BB

LP CAEN

LABORATOIRE DE PHYSIQUE CORPUSCULAIRE

ISMRA - Boulevard Maréchal Juin - 14050 CAEN CEDEX - FRANCE

SCAN-9601210

CERN LIBRARIES, GENEVA

Reaction mechanism in highly fragmented Pb+Au collisions at 29 MeV/u

J. F. Lecomte, D. Durand, M. Aboufirassi, R. Bougault,
J. Colin, A. Genoux-Lubain, C. Le Brun, O. Lopez,
M. Louvel, C. Meslin, G. Rudolf, L. Stuttgé, S. Tomasevic

5096 06

January 1996

LPCC 96-01

Submitted to Physics Letters

INSTITUT NATIONAL
DE PHYSIQUE NUCLEAIRE ET DE PHYSIQUE DES PARTICULES
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

INSTITUT DES SCIENCES
DE LA MATIERE ET DU RAYONNEMENT

UNIVERSITÉ DE CAEN

Téléphone : 31 45 25 00
Télécopie : 31 45 25 49

REACTION MECHANISM IN HIGHLY FRAGMENTED PB+AU COLLISIONS AT 29 MeV/u

J.F. Lecomte^{a)}, D. Durand^{a)}, M. Aboufirassi^{a)}, R. Bougault^{a)}, J. Colin^{a)},
A. Genoux-Lubain^{a)}, C. Le Brun^{a)}, O. Lopez^{a)}, M. Louvel^{a)}, C. Meslin^{a)},
G. Rudolf^{b)}, L. Stuttgé^{b)}, S. Tomasevic^{b)}

*a) Laboratoire de Physique Corpusculaire, ISMRA and Université de Caen
IN2P3-CNRS 14050 CAEN CEDEX, France*

*b) Centre de Recherches Nucléaires, IN2P3-CNRS, Université Louis Pasteur,
B.P. 20 67037 STRASBOURG CEDEX, France*

Abstract

Events in which at least 5 fragments with charge larger than 8 were emitted in dissipative Pb+Au collisions at 29 MeV/u incident energy are studied. An event by event shape analysis is performed and a prescription is proposed to select the most central collisions. For these latter, evidence for the formation (with a very small cross-section) of a long-lived single source is shown by analysing light charged particle patterns and by confronting experimental space-time correlations between fragments with the results of computer simulations.

The reaction mechanisms of very heavy ion collisions (total mass number of the order of 350-400 units) below 20 MeV/u have been studied for a long time (e.g. Refs¹⁾ and ²⁾ and references therein). In this energy range, the main mechanism is the deep inelastic scattering even in the most central collisions mainly because the Coulomb repulsion between the two partners is strong enough to prevent the system to fuse. Recently, the study of such systems has been undertaken around the Fermi energy domain (say between 20 and 50 MeV/u)³⁻⁷⁾. There again, it was shown that most of the cross-section is associated with binary collisions³⁻⁶⁾. However, deviations from this scenario are observed for intermediate impact parameters. These deviations are related to "neck" emissions⁸⁻¹²⁾. In this paper, we are concerned with Pb+Au collisions at 29 MeV/u. Our aim is to select the most central highly fragmented collisions on the basis of a new event-by-event analysis.

The experiment was performed at the Ganil facility in the Nautilus scattering chamber. The data were obtained by bombarding Au targets with Pb projectiles at 29 MeV/u incident energy. Fragments (with atomic numbers larger than 8) were detected in Delf¹³⁾ and XYZT¹⁴⁾. These two detectors constitute an ensemble of 30 position sensitive parallel-plate avalanche counters, each followed by an ionisation chamber. The angular coverage was 3-150 degrees with a geometrical acceptance of 55%. Full detection efficiency for atomic numbers equal to or larger than eight was obtained. The set-up had a low velocity threshold: .5 cm/ns (.13 MeV/u) for Delf and 2 cm/ns (2.07 MeV/u) for XYZT in the forward direction. The measured parameters were the atomic number, Z (with a resolution of about 10%), the fragment velocity, V, and the emission angle with a resolution better than one degree. Light charged particles (hereafter called LCP) were detected in the Mur¹⁵⁾+Tonneau¹⁶⁾ ensemble. These detectors have an angular coverage of 3-150 degrees but since they are located behind the fragment detectors, the overall geometrical efficiency due to shadows is around 50%. The LCP'S are localized and identified in charge by measuring the time of flight and the energy losses. The thresholds are around 2.5 MeV/u and the angular resolution of a few degrees.

