Bimodal Behavior of the Heaviest Fragment Distribution in Projectile Fragmentation

E. Bonnet,[1,*] D. Mercier,[2,3] B. Borderie,[1] F. Gulminelli,[2] M. F. Rivet,[1] B. Tamain,[2] R. Bougault,[2] A. Chbihi,[4] R. Dayras,[5] J. D. Frankland,[4] E. Galichet,[1,6] F. Gagnon-Moisan,[1,7] D. Guinet,[3] P. Lautesse,[3] J. Łukasik,[8] N. Le Neindre,[2] M. Pârlog,[2,9] E. Rosato,[10] R. Roy,[7] M. Vigilante,[10] J. P. Wieleczko,[4] and B. Zwieglinski[11]

(INDRA and ALADIN Collaborations)

[1]*Institut de Physique Nucléaire, CNRS/IN2P3, Université Paris-Sud 11, F-91406 Orsay cedex, France*
[2]*LPC (CNRS/IN2P3, Ensicaen, Université de Caen), F-14050 Caen cedex, France*
[3]*Institut de Physique Nucléaire, CNRS/IN2P3, Université Claude Bernard Lyon 1, F-91406 Orsay cedex, France*
[4]*GANIL (DSM-CEA/CNRS/IN2P3), F-14076 Caen cedex, France*
[5]*IRFU/SPhN, CEA Saclay, F-91191 Gif sur Yvette cedex, France*
[6]*Conservatoire National des Arts et Métiers, F-75141 Paris cedex 03, France*
[7]*Laboratoire de Physique Nucléaire, Département de Physique, de Génie Physique et d'Optique, Université Laval, Québec, Canada G1K 7P4*
[8]*Institute of Nuclear Physics IFJ-PAN, PL-31342 Kraków, Poland*
[9]*National Institute for Physics and Nuclear Engineering, RO-76900 Bucharest-Magurele, Romania*
[10]*Dipartimento di Scienze Fisiche e Sezione INFN, Università di Napoli "Federico II," I-80126 Napoli, Italy*
[11]*The Andrzej Soltan Institute for Nuclear Studies, PL-00681 Warsaw, Poland*
(Received 9 December 2008; published 13 August 2009)

The charge distribution of the heaviest fragment detected in the decay of quasiprojectiles produced in intermediate energy heavy-ion collisions has been observed to be bimodal. This feature is expected as a generic signal of phase transition in nonextensive systems. In this Letter, we present new analyses of experimental data from Au on Au collisions at 60, 80, and 100 MeV/nucleon showing that bimodality is largely independent of the data selection procedure and of entrance channel effects. An estimate of the latent heat of the transition is extracted.

DOI: 10.1103/PhysRevLett.103.072701 PACS numbers: 25.70.Pq, 05.70.Fh

At a first-order phase transition, the distribution of the order parameter in a finite system presents a characteristic bimodal behavior in the canonical or grand canonical ensemble [1–4]. The bimodality comes from an anomalous convexity of the underlying microcanonical entropy [5]. It physically corresponds to the simultaneous presence of two different classes of physical states for the same value of the control parameter and can survive at the thermodynamic limit in a large class of physical systems subject to long-range interactions [6]. In the case of nuclear multifragmentation, a natural order parameter is the size of the heaviest cluster produced in each collision event. Indeed, this observable provides an order parameter for a large class of transitions or critical phenomena involving complex clusters, from percolation to gelation, from nucleation to vaporization, from reversible to irreversible aggregation [4,7,8].

