisions. For these theoretical events the same selection gates on the fragments' momenta and mass numbers as in the experiment were assumed. Depending on the type of given event (binary, ternary, or quaternary), the points representing these events are shown in different colors in Fig. 4. Figure 4 shows that the binary, ternary, and quaternary events are concentrated in different regions along the energy-impact parameter correlation curve. It is thus obvious from viewing this scatterplot that the ternary and quaternary reactions belong to the same wide class of deep-inelastic collisions as the conventional (binary) damped reactions. It is only the question of the impact parameter and the resulting excitation energy that differentiates these reactions and determines which reseparation mode actually takes place.

In view of the energy-impact parameter classical dependence shown in Fig. 3 and the same dependence resulting from the QMD calculations presented in Fig. 4, we can conclude that the binary, ternary, and quaternary reactions with the energy spectra as shown in Fig. 2 indeed belong to a common class of deep-inelastic reactions showing different reseparation modes at different ranges of the impact parameter and inelasticity: binary reactions occur mostly in nearly peripheral collisions ($b \approx 10.5$ fm), while ternary and quaternary partitioning reactions take place in semiperipheral collisions at $b \approx 9.5$ and 7 fm, respectively.

The localization of the ternary and quaternary partitioning processes at small impact parameters probably explains why these fast (collinear) breakup reactions were not clearly observed in earlier studies of deep-inelastic reactions. Simply, in reactions of typical colliding systems (usually lighter than Au + Au), such close collisions at small impact parameters must lead to fusion. Only in collisions of the heaviest systems, such as ^{197}Au + ^{197}Au, when the complete fusion processes are eliminated, can the final stage of these very inelastic collisions manifest itself in the form of exotic ternary and quaternary collinear partitioning processes.

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