# THERMODYNAMICAL ASPECTS IN HEAVY ION REACTIONS

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The excited nuclear systems formed in heavy ion collisions can be studied from a thermodynamical point of view. Charged finite systems have different behaviors with respect to infinite ones. After experimental selection of such equilibrated systems the extraction of thermodynamic coordinates is performed. Different signals compatible with a liquid-gas phase transition have been obtained. In particular a bimodal distribution of the asymmetry between the first two heaviest fragments is presented. Abnormally large fluctuations, which in thermodynamic equilibrium are associated to a negative branch of the heat capacity give indications of a first order phase transition. Perspectives for new generation experiments are indicated.

## 1. Introduction

Heavy ion collisions are routinely used to explore the phase diagram of nuclear matter. In particular the fact that nuclei in their ground state behave like Fermi liquids, and at high excitation energy can be decomposed in a vapor of light particles and clusters, supports the studies of a possible phase transition in the nuclear bulk (see Fig. 1). Several signals of such a phase

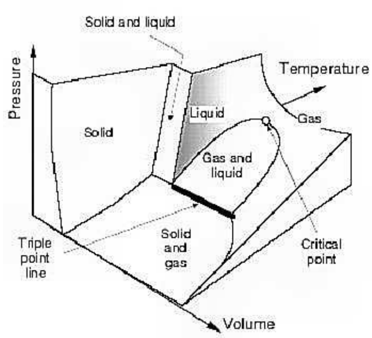


Figure 1. Equation of state for a fluid

change have been found, like a *plateau* in caloric curves[1,2], a sudden onset of multifragmentation and collective expansion, an increased probability for equal sized fragments possibly reminiscent of a spinodal decomposition[3], an abnormal enhancement of partial energy fluctuations tentatively associated to a negative branch of the heat capacity[4], a bimodal distribution of exclusive observables hinting phase coexistence[5], universal scaling laws both for the heaviest fragment and for the droplet distributions[6,7].

In this paper we will present results obtained in peripheral and central collisions of Au projectiles on different targets at 25 and 35 AMeV incident energies[7]. Data have been collected at the NSCL Cyclotron of the Michigan State University with the Multics-Miniball apparatus[8,9].

## 2. Sorting the events

Fig. 2 shows a schematic representation of a typical collision dynamics as predicted by nuclear transport models, for nearly central collisions. After the projectile hits the target, a fast compression phase ($\approx$ 20 fm/c) starts and pre-equilibrium light particles are emitted. Then the system expands and reaches the so-called freeze-out stage ($\approx$ 100 fm/c) where the interactions among the fragments vanish and fragments are chemically and energetically well defined. Excited fragments then undergo a slow secondary

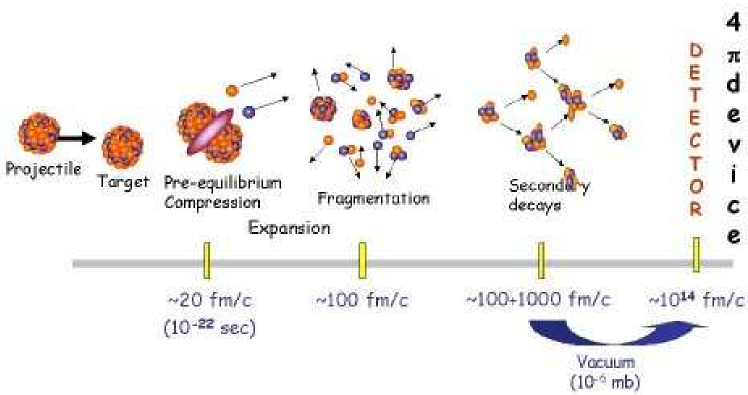


Figure 2. Time evolution of an intermediate incident energy reaction.

decay in vacuum with times of the order of some hundreds of fm/c. Almost all the final products of the reaction are detected by a $4\pi$ device after an almost infinite time (nsec) with respect to the previous time scales.

In order to perform a thermodynamic analysis, data have to be selected to obtain systems as close as possible to a thermodynamic equilibrium, and at different excitation energies, which can be experimentally determined by calorimetry:
$E^* + m_0 = \sum_{i=1}^{M}(m_i + k_i) + M_n(m_n + k_n)$,
where $m_0$, $m_i$ and $m_n$ are the masses of the fragmenting system, of the M fragments and of neutrons, respectively and $k_i$ and $k_n$ are the kinetic energies of fragments and neutrons.