In this context, the recent observation by the INDRA-ALADIN Collaboration [9] of a sudden change in the fragmentation pattern of Au quasiprojectiles, loosely referred to as bimodality, has triggered a great interest in the heavy-ion community [10]. Looking at the correlation between the two heaviest fragments emitted in each event as a function of the violence of the collision, a clear transition is observed between a dominant evaporationlike decay mode, with the biggest cluster much heavier than the second one, and a dominant fragmentation mode, with the two heaviest fragments of similar size. A similar behavior has been reported in Ref. [11]. Different physical scenarios have been invoked to interpret the phenomenon: the finite-system counterpart of the nuclear matter liquid-gas phase transition [9,12,13], the Jacobi transition of highly deformed systems [14], and self-organized criticality induced by nucleon-nucleon collisions [15,16]. In Ref. [11], the two decay modes were associated to different excitation energies, suggesting a temperature-induced transition with nonzero latent heat. The qualitative agreement between Refs. [9,11] suggests that bimodality is a generic phenomenon. However, differences between the two data sets subsist, and trigger or selection bias cannot be excluded. To disentangle between the different scenarios, it is necessary to control the role of the entrance channel dynamics and establish if the transition is of thermal character. In this Letter, to progress on these issues, event ensembles with equiprobable excitation energy distribution are built and compared.

We present a new analysis of quasiprojectiles (QPs) produced in Au + Au collisions measured with the INDRA apparatus [17] at the Gesellschaft für Schwerionenforschung laboratory at incident energies from 60 to

100 MeV/nucleon [18]. The robustness of the signal of bimodality is tested against two different QP selection methods. A weighting procedure [13] is applied to test the independence of the decay from the dynamics of the entrance channel. Finally, a double saddle-point approximation is applied to extract from the measured data an equivalent-canonical distribution that can be quantitatively confronted to statistical theories of nuclear decay [19].

In this energy regime, a part of the cross section corresponds to collisions with dynamical neck formation [20]. We thus need to make sure that the observed change in the fragmentation pattern [9] is not trivially due to a change in the size of the QP. After a shape analysis in the center of mass frame [21], only events with a total forward detected charge larger than 80% of the Au charge were considered (quasicomplete events). Two different procedures aiming at selecting events with negligible neck contribution were adopted. In the first one [9] (I), we eliminate events where the entrance channel dynamics induces a forward emission, in the quasiprojectile frame, of the heaviest fragment Z_1 [22]. For isotropically decaying QPs, this procedure does not bias the event sample but only reduces the statistics. In a second strategy (II), the reduction of the neck contribution is obtained by keeping only "compact" events by imposing (i) an upper limit on the relative velocity among fragments and (ii) a QP size constant within 10%; see [12] for details. In both cases, fission events were removed [9].

The selected samples contain altogether about 30% of the quasicomplete events at the three bombarding energies. The main characteristics of the distribution of the heaviest fragment are presented in Fig. 1, as a function of the total transverse energy of light-charged products ($Z = 1, 2$) [23]. An excitation energy scale, estimated by calorimetry [24,25], is also given.

For increasing violence of the collision, the average size of the largest fragment monotonically decreases. The average behavior is smooth, but higher moments of the distribution reveal a clear change from the high Z_1 evaporation dominated pattern to the low Z_1 multifragmentation dominated one, passing through a region of maximal fluctuations where the skewness changes its sign. These moments appear relatively independent of the selection criterion. About one event out of four is common between the two sets; the differences in the observables evaluated with the two criteria thus give an estimation of the bias induced by the selection of data. The relative abundances observed in the correlation between the charge of the heaviest fragment and the deposited excitation energy are clearly governed by the impact parameter. The presence of a sudden jump in the most probable Z_1 value depends on the selection method and cannot be taken as a signature of a transition, as was proposed in previous works [9,14–16]. The only veritable proof of bimodality would be the observation of two distinct bumps in the Z_1 distribution for a system in thermal contact with a heat reservoir at the

