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Partitions in nuclear fragmentation

E. Bonnet,^{1,2} B. Borderie,² N. Le Neindre,^{2,3} M. F. Rivet,² R. Bougault,³ A. Chbihi,¹ J.D. Frankland,¹
E. Galichet,^{2,4} F. Gagnon-Moisan,^{2,5} D. Guinet,⁶ P. Lantesse,⁶ J. Lukasik,⁷ P. Marini,^{2,1} M. Pârlog,^{3,8}
E. Rosato,⁹ R. Roy,⁵ G. Spadaccini,⁹ M. Vigilante,⁹ J.P. Wieleczko,¹ and B. Zwieglinski¹⁰

(INDRA and ALADIN Collaborations)

¹*GANIL, (DSM-CEA/CNRS/IN2P3), F-14076 Caen cedex, France*

²*Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud 11, F-91406 Orsay cedex, France*

³*LPC, CNRS/IN2P3, Ensicaen, Université de Caen, F-14050 Caen cedex, France*

⁴*Conservatoire National des Arts et Métiers, F-75141 Paris cedex 03, France*

⁵*Laboratoire de Physique Nucléaire, Département de Physique,*

de Génie Physique et d'Optique, Université Laval, Québec, Canada G1K 7P4

⁶*Institut de Physique Nucléaire, CNRS/IN2P3, Université Claude Bernard Lyon 1, F-91406 Orsay cedex, France*

⁷*Institute of Nuclear Physics IFJ-PAN, PL-31342 Kraków, Poland*

⁸*National Institute for Physics and Nuclear Engineering, RO-76900 Bucharest-Magurele, Romania*

⁹*Dipartimento di Scienze Fisiche e Sezione INFN,*

Università di Napoli "Federico II", I-80126 Napoli, Italy

¹⁰*The Andrzej Soltan Institute for Nuclear Studies, PL-00681 Warsaw, Poland*

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Fragment partitions of fragmenting hot nuclei produced in central and semiperipheral collisions have been compared in the excitation energy region where radial collective expansion takes place. It is shown that, for a given total excitation energy per nucleon, the intensity of the radial collective energy fixes the degree of fragmentation (mean fragment multiplicity). It is also shown that the partitions, at a given total excitation energy per nucleon, are completely determined by the reduced fragment multiplicities (fragment multiplicities normalized to source size). Such observations emphasize the subtle role played by the radial collective expansion. They also represent a benchmark against which models describing the fragmentation process of finite systems should be tested.

PACS numbers: 25.70.-z Low and intermediate energy heavy-ion reactions ; 25.70.Pq Multifragment emission and correlations

The process of the total disintegration of a nucleus accompanied by a copious production of nuclear fragments, termed multifragmentation, was discovered more than forty years ago. It was first observed in nuclear reactions induced by intermediate and high-energy protons. With the advent of heavy ions accelerated at intermediate energies, early in the 1980s, more systematic investigations were initiated. However, tremendous progress in the understanding of multifragmentation came during the last fifteen years with the advent of powerful 4π detectors [1–3]. In particular, methods with global variables have shown their efficiency for sorting the topology, in velocity space, of events or subevents which undergo multifragmentation [3, 4]. Then it became possible to select very excited nuclei (> 3 MeV per nucleon) with a high degree of equilibration and produced by different reaction mechanisms. For semiperipheral collisions in particular, it is important to have a tool enabling to reject the part of the cross section which corresponds to collisions with dynamical neck formation [5]. The recent paper [4] contains an extensive comparison of fragment properties from hot nuclei produced in central and semiperipheral collisions. It was demonstrated that the degree of fragmentation, expressed with $\langle M_{frag} \rangle$, the mean number of fragments, increases with the radial collective energy. Moreover, in semiperipheral collisions, it was concluded

