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Neck Formation and Decay in Pb + Au Collisions at 29 MeV/u*

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Three fragment production has been studied in peripheral $^{208}\text{Pb} + ^{197}\text{Au}$ collisions at 29 MeV/u. The data suggests the formation and subsequent decay of necklike structures producing a small fragment emitted at mid-rapidity in between the two partners of a deep inelastic scattering. This process is however in competition with a more probable one in which the neck is absorbed by one of the reactants, this latter decaying further by binary fission.

* Experiment performed at GANIL

Peripheral reactions between heavy nuclei at moderate incident energies (less than 20 MeV/u) are dominated by deep inelastic scattering: a process in which a large amount of the kinetic energy is transformed into heat but in which the identity (mass and charge) of the two incoming partners remain approximately conserved at the end of the interaction until they decay by particle evaporation or fragment emission (see e.g. (1)). Such a reaction mechanism has been shown to be still dominant when the incident energy increases towards the Fermi energy although a strong evolution of the decay modes of the excited species formed in the reaction is observed in this energy range (2). By contrast, nuclear collisions in the relativistic regime are known to be mostly governed by geometrical concepts (see e.g. (3)). This leads to the formation of the so-called participant zone (also named "fireball") formed in the region corresponding to the geometrical overlap of the two nuclei. In addition, two nuclei which are less excited are formed: the "spectators". The "fireball" characteristics allows to study very hot and compressed hadronic matter (4) (including particle production) while "spectators" decay give usefull information on the fate of hot nuclei (5).

The situation is more complicated around and slightly above the Fermi energy. The study of light particle emission pattern reveals an important non-equilibrated contribution which is compatible with a source located at the nucleon-nucleon rapidity (6). This is an indication that violent processes set in at the overlap of the two nuclei. Concerning fragment production, similar trends are observed both for inclusive (7) or exclusive data (8,9). Recently, evidence for the decay of necklike structures has been claimed after analysing kinematical correlations between two detected fragments for the system Xe+ Cu at 50 MeV/u. (10).

In the present work, we concentrate on the study of triple coincidences among fragments emitted in Pb+Au collisions at 29 MeV/u. The analysis is however restricted to events in which at least 80% of total charge and total linear momentum were recorded. A detailed description of the experimental conditions can be found elsewhere (2). The double constraint of conservation of charge and total linear momentum is not sufficient to separate completely true "3-body" events from "incomplete" events in which four fragments were emitted but only three of them were detected and one intermediate mass fragment ($Z < 20$) was missed. We have used a procedure similar to the one described in (11) to estimate on the basis of kinematics the background due to "incomplete" events. To this end, the transverse component V_t of the recoil velocity defined as the mass-averaged sum of the velocities of the detected fragments has been studied. A random exclusion of one fragment in the measured 4-body events has been performed. The remaining 3 fragments are analyzed in the same manner as the measured 3-body events. The two

corresponding distributions of V_t are displayed in Fig. 1 for three different windows of ϵ^* , the excitation energy per nucleon. This latter quantity has been obtained with the same method described in (2). Due to the evaporation of light particles (not taken into account to estimate V_t) the distributions are not peaked at zero and the deviation is stronger and stronger as ϵ^* increases. The dashed histograms in Fig.1 are the contributions of the “incomplete” events. They have been normalized with one single factor for the three panels. They are responsible for the tails observed at large V_t . In the following, all experimental spectra have been estimated both for “true” and “incomplete” events and a systematic background subtraction due to “incomplete” events has been performed.

In the energy range considered in this paper, ternary events mainly originate from deep inelastic scattering followed by binary fission of one of the two partners. To explore quantitatively such a scenario, the experimental relative velocity between fragments (labelled i and j) has been compared with the expectation value suggested by the systematics (12):

$$V_{ij} = \left(\frac{2E_{ij}^c}{\mu_{ij}} \right)^{1/2} \quad (1)$$

$$E_{ij}^c \text{ (MeV)} = .1189 \left(\frac{Z^2}{A^{1/3}} \right) + 7.3 \quad (2)$$