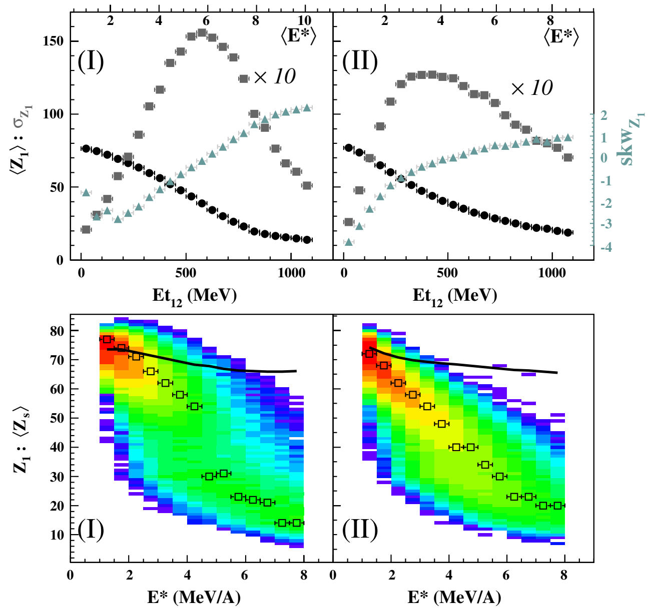

FIG. 1 (color online). Upper part: Average (dots), standard deviation (squares), and skewness (triangles—right Y axis) of the distribution of the heaviest fragment as a function of the light-charged particles transverse energy at an incident energy of 80 MeV/nucleon. Lower part: Correlation between the charge of the heaviest fragment and the calorimetric excitation energy. The open squares indicate the most probable Z_1 values. The average total source size Z_s is given by the full line. Left side: Selection (I); right side: selection (II).

transition temperature [1–4]. However, the distribution of the energy deposit in a heavy-ion collision is not determined by random exchanges with a thermal bath. This means that the experimental ensemble is not canonical and the Z_1 distribution has no meaning in terms of statistical mechanics. To cope with this problem, a simple procedure has been proposed in Ref. [13]. The bimodality in the canonical two-dimensional probability distribution $p_\beta(E^*, Z_1)$ of a system of given size Z_s at a first-order phase transition point reflects the convexity anomaly of the underlying density of states $W_{Z_s}(E^*, Z_1)$ [1,3,4] according to

$$p_\beta(E^*, Z_1) = W_{Z_s}(E^*, Z_1)\exp(-\beta E^*)\mathcal{Z}_\beta^{-1}, \quad (1)$$

where $\mathcal{Z}_\beta$ is the partition function. In an experimental sample, the energy distribution is not controlled by an external bath through a Boltzmann factor, but it is given by a collision and detector dependent functional $g(E^*)$:

$$p_{\exp}(E^*) \propto \int dZ_1 W_{Z_s}(E^*, Z_1) g(E^*). \quad (2)$$

The convexity of the density of states can be directly inferred from the measured experimental distribution, by a simple weighting of the probabilities associated to each deposited energy:

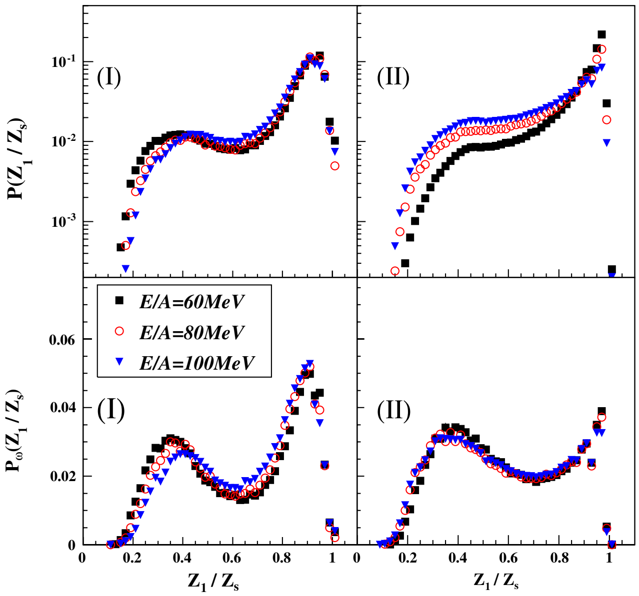

FIG. 2 (color online). Upper part: Measured distribution of the charge of the largest fragment normalized to the charge of the source detected in Au + Au collisions at three different bombarding energies. Lower part: Normalized distributions obtained considering the same statistics for each excitation energy bin. The left [right] side shows distributions obtained with the data selection method (I) [(II)].