that the weak radial collective energy associated to the decaying quasi-projectiles can be ascribed to the thermal pressure. For central collisions in symmetric reactions, the larger radial collective velocities can be mainly related to the particular role played by the compression-expansion cycle [6–8]. Correspondingly, at a given excitation energy per nucleon, a larger average number of fragments with more similar sizes (charges) are produced in central collisions as compared to semiperipheral collisions whereas the average proportion of charge bound in fragments is found independent of the production mode of hot nuclei. The difference between the fragment multiplicities, normalized to source sizes (~ 20 –25%) is larger than what could arise from the influence of the different N/Z of the systems [9]. Indeed measurements for quasi-fused sources from Xe+Sn systems with N/Z going from 1.27 to 1.5 only show an increase of multiplicity of 10% [10].

Theoretical works aiming at understanding the influence of radial collective expansion on multifragmentation properties were recently published [11–14]. In this Letter we pursue the comparison initiated in [4] through a detailed study of fragment partitions as a function of fragment multiplicity.

The experiments were performed with the 4π multidetector for charged reaction products INDRA [15]. For

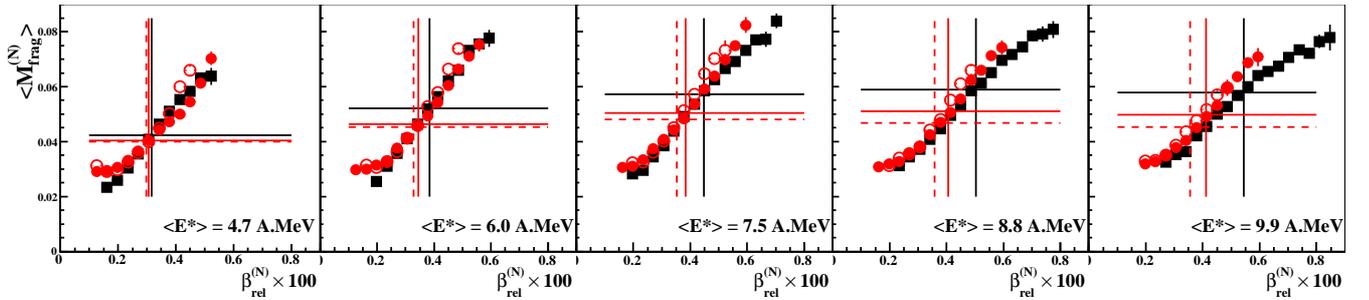


FIG. 1: (color online) Evolution of the average fragment multiplicity normalized to the source charge/size $\langle M_{frag}^{(N)} \rangle = \langle M_{frag}/Z_s \rangle$ as a function of the relative velocity of fragments, $\beta_{rel}^{(N)}$, (see text) for different total excitation energy per nucleon of the sources. Full squares, open and full circles stand respectively for QF sources and QP sources produced at 80 and 100 MeV/nucleon incident energies. Crosses correspond to the mean values of the considered samples for QF (black) and QP (grey dashed-80 MeV/nucleon and full-100 MeV/nucleon) samples, see text.

central collisions, beams of ^{129}Xe , accelerated by the GANIL accelerator in Caen, France, at five incident energies: 25, 32, 39, 45 and 50 MeV/nucleon, bombarded a thin target of natural tin ($350 \mu\text{g}/\text{cm}^2$) and hot quasi-fused (QF) nuclei/sources with Z around 70-100 could be selected [16]. Hot nuclei with lower Z around 60-70 (quasi-projectile, QP, sources) were obtained in semi-peripheral Au+Au collisions at 80 and 100 MeV/nucleon incident energies at the SIS heavy ion synchrotron at the GSI facility in Darmstadt, Germany [17]. In this experiment the ^{197}Au beam was impinging on a $2 \text{ mg}/\text{cm}^2$ thick target. For both experiments, Z identification was obtained over the whole range of fragments produced and the energy calibration was achieved with an accuracy of 4%. Further details can be found in [18–20].

