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CHARGE CORRELATIONS IN MULTIFRAGMENTATION OF A HEAVY SYSTEM AND SPINODAL INSTABILITIES

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Abstract

Multifragmentation of "fused systems" was observed for central very heavy ion collisions between 30 and 50 MeV/u. Most of the resulting charged products were well identified thanks to the high performances of the INDRA 4π array. By comparing two heavy fused systems with different masses and the same available energy ($\sim$ 7 MeV per nucleon), an experimental evidence for bulk effect was observed. This experimental fact can be related to bulk instabilities in the liquid-gas coexistence region of nuclear matter (spinodal instabilities) or perhaps simply taken as a signature of a full exploration of phase space during the multifragmentation process. Experimental charge correlations for fragments show a weak but non ambiguous enhancement of events with nearly equal-sized fragments. Such an enhancement is interpreted as a "fossil" signal of spinodal instabilities in finite nuclear systems.

1 Introduction

The decay of highly excited nuclear systems through multifragmentation (emission of several fragments in a short time scale) is, at present time, a subject of great interest in nucleus-nucleus collisions. If this process has been observed for many years, its experimental knowledge in the Fermi energy domain was strongly improved only recently with the advent of powerful 4π devices. Well defined systems or subsystems which undergo multifragmentation have been carefully selected. Moreover central collisions between heavy nuclei have revealed the importance of a compression phase followed by expansion to cause multifragmentation [1].

We report here on studies performed with INDRA [2] of multifragmentation of very heavy fused systems formed at the same excitation energy : $^{129}Xe+^{nat}Sn$ at 32 MeV/u and $^{155}Gd+^{nat}U$ at 36 MeV/u. They can be identified to well defined pieces of nuclear matter and reveal bulk properties to be compared to models in which bulk or volume instabilities are present.

When studying experimentally multifragmentation of systems with more than 200 nucleons, fragments with Z in the range 20-50 are produced. For such fragments a careful energy calibration was performed for solid state detectors (silicon detectors or mineral scintillators) [3, 4]. Moreover for CsI(Tl) scintillators a better understanding of the light response was obtained; a direct consequence was an improvement for heavy fragment identification in ionization chamber - CsI(Tl) modules [4]

Many theories have been developed to explain multifragmentation (see for example ref. [5] for a general review of models). One can come in particular to the concept of multifragmentation by considering a liquid-gas phase transition in excited nuclear matter. It is commonly believed that, during a collision, a wide zone of the nuclear matter phase diagram may be explored and that 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 incompressibility). Thus, a possible origin of multifragmentation may be found through the growth of density fluctuations in this unstable region.

Among the models some are related to statistical approaches [6, 7] whereas other, more ambitious, try to describe the dynamical evolution of systems resulting from collisions between two nuclei taking into account the dynamics of the phase transition. Thus theoretical dynamical scenarios to be compared with experimental data are simulated via molecular dynamics [8, 9] or stochastic mean field approaches [10, 11, 12]. In this last dynamical approach, spinodal decomposition is simulated using a powerful tool, the Brownian One-Body (BOB) dynamics [13, 14], which consists in employing a Brownian force in the kinetic equations.

2 Experimental evidence for bulk effect in multifragmentation

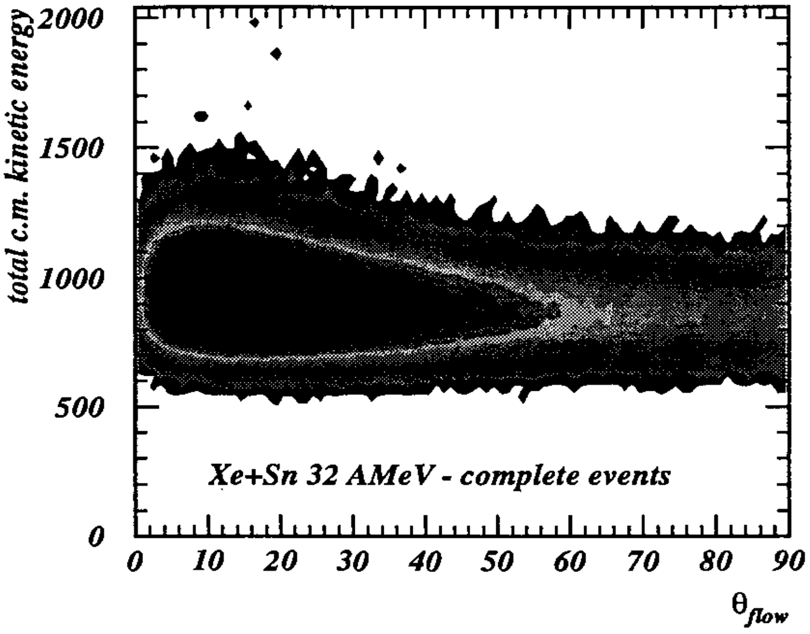

Figure 1: Wilczynski diagram for complete events: correlation between total measured c.m. kinetic energy and flow angle θ_{flow}.

