Letter of intent

Thermodynamical coordinates of excited nuclear systems

M. Bruno, M.D'Agostino, S. Fabbri, E.Geraci, G.Vannini
Department of Physics and INFN,Bologna

L.Bardelli, M. Bini, G. Casini, M. Chiari, P. Del Carmine, A.Nannini, A. Olmi, G. Pasquali, S.Piantelli, G. Poggi
Department of Physics and INFN, Firenze

S. Barlini, F. Gramegna, A. Lanchais, R. A. Ricci, L. Vannucci
INFN, Laboratori Nazionali di Legnaro

C. Birattari, F. Cerutti, A. Clivio, M. Cavinato, E.M. Fabrici, E. Gadioli, E. Gadioli Erba, A. Giussani, A. Moroni
Department of Physics and INFN, Milano

A.Ordine
INFN, Napoli

U. Abbondanno, G. V. Margagliotti
Department of Physics and INFN, Trieste

(**NUCL-EX Collaboration**)

Abstract

The plan of measurements presented by the NUCL-EX collaboration represents a systematic study of the liquid-gas coexistence region, starting from the liquid side.
Many observables will be investigated at the same time and in particular the caloric curve, the size of the heaviest fragment, the critical exponent, the bimodality, the negative branch of the heat capacity.
This study will contribute to a better definition of the path in the plane of the thermodynamical coordinates and to the nuclear equation of state.
We will investigate systems in the $A \approx 100$ region through different reactions in the beam energy range $10 \div 25 AMeV$.
An upgrading of the Garfield apparatus and ancillary detectors will allow to measure also the mass of the charged decay products with $Z \leq 8$.
Finally the use of digital electronics for the signal processing and for the shape analysis will be investigated.

1 Introduction

The nucl-ex collaboration originated from a common interest of researchers, working in different experiments (Costhir, Fiasco and Strega), on investigating dynamical and thermodynamical aspects of heavy ion reactions, through experiments to be performed in the INFN *"Laboratori Nazionali di Fisica Nucleare"* in Legnaro and in Catania. In particular in the Legnaro Laboratories we plan to use the Garfield apparatus, with a suitable upgrading. In this letter of intent we will mainly focus on the thermodynamical aspects.

The existence of different phases for finite nuclear matter, predicted by theoretical calculations since the 60's, has been deduced from several experimental signals which give a circumstantial evidence of this occurrence [1]. The signals for the phase coexistence and phase transition [2, 3, 4, 5, 6, 7] have been extracted from experimental data through procedures which backtrace the information from measured asymptotic data to the initial stage of the reaction. To better clarify this picture, many new and more precise measurements are needed.

We would like to perform a systematic study of the liquid-gas coexistence region, starting from the liquid side, up to some AMeV of center of mass energy. Indeed, from first measurements performed at the ALPI accelerator (LNL) with the Garfield apparatus at relatively low excitation energies ($\sim$ 3 AMeV), it resulted that nuclear multifragmenting sources of A $\approx$ 100, formed in central collisions, already manifest the behavior expected for a system in the coexistence region, i.e. the enhanced production of nearly equal size fragments [8] (see Fig. 1).

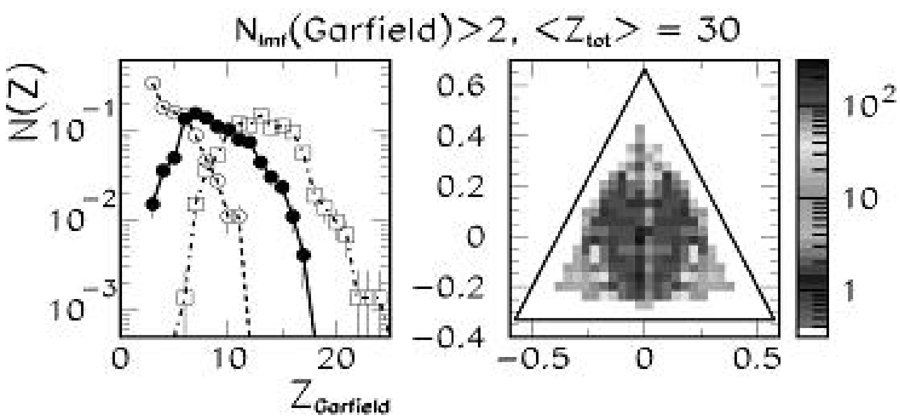

Figure 1: Left panel: Z distribution of the largest fragment (open squares), the second largest (full points) and third largest (open points). Right panel: Dalitz plot of the three largest fragments

It is important for the study of phase transition to perform a series of measurements with 4π second generation apparatuses, in order to investigate several signals of phase transition. From these studies, an experimental plan can also arise, to be performed with exotic beams and third generation apparatuses.

2 Experimental signals of the phase transition

Let's have a short look at the experimental observables which have given some indication of a liquid-gas phase transition and on the experimental difficulties in "measuring" it.

Many of the signals obtained up to now are only qualitative and can give information on the phase space region reached by the system, but not on the detailed trajectory (pressure, volume, temperature, isospin) followed by the system to pass from one phase to the other. Since the trajectory is determined by the equation of state of the finite nuclear matter and by the initial conditions of the system, it is easy to understand the importance of deeper investigations.

Other measured signals, though quantitative (e.g temperature measurements), are anyhow distorted, since the products are detected at an infinite time and not at the production time and therefore they need to be corrected through sophisticated correlation function techniques, as for instance in Ref. [9].

Among the signals we plan to investigate, in Fig. 2 shows:

- the "caloric curve" [2], with a plateau, typical of a first order phase transition;
- the decrease of the size of the heaviest fragment (liquid part) for increasing excitation energy (temperature) of the nuclear system, down to the size of the other fragments [3] (top panels);
- the bimodality [7], i.e the coexistence, in the same temperature interval, of events which remember the liquid phase together with events precursors of the pure "gas" phase;
- the critical exponents [3, 4] (line in the top middle panel);
- the negative branch of the heat capacity [6].

This last signal, measured for the first time in nuclear systems by the Multics collaboration, has been recently confirmed both in nuclear physics [10] and in other fields like the melting of atomic clusters [11] or the fragmentation of hydrogen clusters [12].

One can also investigate the limiting temperature, as defined by Bonche and Levit [13], i.e. the maximal temperature a (liquid) nucleus, with a definite value of N and Z, can stand when statistically evaporating light particles. This temperature has been recently connected [14] with a sudden change of the level density and with the plateau of the caloric curves (see Fig. 3).

The observations made up to now are not sufficient to determine the other thermodynamical coordinates, like volume (density) and pressure. In addition it is not yet well established experimentally how the N/Z ratio of the nuclear system, which enters in the asymmetry term of the nuclear equation of state, influences the decay modes of the excited system.

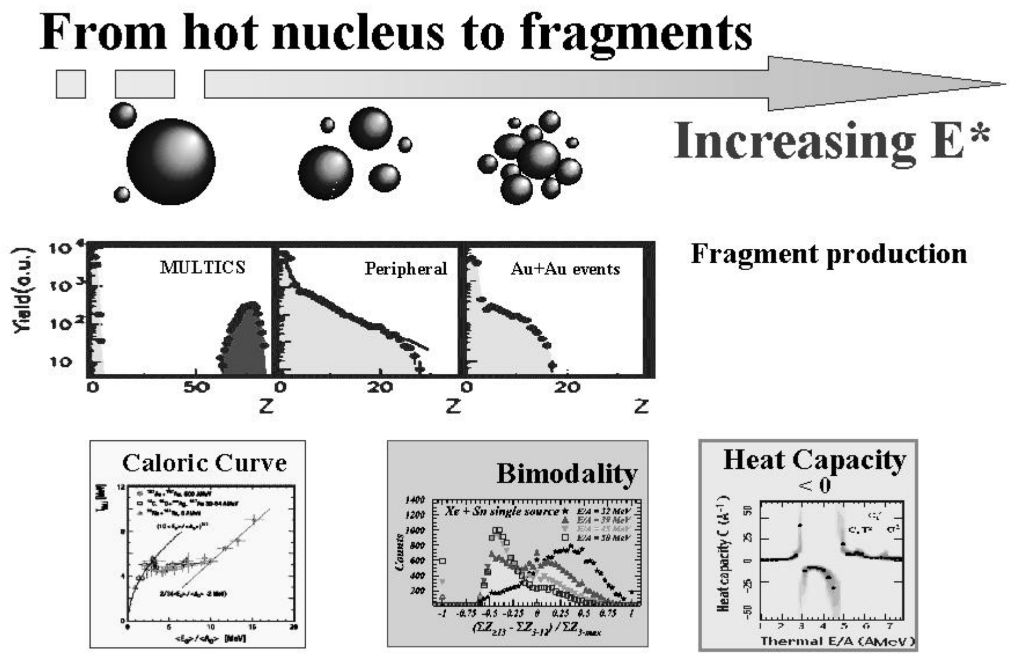

Figure 2: Upper panel: Fragment size distribution for increasing excitation energy [3]. Lower panels - from left to right: caloric curve [2], bimodality [7], negative heat capacity [6].

3 Plan of measurements

As pointed out in the Introduction, from the first experimental results obtained with the Garfield apparatus [8] it appears that even at relatively low excitation energies (< 3 A MeV) the nuclear system manifests the behavior expected in the coexistence region. The fact that the liquid-gas coexistence region starts at $\sim 2.5 \div 3.5$ AMeV excitation energy allows to plan thermodynamical studies at the Legnaro laboratories in the low-energy region. We propose here to experimentally investigate the coexistence region in central collisions of heavy ion reactions in the $10 \div 25$ AMeV range, with projectile-target combinations able to reach available c.m. energies up to $4 \div 5$ AMeV, provided that the Alpi accelerator is upgraded with the new cavities up to 25 AMeV, for intermediate mass beams, as already planned by the Laboratories.

A series of measurements at relatively low energies (up to now never performed with a 4π apparatus) can give quantitative information on thermodynamical characteristics (temperature, excitation energy, volume) of the nuclear system at the opening of different decaying channels, as a function of the isospin (N/Z). This seems of primary importance also from the point of view of the limiting temperature [13].

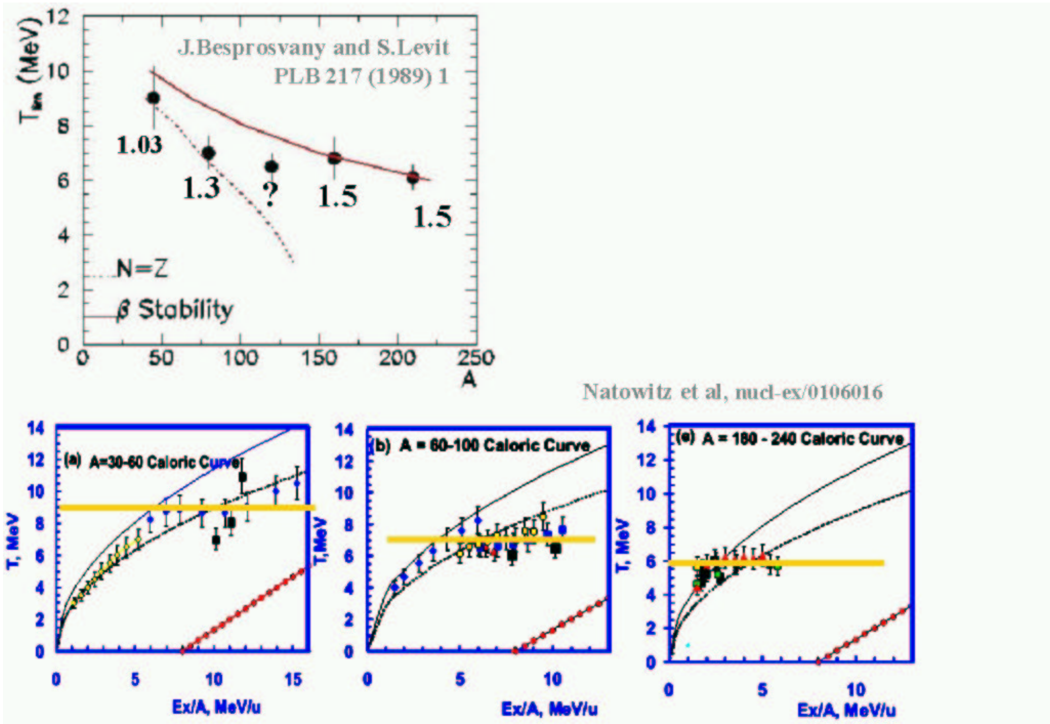

Figure 3: Upper panel: the limiting temperature T_{lim} as a function of the mass number A. The continuous line shows the values for nuclei along the β stability line and the dot-dashed along the N=Z line, as calculated in Ref. [13]. The points show the data collected in several experiments as listed in Ref. [14]. Lower panels: determination of limiting temperature from caloric curve.

We plan to measure different interacting systems in the mass region $A \approx 100$. We have started with a proposal to measure one of these systems at high energy, recently approved by the PAC of the "Laboratori Nazionali del Sud". The energy we have chosen for that experiment is the maximal energy which will be reached with the upgraded Alpi accelerator and therefore it can be one of the points of a systematic measurement at lower energies in Legnaro. The approved reactions are obtained by the collision of neutron rich and neutron poor beams of Nickel isotopes on targets of neutron poor and neutron rich Calcium isotopes. These reactions are expected to give rise to a fused system with Z $\sim$ 40, N/Z $\sim$ 1.02 and 1.28 with about 5 MeV of excitation energy. Due to the different N/Z values, the limiting temperature results 6.5 MeV and 8.4 MeV for the neutron-poor and neutron-rich system, respectively. Different temperatures correspond to different liquid drop level density parameters (8 and 12, respectively) and this should give less liquid (asymmetric) partitions for the decay of the neutron-poor system with respect to the neutron-rich one at the phase coexistence. Also statistical models [15] predict microcanonical temperatures for the neutron-poor systems lower than those of neutron-rich systems over a wide range of excitation energies.

These reactions are well suited to be investigated with the Garfield apparatus, which is characterized by low energy thresholds in a wide angular range.

In order to measure the temperature of the source formed in these reactions it is crucial to get information on the mass and on the charge of the emitted fragments and light particles in the "pre-equilibrium" stage of the reaction, when statistical equilibrium is not yet established. Even at the rather moderate incident energies which may be provided by the Laboratory, measurements of light particle spectra for comparable projectile-target combinations and relative energies have shown that these emissions are not negligible [16] and may reduce in a sizeable way the equilibrated nucleus energy. Besides being important in order to extract the "isotopic temperature", this information can contribute to the determination of the N/Z ratio of the source and to a better calorimetry to extract the excitation energy.

To this aim an upgrading of the Garfield apparatus is needed. A forward detector (Ring counter) has just been completed, and it allows the isotopic identification at small angles (see Fig. 1 of the proposal "Energy response of CsI(Tl) scintillators of the forward RING counter coupled to Garfield apparatus"). It is also planned to cover the Garfield region of about 45^o in azymutal angle and from 30^o to 90^o in polar angle, with additional telescopes able to detect mass and charge also in this angular interval. We will use some spare three-stage telescopes of the Multics apparatus, consisting of ionization chambers, followed by position sensitive Si detectors and CsI(Tl) scintillators. In the past these telescopes resulted very accurate in the isotopic identification of fragments up to Z = 10 [17]. The charge identification thresholds are very low (about 1 AMeV with a pressure of 70 mbar CF_4 in the chambers) and the mass identification threshold is about 4.5 (9) AMeV for $Z = 2$ ($Z = 6$) with 200 μm Si detector.

We will also deeply investigate the use of digital electronics, developed by the Florence group for the Fiasco apparatus, for the shape analysis of the signals coming from the slowest detectors of the apparatus, such as ionization chambers used as Bragg chambers, and CsI(Tl) scintillators [18].

4 Conclusions

In 2003 we plan to work in order to have an apparatus able to detect in a wide angular range, the mass and the charge for isotopes up to Z $\approx$ $6 \div 8$. We will apply for some beam time for calibration and to make tests on the improvements. We will concentrate our efforts in order to plan a series of measurements on this research line, with the presently available energies, starting from the beginning of 2004. Later on, we would like to extend these sustematic studies to the higher energies which could be reached with an upgrade of the Alpi accelerator to 25 AMeV. Therefore this letter of intent aims also at demonstrating our interest with respect to such an upgrade in the next future.

References

[1] Ph. Chomaz: The Nuclear Liquid Gas Phase transition and Phase Coexistence Int. Nucl. Phys. Conference INPC 2001, AIP Proceedings Vol.No.610 2002.

[2] J. Pochodzalla *et al.*, Phys. Rev. Lett **75**, 1040 (1995).

[3] M. D'Agostino *et al.*, Nucl. Phys. **A650**, 329 (1999).

[4] J. B. Elliott *et al.*, Phys. Rev. Lett. **85**, 1194 (2000).

[5] B. Borderie *et al.*, nucl-ex/0102015 and Phys. Rev. Lett. 86, 3252(2001)

[6] M. DAgostino *et al.*, Phys. Lett. B473, 219(2000) and Nucl. Phys. A699 (2002)795.

[7] M. F. Rivet *et al.* nucl-ex/0205010

[8] F. Gramegna *et al.* - Proceedings of the International Conference on Nuclear Physics at Border Lines, Lipari, May 2001.

[9] N. Marie *et al.*, Phys. Rev. C **58**, 256 (1998).

[10] N. Le Neindre Proceedings of Bormio 2002; B. Guiot, thesis, University of Caen (2002).

[11] M. Schmidt *et al.* Phys. Rev. Lett. **79**, 99 (1997).

[12] F. Gobet *et al.* Phys. Rev. Lett. **89**, 183403 (2002).

[13] P. Bonche, S. Levit, H. Vautherin, Nucl. Phys. **A427**, 278 (1984); **A436**, 265 (1986); J. Besprosvany and S. Levit, Phys. Lett. B **217**, 1 (1989).

[14] J. B. Natowitz *et al.*, Phys. Rev. C **65**, 034618 (2002).

[15] J. P. Bondorf, A. S. Botvina, A. S. Iljinov, I. N. Mishustin, K. Sneppen, Phys. Rep. 257, 133 (1995).

[16] K. Yoshida *et al.*, Phys. Rev. C **46**, 961 (1992); M. Cavinato *et al.*, Nucl. Phys. **A679**, 753 (2001).

[17] P. Milazzo *et al.*, Phys. Rev. C 58, 953 (1998).

[18] L. Bardelli *et al.*, Nucl. Instr. and Meth. A **491**, 244 (2002).