# Thermodynamical coordinates of excited nuclear systems: $^{40,48}$Ca + $^{58,64}$Ni and $^{40}$Ca + $^{58}$Fe reactions

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**(NUCL-EX Collaboration)**

**Abstract** The systematic study of the liquid-gas coexistence region, starting from the liquid side, presented by the NUCL-EX collaboration in a previous letter of intent, starts with the measurement of the formation and the decay of an $A \approx 100$ system around 3.5 AMeV excitation energy. Complementary information at higher c.m. energies should come from the measurement of the reaction $^{58,62}Ni +^{40,48} Ca$ at 25 AMeV incident energy, which will be investigated by the group exploiting the Chimera apparatus at the Laboratori Nazionali del Sud.

We are currently working to upgrade the GARFIELD apparatus and ancillary detectors in order to be able to measure also the mass of the charged decay products with Z up to 10 in a sufficiently wide angular range. We are investigating the use of digital electronics for the signal processing and for the shape analysis. The request is for **3 days** of Tandem beams, to set the electronics and measure two points for the energy calibration of the detectors, and **21 days** of Alpi beams: **12** days of $^{40}$Ca and **9** days of $^{48}$Ca in order to measure, at ≈ 15 A.MeV, the reactions $^{40}$Ca + $^{58,64}$Ni,$^{58}$Fe and $^{48}$Ca + $^{58,64}$Ni. A pulsed beam at ≈ 1 ns is needed for the GARFIELD drift chambers.

# 1 The physical motivation

As already pointed out in our letter of intent of the last PAC meeting, we plan to perform experiments at the INFN Legnaro and Catania laboratories, with the aim of a systematic study of the liquid-gas coexistence region [1], starting from the liquid side, up to some AMeV of center of mass energy. We also plan to perform further measurements

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together with the Indra Collaboration aiming to investigate similar systems with the exotic beams delivered by the Spiral accelerator at Ganil.

First measurements at the ALPI accelerator with the GARFIELD apparatus, at relatively low excitation energies ($\sim 3$ AMeV), indicated that nuclear multifragmenting sources of A $\approx 100$ are produced in central collisions and manifest the behavior expected for a system in the coexistence region. In particular Fig. 1 shows the charge distribution of the three largest fragments in each event and the Dalitz plot, indicating that even at these low energies a production of three nearly equal fragments is enhanced [2].

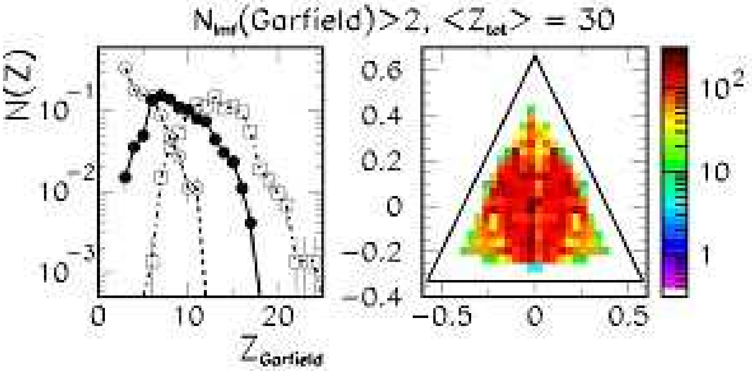

Figure 1: *Charge distribution of the 3 largest fragments in each event (left panel) and Dalitz plot (right panel) for experimental data.*

A series of measurements, with $4\pi$ second generation devices, is important to investigate at the same time several signals of the phase transition. Indeed a phase transition can be established only if several coincident signals are observed, such as the "caloric curve" [3], 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 [4]; the bimodality [5], 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 [4, 6]; the negative branch of the heat capacity [7], and so on. One can also investigate the limiting temperature, as defined by Bonche and Levit [8], i.e. the maximal temperature a (liquid) nucleus, with a definite value of N and Z, can stand while statistically evaporating light particles. This temperature has been recently connected [9] to a sudden change of the level density and to the plateau of the caloric curves.

Systematic measurements at relatively low energies (up to now never performed with a $4\pi$ 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).

We have started our plan of measurements proposing to measure a system with $A \approx 100$ at higher energy at LNS, recently approved by the PAC of the laboratory. The measurements are scheduled for mid July 2003. Therefore we would like to continue our investigation of the same system at the highest energy available at the Alpi accelerator.

