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Constrained caloric curves and phase transition for hot nuclei

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ABSTRACT

Simulations based on experimental data obtained from multifragmenting quasi-fused nuclei produced in central $^{129}Xe + {}^{nat}Sn$ collisions have been used to deduce event by event freeze-out properties in the thermal excitation energy range 4–12 AMeV [S. Piantelli, et al., INDRA Collaboration, Nucl. Phys. A 809 (2008) 111]. From these properties and the temperatures deduced from proton transverse momentum fluctuations, constrained caloric curves have been built. At constant average volumes caloric curves exhibit a monotonic behaviour whereas for constrained pressures a backbending is observed. Such results support the existence of a first order phase transition for hot nuclei.

One of the most important challenges of heavy-ion collisions at intermediate energies is the identification and characterization of the nuclear liquid–gas phase transition for hot nuclei, which has been theoretically predicted for nuclear matter [1–4]. During the last fifteen years a big effort to accumulate experimental indications of the phase transition has been made. Statistical mechanics for finite systems appeared as a key issue to progress, revealing new first order phase transition signatures related to thermodynamic anomalies like negative microcanonical heat capacity and bimodality of an order parameter [5–9]. Before this, correlated temperature and excitation energy measurements, commonly termed caloric curves, were among the first possible signatures to be studied [10–13]. However in spite of the observation of a plateau in some caloric curves, no decisive conclusion related to a phase transition could be extracted [14–16]. The reason is that it is not possible to perform experiments at constant pressure or constant average volume, which is required for an unambiguous phase transition signature. Indeed, theoretical studies show that whereas many different caloric curves can be generated depending on the path followed in the thermodynamical landscape, constrained caloric curves must exhibit two behaviours if a first order phase transition is present: a monotonic evolution at constant average volume and a backbending of curves at constant pressure [17,18].

In Refs. [19,20] we presented simulations able to correctly reproduce most of the experimental observables measured for hot nuclei formed in central collisions (quasi-fused systems, QF, from $^{129}Xe + {}^{nat}Sn$, 32–50 AMeV). The aim of the present Letter is to use the event by event properties at freeze-out which were inferred from these simulations to build constrained caloric curves.

Experimental data were collected with the 4π multidetector INDRA which is described in detail in Refs. [21,22]. Accurate particle and fragment identifications were achieved and the energy of the detected products was measured with an accuracy of 4%.

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Further details can be found in Refs. [23–25]. All the available experimental information (charged particle energy spectra, average and standard deviation of fragment velocity spectra and calorimetry) of selected QF sources produced in central ^{129}Xe + ^{nat}Sn collisions which undergo multifragmentation was used.

The method for reconstructing freeze-out properties from simulations [19,20] requires data with a very high degree of completeness, crucial for a good estimate of Coulomb energy. QF sources are reconstructed, event by event, from all the fragments and twice the charged particles emitted in the range 60–120° in the reaction centre of mass, in order to exclude the major part of pre-equilibrium emission [26,27]; with such a prescription only particles with isotropic angular distributions and constant average kinetic energies are considered. In simulations, excited fragments and particles at freeze-out are described by spheres at normal density. Then the excited fragments subsequently deexcite while flying apart. Four free parameters are adjusted to fit the data at each incident energy: the percentage of measured particles which were evaporated from primary fragments, the collective radial energy, a minimum distance between the surfaces of products at freeze-out and a limiting temperature for fragments. All the details of simulations can be found in Refs. [19,20]. The limiting temperature, related to the vanishing of level density for fragments [28], was mandatory to reproduce the observed widths of fragment velocity spectra. Indeed, the sum of Coulomb repulsion, collective energy, thermal kinetic energy and spreading due to fragment decays accounts only for about 60–70% of those widths. By introducing a limiting temperature for fragments, the thermal kinetic energy increases, due to energy conservation, which produces the missing percentage for the widths of final velocity distributions. The agreement between experimental and simulated velocity/energy spectra for fragments, for the different beam energies, is quite remarkable (see Fig. 3 of [20]). Relative velocities between fragment pairs were also compared through reduced relative velocity correlation functions [29,30] (see Fig. 4 of [20]). Again a good agreement is obtained between experimental data and simulations, which indicates that the retained method (freeze-out topology built up at random) and the deduced parameters are sufficiently relevant to correctly describe the freeze-out configurations, including volumes. However it should be noted that the agreement between experimental and simulated energy spectra for protons and alpha-particles (see Fig. 5 of [20]) is not so good; this may come from the fact that we have chosen a single value, at each incident energy, for the percentage of all measured particles which were evaporated from primary fragments to limit the number of parameters of the simulation. We shall come back to this point later.

