TEMPERATURE AND DENSITY IN HEAVY ION REACTIONS AT INTERMEDIATE ENERGIES

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Abstract

A wide range of incident energies, projectile and target masses have been investigated at the LNS (Catania) with the Fiasco multi-detector array and the Hodo-CT. This experimental setup allowed, simultaneously, a complete reconstruction of the projectile decay, hence of the dissipated energy, and a determination of temperatures and densities of systems at midrapidity.

The preliminary data show, in this energy regime and for mid-peripheral collisions, the formation of neutron-rich neck-like structures characterized by extremely low densities as indeed predicted by dynamical calculations.

For the same data set, a calorimetric study has been performed for the most central collisions and the nuclear caloric curve has been extracted: the trend confirms the plateau-like behavior of the nuclear caloric curve and the mass dependence of the corresponding limiting temperature.

1 INTRODUCTION

The production of intermediate mass fragments (IMF $3 \leq Z \leq 20$) is the distinguishing feature of intermediate energy heavy ion collisions. A possible scenario for IMF emission involves the development of bulk instabilities in nuclear matter, which lead to a statistical fragmentation. This is supported by several experimental results concerning both the decay of unique source formed in central collisions and the disassembly of quasi-target and quasi-projectile in dissipative peripheral collisions [1].

On the other hand, theoretical studies of the collision dynamics predict the formation of highly deformed nuclear systems in this energy regime [2] and experimental evidences have been collected of the role of the formation and decay of neck-like structures in IMF production [3].

The emission of IMF has been lately indicated as a signal of the liquid-gas phase transition in nuclear matter already observed in the shape of the caloric curve of projectile fragmentation at high energy measured in ^{197}Au+^{197}Au at 600AMeV reactions [4]. The similarity of such a curve to the first-order liquid-gas phase transition in macroscopic systems has initiated a widespread activity, both theoretical and experimental.

One of the goals of the present work was to study the excitation energy-temperature correlation, measuring both quantities for a variety of systems in the 17-40 AMeV incident energy range. In the same conditions, particle-particle correlations allowed source spatial distribution determination and, knowing its mass, density measurement. In particular the chosen setup allowed a study of the features of midrapidity emission at intermediate energies and its isospin and mass dependence.

2 EXPERIMENTAL SETUP

The experiment was performed at the Laboratori Nazionali del Sud (Catania, Italy). A wide range of projectiles (^{93}Nb, ^{116}Sn, ^{120}Sn), targets (^{58}Ni, ^{93}Nb, ^{116}Sn, ^{124}Sn, ^{197}Au) and incident energies (between 17 and 40 AMeV) was explored in order to cover the largest range of isospin and mass in the entrance channel and to follow the path of the reaction mechanisms around the Fermi energy.

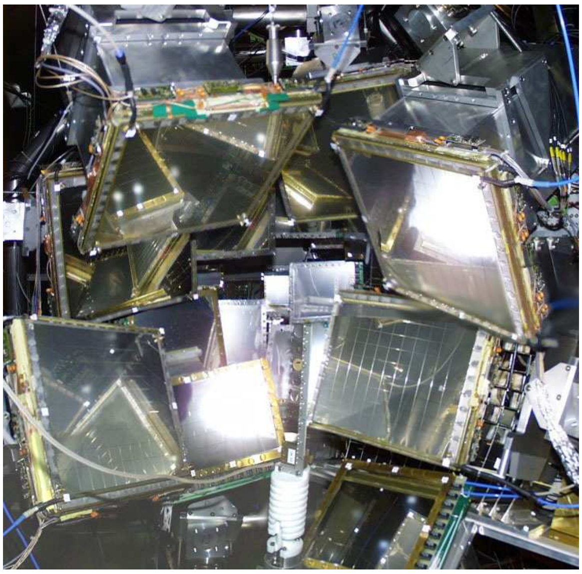

Figure 1. View of the experimental setup.

A view of the experimental setup is shown in Fig.1. A high granularity hodoscope (HODO-CT) was used to identify excited particle-unstable resonances in light fragments from the correlated detection of their decay products and to simultaneously measure the yields of isotopically resolved fragments. It was set up at a distance of 0.6 m from the target and consisted of 96 three-folds telescopes: 50 μm + 300 μm Silicon detectors 3×3cm^2 active area followed by a 6 cm long CsI(Tl). It covered the angular range θ_{lab} = 25° ÷ 55°. The multi-detector FIASCO [5] allowed, event-by-event, the complete reconstruction of the *quasi*-projectile decays.