Some aspects of Pb+Au dissipative collisions at 29 MeV/u have already been discussed in previous papers:

- the dissipated energy can be very large and values corresponding to nearly full damping are observed with a sizeable cross-section¹⁷⁾.

- various decay channels (evaporation, binary fission, multifragmentation) compete strongly as a function of the excitation energy deposited in the system¹⁸⁾. For the largest dissipation, a complete disassembly of the system is observed and the corresponding temperatures can reach values as large as 8 MeV^{19,20)}.

- for semi-peripheral collisions, the formation and decay of neck-like structures

can occur with a sizeable probability¹²⁾.

- most of the total cross-section corresponds to collisions that remain essentially binary in the sense that no compound nucleus formation is observed¹⁷⁾.

However, we will show in the following, with help of a new more precise selection of very central collisions, that a transient very heavy compound is created with a small cross section of the order of a few mbarns. The decay mode of this compound will be analyzed in a next paper²¹⁾. Our first aim is thus to select the most central collisions. To this end, events are analysed with help of an event shape analysis. This method consists in building the kinetic energy flow tensor considering all fragments emitted in the collision¹⁷⁾ defined as:

$$F_{ij} = \sum_{v=1}^N \gamma_i \cdot p_i^{(v)} \cdot p_j^{(v)} \quad (1)$$

in which p_i is the momentum of fragment i and $\gamma_i = 1/2m_i$ (m_i is the mass of fragment i). By diagonalizing this tensor, three eigen-vectors (λ_i , $i=1,3$) are obtained specifying the shape of the so-called ellipsoid as well as its orientation in space. These quantites can be normalized to their sum and ordered such that $\lambda_1 > \lambda_2 > \lambda_3$. The angle between the beam axis and the largest eigen-vector is called θ_{CM} :

$$\cos(\theta_{CM}) = \bar{\lambda}_1 \cdot \bar{z} \quad (2)$$

in which z is the beam axis. This angle is a measure of the orbiting of the system and is thus related to the violence of the collision. In addition, two variables characterizing the shape of the ellipsoid can be defined by combining the moduli of the three eigen-vectors. These are respectively the sphericity S and the coplanarity C :

$$S = \frac{3}{2}(1 - \lambda_1) \quad (3)$$

$$C = \frac{\sqrt{3}}{2}(\lambda_2 - \lambda_3) \quad (4)$$

Last, we define the TKE variable as the sum of the kinetic energies of all emitted fragments in the collision. By correlating θ_{CM} and TKE, we obtain the so-called Wilczynski plot displayed in fig. 1. We recall that this plot has been obtained by considering events in which at least 5 fragments were detected. The trend of the plot is very similar to the one observed at much lower incident energies²²⁾. However, the most peripheral collisions (those corresponding to the largest TKE values) are not much populated because, in this TKE range, the main decay mode is not fragmentation but rather binary fission of each partner of the collision thus leading to

4 fragments in the final state ("double fission" events).

In the following, we have divided the Wilczynski plot into five different regions labelled from 1 to 5 according to the centrality of the collision. The reason why we made such cuts is suggested by the fact that the θ_{CM} distribution (not shown here) displays a strong decrease from 10 degrees up to 60 degrees and then stays roughly constant up to 90 degrees. This fact may be due to a change in the reaction mechanism: superimposed on the θ_{CM} distribution associated with deep inelastic scattering, there is a (very) small contribution associated with fusion or at least incomplete fusion for which θ_{CM} is randomly distributed over the whole angular range. This contribution is masked at low θ_{CM} and can only be observed at large angles where the deep inelastic contribution has vanished. For each region, the corresponding Sphericity (S)-Coplanarity (C) plot has been displayed (in the first window, the loci of three typical configurations (rod, disk and sphere) have been recalled). In region 1, the C-S plot exhibits very elongated shapes corresponding to the decay of two well separated sources in space-time. Then, as the centrality of the collision is increased, shapes become more and more compact.

