SYSTEMATIC STUDY OF THERMODYNAMIC OBSERVABLES AND NUCLEAR CALORIC CURVE

G.Immé[a,*], U.Lynen[b], W.F.J.Müller[b], B.Ocker[b], T.Odeh[b], J.Pochodzalla[b], G.Raciti[c], G.Riccobene[c], A.Saija[a], C.Schwarz[b], V.Serfling[b], W.Seidel[d], C.Sfienti[c], W.Trautmann[b], A.Trzcinski[e], G.Verde[a], B.Zwieglinski[e].

a) INFN Sezione di Catania and Dipartimento di Fisica e Astronomia dell'Università di Catania, Catania, Italy

b) Gesellschaft fur Schwerionenforschung, D-64291 Darmstadt, Germany

c) INFN Laboratori Nazionali del Sud and Dipartimento di Fisica e Astronomia dell' Università di Catania, Catania, Italy

d) Forschungszentrum Rossendorf, D-01314 Dresden, Germany

e) Soltan Institute for Nuclear Studies, 00-681 Warsaw, Hoza 69, Poland

[*]*Corresponding author, e-mail: imme@ct.infn.it*

Abstract

Thermodynamic observables characterizing multifragmenting systems were investigated. Isotopic and emission temperatures were simultaneously extracted and their disagreement related to the space-time evolution of the fragmentation process. As a confirm density measurements were performed via particle-particle HBT interferometry. A dependence of the Nuclear Caloric Curve on the system size was evidenced.

1 INTRODUCTION

Some years ago the correlation between excitation energy of the decaying projectile spectator, obtained in the Au+Au collisions at E_{inc} =600 MeV/u, and isotope temperature of the produced fragments, was reported [3] as the Nuclear Caloric Curve (NCC). In particular the excitation energy was measured by summing the kinetic energies and the total binding energy of the decay products, the isotope temperature was determined via the double ratios of isotope (^{3,4}He and ^{6,7}Li) yields [2]. The observed behaviour of the NCC is reminiscent of a first-order liquid-gas phase transition in macroscopic systems and has induced to further investigation on details of the nuclear caloric curve. In particular experiments were performed in a large dynamical range, in order to explore the dependence of the NCC on the used thermometer, on the incident energy, on the reaction mechanism involved to produce the decaying system and on its space-time extent.

For a cross comparison of different thermometers we measured simultaneously both isotope yields and particle-particle correlations from the decay of unstable states in the emitted fragments.

HBT interferometry technique was applied to charged particle relative momentum correlation functions in order to measure size and density of the decaying system.

Moreover, in order to justify some discrepancies between caloric curves obtained for different systems, a size dependence can be suggested, as well as a size dependence of thermodinamical observables on atomic scale has recently been reported [16].

2 EXPERIMENTS

A systematic investigation on the calorimetric measurement dependence on the system size, incident energy and impact parameter was performed. The reported experiments cover the full range of decay modes from compound nucleus emission to nearly complete vaporization. In particular, in a series of experiments at GSI-Darmstadt, we investigated the spectator decay in the ^{197}Au + ^{197}Au collisions at 1. GeV/u [4,8,9] and we studied the decay of the participant region in the mid-central Au+Au collisions at 50, 100, 150 and 200 MeV/u [5]. In order to investigate on system size dependence, we studied central collisions ^{84}Kr+^{93}Nb at NSCL of MSU [6] at incident energies from 35 to 120 MeV/u and ^{40}Ca+^{45}Sc at 40 MeV/u at the LNS-Catania [7].