It includes 24 position sensitive gas detectors (PPAD) for the determination of the velocity vectors of heavy fragments (A>20), 96 silicon telescopes for the measurement of the projectile like fragments (PLF) secondary quantities (energy and charge) and 158 phoswich telescopes for the identification of light charged particles and intermediate mass fragments and the measurement of their time of flight.

3 REACTION CHARACTERISATION

The reconstruction, event-by-event, of dissipated energy has been performed through the Kinematics Coincidence Method [6]: each event has been reconstructed cinematically from the measured velocity vectors of the *quasi*-projectile (QP) and the *quasi*-target detected (QT) by FIASCO.

At these incident energies an often-used quantity is the total kinetic energy loss (TKEL), which is a measure of the degree of dissipation of the reaction as well as of the impact parameter. The data have been, therefore, selected in bins of this quantity and correspondingly peripheral, semi-peripheral and semi-central collisions have been analyzed. By means of BNV dynamical model calculation [7] the correlation between impact parameter and TKEL can be established for values of TKEL which do not exceed approximately 1000 MeV depending on the interaction system.

The presence of two sources one centered at the velocity of the projectile and the second at the center-of-mass, can be observed for the highest incident energies from the correlation between the velocity of the detected fragments and the mass of the reconstructed QP especially in the most peripheral bins (figure 2). As visible in figure 2, in the angular range covered by the hodoscope, mainly fragments coming from the mid-rapidity source are detected. Both these sources are also evident in the correlation of the parallel versus perpendicular component of the particle velocity (*rapidity plot*) once the contribution of evaporative emission from the QP has been subtracted from the data [5]. From inspection of figure 3, where the correlation between the velocity of the fragments and the TKEL is shown, for events in which the entire QP mass has been reconstructed, one may observe that the midrapidity source contribution disappears at 17AMeV incident energy. At these low incident energies a pure deep-inelastic process might take place especially for small value of TKEL.

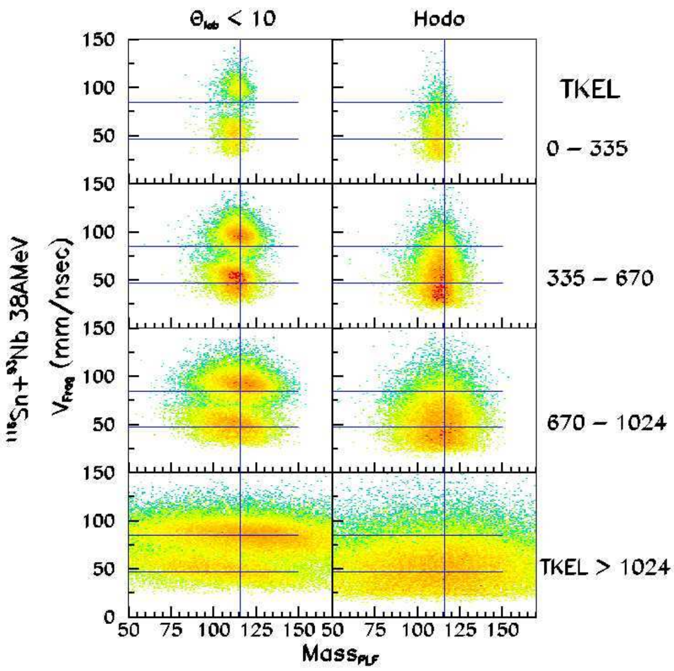

Figure 2. Fragment velocities as a function of the reconstructed projectile masses. The left column refers to fragments detected in forward direction whereas the right one to those detected in the angular range covered by the hodoscope.

That this two source-decay scenario is not the result of the superimposition of independent reaction mechanisms, each contributing with different cross section can be established by inspecting those events where at least one PLF has been detected. Also in these selected events, an enhanced emission of IMF at mid-rapidity characterized by high transverse velocities is observed. This simultaneous emission from two separated space regions confirms the hypotheses of a neck formation at these incident energies.