Multifragmenting fused systems have been carefully selected for two reactions leading to the same available excitation energy per nucleon ($\sim 7MeV$) : $^{129}Xe +^{nat} Sn$ at 32 MeV/u and $^{155}Gd +^{nat} U$ at 36 MeV/u. The selection was performed by requiring the detection of a significant fraction ($\geq$ 80%) of the total charge; these selected events are called complete events. Then reaction products with charge Z $\geq$ 5 were defined as fragments. Finally the preferred direction of emission of matter in the center of mass of the reaction (flow angle) was determined from the calculation of the energy tensor of fragments, and the requirement was made that this angle be larger than 60^o [15, 16]. The main argument underlying the chosen selection is that while a fused system should be present at all flow angles, binary dissipative collisions should vanish when this angle is large, giving way to an almost pure phenomenon. Figure 1 exhibits, for the reaction $^{129}Xe +^{nat} Sn$, how complete events populate the flow angle domain as a function of their measured total kinetic energies (emitted

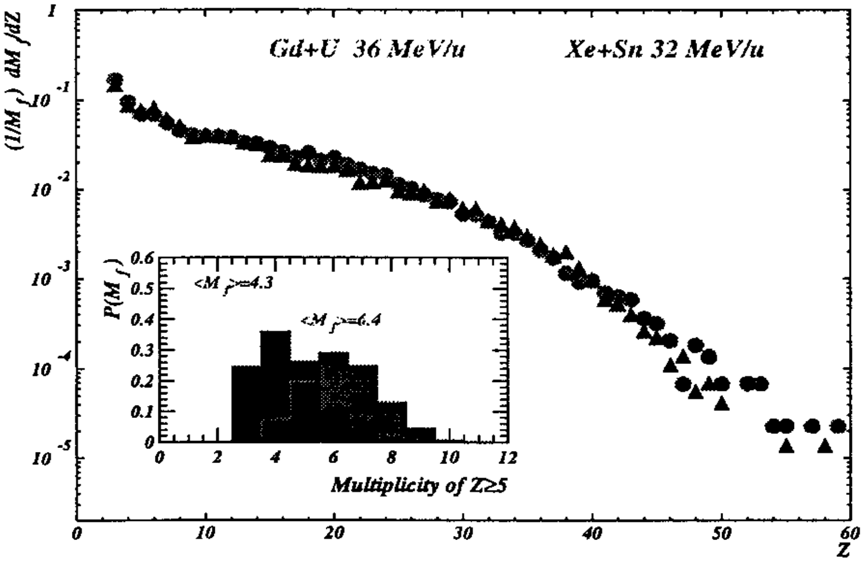

Figure 2: Experimental fragment multiplicity distributions and differential charge multiplicity distributions for the 32 MeV/u Xe+Sn (black histogram and triangles) and 36 MeV/u Gd+U (grey histogram and circles).

fragments + light charged particles). The same picture is observed for the heavier system. Fig 2 shows that, for the two fused systems, we observe the same Z distribution for fragments while the fragment multiplicities scale as the size of the total systems. This independence of the Z distribution, experimentally observed for the first time [17], can be considered as a strong evidence of a bulk effect for producing fragments. It can be related to bulk instabilities in the liquid-gas coexistence region of nuclear matter (spinodal region) or perhaps simply taken as a signature of a full exploration of phase space for such heavy systems. Indeed multiplicities, charge distributions and average kinetic energies of fragments compared with values for both the dynamical (BNV/BOB) and the statistical (SMM) approaches including secondary decays well match the experimental ones [18, 19, 20, 21]. In SMM the dynamical phase of the reaction is ignored and parameters such as the mass and charge of the multifragmenting system, its excitation energy, its volume (or density) and the added radial expansion have to be backtraced to the experimental data.