$$p_w(E^*, Z_1) = \frac{p_{\exp}(E^*, Z_1)}{p_{\exp}(E^*)} = \frac{p_\beta(E^*, Z_1)}{p_\beta(E^*)} = \frac{W_{Z_s}(E^*, Z_1)}{W_{Z_s}(E^*)}. \quad (3)$$

This procedure allows us to get rid of the entrance channel impact parameter geometry that naturally favors the lower part of the E^* distribution. To produce a flat E^* distribution according to Eq. (3), we have weighted the Z_1 yields in each E^* bin with a factor proportional to the inverse of the bin statistics.

The results obtained with the two different selection methods are given in Fig. 2 (bottom). To take into account the small variations of the source size, the charge of the heaviest fragment Z_1 has been normalized to the source size. After the weighting procedure, a bimodal behavior of the largest fragment charge clearly emerges in both cases.

Equation (3) holds only if the bias function g in Eq. (2) does not explicitly depend on Z_1, which is a phase-space dominance assumption. The physical meaning of this hypothesis is that the entrance channel geometry and dynamics (as well as the bias induced by the detection system and data selection) determine only the energy distribution and size (Z_s) of the QP, while for each given value of E^* and Z_s the size of the heaviest fragment (Z_1) is dominated by the corresponding available phase space. The similarity of the two samples at 80 MeV/nucleon, after the weighting procedure, is an indication that the bias induced by the data sorting is small. The phase-space dominance hypothesis can further be checked by comparing the effect of the weighting procedure on data issued from different entrance channel dynamics. This is done in Fig. 2, where the same weighting method has been applied on data at different bombarding energies. The comparison is not conclusive in the case of selection (I), where the excitation energy distributions obtained at the different incident energies happen to be largely superposable (Fig. 2, top left), and we cannot *a priori* exclude a bias function. Conversely, in the case of selection (II), we can see that the weight of the low Z_1 component, associated to more fragmented configurations and higher deposited energy, increases with the bombarding energy. This difference disappears when data are weighted, showing the validity of the phase-space dominance hypothesis.

The three studied energies and the two selection criteria (I) and (II) produce similar but not identical distributions even after renormalization, meaning that a residual bias on the density of states exists. One may ask whether this bias prevents a sorting and dynamic-independent extraction of the entropic properties of the system. To answer this question, we can compare the information on the coexistence zone in the (Z_1, E^*) plane extracted from the different samples. We thus have to solve Eq. (3) for the canonical distribution $p_{\beta_t}(E^*, Z_1)$ at the transition temperature β_t at which the two peaks of the energy distribution have the same height [4]. This is easily obtained in a double saddle-point approximation [13]:

$$p_{\beta_t}(E^*, Z_1) = \sum_{i=l,g} N_i \frac{1}{\sqrt{\det \Sigma_i}} \exp\left(-\frac{1}{2}\vec{x}_i \Sigma_i^{-1} \vec{x}_i\right), \quad (4)$$

where $\vec{x}_i = (E^* - E_i, Z_1 - Z_i)$. Σ_i represents the variance-covariance matrix and is related to the entropy curvature matrix [see formulas (10), (11), and (12) of [13]]. The correlation coefficient $\rho = \sigma_{Z_1E^*}/\sigma_{Z_1}\sigma_{E^*}$, which is one

TABLE I. Parameters of the equivalent-canonical distribution Eq. (4) at the transition temperature as estimated from the two data selection methods. The χ^2 of the fit is also given.

