LIQUID-GAS COEXISTENCE REGION IN CENTRAL Xe+Sn REACTIONS

B. BORDERIE\textsuperscript{1}, M.F RIVET\textsuperscript{1}, G. TĂBĂCARU\textsuperscript{1,2}, M. COLONNA\textsuperscript{4}, P. DÉSESQUELLES\textsuperscript{9}, M. PĂRLOG\textsuperscript{2}, and G. AUGER\textsuperscript{3}, Ch. O. BACRI\textsuperscript{1}, N. BELLAIZE\textsuperscript{5}, R. BOUGAULT\textsuperscript{5}, B. BOURIQUET\textsuperscript{3}, A. BUTA\textsuperscript{5}, A. CHBIHI\textsuperscript{3}, J. COLIN\textsuperscript{5}, A. DEMEYER\textsuperscript{7}, E. GALICHET\textsuperscript{1,10}, E. GERLIC\textsuperscript{7}, D. GUINET\textsuperscript{7}, B. GUIOT\textsuperscript{3}, S. HUDAN\textsuperscript{3}, P. LÁUTESSE\textsuperscript{7}, F. LAVAUD\textsuperscript{1}, J.L. LAVILLE\textsuperscript{3}, J.F. LECOLLEY\textsuperscript{5}, C. LEDUC\textsuperscript{7}, R. LEGRAIN\textsuperscript{6}, O. LOPEZ\textsuperscript{5}, M. LOUVEL\textsuperscript{5}, J. NORMAND\textsuperscript{5}, P. PAWLOWSKI\textsuperscript{1}, E. ROSATO\textsuperscript{8}, J.C. STECKMEYER\textsuperscript{5}, B. TAMAIN\textsuperscript{5}, L. TASSAN-GOT\textsuperscript{1}, E. VIENT\textsuperscript{5}, J.P. WIELECKZO\textsuperscript{3}

INDRA Collaboration

\textsuperscript{1} Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France.
\textsuperscript{2} National Institute for Physics and Nuclear Engineering, RO-76900 Bucharest-Măgurele, Romania.
\textsuperscript{3} GANIL, CEA et IN2P3-CNRS, B.P. 5027, F-14076 Caen Cedex, France.
\textsuperscript{4} Laboratorio Nazionale del Sud, Viale Andrea Doria, I-95129 Catania, Italy.
\textsuperscript{5} LPC, IN2P3-CNRS, ISMRA et Université, F-14050 Caen Cedex, France.
\textsuperscript{6} DAPNIA/SPhN, CEA/Saclay, F-91191 Gif sur Yvette Cedex, France.
\textsuperscript{7} Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-69622 Villeurbanne Cedex, France.
\textsuperscript{8} Dipartimento di Scienze Fisiche e Sezione INFN, Università di Napoli “Federico II”, I80126 Napoli, Italy.
\textsuperscript{9} Institut des Sciences Nucléaires, IN2P3-CNRS et Université, F-38026 Grenoble Cedex, France.
\textsuperscript{10} Conservatoire National des Arts et Métiers, F-75141 Paris cedex 03.

Abstract

Charge partitions and distributions of fragments emitted in multifragmentation of fused systems produced in central collisions are studied over the incident energy range 32-50 MeV per nucleon. Most of the charged products are well identified thanks to the high performances of the INDRA $4\pi$ array. Supported by dynamical calculations, charge correlations are used to evidence, or not, spinodal instabilities and consequently the liquid-gas coexistence region over the considered incident energy range. It was claimed in the last few years that mass/charge distributions should follow a power law behavior in the coexistence region. The Z distributions measured are discussed. A first attempt is made to derive in which Z region the border between liquid and gas parts is located.
1 Introduction

Despite the large amount of experimental studies regarding the nuclear liquid-gas phase transition, fundamental questions have mostly eluded conclusive answers. We shall discuss two questions in this contribution. A first one regards the mechanism of phase separation for matter which is expanding through a density-temperature region inside the liquid-gas coexistence region. And the second is whether power laws claimed to be observed for fragment mass/charge distributions are related or not to this region; power laws are indeed only expected at or near the critical point.