The measured cross-sections for events with 5 fragments (not corrected for efficiency) are respectively 4.4, 1.1 and .2 mbarns for regions 3, 4, 5. A rough estimation of the efficiency gives correction factor of the order of 5. As previously mentioned, for angles larger than 60 degrees, the θ_{CM} distribution is flat suggesting the onset of fusion-like processes. We now address this question of the formation of a long-lived compound system by discussing the characteristics of LCP's emitted in coincidence with the fragments. To this end, the invariant cross-section plots $V_{par}-V_{per}$ are displayed in fig. 2 together with those for fragments (for LCP's, the plots have been symmetrized). The velocities have been calculated in the ellipsoid frame deduced from the shape analysis discussed previously. We find some very interesting features. Concerning the fragments, we observe qualitatively the trends already guessed from the event shape. In region 3, there is no isotropy in the fragment emission although the dissipated energy is very large and correspond to fully damped collisions. The situation evolves gradually from region 3 to region 5 in which the pattern becomes symmetrical. The same conclusions hold when examining the corresponding LCP patterns. They evolve from an elongated shape towards an isotropic configuration. In order to check whether cuts in the TKE- θ_{CM} correlation constitutes a good centrality selection, we show in table I the corresponding $Z=1, 2$ multiplicities. These numbers are not corrected for detector efficiency: the correcting factor should be roughly 2 to account for dead zones induced by the fragment detectors. There is an increase in the multiplicities as far as TKE decreases but for the last three regions associated with full damping, no more evolution is observed. This remarkable fact tells us that the LCP multiplicity cuts are not a good criterion to select properly central collisions in the

sense that different event shapes are present for the same LCP multiplicity range.

In the following, the evolution from region 3 to region 5 is analysed in terms of time-scales. In region 3, the orbiting of the system is very small suggesting that the interaction time is rather short before the two partners eventually re-separate. Although these collisions are very dissipative, these are not the most central ones. If the interaction time is shorter than the time needed for the hot nuclei to disassemble, the fragmentation patterns exhibit two separated sources²³⁾. In region 5, the interaction time is longer, and therefore the system breaks before re-separation of the two partners thus displaying a single source pattern. In order to check this assumption quantitatively, we now compare our data with the results of computer simulations.

Our model is based on the ideas and assumptions developed in²⁴⁾ and constituting the so-called WIX model. However, some new features have been taken into account to deal with very heavy systems and various shape configurations. Indeed, it appears that WIX was not able to reproduce the charge distribution of our events so that we decided to generate the mass partition by a more simple ad-hoc procedure. The fragment multiplicity is chosen in order to get a good agreement with the experimental multiplicity distribution once the detector acceptance is taken into account. Partitions were thus chosen at random. It turned out that this simple recipe was enough to reproduce rather accurately the experimental Z-distribution. Our model allows to "prepare" the system in various geometrical configurations (sphere, bubble, toroid, triaxial shapes with various aspect ratio...) with help of a minimization procedure²⁵⁾. An interesting point is the possibility to simulate the decay of two sources separated in space-time. In such calculations, space-time correlations between fragments and particles emitted by two different sources are conserved.

Concerning the kinematics of the fragments, some initial velocities (other than thermal) can be added in order to mimic collective motion of the matter in a self-similar expansion (i.e initial velocities proportionnal to the distance between the fragment and the center of the system). Evaporation of light particles and also secondary fragment emission are taken into account at all stages of the decay process. All generated particles are propagated in the overall Coulomb field. When both the excitation energy and the particle-particle potential energies are negligible, the calculation is stopped. The generated events are then filtered through the experimental device to be compared with the data.