3 Charge correlation of fragments and spinodal decomposition

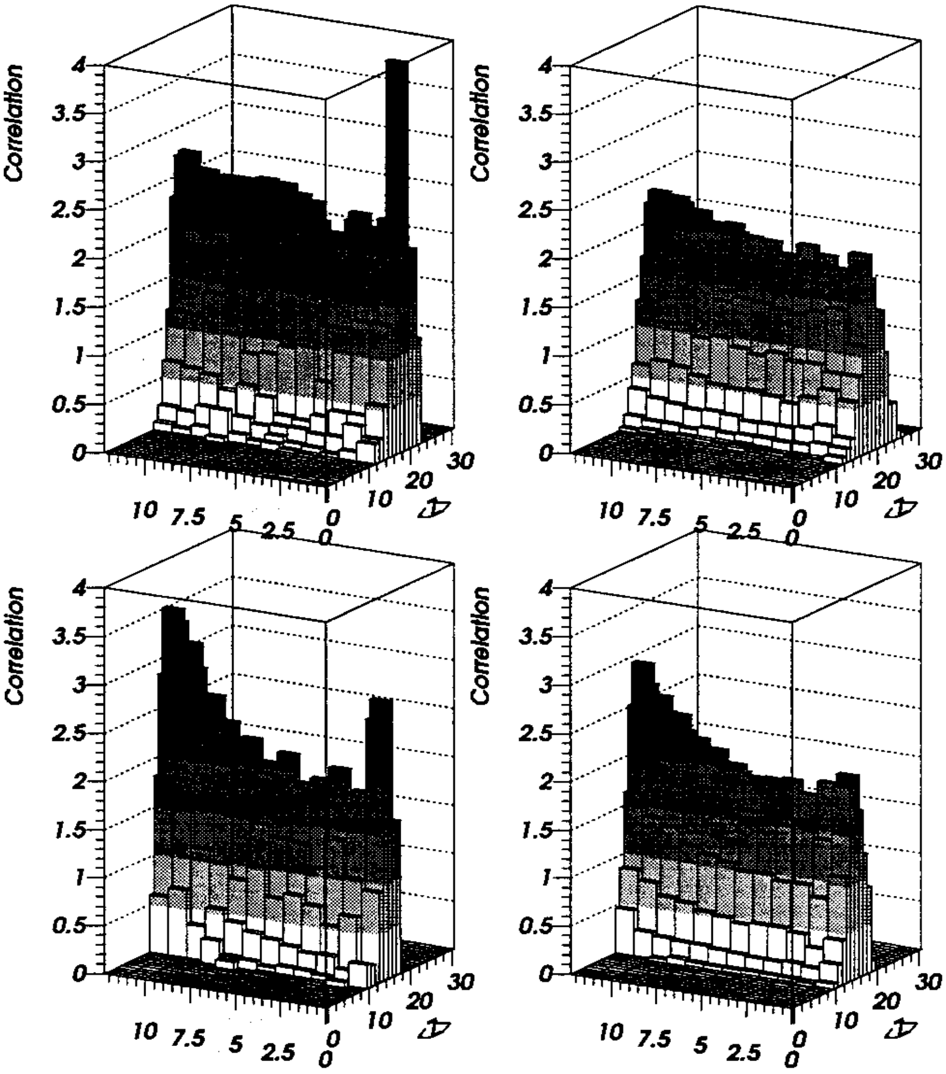

Figure 3: Fragment charge correlations for the reaction ^{129}Xe+^{nat}Sn at 32 MeV/u: comparison between isolated fused events ($\theta_{flow} \geq 60^o$-left) and most dissipative events (see text-right) for fragment multiplicities equal to 3 (up) and 4 (down) (from [22]).

To put ultimate constraints on models, we can and should also compare fragment correlations in events, which are fully meaningful experimentally because of the completeness of the detection and of the quality of Z identification.