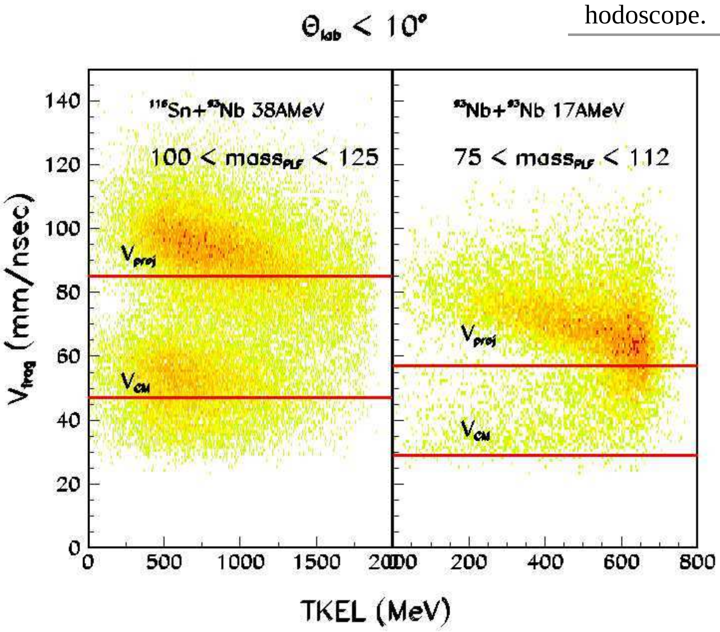

Figure 3. Fragment velocities as a function of the TKEL for those event for which all the projectile mass have been reconstructed

Moreover, similar observations have been extracted from dynamical calculation [8]: even for relatively small impact parameters, BNV calculations predict, for the studied systems, the formation and subsequent decay of neutron-rich neck structures whose density evolves with time.

4 ISOSPIN DIFFUSION

Fragment kinetic energy spectra in the laboratory as detected in the angular range covered by the hodoscope, have been described as the superposition of two Maxwellian sources: a QP and a midvelocity one. Isotopic yields from the neck emission have been deduced from the corresponding integrated double differential cross section of the second contribution.

As indicated by theoretical calculation [9], ratios of isotopic yields are sensitive to the neutron enrichment of nuclear matter. Therefore ratios of different isotopes emitted at midrapidity, have been extracted for the studied reactions at 38AMeV. As shown in figure 4 for the case of the t/^{3}He ratio, the values are always greater than 1 indicating a neutron enrichment of the neck matter. While for the symmetric system, a constant value of such a ratio is observed, in the case of the asymmetric system the TKEL dependence resembles the mass-to-neutron-richness composition of one reaction partner with respect to the other. The highest values are observed for the case of the ^{116}Sn heavier and more neutron-rich target. The latter observation agrees well with the prediction of isospin diffusion in the neck in these collisions[10] indicating moreover a strong size and N/Z dependence of such an effect.

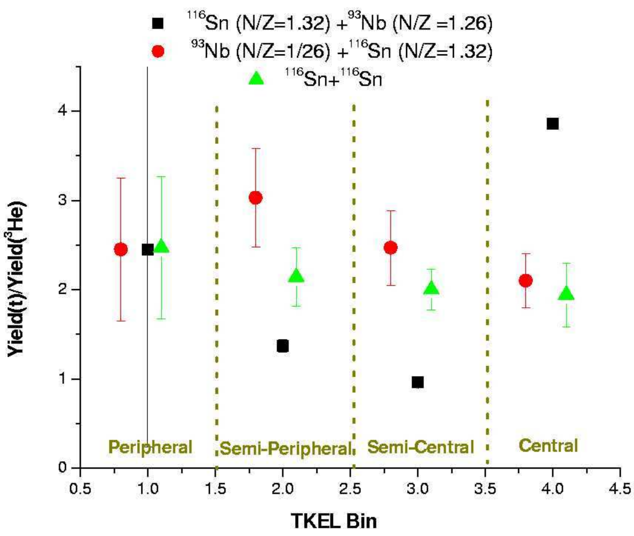

Figure 4. t/^{3}He ratio for the analysed centrality bin.

Due to the large experimental error it is not yet possible to draw any firm conclusion of isospin equilibration from the equal value exhibited in the most peripheral bin by all the analysed system. At the same time, the larger ratio observed in the most central collision in the case of the ^{116}Sn+^{93}Nb system has to be understood.