We report here on studies performed with INDRA [1] of multifragmentation of very heavy fused systems formed in central collisions between $^{129}\text{Xe}$ and $^{nat}\text{Sn}$ at 32,39,45 and 50 AMeV. These fused systems can be identified to well defined pieces of nuclear matter and eventually reveal fragmentation properties to be compared to models in which bulk instabilities are present.

Detailed information on the experiment, on calibration, identification and on the selection of fused events can be found in [2–6]. Reaction products with charge $Z \geq 5$ were defined as fragments.

2 Enhancement of equal-sized fragment partitions and spinodal instabilities

Many theories have been developed to explain multifragmentation (see for example ref. [7] for a general review of models). One can come in particular to the concept of multifragmentation by considering volume instabilities of the spinodal type. Indeed during a collision, a wide zone of the nuclear matter phase diagram may be explored and the nuclear system may enter the liquid-gas phase coexistence region (at low density) and even more precisely the unstable spinodal region (domain of negative compressibility). Thus, a possible origin of multifragmentation may be found through the growth of density fluctuations in this unstable region. Within this theoretical scenario a breakup into nearly equal-sized “primitive” fragments should be favored in relation with the wave-lengths of the most unstable modes present in the spinodal region [8]. However this simple picture is expected to be strongly blurred by several effects: the beating of different modes, the presence of large wave-length instabilities, eventual coalescence of nascent fragments, secondary decay of excited fragments and mainly the finite size of the system [9,10]. Therefore only a weak proportion of multifragmentation events with nearly equal-sized fragments is expected. To search for such events a very sensitive correlation method was used, which is called “higher order correlations” and was proposed in ref [11]. Its originality consists in the fact that all information on fragments of one event is condensed in two variables (average fragment charge $< Z >$ and standard deviation $\Delta Z$).
Figure 1: Higher-order charge correlations: quantitative results for experimental data (up) and simulations (down). Symbols indicate the events where $\Delta Z = 0-1$, curves show the background (see text). Vertical bars correspond to statistical errors and horizontal bars define $Z_{tot}$ bins.
The charge correlation is defined by the expression:

\[
\frac{Y(\Delta Z, < Z >)}{Y'(\Delta Z, < Z >)}_{M}
\]  

(1)

Here, \(Y(\Delta Z, < Z >)\) is the yield of selected events with \(< Z >\) and \(\Delta Z\) values and \(M\) is the fragment multiplicity.

The denominator \(Y'(\Delta Z, < Z >)\) which represents the uncorrelated yield is built, for each fragment multiplicity, by taking fragments in different events of the selected sample. The number of uncorrelated events was chosen large enough (10^3 per true event) to strongly reduce their contribution to statistical error. With such a correlation method, if events with nearly equal-sized fragments are produced, we expect to see peaks appearing at \(\Delta Z\) values close to zero. Taking into account secondary decay of fragments, the bin \(\Delta Z=0-1\) was only considered. At 32 AMeV incident energy peaks were observed in this bin for each fragment multiplicity [12, 13].

We can now estimate whether the enhancement of events with equal-sized fragments is statistically significant and quantify their occurrence. In this aim we built charge correlations for all events, whatever their multiplicity, by replacing the variable \(< Z >\) by \(Z_{tot} = M \times < Z >\). For this compact presentation uncorrelated events are built and weighted in proportion to real events of each multiplicity. For each bin in \(Z_{tot}\), fixed at six atomic number units, an exponential evolution of the correlation function is observed from \(\Delta Z=7-8\) down to \(\Delta Z=2-3\). This exponential evolution is thus taken as “background” to extrapolate down to the first \(\Delta Z\) bin. Higher order correlation functions for the first bin in \(\Delta Z\) are displayed in Fig. 1 with their statistical errors; the full line corresponds to the extrapolated “background”. All events corresponding to the points whose error bar is fully located above this line correspond to a statistically significant enhancement of equal-sized fragment partitions. The probabilities that these values higher than the background simply arise from statistical fluctuations are in the range 0.05-0.02 depending on \(Z_{tot}\). The number of significant events amounts to 0.1% of the selected fusion events.