The procedures used to select the studied nuclei/sources are the following. First of all poorly-measured events were rejected by requiring the detection of at least 80% of the charge of the initial system (projectile plus target for QF sources, projectile only for QP sources). Then compact sources were selected by using topology selectors in velocity space. For QF sources the constraint of large flow angle ($\geq 60^\circ$) calculated with the kinetic energy tensor for fragments ($Z \geq 5$) in the center of mass of the reaction was imposed (for details see [16]). For QP sources it was done by imposing a maximum value (2/3 of the QP velocity) of the mean relative velocity between fragments emitted in the forward hemisphere of the center of mass (see Eqs.(1),(2) and [4] for details). A QP size constant within 10% was additionally required. Note that for QP sources fission events were removed [21]. Further information concerning selections and light charged particles associated to sources can be found in [4]. The following step consists in the evaluation of the total excitation energy of the different sources. The calorimetric method [22] was used event by event. Hypotheses which have been made for QF sources are the following: a level density parameter equal

to $A/10$, the average kinetic energy of neutrons equal to their emitting source temperature and the Evaporation Attractor Line formula ($A=Z(2.072+2.32 \times 10^{-3}Z)$) [23] used to calculate fragment masses. EAL is especially well-adapted when heavy fragments ($Z > 20$) result from the deexcitation of neutron deficient sources. For QP sources the hypotheses are identical except for calculated fragment masses for which we use the formula ($A=Z(2.045+3.57 \times 10^{-3}Z)$) [23], better adapted for excited nuclei close to the beta-stability valley. Note that, compared to the EAL formula, differences appear only for masses associated to Z greater than 40.

In the following, we will use as main sorting parameter the total excitation energy per nucleon, $\langle E^* \rangle$, to compare fragment properties of both QF and QP sources. Mean excitation energies of selected samples have been fixed by values calculated for QF sources at the five incident energies and excitation energies of samples are limited to $\langle E^* \rangle \pm 0.3\sigma$. These values are reported in the panels of each figure.

We suppose that fragment velocities, in their source frame, are the results of the composition of at most three components: a randomly-directed thermal contribution, a Coulomb contribution dependent on the fragment charges and source sizes, and a radial collective energy. To evaluate the radial collective energy involved in the de-excitation of the different sources the mean relative velocity between fragments

$$\beta_{rel} = \frac{2}{M_{frag}(M_{frag} - 1)} \sum_{i < j} |\vec{\beta}^{(ij)}| \quad (1)$$

$$\vec{\beta}^{(ij)} = \vec{\beta}^{(i)} - \vec{\beta}^{(j)} \quad (2)$$

is used, which is independent of the reference frame. Only events or subevents (for QP sources) with fragment multiplicities M_{frag} greater than one are considered. It was shown in [4] that this observable is a good measure of the amount of radial collective energy. The thermal compo-

ment of fragment velocities has a negligible contribution to their mean relative velocity, while increasing the size of fluctuations. The effect of the Coulomb contribution is removed by using a simple normalization

$$\beta_{rel}^{(N)} = \frac{\beta_{rel}}{\sqrt{\langle Z \rangle (Z_s - \langle Z \rangle)}} \quad (3)$$

which takes into account, event by event, the Coulomb influence of the mean fragment charge ($\langle Z \rangle$) on the complement of the source charge ($Z_s - \langle Z \rangle$).

We first look at the degree of fragmentation. Figure 1 shows that, for a given total excitation energy per nucleon, the mean fragment multiplicity normalized to the source charge/size $\langle M_{frag}^{(N)} \rangle = \langle M_{frag}/Z_s \rangle$ is strongly correlated with the amount of radial collective expansion, as measured by $\beta_{rel}^{(N)}$. Crosses correspond to mean values for each type of source. Depending on the source type the relative contributions of radial collective energy (thermal pressure and compression-expansion cycle) strongly differ [4] but in all cases $\beta_{rel}^{(N)}$, representative of the total collective energy, fixes the degree of fragmentation. Note that for the largest $\beta_{rel}^{(N)}$ values (above 0.006) reached only at the higher excitation energies for QF sources, normalized fragment multiplicities increase more slowly. In that case the average size of fragments decreases and a larger fraction of them have a charge below our fragment limit $Z=5$.