In the following, we have tried to fit our data with such a model. To this end, we have performed calculations with the hypothesis of two sources constituted by the partners of a deep inelastic scattering, each of them decaying at a time τ_{sep} defined as the time between re-separation of the two partners and fragmentation (assumed to be simultaneous) by the two outgoing nuclei. At that time, the relative velocity between the two partners is obtained by solving classically the relative motion of the two nuclei

in their interaction potential and by incorporating dissipation¹⁷⁾. We define the lifetime τ (that is the time needed for the disassembly of the hot nuclei) as the sum of τ_{sep} and τ_{inter} . τ_{inter} is the interaction time, that is the time between first contact and separation (if any) of the two incoming nuclei.

We have found that a suitable observable to compare the data with the results of our calculations was the relative angle θ_{ij} between fragments taken two by two. Why such a choice? In peripheral collisions, τ is very long compared to τ_{inter} because the system is not very excited. More, the velocity of each partner is large as compared to the center-of-mass velocity of the emitted fragment resulting in a strong focussing of the emitted fragment along the axis connecting the velocities of the two partners. Therefore, two different contributions to the values of θ_{ij} are expected: one which corresponds to angles between fragments originating from the same source and the other associated with fragments from two different origins. In the first case, the θ_{ij} distribution is peaked at small angles because of the focussing effect discussed above while in the second case the distribution is peaked at large angles. Thus, the global shape of the distribution is a two-bump curve. As far as the centrality increases, τ becomes shorter and τ_{sep} is expected to decrease, thus the two contributions should come closer until they merge when τ becomes of the order or even smaller than τ_{sep} . This is the situation corresponding to the decay of a single source.

The first two panels of fig. 3 show the θ_{ij} distributions for zone 1 and 2 of fig. 1. As expected, there are two contributions which tend to come closer (fig. 3-a,b). Calculations have been performed for the most dissipative collisions leading to 5 fragments (zone 3 to 5, fig 3-c to 3-d). The results of the simulations have been compared with the data. In region 3, the distribution is correctly reproduced (apart from small discrepancies around $\theta_{ij}=80$ degrees) for a value of τ_{sep} around 200 fm/c. This value is the same as the one found in²³⁾ although the methods used in the two papers are different. In order to reproduce the characteristics of events in region 4, τ_{sep} has to be decreased around 100 fm/c. When coming to events in zone 5, we found that it was impossible to reproduce the data unless τ_{sep} is put equal to zero suggesting that this region of the Wilczynski plot is indeed associated with a long-lived single source. In order to check the role of the fragment multiplicity M_f , the same analysis was performed in the case of $M_f=4$ (fig. 3-f-g-h). We found very similar results.

To conclude, highly fragmented events produced in Pb+Au dissipative collisions at 29 MeV/u have been studied. A centrality criterion has been obtained by analysing different regions in the Wilczynski diagram. For the most central collisions, evidence for the formation of a long-lived single source has been found. This statement is supported by the isotropy of LCP's patterns in the ellipsoid frame and also by the analysis of space-time correlations between fragments. Concerning this last point, the comparison of the relative angle experimental distributions with those obtained with

help of a computer simulation leads to the following conclusion: for mid-central events (region 3 in fig. 1 corresponding to the major part of the cross-section for the most dissipative collisions), we found a time τ_{sep} between re-separation and fragmentation similar to the one quoted in²³⁾. For more central collisions (regions 4 and 5), τ_{sep} becomes shorter. We would like to stress that this does not imply a reduction of the life-time τ . Indeed for such collisions with more orbiting, the interaction time τ_{inter} (this is the time needed for the partners to re-separate) is longer. In fact, when summing τ_{inter} obtained with help of macroscopic calculations with τ_{sep} the separation time as deduced from the experimental data, we obtain approximatively constant values for τ around 300-350 fm/c. This suggests that τ is constant as one goes from region 3 to 5 as it should be because all these events correspond to the same dissipated energy since they are associated with the same LCP multiplicities (see table I). For central collisions, dynamical calculations indicate that the interaction time becomes larger than 300-400 fm/c^{26,27)}. Then, for the most central collisions, τ becomes of the order or even smaller than τ_{inter} thus leading to $\tau_{\text{sep}} = 0$. Therefore, for these collisions, the fragment as well as the LCP patterns exhibit the features of a single long-lived source. In a next paper²¹⁾, we analyse the shape of these events produced in very central collisions.