This proportion has to be compared with what is expected for a complete 3D simulation in which all events arise from spinodal decomposition. In this aim, dynamical stochastic mean-field simulations [14, 15] were performed for head-on collisions. Spinodal decomposition was simulated using the Brownian one-Body (BoB) dynamics [16–18], which consists in employing a Brownian force in the kinetic equations. As a last step the spatial configuration of the primary fragments, with their excitation energies as produced by BoB, was taken as input in the SIMON code [19] to follow the fragment deexcitation while preserving space-time correlations. Finally the events were filtered to account for the experimental device. These complete simulations well reproduce multiplicity and charge distributions of fragments and their average kinetic energies [18]. Although all events in the simulation arise from spinodal
Figure 2: Higher-order charge correlations: quantitative results for experimental data at different incident energies. Symbols indicate the events where $\Delta Z = 0$-1, curves show the background (see text). Vertical bars correspond to statistical errors and horizontal bars define $Z_{tot}$ bins.
decomposition, the proportion statistically significant of equal-sized fragment partitions is similar (0.15%) to the experimental one.

A detailed quantitative comparison is displayed in fig. 1. The similarities between experimental and calculated events allow to attribute all fusion-multifragmentation events to spinodal decomposition. The peaks observed near $\Delta Z = 0$ in the higher-order charge correlations are thus fossil fingerprints of the partitions expected from spinodal decomposition.

What are now the quantitative experimental results for the different incident energies above 32 AMeV? The energy dependence of the correlation function for fused events where $\Delta Z = 0$-1 is shown in fig. 2. No enhancement of nearly equal-sized fragment partitions is observed for the two higher energies: 45 and 50AMeV. A similar negative result was mentioned in ref. [11] for the Xe+Cu system at 50 AMeV. At 39 AMeV incident energy three points are located above the extrapolated background. The probabilities that these values simply arise from statistical fluctuations are 0.13 for $Z_{\text{tot}} = 39$, 0.0002 for $Z_{\text{tot}} = 45$ and 0.14 for $Z_{\text{tot}} = 51$. The observed enhancement amounts to about 0.2% of events.

For the same selected fused events negative microcanonical heat capacities, which are predicted to sign a first order phase transition [20], have also been measured at 32 and 39 AMeV [21]. The coincidence with present observations is very appealing. Indeed, supported by theoretical simulations, the observed weak but unambiguous enhanced productions of events with equal-sized fragments at 32 and 39 AMeV can be interpreted as a signature of spinodal instabilities as the origin of multifragmentation in the Fermi energy domain. Moreover the occurrence of spinodal decomposition signs the presence of a liquid-gas coexistence region and consequently, although indirectly, a first order phase transition.

So dynamical (spinodal instabilities) and statistical (negative heat capacities) arguments are in favor of a first order phase transition. The following scenario can be proposed: spinodal instabilities cause multifragmentation but when the system reaches the freeze-out stage, it has explored enough of phase space in order to be describable through an equilibrium approach. The agreement between data and dynamical and statistical models [18, 22, 23] for static (multiplicity, $Z$ distribution, size of heaviest fragments) and kinetic properties of fragments fully supports this scenario.

### 3 Fragment charge distributions, power laws and event distributions

A power law behavior, which was claimed to be observed in the charge (mass) distribution of multifragmenting systems, has been sometimes interpreted as an evidence for a second order phase transition. Indeed, in the Fisher droplet model a power law behavior is expected at the critical point when the liquid
Figure 3: Fragment charge distributions observed at different incident energies. \( \tau \) values refer to power laws observed (full lines).
and gas chemical potentials are equal and the surface tension is zero \[24\]. More recently a great theoretical effort was done, using Classical Molecular Dynamics \[25\], Lattice Gas Model \[26, 27\] and statistical models \[28, 29\], to give information on fragment distributions when multifragmentation of finite systems occurs in the coexistence region. Two of the main conclusions are the following:

i) power laws are observed in the coexistence region which disappear as soon as large systems are considered;

ii) within the microcanonical framework the exponent of the power law is close to the one expected for the liquid-gas universality class (\(\tau=2.33\)) only at the critical point.