	ρ	Z_l	σ_{Zl}	E_l	σ_{El}	Z_g	σ_{Zg}	E_g	σ_{Eg}	$\chi^2/N_{\rm dof}$
Set (I) $E/A = 80$ MeV	−0.861	72.5	16.5	1.42	2.25	12.1	13.4	8.52	2.62	0.53
Set (I) $E/A = 100$ MeV	−0.861	69.3	15.9	1.67	2.30	12.1	13.7	8.76	2.83	0.59
Set (II) $E/A = 80$ MeV	−0.925	69.1	12.6	1.02	1.78	2.10	24.6	10.4	4.04	0.80
Set (II) $E/A = 100$ MeV	−0.925	68.3	12.5	1.07	1.77	2.96	24.4	10.2	3.96	0.96

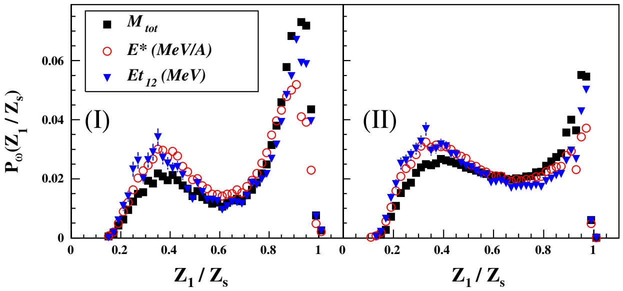

FIG. 3 (color online). Experimental distribution of the largest cluster charge normalized to have identical statistics for each excitation energy bin, with the two different data selection techniques (I) and (II) and for 80 MeV/nucleon incident energy. Different estimators of the deposited excitation energies are considered.

of the parameters, was calculated from the data at the three incident energies, before the weighting procedure and for each selection method, on the largest validity domain, i.e., 1–8 MeV/nucleon for (I) and 1–12 MeV/nucleon for (II) (see Table I). Σ_i is evaluated at the liquid l (gas g) solution, and N_i are the proportions of the two phases, with $N_l/N_g = \sqrt{\det\Sigma_l}/\sqrt{\det\Sigma_g}$.

The weighted experimental distribution can be fitted with the function $p_w(E^*, Z_1) = p_{\beta_t}(E^*, Z_1)/p_{\beta_t}(E^*)$, which, using Eq. (4), is an analytic function. ρ being fixed, we have performed an 8-parameter fit with the two data sets corresponding to the two selection procedures at the two higher bombarding energies on the excitation energy range 2–7 MeV/nucleon; to avoid small number effects, only 2D bins with significant statistics (>0.5% of the corresponding E^* slice) were used. The obtained parameter values are given in Table I. In particular, we can estimate the latent heat of the transition of the heavy nuclei produced as $\Delta E = E_g - E_l = 8.1(\pm 0.4)_{\rm stat}(^{+1.2}_{-0.9})_{\rm syst}$ MeV/nucleon. Statistical error was derived from statistical errors on E_l and E_g and systematic errors from the comparison between selections (I) and (II). The latent heat is derived from a difference, and so the possible effect of systematic errors in the determination of excitation energy by calorimetry due to detection limitations (neutrons are not detected nor fragment masses measured) [26] should be included in given error bars. Note also that the deduced parameter values E_l and E_g are outside the excitation energy range used for the fit.

Finally, we use other estimators such as the total forward charged product multiplicity $M_{\rm tot}$ and the transverse energy Et_{12}. The measured distributions weighted via Eq. (3) with these different estimators are presented in Fig. 3. We can see that bimodality is preserved in all cases, and the different energy estimators predict close positions for the two peaks.

In conclusion, in this Letter we have presented a comparative analysis of the quasiprojectile Au + Au data collected with the INDRA apparatus at incident energies between 60 and 100 MeV/nucleon. Two different methods for quasiprojectile selection have been used, which do not select the same physical events. Once the trivial entrance channel effect of the impact parameter has been removed by weighting the Z_1 distribution by the statistics of the excitation energy distribution, a clear indication of bimodality in the decay pattern is observed. This behavior appears to be robust against the selection method, the entrance channel dynamics, and the estimator of the deposited excitation energy. This analysis supports the interpretation of the discontinuity already observed in the decay pattern [9] as the finite-system counterpart of a first-order phase transition. A multidimensional fit allows us to extract, through a double saddle-point approximation, the coexistence zone and a first estimate of the latent heat of the transition.