The intensity of the radial collective energy fixes the degree of fragmentation. Does it also govern the details of fragment partitions, namely the relative charge/size of fragments in partitions? We first consider the evolution of the mean source size with the fragment multiplicity, M_{frag} , shown in Fig. 2 (left side) for the different excitation energies per nucleon. We note a correlation between the source size and the fragment multiplicity for QF sources: the larger the multiplicity the heavier the source. That correlation is reduced for QP sources due to our size selection constraint. Figure 2 (right side) shows the evolution of the total charge bound in fragments normalized to the source charge/size, $Z_{frag}^{(N)}$, as a function of the reduced fragment multiplicity $M_{frag}/\langle Z_s \rangle$ for the different excitation energies per nucleon. We observe that the mean values of $Z_{frag}^{(N)}$ are independent of the source type. To go deeper into the details of partitions one can now consider the size of the heaviest fragment for given total excitation energies and for different reduced fragment multiplicities. On the left side of Fig.3 average values of the heaviest fragment charge, Z_1 , are reported: values for QP and QF sources follow exactly the same evolution. The independence of Z_1 on the system size was already observed and is valid as long as the total system or projectile mass is above 190 [3, 24]. Finally the division of the charge among the other fragments is investigated using the generalized charge asymmetry of

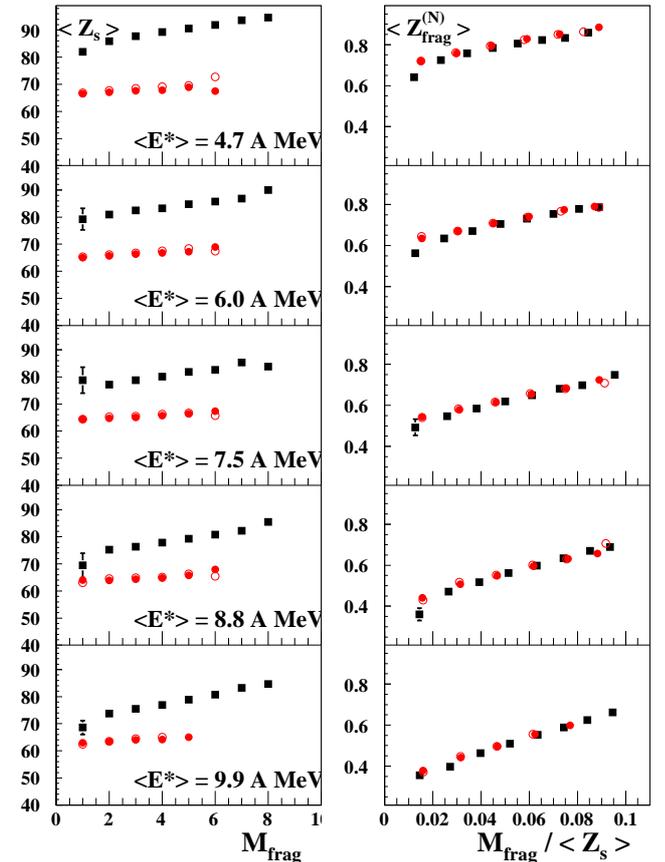


FIG. 2: (color online) Left side refers to mean values of source charges as a function of fragment multiplicity for different total excitation energy per nucleon of the sources. Right side shows the evolution of the total charge bound in fragments normalized to the source charge/size, $Z_{frag}^{(N)}$, as a function of the reduced fragment multiplicity $M_{frag}/\langle Z_s \rangle$ for the same total excitation energies. Full squares, open and full circles stand respectively for QF sources and QP sources produced at 80 and 100 MeV/nucleon incident energies.

the fragment partitions,

$$A_Z = \frac{1}{\sqrt{M_{frag} - 1}} \frac{\sigma_Z}{\langle Z \rangle} \quad (4)$$

which was introduced in [4]. One can re-calculate the generalized asymmetry by removing Z_1 from partitions with at least 3 fragments noted $A_Z \setminus \{Z_1\}$. The results are displayed in Fig. 3 (right side). They follow a linear behavior and do not depend on the source type at a given total excitation energy per nucleon. Such a result shows the subtle role played by the radial collective energy. It influences the overall degree of fragmentation but it does not affect the relative size of fragments in partitions for fixed reduced fragment multiplicities.

