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Phase transition dynamics for hot nuclei

INDRA Collaboration

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ABSTRACT

An abnormal production of events with almost equal-sized fragments was theoretically proposed as a signature of spinodal instabilities responsible for nuclear multifragmentation in the Fermi energy domain. On the other hand finite size effects are predicted to strongly reduce this abnormal production. High statistics quasifusion hot nuclei produced in central collisions between *Xe* and *Sn* isotopes at 32 and 45 *A* MeV incident energies have been used to definitively establish, through the experimental measurement of charge correlations, the presence of spinodal instabilities. N/Z influence was also studied.

During the last decades the thermodynamics of finite nuclear systems was widely studied with heavy-ion collisions at intermediate and relativistic energies and with hadron–nucleus collisions at relativistic energies [1,2]. With such collisions, depending on impact parameter, a nuclear system can be heated, compressed and then diluted. These systems are expected to undergo a liquid-gas type phase transition that manifests itself through nuclear multifragmentation [3]. This theoretical expectation, discussed for many years for nuclear matter [4–7] is due to the similarity between the nuclear interaction and the Van der Waals forces acting in classical fluids [6,8]. However, a nucleus (or a nuclear system) is a finite system which shows specific behaviors in the transition region. Most of the predicted specific signals of phase transition are a direct consequence of the local convexity of the entropy which is expected for finite systems having a discontinuous transition in the thermodynamic limit [9–11,1]. By considering the microcanonical ensemble with energy as extensive variable, the convex intruder implies a backbending in the temperature (first derivative of entropy) at constant pressure and correlatively a negative branch for the heat capacity (second derivative). Experimentally, these

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two converging signatures have been observed from very different analyses. Negative heat capacities with a microcanonical sampling, were observed for 35 A MeV Au+Au semi-peripheral collisions [12] and confirmed by the INDRA collaboration for 32–50 A MeV Xe+Sn central collisions [8]. For caloric curves, their shape depends on the path followed by the system on the microcanonical equation of state surface, and a backbending (direct signature) can only be observed for a transition at constant pressure [13]. This was evidenced very recently for central 32–50 A MeV Xe+Sn collisions, thanks to a simulation based on experimental data [14] where a quantal temperature was calculated from the momentum fluctuations of protons present at freeze-out [15]. Pressure and volume-constrained caloric curves could be built and the expected behaviors were observed: a backbending for selected ranges of pressure and a monotonous increase at constant average volume [16]. Another consequence of the entropy curvature anomaly manifests itself when systems are treated in the canonical ensemble. In this case a direct phase transition signature is the presence of a bimodal distribution of an order parameter [17] like the charge (size) of the largest fragment (Z_{max}) of multifragmentation partitions. Bimodality was observed (with a canonical sampling) in 60–100 A MeV Au+Au semi-peripheral collisions, allowing moreover to estimate the latent heat for nuclei close to gold around 8 MeV per nucleon and to set the appearance of the pure gas phase above 9–10 MeV per nucleon excitation energy [18].

The answer to a key point was still pending: it concerns the nature of the dynamics of the transition, i.e. fragment formation. Two mechanisms have been proposed. On one side, stochastic mean field approaches predict the fragmentation process to follow the spinodal fragmentation scenario triggered by phase-space fluctuations amplified in an unstable medium and, on the other side, in molecular dynamics models (QMD, AMD) many-body correlations are sufficient to produce fragments at early times even in absence of unstable conditions [10,19–24]. Experimentally, there was an indication that multifragmentation may be induced by spinodal instabilities but the confidence level of the fossil signature was not sufficient (3–4 σ), due to low statistics, to allow drawing any definitive conclusion [25–27]. Such instabilities may occur when the system evolves through the mechanically unstable spinodal region of the phase diagram, located at densities $\rho \le \rho_0$ and temperatures below the critical temperature. Such conditions are well explored in central nuclear collisions around Fermi energy [28]. Moreover, if spinodal instabilities are at the origin of fragmentation, a reduction of instabilities for N/Z asymmetric systems in relation with an increase of the instability growth time is theoretically predicted [29]. In this letter we shall describe studies obtained with very high statistics (a factor 10 to 15 higher as compared to previous experiments) aiming to give a final answer as far as spinodal fragmentation is concerned and, secondly, to search for the related isospin effects.