Experimentally the well defined multifragmenting pieces of nuclear matter presently studied can be used to bring some information. Let us start considering the fragment charge distribution for the lower incident energy (32 AMeV). At first glance a power law dependence with \(\tau=1.1\) rather well fits the Z distribution over the range Z=5-15. Finite size effects break this law for higher charges and the heaviest fragment is completely excluded from this dependence. Removing this heaviest fragment we can examine now in details the charge distributions measured at the different incident energies. Such distributions are displayed in fig. 3 in a double logarithmic scale. Valuable power laws are only observed on the reduced domain Z=6-9 and clearly a small bump with a maximum centered around Z=10-12 is present in distributions for the two lower incident energies. \(\tau\) values are equal to 1.9 for 32 and 39 AMeV incident energies. At higher incident energies for which neither negative microcanonical heat capacity nor fossil signatures of spinodal decomposition were observed, \(\tau\) values increase. Note that at 45 AMeV \(\tau\) is equal to 2.2, i.e. close to the one expected in the critical region. Due to the reduced Z range where power laws are really observed, precise experimental values of \(\tau\) will be only obtained from fragment mass distributions.

From the peculiar shapes of Z distributions observed in fig. 3, it is very tempting to consider that the bump centered around Z=10-12 can indicate that other among the heavier fragments can belong to the liquid fraction; the heaviest fragment, generally considered as the liquid fraction was already removed for distributions presented in fig. 3. With such an hypothesis power law concerns only a part of the gas fraction.

We can try to go further by considering that a separation between liquid and gas fractions is around Z=12. This separation, if not over-simple, can be revealed in event distributions using as a variable the normalized difference between the liquid and gas \(Z_{\text{bound}}\). Fig. 4 shows event distributions for the different incident energies considering only \(Z\geq3\); indeed light charged particles are a mixing of particles emitted at different stages of the collisions and can not bring reliable information. We observe a rather constant evolution of the distributions between 32 AMeV (dominated by the “liquid fraction”), 39
Figure 4: Event distributions observed at different incident energies. Points located at the value -1 are divided by 10; See text for the variable used for event distribution.

AMeV (equilibrated “mixed phase”) and 45 AMeV (dominated by the “gas fraction”). Inversely, distributions at 45 and 50 AMeV are very similar and could characterize the fact that these events are produced at the border or outside the coexistence region. This part of the work is a first attempt to study new observables related to the existence of a first order phase transition. This is done in the spirit of theoretical propositions made in ref. [30]. It is also discussed in contributions [31, 32] during this meeting.

4 Summary

In summary, the above studies illustrate:

• an enhancement of nearly equal-sized fragment partitions in multifragmentation of a heavy system formed on a restricted domain of incident energies (32 and 39 AMeV);
• that supported by dynamical calculations this enhancement is interpreted as a signature of spinodal instabilities as the origin of multifragmentation in the Fermi energy domain;
• the coincidence, at 32 and 39 AMeV, between observations of spinodal...
instabilities and negative heat capacities;

- that dynamical (spinodal instabilities) and statistical (negative heat capacities) arguments are in favor of a first order phase transition in finite systems (~200 nucleons);
- that the following scenario for multifragmentation in the Fermi energy domain can be proposed: spinodal instabilities cause multifragmentation but when the system reaches the freeze-out stage, it has explored enough of phase space to be describable through an equilibrium approach;
- that, for fragment charge distributions, power laws are only observed on a reduced domain in Z, from 6 to 9;
- that $\tau$ is equal to 1.9 in the “coexistence region” and reaches a value close to the one expected in the critical region at 45 AMeV incident energy;
- that the peculiar shapes of Z distributions observed in the “coexistence region” suggest that, as expected from spinodal decomposition, more than one heavy fragment contribute to the liquid fraction;
- that event distributions experimentally observed can also reveal the existence of a first order phase transition.

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