The present results are coherent with other signals from Au quasiprojectiles considered indicative of a first-order phase transition like a fossil signal of spinodal fluctuations and configurational energy fluctuations associated with negative heat capacity [27,28]. Interpretations given in Refs. [14–16] do not register in that coherent picture. However, it would be interesting to know if those interpretations can verify the bimodality of Z_1 for the weighted distribution and its independence of the incident energy as it is observed in that work.

*Present address: GANIL (DSM-CEA/CNRS/IN2P3), F-14076 Caen cedex, France.

[1] K. Binder and D. P. Landau, Phys. Rev. B **30**, 1477 (1984).
[2] Ph. Chomaz, F. Gulminelli, and V. Duflot, Phys. Rev. E **64**, 046114 (2001).
[3] K. C. Lee, Phys. Rev. E **53**, 6558 (1996); Ph. Chomaz and F. Gulminelli, Physica (Amsterdam) **330A**, 451 (2003).
[4] F. Gulminelli, Ann. Phys. (Paris) **29**, 1 (2004).
[5] D. H. E. Gross, *Microcanonical Thermodynamics: Phase Transitions in Small Systems*, Lect. Notes Phys. Vol. 66 (World Scientific, Singapore, 2001).
[6] *Dynamics and Thermodynamics of Systems with Long Range Interactions: Theory and Experiments*, AIP Conf. Proc. Vol. 970 (AIP, New York, 2007).
[7] R. Botet and M. Ploszajczak, Phys. Rev. E **62**, 1825 (2000).
[8] J. D. Frankland *et al.* (INDRA and ALADIN Collaborations), Phys. Rev. C **71**, 034607 (2005).
[9] M. Pichon *et al.* (INDRA and ALADIN Collaborations), Nucl. Phys. **A779**, 267 (2006).
[10] O. Lopez and M. F. Rivet, Eur. Phys. J. A **30**, 263 (2006).
[11] M. Bruno *et al.*, Nucl. Phys. **A807**, 48 (2008).
[12] E. Bonnet *et al.* (INDRA and ALADIN Collaborations), Nucl. Phys. **A816**, 1 (2009).
[13] F. Gulminelli, Nucl. Phys. **A791**, 165 (2007).
[14] O. Lopez *et al.*, Phys. Rev. Lett. **95**, 242701 (2005).
[15] W. Trautmann, arXiv:0705.0678.

[16] A. Le Fèvre and J. Aichelin, Phys. Rev. Lett. **100**, 042701 (2008).
[17] J. Pouthas *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **357**, 418 (1995).
[18] A. Trzcinski *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **501**, 367 (2003); J. Lukasik *et al.* (INDRA and ALADIN Collaborations), Phys. Lett. B **566**, 76 (2003).
[19] G. Chaudhuri and S. Das Gupta, Phys. Rev. C **76**, 014619 (2007).
[20] M. Di Toro, A. Olmi, and R. Roy, Eur. Phys. J. A **30**, 65 (2006).
[21] J. Cugnon and D. L'Hote, Nucl. Phys. **A397**, 519 (1983).
[22] J. Colin *et al.* (INDRA Collaboration), Phys. Rev. C **67**, 064603 (2003).
[23] J. Lukasik *et al.* (INDRA Collaboration), Phys. Rev. C **55**, 1906 (1997).
[24] V. E. Viola and R. Bougault, Eur. Phys. J. A **30**, 215 (2006).
[25] To minimize the bias induced by preequilibrium emission on calorimetry, only the light-charged particles forward-emitted in the quasiprojectile frame are considered in the energy balance, and their contribution is doubled to account for backward-emitted particles.
[26] M. D'Agostino *et al.*, Nucl. Phys. **A699**, 795 (2002); E. Vient *et al.*, Nucl. Phys. **A700**, 555 (2002).
[27] E. Bonnet, thèse de doctorat, Université Paris-Sud 11, http://tel.archives-ouvertes.fr/tel-00121736.
[28] B. Borderie and M. F. Rivet, Prog. Part. Nucl. Phys. **61**, 551 (2008).