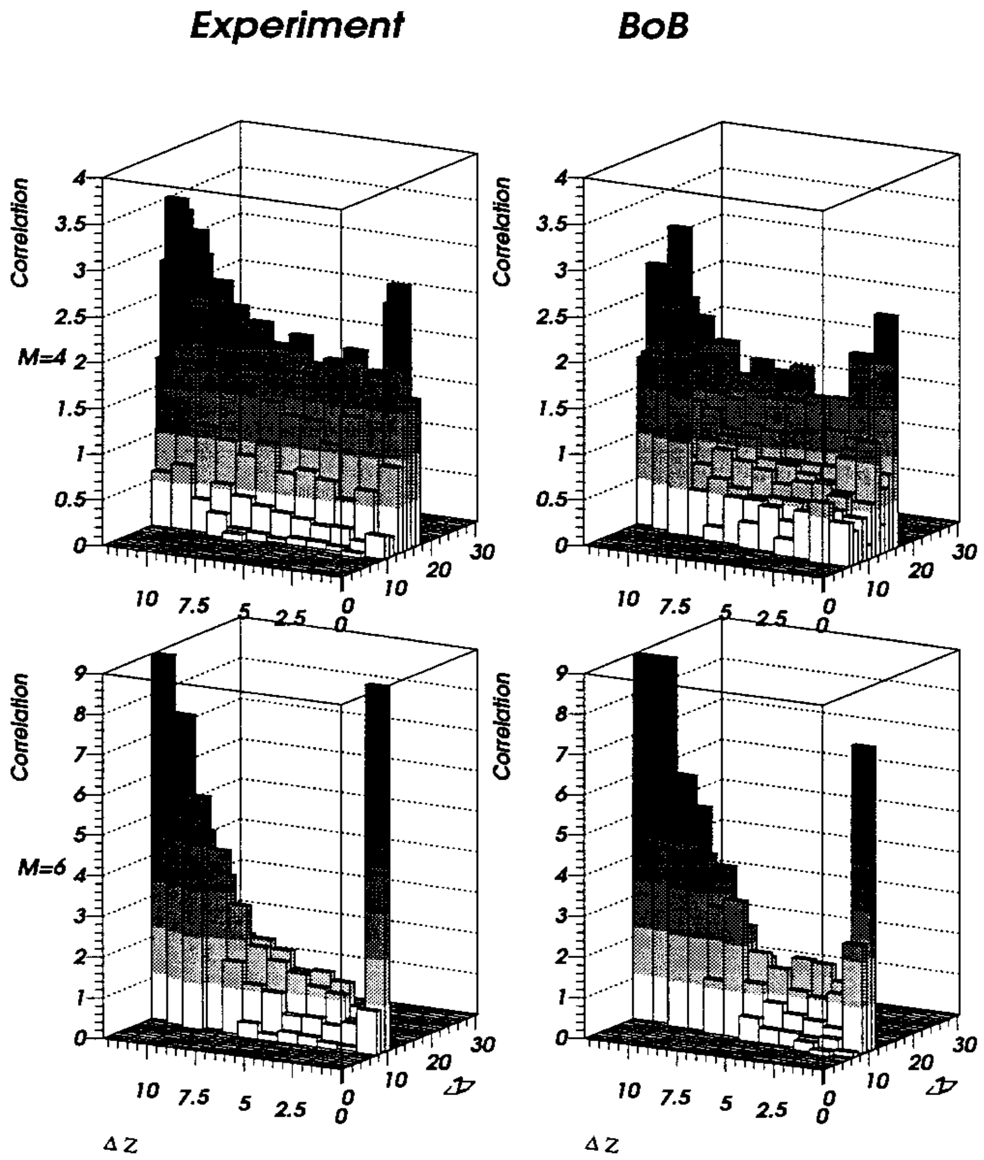

Figure 4: Fragment charge correlations for the reaction ^{129}Xe+^{nat}Sn at 32 MeV/u: Comparison between experiment (left) and BOB calculations (right) for fragment multiplicities equal to 4 and 6 (from [22]).

If spinodal instabilities occur the most unstable modes present in the spinodal region are predicted to favor "primitive" partitions of nearly equal-sized fragments (Z:10-15) [23]. But this simple picture is expected to be blurred