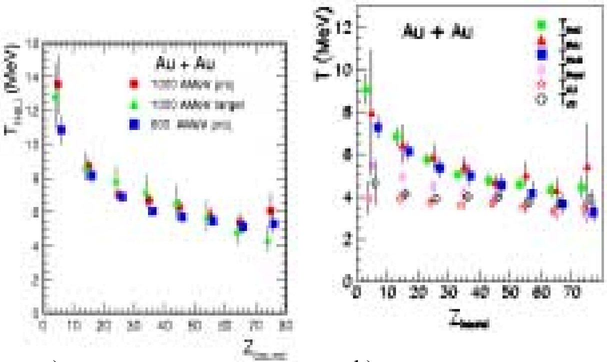
2.1 Experimental set-up

The experiments were performed at the SIS accelerator of the GSI, at the NSCL of MSU and at the LNS-Catania. In the GSI experiments [4,5,8,9] three large area modular hodoscopes (one 64 elements from GSI, one 96 elements from Catania HODO-CT and the third one from the MSU), each consisting of Si-CsI(Tl) telescopes (Si: 3x3 cm^2, 300μm thick and CsI scintillator: 3x3 cm^2 6 cm long with photodiode readout), were optimized in angular resolution and granularity in order to allow to reconstruct the yield of fragment unstable states from resonances in the correlation functions of their decay products. A set of seven telescopes (Si 50μm, 300μm and 1000 μm, CsI 4cm) at selected angles around the target, allowed isotope identification of fragments up to Z=6. At 1. GeV/u, in order to select the target spectator fragmentation, the hodoscopes were placed at backward angles with respect to the beam axis, in such a way contributions from the fireball were reduced. The impact parameter was deduced from the quantity Z_{bound} (sum of all Z>1 fragments belonging to the projectile detected in the forward ToF wall of the ALADiN setup [17]). At lower bombarding energies, in order to study the interaction region in central collisions, the hodoscopes, placed in the forward hemisphere, covered the angular region around 90° in the center of mass system, where contributions from remnants of the projectile and target should be minimal. The associated charged particle multiplicity was sampled, at forward angles, with an array of 36 CaF_2-plastic phoswich telescopes (ZDO) and with a set of 6 Si-strip 16-fold detectors with 300 μm thickness and 5×5 cm^2 surface.
At the NSCL-MSU the ^{84}Kr+^{93}Nb reaction at E_{inc}= 35,70,120 MeV/u was studied [6] by coupling the HODO-CT with the Soccer Ball 4π detector used as impact parameter filter.
At the LNS laboratory we studied [7,15] the ^{40}Ca + ^{45}Sc reaction at 40 MeV/u with two high granularity hodoscopes, in order to measure simultaneously particle-particle correlations and yields of isotopically resolved fragments. One, the HODO-CT already used at GSI was improved with 50μm Si-detectors in front of each telescope, for reducing the detection threshold. The second one, HODO-FWD, covered the angular range θ_{lab} = 5° ÷ 11° around the beam axis in order to detect projectile fragmentation. It consisted in 80 two-folds telescopes (300μm 1×1 cm^2 Si detectors followed by 10cm long CsI(Tl)) and 40 three-folds telescopes similar to the HODO-CT's ones. Impact parameter selection was achieved from charged particle multiplicity through a set of 12 Si strip detectors 16-folds placed around the target.

3. TEMPERATURE MEASUREMENTS

As known, the Caloric Curve of Ref. [3] was built by correlating excitation energy with "isotope" temperature, i.e. the one deduced from the yield double ratio of isotopes differing by one nucleon [2]. In the studies here reported we measured simultaneously both isotope yields and particle-particle correlations from the decay

of unstable states in the emitted fragments []. One of the goals of the reported experiments was to compare the temperature derived applying these two methods to the same class of events of the decay of the same nuclear system.
In particular indication for equilibrium in the spectator system was related to the universality with respect to the colliding systems and the incident energy [18] and to a good agreement with the statistical multifragmentation models

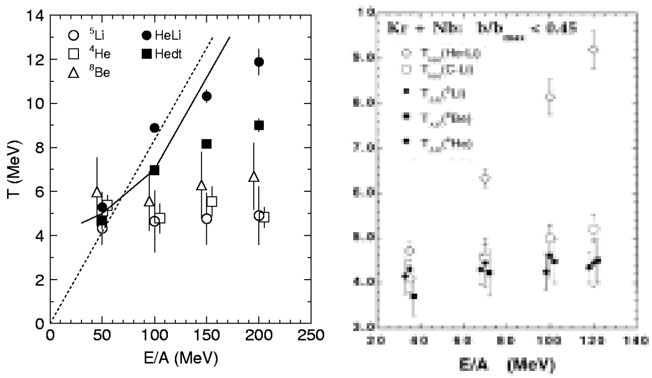


a) b)

[19].