REFERENCES

- 1) W. U. Schröder and J.R. Huizenga:
Treatise on heavy -ion science, ed. D. A. Bromley, Vol. 2 (Plenum, New York, 1984)
- 2) M. Lefort and C. Ngô, *Ann. Phys. (Paris)* 3 (1985) 5
- 3) D. R. Bowman et al, *Phys. Rev. Lett.* 67 (1991) 1527
- 4) B. Lott et al, *Phys. Rev. Lett.* 68 (1992) 3141
- 5) B. M. Quednau et al, *Phys. Lett.* B309 (1993) 10
- 6) S. P. Baldwin et al, *Phys. Rev. Lett.* 74 (1995) 1299
- 7) M. D'Agostino et al, *Phys. Rev. Lett.* 75 (1995) 4373
- 8) L. Stuttgé et al, *Nucl. Phys.* A539 (1992) 511
- 9) G. Casini et al, *Phys. Rev. Lett.* 71 (1993) 2567
- 10) W. Lynch, *Nucl. Phys.* A583 (1995) 471c
- 11) J. Toke et al, *Phys. Rev. Lett.* 75 (1995) 2920
- 12) J. F. Lecolley et al, *Phys. Lett.* B354 (1995)
- 13) R. Bougault et al, *NIM* A259 (1987) 473
- 14) G. Rudolf et al, *NIM* A307 (1991) 325
- 15) G. Bizard et al, *NIM* A244 (1986) 489
- 16) A. Peghaire et al, *NIM* A295 (1990) 365
- 17) J. F. Lecolley et al, *Phys. Lett. B* 325 (1994) 317
- 18) R. Bougault et al, *Nucl. Phys.* A587 (1995) 499
- 19) E. Piasecki et al, *Phys. Rev. Lett.* 66 (1991) 1291
- 20) M. Morjean et al, *Nucl. Phys.* A591 (1995) 371
M. Morjean et al, *Nouvelles du Ganil*, N° 56, (1995)
- 21) D. Durand et al, (submitted to *Phys. Lett.*)
- 22) J. Wilczynski et al, *Phys. Lett.* B47 (1973) 484
- 23) D. Durand et al, *Phys. Lett. B* 345 (1995) 397
- 24) J. Randrup, *Comp. Phys. Comm.* 77 (1993) 153
- 25) D. Durand, O. Lopez, A.D. Nguyen, *Computer code SIMON* (in preparation)
- 26) F. Gulminelli, *BNV calculations*, Private Communication
- 27) B. Jouault et al, *Nucl. Phys.* A591 (1995) 497

Zone	1	2	3	4	5
$M_{Z=1}$	3.05	5.32	6.35	6.50	6.51
$M_{Z=2}$	2.79	5.15	6.52	6.73	6.56

Table I: Average multiplicities for particles with $Z=1$ and $Z=2$ as a function of the zone defined in the two-dimensionnal plot of fig.1.

Figure Captions:

Fig. 1-a: Two-dimensional plot TKE (GeV) vs θ_{CM} . Events with 5 detected fragments with charge larger than 8 have been selected.

1- b-f: Two dimensional plots Sphericity vs Coplanarity. The label in each panel is associated with the same labelling in fig. 1-a. In fig 1-b, the loci of some generic shapes have been indicated.

Figure 2: Two-dimensional contour plot V_{par} - V_{per} for fragments (up) particles with $Z=1$ (middle) and $Z=2$ (down). Each panel is labelled from 3 to 5 with the same convention as in fig. 1. The scales for the six first panels are the same as for the last three ones.

Figure 3: Relative angle distribution between fragments taken two by two for the three regions labelled from 3 to 5 as defined in fig. 1. Black points are the experimental data while the histograms are the results of the calculations described in the text. τ_{sep} is the average time between the re-separation of the two partners and their subsequent decay. With this definition of τ_{sep} , $\tau_{sep}=0$ means that the two partners disassemble before they re-separate.

Fig 1. "Reaction mechanism..."

JF Lejoly et al

Fig 2

" Reaction mechanism...

JF Newbery et al

Fig 3

"Reaction mechanism..."

JF Legley et al