This can be achieved by peripheral reactions, where the excitation function of the Quasi-Projectile (QP) can be studied with only one reaction, or by several measurements of central reactions with different beam energies. Global variables or more sophisticated statistical methods can be used to perform a centrality sorting of the events. One of these is the flow-tensor method[10], where the fragment momenta covariance matrix is diagonalized and the main eigenvector direction provides the average flow direction.

## 3. Equilibrium partitions

After the events have been sorted, one needs to check the statistical nature of the source emission. This can be done in several ways. From a pure experimental point of view the isotropic emission of all the particles and fragments emitted by the excited sources can be assessed, both in peripheral and in central collisions[11].

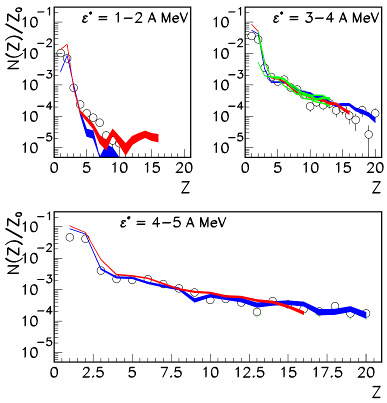


Figure 3. Charge distribution of all detected fragments but the heaviest for Au QP source (symbols) compared to central *Au + C, Au + Cu* collisions (dark grey lines) and the FASA (p,$\alpha$ + Au at 8.1, 4 and 14.6 GeV)[12] and ISIS data ($\pi$ + Au)[13] (light grey lines) in the same calorimetric energy bins. The distributions are normalized to the charge of the emitting source.

A second check is to compare the measured distributions to predictions of a statistical multifragmentation model, which assumes a freeze-out equilibrium stage and a uniform phase space population with the same constraints as in the data. The comparison of charge and kinetic energy distributions show a very good agreement in the whole range of excitation energies[7].

A third way of assessing equilibrium can be obtained by comparing several observables in the same interval of the excitation energy, independent on the way the excited sources are formed. In Fig. 3 a very good agreement has been obtained between peripheral and central heavy ion reactions, as well as with excited sources obtained with pions or light particles as projectiles[12,13].

## 4. Self-similarity and scalings

The charge distribution in the 4-5 AMeV excitation energy range exhibits a power law behavior with an exponent close and greater than 2[7] (see Fig. 3), as expected at the critical point of the nuclear liquid gas phase transition[14], or inside the coexistence region of finite systems undergoing a first order phase transition[15].

Two different "critical" analyses have been performed, the first based on the moments of the size distribution[16] and the second on the Fisher droplet model[17]. This last method shows a universal straight line in the scaled yield of fragments, $n_A/(q_0 A^{-\tau})$ *vs.* the scaled temperature $\epsilon A^\sigma/T$ in a semi-logarithmic presentation (see Fig. 4). $q_0$ is a normalization constant depending only on the value of $\tau$[18]. This scaling[7] yields "critical" parame-

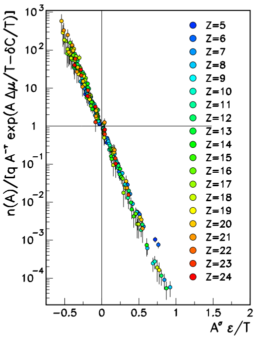


Figure 4. Scaled yield for Au QP events as a function of the scaled temperature.

ters $\sigma$ and $\tau$ very similar to the ones for a liquid-gas phase transition at a "critical" excitation energy $\epsilon_c \approx 4.4\ AMeV$, the very same parameters obtained in a moment analysis[19]. The scaling is consistent with similar results obtained by the EOS[6] and ISIS[20] collaborations.

## 5. Thermodynamics

To get additional information on the behavior of excited nuclear systems a thermodynamic analysis has to be performed. This can be done in the framework of a "canonical" or "microcanonical" treatment.

### 5.1. *"Canonical" treatment*

In the thermodynamic limit, the order parameter of a first order phase transition presents an abrupt jump at the transition temperature from the ordered (liquid like) to the disordered (gas like) phase.

For finite systems the transition is smoothed, and in the vicinity of the transition the two phases are populated at the same temperature[21]: the probability distribution of the matter density, and of all other observables correlated to an order parameter like the size of the heaviest fragment, show a bimodal behavior.