Figure 1: a) Temperatures T_{HeLi} for target (E=1. GeV/u) and projectile spectators (E=600 and 1000 MeV/u) as a function of Z_{bound}. b) QSM-corrected isotope temperatures for ^{197}Au target spectator at E=1.GeV/u as a function of Z_{bound}.

As a further confirm of that, in Fig. 1-a T_{HeLi} vs Z_{bound} are shown for spectator fragmentation, in three different ^{197}Au + ^{197}Au experiments. Integrated yields of ^{3,4}He and ^{6,7}Li isotopes were measured, for the projectile-spectator breakup at forward angles by the ALADIN spectrometer, and for the target spectator, by a standard moving source fit procedure of the energy spectra measured in the backward region with the four-element telescopes. In both cases Z_{bound} was determined from the coincident projectile fragments detected by the ALADIN setup.
Moreover, since theoretical and experimental studies evidenced the dependence of the measured temperatures on the selected isotope pairs [22,23], in Fig.1-b results from a variety of isotope thermometers are reported, all characterized by a double difference of the binding energies ΔB>10MeV. Secondary decay effects were evaluated [1] on the basis of the predictions of the quantum statistical model (QSM) [24]. The agreement among the different thermometers $T_{H,He}$ and T_{BeLi} (^{7,9}Be and ^{6,8}Li isotope ratios), in particular the rise at small Z_{bound} , demonstrates that the isotope temperature is not related to a particular behavior of either ^{3}He or ^{4}He and is not very much affected by the sequential feeding for the quoted thermometers.
In order to permit a cross comparison of two different thermometers we measured, for the same class of events of the same fragmenting system, both "isotope" and "emission" temperatures. The latter can be calculated assuming that the states of the decaying fragments are populated according to a Boltzmann law. Therefore from peaks in relative momentum correlation functions due to resonant decay of two coincident particles, acceptance corrected yields of fragments excited states have been determined [5].



a) b)

Figure 2: a) Emission temperatures extracted from the excited states of ^{4}He, ^{5}Li, ^{8}Be and isotope temperature are shown as a function of the bombarding energy for central Au+Au collisions [5]. b) Same for Kr+Nb central collisions [6].

Figure 2 shows the comparison of the isotope and emission temperatures measured in central collisions in the Au+Au and Kr+Nb reactions at different incident energies. Differences up to 8 MeV between the two thermometers are reached at the highest bombarding energy. The different energy dependence of the two thermometers can be explained by different freeze-out conditions for the chemical and internal degrees of freedom In a simple model of an adiabatically expanding ideal gas (lines in fig.2), the isotope temperature

is related to the first stages of the expansion, while emission temperatures should be related to a later stage of the adiabatic expansion when the system has cooled down [5,15].
Since this cooling is intimately related to the existence of collective radial flow, it may not be too surprising that the discrepancy between the isotope and emission thermometers arises at beam energies where collective radial flow becomes important.

3 DENSITY MEASUREMENTS

The role of the expansion can be confirmed by means of particle-particle HBT interferometry [11]. Following the common approach used in p-p HBT interferometry, we constructed the experimental correlation functions from measured coincident proton events. Source sizes were deduced by comparing the experimental correlation functions with predictions of the Koonin-Pratt formalism [14] corrected for the emission of long-lived resonances. A Monte Carlo generated expanding emission source with zero lifetime and maxwellian shapes for the energy spectra served as input for this theoretical description.
The collective expansion, that represents a significant fraction (about 40%) of the energy available in the center of mass frame, was taken into account.
In order to get more information on the time-space extent of the emission source we considered also correlation functions for different pairs of particles, p-α and d-α. In Figure 3-a we report the extracted radii versus the incident energy. The constant values measured from p-α and d-α contrast with the ones from p-p that drop with increasing beam energy.
These differences could be related to the lower density reached by the expanding system at the freeze-out time, when the alpha correlations sample the emitting source. This scenario agrees well with the EES [15] prediction that the emission time for α's and larger clusters is delayed with respect to p,d,t and 3He.