with $A=A_i+A_j$, $Z=Z_i+Z_j$, $\mu_{ij}=m_0 A_i A_j / (A_i+A_j)$. The mass numbers A_i have been estimated assuming fragments along the beta stability line (m_0 is the free nucleon mass). Event by event and for each possible pair of fragments, the difference Δ_{ij} between the measured relative velocity and the expectation value is estimated. Thus, three Δ_{ij} -values are calculated per event. They are displayed in Fig. 2a. The distribution shows two components. The peak at $\Delta_{ij}=0$ is a strong indication for a Coulomb repulsion between two of the three detected fragments. This is corroborated by the fact that more than one third of the Δ_{ij} -values (at least one pair per event) are less than 1 cm/ns. For each event, we associate the lowest Δ_{ij} -value with a pair of fragments labelled respectively 1 and 2. In the rest frame of this pair, we define θ_{i3} ($i=1, 2$) the angle of the velocity vector of fragment i with respect to the velocity of the third fragment labelled 3 as illustrated in Fig. 2b. The correlation between the atomic number Z_i and the associated angle θ_{i3} is plotted in Fig. 2c. As already observed in $^{129}\text{Xe} + ^{122}\text{Sn}$ collisions at 12.5 MeV/n (13), the lighter fragment (labelled 1) is emitted preferentially in the direction of the third fragment (corresponding to positive values of $\cos \theta_{i3}$). Moreover, when the lighter fragment is

an intermediate-mass fragment ($Z_1 < 20$), we observe a focussing at $\cos \theta_{13} \simeq 1$ indicating that the three fragments are located along a single axis ($\theta_{13} + \theta_{23} = 180^\circ$).

In the following, we consider two classes of events separated by the square delimited by $Z_1 < 20$ and $\cos \theta_{13} < 0.8$ in Fig. 2c. The events located inside the square are denoted events of class I while the others are denoted events of class II. The three relative velocity distributions for events of class I are displayed in Fig. 3a. The distributions of the pairs (1, 2) and (1, 3) are both centered close to a value of 3.5 cm/ns. This value is in agreement with the systematics (formula 1) and suggests a process schematically depicted in Fig 3g. Two large fragments with masses close to those of the projectile and target move away after the collision with a large relative velocity leaving behind them a small fragment emitted at rest in the center-of-mass frame. Such a picture suggests the formation of a neck in between the two interacting nuclei and its subsequent decay due to Rayleigh instabilities: the neck is stretched and elongated as the two nuclei fly apart, then the density drops down and the ratio of the surface over the volume increases strongly leading to neck rupture (14).

Possible distortions induced by the limitations of the experimental apparatus have been investigated with help of simulations. These latter consist in generating a new set of events starting from the real ones by applying a random rotation to the two fragments labelled 1 and 2 in their own rest frame. After filtering these new events to take into account the dead zones of the experimental device, a comparison between simulated and real events was possible. We found no significant difference and concluded that the distributions were not biased by the experimental set-up.

Events of class II corresponds to 90 % of the 3-body events. For those events, a break-up of the pair (1, 2) is observed with a relative velocity peaked at 2.4 cm/ns (Fig 3b). This is in agreement with the expectation value for the symmetric splitting of a nucleus with mass number around 200. Therefore, it can be concluded that these events result from a deep inelastic scattering followed by symmetric binary fission of one of the two partners as depicted in Fig. 3h. One should also note a (small) dependance of the relative velocity of the fission fragments with fragment 3 as a function of the mass.

In Fig.3c and Fig.3d, we examine the mean atomic number of each fragment as a function of ϵ^* for the two classes of events. For events of class I, $\langle Z_1 \rangle$ (the atomic number of the fragment emitted by the neck) remains small at a value around 10 with a small increase as a function of ϵ^* . This value is close to the threshold of the detector and thus constitutes only an upper limit: smaller fragment not detected in this experiment may also originate from the neck. Concerning $\langle Z_2 \rangle$ and $\langle Z_3 \rangle$, their values are, as expected, comparable since the system is almost symmetric. A monotonic decrease is observed when ϵ^* increases due to light particle evaporation. Events of class II are displayed in Fig.3d. The evolution of $\langle Z_3 \rangle$ is comparable with

the one for events of class I: this is expected since the characteristics of fragment 3 does not depend on the particular class of events. By contrast, $\langle Z_1 \rangle$ and $\langle Z_2 \rangle$ are equal (not shown in the figure) at variance with events of class I. However, the sum $\langle Z_1 + Z_2 \rangle$ is comparable in both cases and decreases slowly as a function of ϵ^* . A possible interpretation is that the neck may fuse either with the projectile-like or with the target-like. In this case, the charge and hence the fissility of the nucleus which absorbs the neck increase. Therefore, the fission probability is strongly enhanced leading to three fragment configuration in the final state.