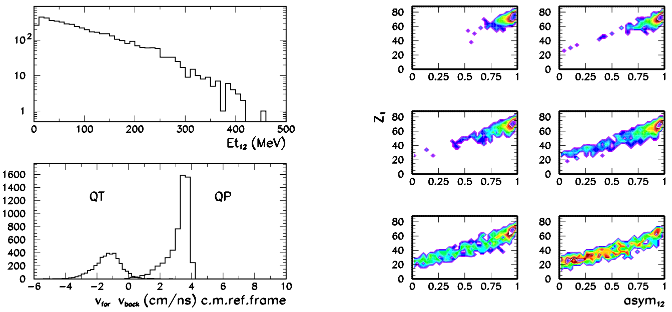


Figure 5. Lower left panel: plot of parallel velocity in peripheral Au + Au at 35 AMeV. QP and quasi-target (QT) emissions are clearly separated. Upper left panel: light particle (Z =1 and Z =2) transverse energy for QT. Right panel: Size of the heaviest fragment as a function of heaviest and second heaviest fragment asymmetry for six different transverse energy bins. The transverse energy increases from the top left to the bottom right panels. Nearly symmetric fission events have been removed[19].

From an experimental point of view, in a sample of binary peripheral events, one cannot fix the temperature of the system, but it is possible to make a canonical-like sorting of the data using, as sorting parameter, the transverse energy of light particles emitted by the quasi-target source. The asymmetry between the two heaviest fragments emitted by the quasi-projectile has been proposed as a possible candidate for the order parameter[5]. In Fig. 5 we show in the left panels the velocity distribution of the fragments indicating a binary collision and the distribution of the transverse energy of Z = 1 and 2 particles emitted by the quasi-target. The right panels show the size of the heviest fragment vs. the asymmetry distribution in equally spaced bins of the transverse energy. A bimodal distribution clearly appears at least in the fourth and fifth bins, where the excitation energy is around 4.4 AMeV, as in the "critical" analysis (see sect. 4).

### 5.2. *"Microcanonical" treatment*

A straightforward way of sorting experimental events is as a function of the total deposited energy. In the limiting case of a perfect detection, this corresponds to a microcanonical sorting.

The excitation energy is composed by a configurational part, due to Coulomb and Q-values of the partitions, and a kinetic part consisting in the translational energy plus the internal energy of fragments at the freeze-out stage:
$E^* = E_{config} + E_{kin} = E_{coul}(V) + Q_v + T_{tr}(T) + E_{int}(T)$.
This decomposition of the measured energy needs an estimation of the average volume $V$ and temperature $T$ of the system at the freeze out stage.

In the absence of collective flows, the average volume at freeze out can be backtraced from the measured mean kinetic energy of the final fragments. The result is a volume about 2.7 times the normal density one, consistent with spherical fragments close to normal density at freeze out[11]. Different thermometers have been used to estimate the temperature [4,11,22] showing a good consistency and a global agreement with other temperature systematics[1,2] and fragment internal excitation energy evaluation[23].

In thermodynamic equilibrium, the fluctuations $\sigma^2_{kin}$ of the kinetic energy $E_{kin}$ are linked to the heat capacity through the relation
$\frac{C_{kin}}{C} = 1 - \frac{\sigma^2_{kin}}{\sigma^2_{can}}$, where $\sigma^2_{can} = T^2 C_{kin} = T^2 \frac{dE_{kin}}{dT}$.
In a first order phase transition with finite latent heat, $\sigma^2_{kin}$ exceeds the canonical fluctuations $\sigma^2_{can}$ and the heat capacity is negative[4,24].

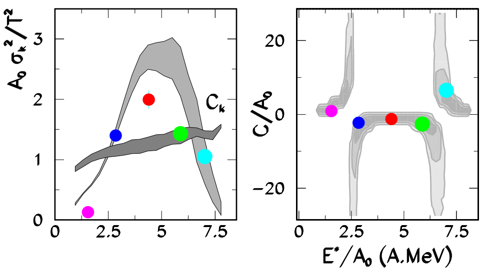


Figure 6. Left panel: normalized partial energy fluctuations for QP events (gray contours) and central Au + C, Au + Cu and Au + Au central events (symbols). Right panel: estimate of the heat capacity per nucleon of the source.

The results are shown in Fig. 6 where two divergences and a negative branch of the heat capacity clearly appear, both for peripheral and central collisions. The separation between the two divergences is related to the latent heat. In the framework of thermodynamic equilibrium these results are a serious evidence of a first order phase transition and have been confirmed by other collaborations[11,25].