To conclude, in this Letter we have presented a detailed comparative analysis of fragment partitions for multifragmenting hot heavy nuclei produced in central

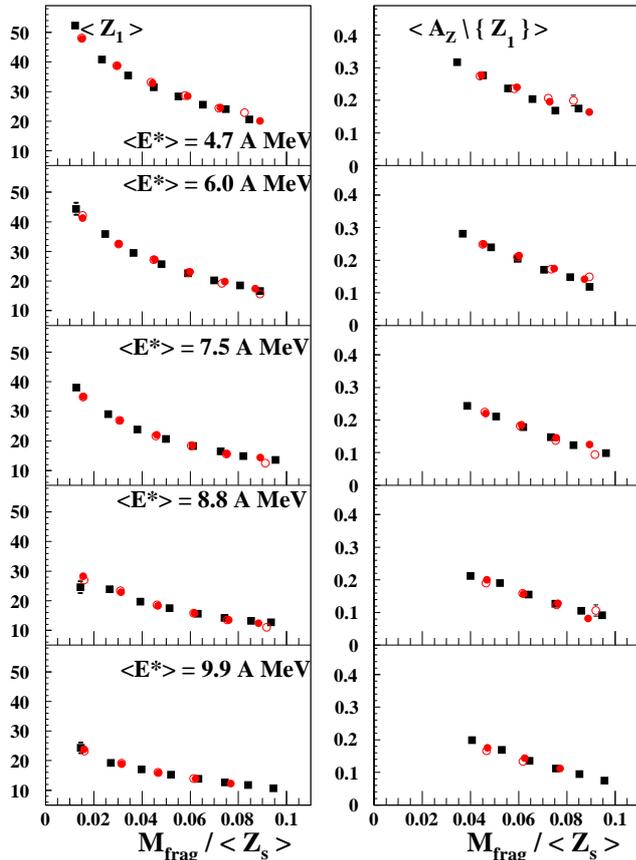


FIG. 3: (color online) Left and right sides refer respectively to the mean charge of the heaviest fragment of partitions, $\langle Z_1 \rangle$, and to the generalized asymmetry in charge of the fragment partitions without the heaviest one, $A_Z \setminus \{Z_1\}$, (see text) as a function of the reduced fragment multiplicity, $M_{frag} / \langle Z_s \rangle$, for different total excitation energy per nucleon of the sources. Full squares, open and full circles stand respectively for QF sources and QP sources produced at 80 and 100 MeV/nucleon incident energies.

and semiperipheral collisions, to emphasize the role of radial collective expansion. For central collisions hot nuclei were produced by quasi-fusion between ^{129}Xe projectiles and a natural tin target at various incident energies (25–50 MeV per nucleon). For semiperipheral collisions hot quasi-projectiles from Au+Au reactions were used at incident energies of 80 and 100 MeV/nucleon. It is first shown that the amount of the radial collective energy governs the degree of fragmentation of hot nuclei. Taking into account the charge/size of multifragmenting nuclei, details of fragment partitions for a given total excitation

energy per nucleon and a given reduced fragment multiplicity are presented. They show that these two quantities completely fix the relative charge/size of fragments whatever the radial collective energy, which is limited in the multifragmentation regime (3–10 A.MeV) to at most 20% of the total excitation energies involved [4]. The different scalings presented in this letter represent a benchmark against which models describing fragmentation of finite systems should be tested.

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