The importance of the expansion was evidenced also for spectator systems in Au+Au reactions at 1.GeV/u. Infact, despite radii values are constant for different bins of Z_{bound}, the derived densities (Fig.3-b) vary considerably with impact parameter, roughly in proportion to the variation of the spectator mass. In the p-p case, the mean relative densities decrease from $\tilde{\rho}/\rho_0$ = 0.4 for the near peripheral to below $\tilde{\rho}/\rho_0$ = 0.2 for the most central collisions [4].

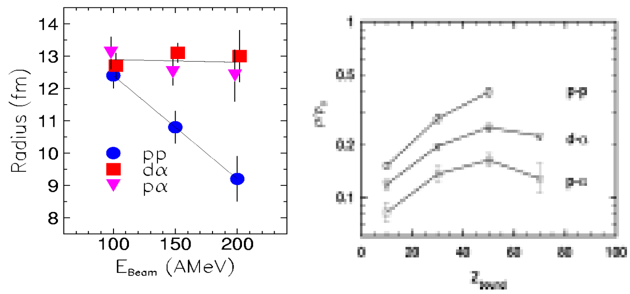


Figure 3: a) Radii extracted from p-p, pα and dα correlation functions [15,28]; b) Breakup density $\tilde{\rho}/\rho_0$ as deduced from p-p, p-α, and d-α correlation functions for ^{197}Au + ^{197}Au collisions at 1000 MeV/u. The error bars represent the statistical uncertainty

These values compare well with the densities assumed in the statistical multifragmentation models [24]. The lower values related to the p-α and d-α correlations could indicate a moderate expansion of the system.

5. SIZE EFFECT ON THE CALORIC CURVE

Figure 4-a shows a comparison among the ALADiN Caloric Curve, the INDRA one [12], obtained for ^{40}Ar projectile fragmentation at 95 MeV/u, and the isotope temperatures T_{HeLi} measured in the ^{84}Kr+^{93}Nb central collisions at different energies [6] and in ^{40}Ca+^{45}Sc at 40MeV/u. The excitation energy for the ^{84}Kr+^{93}Nb central collisions was evaluated roughly from the C.M. available kinetic energy reduced by the collective radial expansion term deduced from the systematics [10]. The intermediate source excitation energy in ^{40}Ca+^{45}Sc was evaluated considering the complete transfer of the available kinetic energy

to an incomplete fused system of 82 nucleons,as suggested from the C.M. velocity spectra fit [7]. As it can be noted, projectile-like (A<40) and incomplete fused system (A=82) temperatures fall into the INDRA data, measured for a system of A=36 nucleons. Moreover, at the same excitation energy (E/A≈8MeV) corresponds higher temperature in the system produced in the $^{40}Ca+^{45}Sc$ (A=82) than in the A≈170 system selected in the $^{84}Kr+^{93}Nb$ central collisions.
The comparison suggests a size dependence of the temperature-excitation energy correlation, as explaination of the difference between ALADiN and INDRA caloric curve.
The same indication is given by the latent heat reported in Fig 4-b versus the mass of the investigated systems. The latent heat values were deduced from the caloric curves of [3] [12] and [13] by integrating the gaussian shapes of the $\Delta E/\Delta T$ functions around the transition temperature[7]. The obtained values increase with the system mass, inconsistently with a volume dependence (red curve in fig 4-b) and well reproduced by a urface and coulombian dependence (blue curve in fig.4-b).