From the simulations we deduce, event by event, various quantities needed to build constrained caloric curves, namely the thermal excitation energy of QF hot nuclei, E^* (total excitation minus collective energy) with an estimated systematic error of around 1 AMeV, the freeze-out volume V (see envelopes of Fig. 8 from [20]) and the total thermal kinetic energy at freeze-out K. Events are sorted into E^* bins of 0.5 AMeV with their associated kinetic temperature T_{kin} at freeze-out. In simulations, Maxwell–Boltzmann statistics are used for particle velocity distributions at freeze-out and consequently the deduced temperatures, T_{kin}, are classical. It is important to stress here that, at present time, there is no unique thermometer and, depending on the excitation energy range, disagreements can be observed between kinetic, chemical temperatures and temperatures deduced from excited states [15,16,31,32].

With regard to the pressure at freeze-out, it can be derived within the microcanonical ensemble. Let us consider fragments interacting only by Coulomb and excluded volume, which corresponds to the freeze-out configuration. Within a microcanonical ensemble, the statistical weight of a configuration C, defined by the mass, charge and internal excitation energy of each of the constituting M_C fragments, can be written as

$$\begin{aligned} W_C(A,Z,E,V) = {} & \frac{1}{M_C!}\chi V^{M_C}\prod_{n=1}^{M_C}\left(\frac{\rho_n(\epsilon_n)}{h^3}(mA_n)^{3/2}\right) \\ & \times \frac{2\pi}{\Gamma(3/2(M_C-2))}\frac{1}{\sqrt{(\det I)}} \\ & \times \frac{(2\pi K)^{3/2M_C-4}}{(mA)^{3/2}}, \end{aligned} \tag{1}$$

where A, Z, E and V are respectively the mass number, the atomic number, the excitation energy and the freeze-out volume of the system. E is used up in fragment formation, fragment internal excitation, fragment–fragment Coulomb interaction and thermal kinetic energy K. I is the inertial tensor of the system whereas χV^{M_C} stands for the free volume or, equivalently, accounts for inter-fragment interaction in the hard-core idealization.

The microcanonical equations of state are

$$\begin{aligned} T &= \left(\frac{\partial S}{\partial E}\right)^{-1}\Bigg|_{V,A}, \\ P/T &= \left(\frac{\partial S}{\partial V}\right)\Bigg|_{E,A}, \\ -\mu/T &= \left(\frac{\partial S}{\partial A}\right)\Bigg|_{E,V}. \end{aligned} \tag{2}$$

Taking into account that $S = \ln Z = \ln\sum_C W_C$ and that $\partial W_C/\partial V = (M_C/V)W_C$, it comes out that

$$\begin{aligned} P/T = \left(\frac{\partial S}{\partial V}\right) &= \frac{1}{\sum_C W_C}\sum_C \frac{\partial W_C}{\partial V} \\ &= \frac{1}{V}\frac{\sum_C M_C W_C}{\sum_C W_C} = \frac{\langle M_C\rangle}{V}. \end{aligned} \tag{3}$$

The microcanonical temperature is also easily deduced from its statistical definition [33]:

$$\begin{aligned} T = \left(\frac{\partial S}{\partial E}\right)^{-1} &= \left(\frac{1}{\sum_C W_C}\sum_C W_C(3/2M_C-5/2)/K\right)^{-1} \\ &= \big\langle(3/2M_C-5/2)/K\big\rangle^{-1}. \end{aligned} \tag{4}$$

As M_C, the total multiplicity at freeze-out, is large, we have

$$T \approx \frac{2}{3}\left\langle\frac{K}{M_C}\right\rangle \tag{5}$$

and the pressure P can be approximated by

$$P = T\frac{\langle M_C\rangle}{V} \approx \frac{2}{3}\frac{\langle K\rangle}{V}. \tag{6}$$

Knowing $\langle K\rangle$ and V from simulations, pressure P can be calculated for events sorted in each E^* bin. The temperature T_{kin} that we obtain from the simulations is identical to the microcanonical temperature of Eq. (5). One can also note that the free Fermi gas pressure exactly satisfies Eq. (6).

Constrained caloric curves, built with correlated values of E^* and T_{kin} have been derived for QF hot nuclei with Z restricted to the range 80–100, which corresponds to the A domain 194–238, in order to reduce effects of mass variation on caloric curves [13]; they are presented in Fig. 1. Curves for internal fragment temperatures, T_f, are also shown in the figure. For two different average