## 6. Perspectives and conclusions

All results of the analyses described in the previous sections, are compatible with a phase coexistence, however the quantitative determination of the nuclear phase diagram is far from being achieved. In particular "contextual" experimental information are needed on the partitioning of the system, fluctuations, and event by event calorimetric excitation energy. To this aim a $4\pi$ mass and charge detection system is necessary.

In addition the extra degree of freedom in the nuclear equation of state, the isospin, has to be investigated. New generation devices and exotic beams are needed to fully investigate the phase transition by changing the Coulomb properties and the isospin content (N/Z) of the fragmenting systems. Hot liquid-drop model calculations[26] of the limiting temperature, i.e. the maximal temperature a nucleus can stand while evaporating and a systematic analysis of the saturation temperature (in the caloric curve) as a function of the size of the system[2] lead to the expectation that for $A \approx 100$ proton very rich nuclei the limiting temperature vanishes.

With all this in mind the NUCL-EX collaboration[a] began an experimental campaign aiming to thermodynamically explore systems of

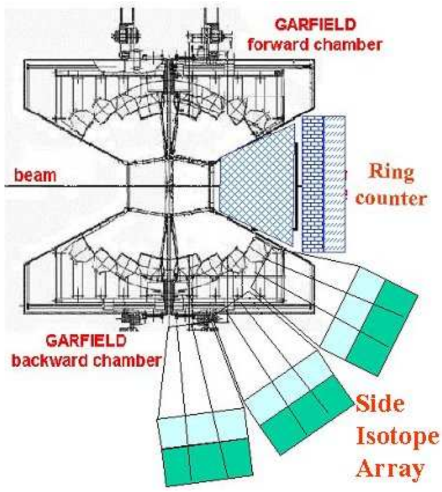


Figure 7. Schematic drawing of the Garfield apparatus

$A \approx 100$ starting from the liquid side. The first experiment with 25 AMeV

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Ni beams on Ca targets has been performed with the Chimera apparatus at the INFN LNS in Catania. The experimental program will continue at the INFN LNL in Legnaro with the GARFIELD apparatus[27] (see Fig. 7). The apparatus consists in two drift chambers covering a large solid angle region where energy loss and residual energies of light particles and fragments are measured with very low thresholds by micro-strip gas chambers and CsI crystals. The two chambers are complemented[28] with a forward annular device (Ring Counter) covering the forward region $6^o \div 18^o$ and another device (Side Isotope Array) which covers from $20^o$ to $90^o$ in the horizontal plane. These two devices consist in three stage (ionization chamber, silicon detector and CsI scintillator) telescopes allowing mass and charge determination up to Oxygen isotopes.

The use of newly designed digital electronics[29] will allows to use a pulse-shape discrimination technique in the CsI crystals in order to have, over the whole solid angle, the isotope determination of light particles and fragments ($Z \leq 4$). First results with a S beam on Ni isotopes at 14.5 AMeV show a very good charge and mass identification[28] and allow also for evaporation residues identification.

In order to have information on fragment multiplicity at the freeze-out

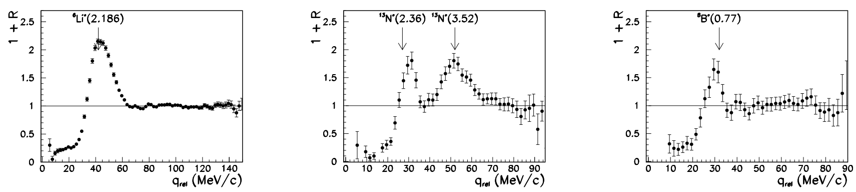


Figure 8. Left panel: deuteron - $\alpha$; middle panel: proton - Carbon; right panel proton - Berillium correlation functions in $^{32}S$ + $^{64}Ni$ reaction at 14.5 AMeV

stage, the correlation between light particles and fragments (see Fig. 8) allow to extract information on the secondary decays and therefore to have information on primary partitions and, consequently, better determination of temperatures from isotope abundance.

The analysis is in progress to characterize the source and check the fragment emission time scales.

In conclusion, the physics of hot nuclei is a unique laboratory for the thermodynamics of finite, charged, two component systems and for a quantitative nuclear metrology. Interdisciplinary connections are also important. In Fig. 8 p + $^7Be$ and p + $^{12}C$ correlation functions are shown, indicating $^8B^*$ and $^{13}N^*$ excited state formation inside the nuclear medium. This has also astrophysical interests since these processes are important in the stellar evolution.

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