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Ternary and quaternary re-separation of heavy colliding systems

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PoS(Bormio 2011)059

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Collisions of two very heavy nuclei, ^{197}Au + ^{197}Au, were studied at a beam energy of 15 MeV/nucleon. Such a heavy system cannot fuse and form a compound nucleus. Therefore main re-separation modes of the colliding system can be studied in a wide range of impact parameters: in near-central as well as semi-peripheral collisions. The experiment was carried out at the Laboratori Nazionali del Sud in Catania. The ^{197}Au beam was accelerated to the energy of 15 MeV/nucleon with the LNS Super-Conducting Cyclotron and bombarded a 273 mg/cm^2 – thick ^{197}Au target, placed inside the Charge Heavy Ion Mass and Energy Resolving Array (CHIMERA). A new reaction mechanism of fast collinear ternary and quaternary fast breakup processes has been observed. Results show that these ternary and quaternary reactions occur at extremely deep-inelastic collisions corresponding to small values of the impact parameter.

XLIX International Winter Meeting on Nuclear Physics- BORMIO2011
Bormio, Italy
January 24–28 2011

 http://pos.sissa.it

PoS(Bormio 2011)059

In Ref. [1] we reported results of an experiment in which ^{197}Au + ^{197}Au collisions were studied at 15 MeV/nucleon and a new reaction mechanism of fast, almost collinear breakup of this very heavy nuclear system into three and/or four fragments of comparable size was observed. In further analysis [2], [3], it was shown that these *ternary* and *quaternary* breakup reactions represent an unknown yet form of deep-inelastic reactions which occur in rather unexplored range of close contact collisions at small values of impact parameter, while more peripheral collisions lead to well known *binary* deep-inelastic reactions.

As shown in [1], [2], the re-separation of the colliding system is essentially binary in the first stage of reaction when two main fragments, a projectile-like fragment, PLF, and a target-like fragment, TLF, are formed after the collision. Depending on the impact parameter and total amount of excitation energy generated in a given collision either (i) both PLF and TLF survive (binary reaction), or (ii) one of the primary fragments, either PLF or TLF, breaks up (ternary reaction), or (iii) both, PLF and TLF break up (quaternary reaction):

$$^{197}\mathrm{Au} + {}^{197}\mathrm{Au} \rightarrow \mathrm{TLF} + \mathrm{PLF} \tag{1}$$

$$^{197}\mathrm{Au} + {}^{197}\mathrm{Au} \rightarrow \mathrm{TLF} + \mathrm{PLF} \rightarrow \mathrm{TLF} + \mathrm{F1} + \mathrm{F2} \tag{2}$$

$$^{197}\mathrm{Au} + {}^{197}\mathrm{Au} \rightarrow \mathrm{TLF} + \mathrm{PLF} \rightarrow \mathrm{F1} + \mathrm{F2} + \mathrm{F3} + \mathrm{F4} \tag{3}$$

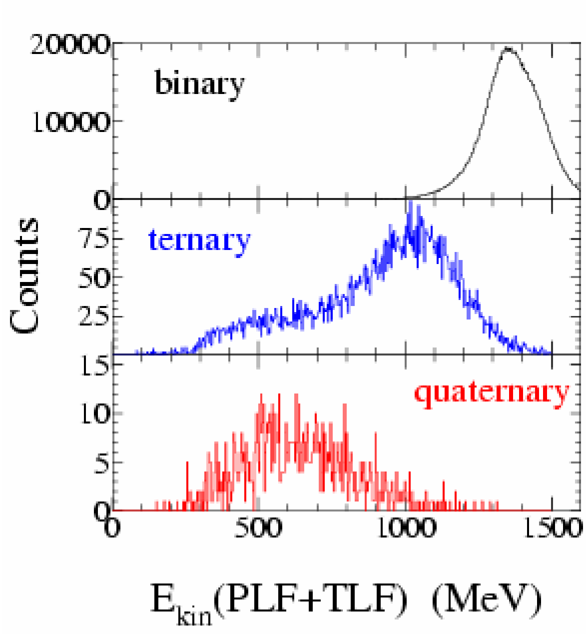

Fig. 1 Total kinetic energy spectra of fragments for binary (top), ternary (middle) and quaternary (bottom) reactions. For ternary and quaternary reactions E_{kin}(PLF+TLF) is determined as the kinetic energy of the *primary* PLF+TLF system. The velocity vector of PLF

was reconstructed, event by event, from velocity vectors of two fastest fragments F1 and F2. For quaternary reactions, the velocity vectors of the primary fragments PLF and TLF were reconstructed from velocities of two fastest fragments (F1 and F2) and two slowest fragments (F3 and F4), respectively.

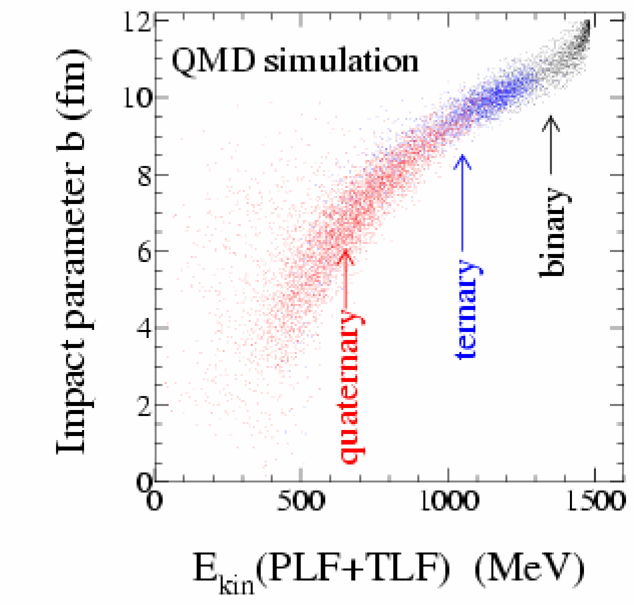

Fig. 2 Correlation between the total kinetic energy and impact parameter for binary, ternary and quaternary reactions in $^{197}Au + {}^{197}Au$ collisions at 15 MeV/nucleon, simulated with the QMD model of Łukasik [4]. Points representing binary, ternary and quaternary events are marked with different colors: black, blue and pink, respectively. This correlation can be used to calibrate the observed inelasticity of the reaction as a measure of the impact parameter.

Distributions of the total kinetic energy of the primary TLF+PLF system in binary, ternary and quaternary reactions (1), (2), (3) are shown in Fig. 1. From the measured inelasticity, one can infer the localization of a given reaction in the impact parameter space, by using, for example, predictions of the Quantum Molecular Dynamics (QMD) model [4] to calibrate the correlation between E_{kin}(PLF+TLF) and impact parameter, see Fig. 2.

The deduced distinct localization of different re-separation modes in the impact parameter space suggests that the observed fast ternary and quaternary breakup reactions can be viewed as a natural extension of typical (binary) deep-inelastic collisions to the region of very small impact parameters and very large inelasticity.

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