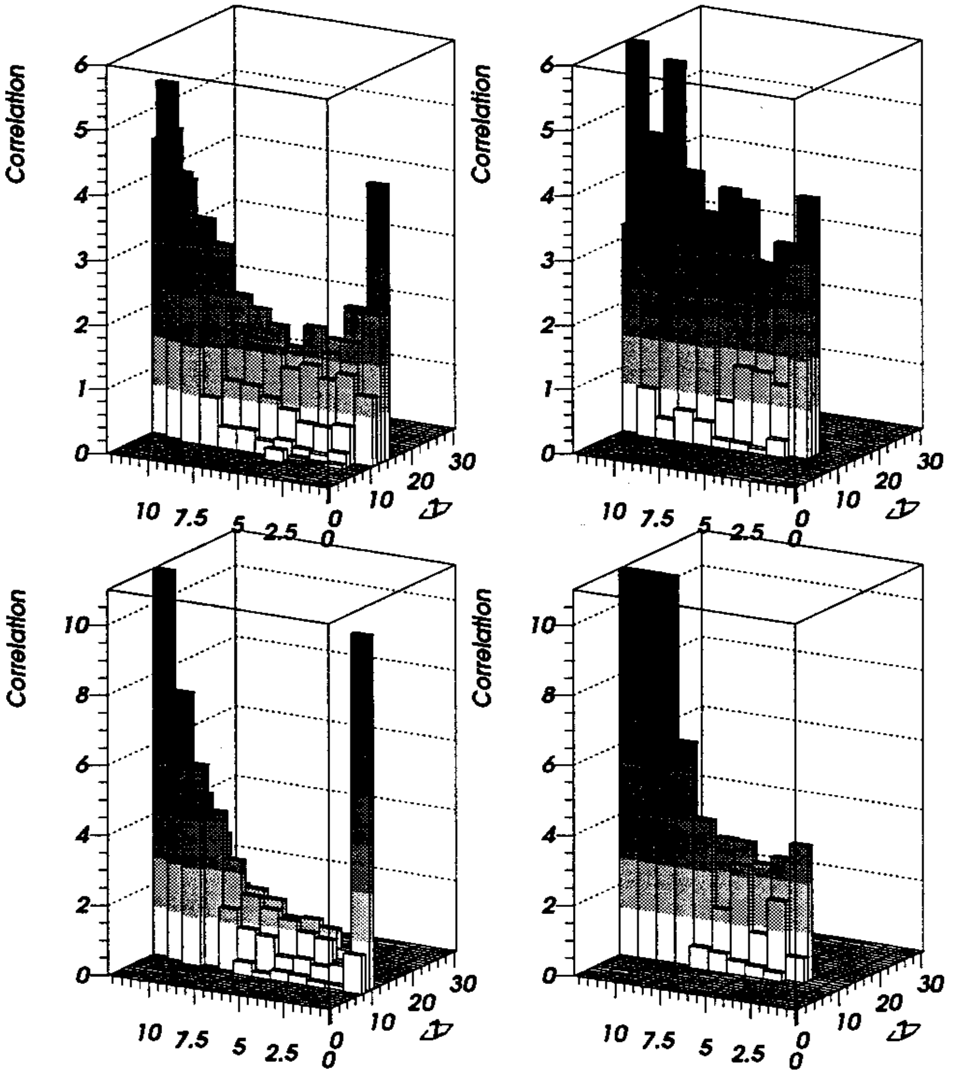

Figure 5: Fragment charge correlations for the reaction ^{129}Xe+^{nat}Sn at 32 MeV/u: Comparison between experiment (left) and SMM calculations (right) for fragment multiplicities equal to 5 and 6 (from [22]).

by several effects: the beating of different modes, eventual coalescence of the "primitive " fragments and the finite size of the system, and indeed experimental Z distributions (see fig 2) do not present any visible enhancement around Z=10-15. Then how to search for a possible very weak "fossil" signature of spinodal decomposition? A few years ago a new method called higher order charge correlations was proposed in [24]. To search for very weak signals, all fragments in one event (average fragment charge Z and the standard deviation per event △Z) are used to build the charge correlation for each fragment multiplicity. Due to statistics in experiments this method was only applied on the Xe+Sn system [22]. A signal is observed for the different multiplicities from 3 to 6. Examples of the observed experimental correlations are shown in figure 3 (left part). Note that if we enlarge our data sample to all very dissipative collisions (total c.m. kinetic energy lower than 1170 MeV whatever θ_{flow}- see figure 1), which are dominated by binary collisions, the signal is no more present (right part). It clearly shows the importance of a thorough selection to observe this signal which concerns 0.1% of the considered events.

Concerning the models we again observe an impressive agreement of the BNV/BOB simulation (simulated events are filtered to take into account the experimental set-up) with the data (see figure 4). We learn also from these simulations that secondary deexcitations (deexcitation part of the SIMON code) modify very slightly the signals. The bin in △Z used in all this work was fixed by studying secondary deexcitations for primary fragments with Z=15 produced in BNV/BOB simulations. From excitation energy and mass distributions of these primary fragments a secondary Z distribution was deduced : it is centered at Z=14 with a standard deviation of 0.6. Thus to take into account secondary decays, △Z was fixed to one atomic number unit. In figure 5 correlations built with SMM events are presented and compared to experimental data: they do not show any signal for an enhancement of events with equal-sized fragments.

4 Conclusions

A "fossil" signature of spinodal decomposition as the mechanism responsible for multifragmentation of heavy systems in the Fermi energy domain is observed for the first time. It consists in an enhancement of events with equal-sized fragments. A full dynamical model including also the dynamics of spinodal instabilities which was found to well reproduce all the experimental observables also reproduces the observed signal. A statistical model, when adding a radial expansion, reproduces also very well the experimental observables but the weak "fossil" signal. This fact indicates that dynamical instabilities are responsible for mutifragmentation and that they lead to an exploration of practically all phase space.

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