## 2 The proposal

The plan of measurements involves neutron rich and neutron poor beams of Calcium isotopes on neutron poor and neutron rich Nickel targets:

$$^{40}Ca +^{58,64} Ni \quad and \quad ^{48}Ca +^{58,64} Ni$$

and a reaction using a target with a Z value differing by two units with respect to Ni:

$$^{40}Ca +^{58} Fe.$$

These reactions are expected to give rise to a fused system with Z $\sim$ 40, N/Z from $\sim$ 1 to 1.3 with about 3 AMeV excitation energy. The expected cross section for these fusion processes are estimated of the order of 200 $\div$ 300 mb. Due to the different N/Z values, the limiting temperature [8, 9] results 6.0 MeV and 8.3 MeV for the most neutron-poor and neutron-rich systems, respectively. Different temperatures correspond to different liquid drop level density parameters (8 and 12, respectively) and this should give different partitions for the decay of the neutron-poor system with respect to the neutron-rich one, at the phase coexistence. These reactions are well suited to be investigated with the GARFIELD apparatus, which is characterized by low energy thresholds in a wide angular range.

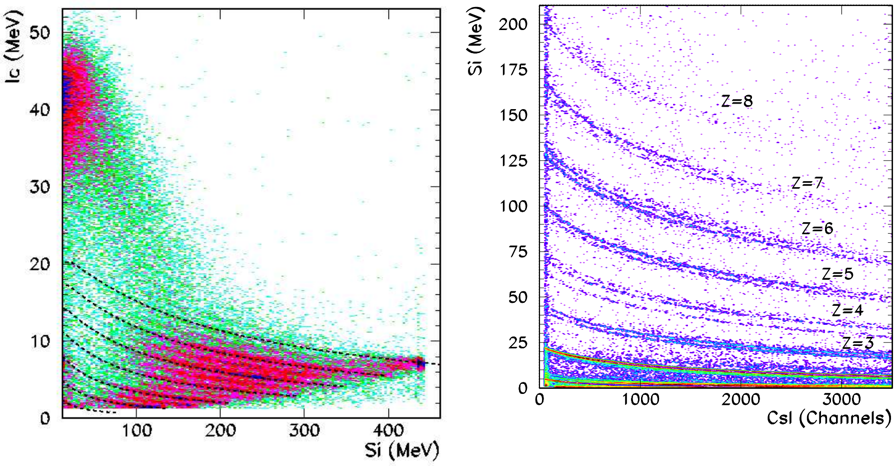

Figure 2: *Left part: Ionization chamber - Silicon matrix. Right part: Isotope identification in Si - CsI telescope*

In Fig. 2 the results obtained for the reaction $^{32}S +^{58} Ni$ at 15 AMeV are shown. In particular in the left side a $\Delta E - E$ matrix of ionization chamber - silicon detector shows the presence of an evaporation residue, with a charge $\approx$ 80% of the total charge. In the right side a $\Delta E - E$ matrix of silicon detector - CsI scintillator shows a very good isotopic resolution.

In order to measure the temperature of the source formed in these reactions it is indeed crucial to get information on the mass and on the charge of the emitted fragments and light particles. This information can also contribute to the determination of the N/Z ratio of the source and to a better calorimetry, apt to extract the excitation energy. To this aim a further upgrading of the GARFIELD apparatus is needed. In addition to the FORWARD RING detector, which allows the isotopic identification at small angles (see Fig. 2), it is planned to cover the GARFIELD region of about $45^o$ in azymutal angle with an additional SIDE ISOTOPE detector, able to measure the energy and detect mass and charge also from $30^o$ to $90^o$ in polar angle in the lab. We will use three-stage telescopes, consisting of ionization chambers, followed by strip Si detectors and CsI(Tl) scintillators. In the past this kind of telescopes, used in the Multics apparatus, resulted very accurate in the isotopic identification of fragments up to Z = 10 [10], with very low charge identification thresholds (about 1 AMeV with a pressure of 70 mbar $CF_4$ in the chambers) and mass identification threshold about 4.5 (9) AMeV for $Z = 2$ ($Z = 6$) with 200 $\mu m$ Si detector. We will also thoroughly investigate the use of digital electronics, similar to the one 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 CsI(Tl) scintillators [11].