This finding is supported semi-quantitatively by classical trajectories calculations (2) if one assumes that the overlap region between the two interacting nuclei fuses with one of the two partners in the exit channel. For each impact parameter, we compute the excitation energy and the kinematical characteristics of the projectile-like and the target-like nuclei. The de-excitation is treated using a simplified evaporation model (15). Within this simple picture, the charges of the two primary partners are roughly reproduced (solid lines in Fig. 3d).

Last, we examine the dependance of neck formation with the excitation energy ϵ^* and the impact parameter. The most probable ϵ^* for the formation of the neck is around 2 MeV/u (see fig. 3e) while the process depicted in fig. 3h is the most probable at moderate ϵ^* although it is present in the whole range of available excitation energy (see fig. 3f). The simple model used in (2) suggests a corresponding impact parameter value around 12 fm for the formation of neck-like structures. Such a value is compatible with the one found in calculations based on semi-classical approaches (16).

To conclude, we have studied triple coincidences among fragments produced in $^{208}\text{Pb} + ^{197}\text{Au}$ interactions at 29 MeV/n. A selection based on both the total detected charge and the total measured linear momentum has been used. In addition, a background subtraction deduced from the analysis of "incomplete" events has been performed. By analysing the relative velocities between the three detected fragments, two different classes of events have been observed. The first class shows evidence for the formation and the decay of a neck in peripheral collisions ($\epsilon^* \simeq 2$ MeV/n and impact parameter around 12 fm). This process consists in the emission of a small fragment at mid-rapidity along an axis connecting the projectile-like and the target-like nuclei. The measured probability for such a process is relatively small but this may be due to the threshold on charge detection ($Z > 8$ for full efficiency). Last, a second class of events shows the formation of an elongated di-nuclear system leading to the fusion of the neck with either the target-like or the projectile-like nucleus. This first stage is followed by the binary fission of the nucleus which has absorbed the neck.

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FIGURE CAPTIONS

Fig. 1 : Distribution of the transverse component V_t of the recoil velocity for three windows in excitation energy per nucleon ϵ^* . The black points are for 3-body events, the dashed histogram is the contribution of the “incomplete” events (see text).

Fig. 2 : a) Distribution of $\Delta_{ij} = |v_{rel}^v - v_{rel}^{exp}|$ in cm/ns.
b) Schematic picture of the three-body decay with notations used in the text.
c) Contour plot of the atomic number Z_i versus $\cos \theta_{i3}$ ($i = 1, 2$). Events in the square located at $\cos \theta_{i3} > .8$ and $Z_i > 20$ correspond to the emission of a small fragment labelled 1 in the direction of fragment labelled 3.

Fig. 3 : a) and b) Relative velocities between the fragments taken two by two. Each curve is labelled according to the considered pair of fragments.

c) and d) Mean atomic number Z vs excitation energy per nucleon ϵ^* . The solid lines in panel d) is the result of a calculation described in the text in which the neck is absorbed by one of the reactants.

e) and f) Excitation energy distribution of the events according to their class. In fig f, black points correspond to target-like fission while open points correspond to projectile-like fission.

g) and h) Schematic representation of the two different processes leading to 3-body final state studied in this paper. Fragments have been labelled according to a convention explained in the text.

All figures in the left panel correspond to events leading to the formation and decay of a neck (events of class I) while figures in the right panel refer to events of class II (see text)

Fig 1. "Neck formation and decay..." by JF Leal et al

Fig 2: "Neck formation and decay..." by J. J. Gooding et al.

Fig 3 "Neutrino formation and decay ..." by JF de Boer et al