The experiment was performed at GANIL (Grand Accélérateur National d'Ions Lourds) and two reactions were used ^{124,136}Xe+^{112,124}Sn at two bombarding energies, 32 and 45 A MeV, The beam, impinging on thin targets (530 μg cm^{-2}), had an intensity of about 3–5 10^7 ions per second to avoid event pile-up. Experimental data were collected with the 4π multidetector INDRA which is described in detail in Refs. [30,31]. Accurate particle and fragment identifications were achieved and the energy of the detected products was measured with an accuracy of 4%. Further details can be found in Refs. [32–34].

The data used in the analysis were obtained with an on-line multiplicity trigger of 4 or more detected reaction products. The number of such recorded events was between 60 and 80 million events for each colliding system. Quasi-complete events are selected by requiring that at least 80% of the total charge of the system is measured. We then isolate compact shape events (quasi-fusion) through the additional condition that the flow angle (θ_{flow}) be larger than 60°. Let us recall that θ_{flow} characterizes the main direction of matter emission in the center of mass of the reaction and is determined by the kinetic energy flow tensor calculated from fragments ($Z \geqslant 5$) [35]. Measured cross-sections corresponding to selected events are ≈ 40 mb at 32 A MeV and 25 mb at 45 A MeV. They were derived from the measured target thicknesses, the counting of ions collected in the Faraday cup located at the end of the beam line and the acquisition dead time. The charge of ions reaching the cup was obtained using the formulas of Ref. [36]. Total cross-sections for quasifusion events, taking into account detection efficiency and selection biases, are estimated to be ∼ 250 mb at 32 A MeV, and ∼ 180 mb at 45 A MeV.

In infinite nuclear matter the signature of spinodal instabilities is the formation of equal-sized fragments due to density fluctuations which grow exponentially with time. The most unstable modes correspond to wavelengths lying around $\lambda \approx 10$ fm and the associated characteristic times are equal to around 30–50 fm/c, depending on density ($\rho_0/2 - \rho_0/8$) and temperature (0–9 MeV) [37,38]. A direct consequence of the dispersion relation is the production of "primitive" fragments with size $\lambda/2 \approx 5$ fm which correspond to $Z \approx 8$–10. However, this simple picture is expected to be largely blurred by several effects. The beating of different modes occurs. Coalescence effects due to the nuclear interaction between fragments before the complete disassembly are also expected. For finite systems the situation is even more complicated. The presence of a surface introduces an explicit breaking of the translational symmetry with the important result that the growth rates are nearly the same for different multipolarities, which indicates that the unstable finite system breaks into different channels depending on multipolarity L [39]. Equal-sized "primitive" fragments are then expected to be produced with sizes in the range $A_F/2 - A_F/L_{max}$; A_F being the part of the system leading to fragments during the spinodal fragmentation. Moreover the finite system produced during the nucleus–nucleus collision has to stay or live long enough in the spinodal region (∼ 3 characteristic time – 100–150 fm/c – for symmetric matter) to allow an important amplification of the initial density fluctuations. And finally, we experimentally detect fragments after secondary decay, which introduces a broadening of the fragment size distribution. Taking into account the accumulation of all these effects on the final extra production of equal-sized fragments, it is clear that any signature that spinodal fragmentation is responsible for the phase transition dynamics can only be what we have called a fossil signature. A full simulation of the spinodal decomposition of quasifused sources using Brownian One-Body dynamics calculations [26] already testified to this fact, with less than 1% of events with equal-sized fragments. It is the reason why the signature is difficult to observe experimentally.

Twenty years ago an intra-event correlation function called higher order charge correlations [40] was proposed to enlighten any extra production of events with specific fragment partitions. The high sensitivity of the method makes it particularly appropriate to look for small numbers of events as those expected to have kept a memory of spinodal fragmentation properties.

All fragments of one event with fragment multiplicity $M = \sum_Z n_Z$, where n_Z is the number of fragments with charge Z in the partition, are taken into account. By means of the normalized first order:

$$\langle Z \rangle = \frac{1}{M} \sum_Z n_Z Z \qquad (1)$$

and second order: