

Thermodynamical coordinates of excited nuclear systems

NUCL-EX collaboration:

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Abstract The updated situation of the NUCL-EX proposal, presented to the Commissione Scientifica Nazionale III of the INFN in June 2002, is presented.

The working program of this collaboration concerns an experimental campaign devoted to perform experiments at the INFN National Laboratories of Legnaro (LNL) and Catania (LNS), to study in a systematic way the liquid-gas coexistence region starting from the liquid side at LNL (≈ 3.6 AMeV of center of mass energy) up to ≈ 8.5 AMeV of c.m. energy at LNS. Composite systems of $A \approx 100$ were chosen to be studied in the first part of this campaign since in this mass region a wide range of N/Z values can be spanned also with stable beams.

In a second step, joint measurements with the INDRA Collaboration are also planned, in order to investigate similar systems reached by means of the exotic beams delivered by the SPIRAL accelerator at GANIL.

1 Physical motivations

Since the part concerning LNL of the NUCL-EX programme has been presented with a detailed letter of intent in January, 2003 and approved (03-39 proposal) after the oral presentation in June, 2003, only the main goals of this experimental programme are recalled here.

Measurements with 4π second generation devices allow to investigate the possible onset of a phase transition by looking at several signals at the same time. In fact, a phase transition can be established by the observation of several coincident signals, such as a plateau in the "caloric curve" [1]; the decrease down to the size of the other fragments of the size of the heaviest one (liquid part) for increasing excitation energy (temperature) of the nuclear system [2]; the bimodality [3], 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 [2, 4]; the negative branch of the heat capacity [5].

The importance of the isospin degree of freedom on the thermodynamical coordinates of the multifragmenting excited systems is another important subject. In fact, the observation of a dependence of the plateau value of the caloric curves on the N/Z value of the fragmenting systems [1] has been related to the maximal (limiting) temperature that the composite system can sustain while statistically evaporating light particles [6].

Particular interest has to be devoted to the low energy region of the caloric curve in order to investigate the importance of the isospin of the system at the threshold of the multifragmentation regime. The GARFIELD apparatus that will be used at LNL (as well as CHIMERA at LNS) has not only the capability of measuring the charge, the energy and the emission angles of nearly all the reaction products, but it also provides information on the mass. In fact, for the most forward angles (from 6° to 17° in the laboratory system) an isotopic resolution up to $Z=8$ can be easily obtained from $\Delta E-E$ technique. For larger angles (from 30° to 85° in the laboratory system), after very succesful tests performed in 2002 and 2003, the GARFIELD apparatus has been equipped with digital electronics [7], allowing mass identification over a wide solid angle for light fragments. In addition, precise measurements of the relative momentum between charged decay products are also possible, allowing to calculate the temperature of the fragmenting system not only through isotope double ratios, but also from the excited states probability.

Recent theoretical and experimental studies [8, 9] have also shown the importance of isotopic degree of freedom not only on the behavior of the caloric curve and of the free neutron and proton densities [10], but also but also in the properties of the symmetry term of the nuclear EOS.

The essential feature of this kind of measurements consists in the comparison between the emission probability of neutron rich and neutron poor reactions, leading to excited composite systems differing *only* for their isospin coordinate. The experimental protocol established in Ref. [10] indicates that sophisticated statistical analyses on the measured events are necessary to verify the equilibration of the emitting systems. In addition, the thermodynamical coordinates of the excited sources (excitation energy, temperature and volume) have to be carefully determined, through calorimetry, model comparisons and correlation functions of the emitted decay products. In this respect, the study of any type of pre-equilibrium emission is also very important. A remarkable emission of nucleons, light particles and even larger mass fragments can in fact occur before a thermally equilibrated nuclear system is produced. These emissions not only reduce the excitation energy deposited into the equilibrated sources, but may also change the isotopic composition of the intermediate system created when the projectile and the target nucleus overlap. The estimation of the extent and the importance of fluctuations of these quantities is one of the significant aims of the present experiment and represent a key issue of the NUCL-EX-DYNA experiments already performed at LNS in 2004 and presently planned at LNL (see the relative letter of intent to the LNL/PAC).

Suitable correlation data are necessary to achieve this goal. An approach, based on the Boltzmann Master Equation theory, resulted very suitable, for a wide range of projectile-target combinations and energies, to reproduce accurately the double differential spectra of nucleons or light particles [11], and intermediate mass fragments [12] emitted in the first stage of the reaction.

It must be underlined that a high statistics is required for these studies, since equilibrated central collisions account only for a few percent of the total measured reaction cross section.

Therefore, the NUCL-EX experimental campaign plans to investigate the phase co-existence and its isospin dependence, by looking at nuclear, finite and excited systems of $A \approx 100$, formed in central collisions at several center of mass incident energies by incomplete fusion of the projectile and the target. As already underlined, systems of $A \approx 100$ can be formed with a wide range of N/Z, even with stable beams.

To realize this programme, several experiments were proposed to the LNL and LNS PAC's:

- **LNS:**

- In July 2003, the inverse kinematic reactions $^{58,62}\text{Ni} + ^{40,48}\text{Ca}$ at 25 AMeV incident energy (about 6 AMeV c.m. energy) were measured at the Cyclotron of LNS with the CHIMERA device. The analysis of these data is now in progress.
- In December 2004 another proposal to measure the same reaction at 35 AMeV incident energy (about 8.5 AMeV c.m. energy) with CHIMERA was presented and approved by the LNS PAC Committee. These measurements are planned by the end of 2005.

- **LNL:**

- In January 2003 we sent a Letter of Intent to the LNL PAC, followed in June 2003 by the approved 03-39 proposal. The requirement was for $^{40,48}\text{Ca}$ beams accelerated on $^{58,64}\text{Ni}$ targets at about 15 AMeV incident energy (about 3.5 AMeV c.m.energy). One half of the requested beam time was allotted by the LNL PAC, and the second part was postponed due to the huge beam time request by other ALPI users.
- In March 2004 we started the measurement at ALPI using the GARFIELD array. The whole apparatus was completely working and suitable for the proposed measurements.

Unfortunately, the Ca beam delivered by the ALPI accelerator showed extremely severe problems as far as alignment, intensity and timing are concerned. The experiment failed completely because of these machine problems.

2 Requested time and beams

After the failure of March, 2004, the accelerator staff performed some tests related to our requirements, in order both to optimize the transport of the beams and to check the possibility to provide Ca beams. Presently (April 15, 2005) we do not know the results of these checks, even if our collaboration has twice (December 21, 2004 and March 29, 2005) asked the Direction staff to give a clear answer on the availability of such beams, with the intensity and the timing required for high-statistics and precise measurements.

We are also open to second level solutions:

- We could fall back on the measurement of the inverse kinematics reactions $^{58,64}\text{Ni} + ^{40,48}\text{Ca}$ at the maximum energy deliverable by ALPI, even if that would force us

to reduce the overall solid angle, since it would be necessary to increase the size of the forward diaphragm to reduce the intense flux of elastically scattered projectiles which can give spurious events and seriously damage the silicon detectors.

- If Nickel beams are not going to be available, we might plan (although this somewhat changes the size of the investigated systems and thus the related physical problematics) the use of the easier available ^{32}S and ^{36}S beams at the highest possible energies.

In this respect a clear and quick answer would be highly desirable.

In the case Ca beams are definitely not available, we require by the end of 2005 to measure $^{58}\text{Ni}+^{40,48}\text{Ca}$ for the 12 days of beam time already assigned in 2003 by the LNL PAC (03-39 proposal) and not yet used. To complete the measurement at LNL we also ask for further 12 days of ^{64}Ni beam. Due to the importance of the stability of the experimental conditions when changing only the isospin of the projectile, we ask these additional 12 days just after the assigned and to be re-scheduled period and in any case by the beginning of 2006.

We estimate that the beam time, needed to collect a sufficient number of events in complete central events (with a fusion cross section of $200 \div 300$ mb, a beam intensity of ≈ 0.5 pA and a target thickness of about $500 \mu\text{g}/\text{cm}^2$) would be 6 days for each projectile-target combination. This would allow to calculate correlation functions between isotopes and to study in detail the isoscaling. We also underline that the GARFIELD drift chambers require ALPI beams pulsed at $\approx 1-2$ ns.

We also ask for two days of ^{58}Ni beam, some days before the real measurements, with the double aim of tuning the apparatus and to verify that the beam characteristics are satisfactory for our purposes.

According to the proposal presented to INFN, to our previous letter of intent and to the 03-39 proposal, these measurements represent the first part of the systematic investigation on hot and excited nuclear systems. These measurements are competitive and complementary with respect to experiments in the same field proposed in other laboratories, like Texas A&M and GANIL. All these experiments can be also viewed as a first step for future researches with exotic beams. To this end we recall also our interest in the upgrade of the ALPI-PIAVE complex, to extend our studies to heavier beams.

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