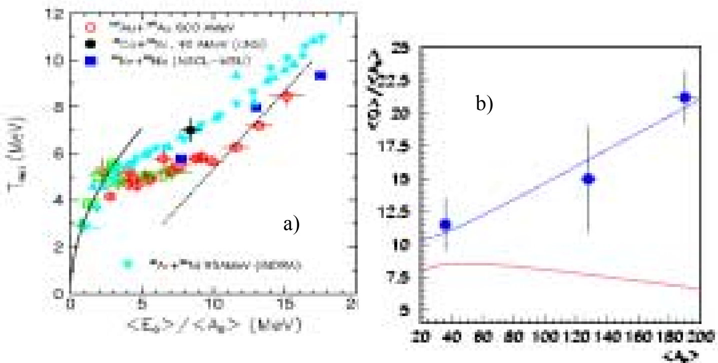


Figure 4: a) Cross comparison between caloric curves of nuclei and b) the related latent heat/nucleon. [7]

Recently [16] the melting points of ionized sodium clusters (70-200 atoms) have been measured and for them large variations, as well as in latent heat values, have been observed with changing cluster size. Even if these variations, not yet explained, refer to microscopic structures and phase transitions in a different scale, it has to be emphasized that a size dependence of thermodynamical properties has already been found for finite systems.

Recent experiments, performed at LNS in 2001, on the reactions ^{93}Nb, $^{116}Sn+^{58}Ni$, ^{93}Nb, ^{116}Sn, ^{120}Sn, ^{197}Au at E_{inc}=17,23,30,38 MeV/u, and the future ones at GSI could confirm this size dependence and give indication also on the isospin role on the caloric curve.

REFERENCES

[1] J.Pochodzalla, Prog.Part.Nucl.Phys.37 (1997) 443 and references therein
[2] S.Albergo et al., Il Nuovo Cimento 89A (1985) 1.
[3] J.Pochodzalla et al., Phys. Rev. Lett. 75 (1995) 1040.
[4] S. Fritz et al., Phys. Lett. B 461(1999)315.
[5] V. Serfling et al., Phys. Rev. Lett. 80 (1998) 3928.
[6] H. Xi et al., Phys. Rev. C 58 (1998)2636.
[7] C.Sfienti, PHD Thesis -Univ Catania 2000
[8] Hongfei Xi et al., Z.Phys. A359 (1997)397.
[9] T. Odeh et al., Phys. Rev. Lett. 84 (2000)4557.
[10] W.C.Hsi et al., Phys. Rev. Lett. 73(1994)3367 and M.A. Lisa et al., Phys. Rev. Lett. 75(1995)2662 and G. Poggi et al., Nucl. Phys. A586(1995)755.
[11] S.E. Koonin, Phys. Lett. B70(1977)43, D.H.Boal et al. Rev. Mod. Phys. 62 (1990) 553
[12] Y.G..Ma et al., Phys. Lett. B390(1997)41.
[13] G.Auger et al. Proceedings of CRIS 96 Ed.World Scientific (1996), 133
[14] J.A.Hauger et al. Phys Rev Lett. 77(1996) 235
[15] G.Raciti et al. Nuovo Cimento A111(1998)987
[16] M. Schmidt et al., Nature 393 (1998)238.
[17] J. Hubele et al., Z.Phys. A340 (1991)263.
[18] A.Schüttauf et al., Nucl. Phys. A607 (1996)457.
[19] A.Botvina et al., Nucl Phys. A584 (1995) 737
[20] M.B. Tsang et al., Phys.Rev.Lett 78(1997)3836.
[21] H.Xi et al. Phys. Rev. C59 (1999) 1567
[22] A.Siwek,et al. Phys. Rev. C57 (1998) 2507
[23] H.Raduta, R.Raduta Proceedings of this Conference
[24] D.H.E.Gross, Rep. Prog. Phys. 53(1990)605, J.P.Bondorf et al., Nucl. Phys. A444 (1985)460. J.P.Bondorf et al., Phys Rep. 257(1995)133.
[25] A.S. Goldhaber, Phys.Lett. B53 (1974)306.
[26] W. Bauer, Phys.Rev. C51(1995)803.
[27] C.Schwarz et al.. Proceedings of this Conference
[28] G.Immè et al. Proceedings of CRIS 98 Ed.World Scientific (1999) 289
[29] W.A. Friedmann, Phys. Rev. C42 (1990)667
[30] E.Bauge et al. Phys Rev Lett. 70 (1993) 3705
[31] C. Fuchs et al., Nucl. Phys. A 626 (1997)987.