The thermodynamical study of the systems will be performed by evaluating the average volume of the system from Coulomb trajectory calculations and its isospin from the N/Z ratio of the decay products; the thermodynamical coordinates (T - $\rho$ and isospin) of the finite and equilibrated source at the phase coexistence can provide experimental information on the nuclear phase diagram. One of the first results of the analysis of the $^{32}S +^{58,64} Ni$ reactions shows (See Fig. 3) that the fragment isotope production is very sensitive even to a small change of the N/Z of the composite system (6 neutrons difference on a total mass of 96). Up to now similar effects have been observed for changes of the N/Z ratio larger than 10% and for heavier systems. Therefore we would like to investigate in detail the dependence of these effects on the difference on the number of neutrons. The 2 reactions with the $^{40}$Ca projectile differ by 6 neutrons and the 2 reactions with extreme values for N/Z differ by 14 neutrons. The crossed reaction are useful to check the results with the neutron excess in the projectile or in the target, to investigate some structure effects. The reaction with the $^{58}$Fe as target could show if some difference arises when non magic nuclei are involved in the reactions.

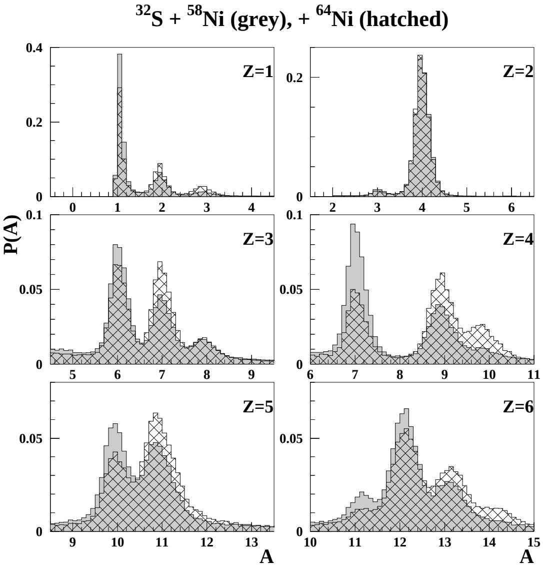

Figure 3: *Experimental isotope production. Grey area - neutron rich, hatched area neutron-poor reaction*

In this investigation an important aspect is the characterization of the equilibrated source formed in central collisions. In this respect it is very important the study of any type of pre-equilibrium emission. A sizeable emission of nucleons, light particles and even larger mass fragments can occur before producing thermally equilibrated nuclear systems. 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 a significant aim of the present experiment. This may be achieved by investigating suitable correlations. An approach, based on the Boltzmann Master Equation theory [12], resulted very suitable, for a wide range of projectile - target combinations at many incident energies, to reproduce accurately the double differential spectra of nucleons or light particles [12], and intermediate mass fragments [13] emitted in the first stage of the reaction.

Since we would like in the future to extend these systematic studies to the highest energies which could be reached with an upgrade of the Alpi accelerator (up to $\approx 25$ AMeV), we stress our interest with respect to such an upgrade.

## 3 Requested time and beams

We estimate that the beam time, needed to collect a sufficient number of the most probable Carbon isotopes in complete central events (with a cross section of $200 \div 300$ mb, a beam intensity of $\approx 0.5$ pnA and a target thickness of about 200 $\mu$g/cm$^2$ would be 5 days for each combination of projectile/target/energy. This would allow to calculate correlation functions between isotopes and to study in detail the isoscaling. We therefore ask for 5 days for both the reactions of neutron-poor projectiles on neutron-poor targets and neutron-rich projectiles on neutron-rich targets (the two extreme N/Z reactions). For the other combinations we estimate that 3 days of measurements are sufficient to give additional relevant information. In Table I a summary of the beam time request is presented. The energies required for the Tandem beams are the maximal and the minimal energy allowed by the Tandem. For the Alpi beams we need $\approx 15$ AMeV. A pulsed beam at $\approx 1$ ns is needed for the GARFIELD drift chambers.

**Table I - Plan of beams and energies**

| days | beam | accelerator | energies | aim |
|---|---|---|---|---|
| 3 | $^{40}Ca$ | Tandem | 2 | focus and set up the electronics<br>calibration of detectors |
| 1 | $^{40}Ca$ | Alpi | 1 | focus and set up the electronics |
| 5 | $^{40}Ca$ | Alpi | 1 | measurement $^{40}Ca +^{58} Ni$ |
| 3 | $^{40}Ca$ | Alpi | 1 | measurement $^{40}Ca +^{64} Ni$ |
| 3 | $^{40}Ca$ | Alpi | 1 | measurement $^{40}Ca +^{58} Fe$ |
| 1 | $^{48}Ca$ | Alpi | 1 | focus and set up the electronics |
| 5 | $^{48}Ca$ | Alpi | 1 | measurement $^{48}Ca +^{64} Ni$ |
| 3 | $^{48}Ca$ | Alpi | 1 | measurement $^{48}Ca +^{58} Ni$ |

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