The same pattern appears also in the ^{9}Be/^{7}Be ratio: however in this case, the final yield could be affected, particularly going towards central collisions by sequential feeding. Sequential decay calculations taking into account such an effect are currently being undertaken.

5. DENSITY MEASUREMENT

In order to gain more understanding on the dynamics of the reaction, HBT interferometry was applied to particle-particle correlation functions at midvelocity.

The contribution of the QP decay in the angular range covered by the hodoscope, was reduced by applying to the TKEL selected data an additional cut, symmetric around the center-of-mass velocity of the reaction, on the particle velocities.

The correlation functions were constructed dividing the spectrum of relative momenta of the two coincident particles by the spectrum of pair from different events (event mixing technique). At a relative momentum of q ≈ 20MeV/c, one observes a maximum of the proton-proton correlation function whose height is inversely related to the radius of a supposed spherical source for simultaneous emission [11]. Directional cuts on the angle between sum momentum and relative momentum (longitudinal and transversal correlation functions) allow the determination of the spatial and temporal separation of the two protons emission.

The analysis of the p-p correlation functions was performed within the Koonin-Pratt formalism [11] and by applying the source imaging technique [12] thus allowing a direct cross-comparison between the two different methods. Radii were deduced in the limit of zero-lifetime for the source.

The similarity of the longitudinal and transverse p-p correlation functions corroborate the assumed time independence [13] for all the TKEL bins except the most central ones, where the differences between these two correlation functions indicate a strong contribution of different emission times. A more quantitative χ^2 analysis to confirm such an instantaneous breakup assumption also in the peripheral bins is nevertheless needed and currently under investigation.

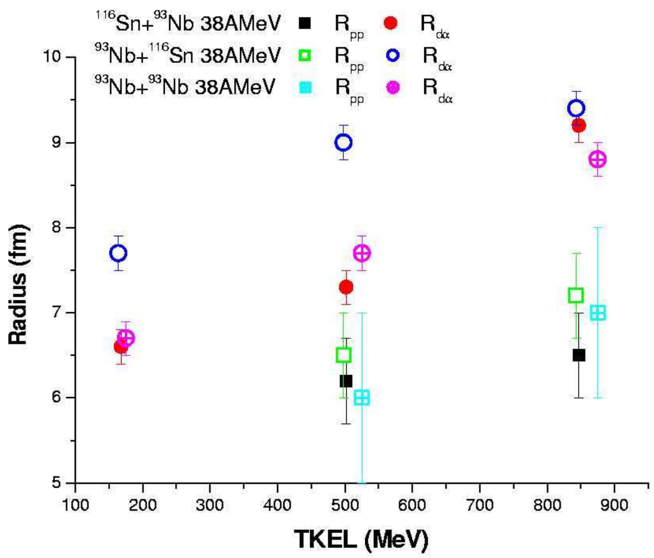

Figure 5. Extracted neck radii as a function of TKEL for some of the analyzed systems.

In the p-α and d-α correlations analysis, the numerical results obtained for a discrete set of source radii by Boal and Shillcock [14], were interpolated. A Montecarlo procedure was used for an event-by-event simulation of the effect of multiple scattering in the target, and of the spatial and energy resolution of the detection system. The obtained values of the radii are reported in fig. 5: the one extracted from the p-p correlation function are always smaller than the one obtained from the d-α [13].

The radii extracted from the p-p correlation functions remain almost constant by varying TKEL and colliding systems. The ones deduced from d-α correlation functions exhibits a monotonous increase by increasing TKEL (or equivalently decreasing impact parameter) and a dependence on the systems.

In fact, we observe the biggest size in the case of the ^{116}Sn heavier target, which, as already shown, exhibits the largest neutron enrichment. However, going towards central collisions this difference vanishes. Once measured the radii, to determine the corresponding densities a measure of the mass of the system is, of course, needed.

Unfortunately, the present experimental setup did not allow neutrons detection and the IMF mass determination in the whole range, therefore, the system mass could only be inferred by doubling the value of the sum of charges detected at midrapidity.

The obtained values agree within the error bars with theoretical expectation [8,15] and with the values, extracted from a careful analysis of the QP decay [16]. The deduced densities are reported in figure 6.

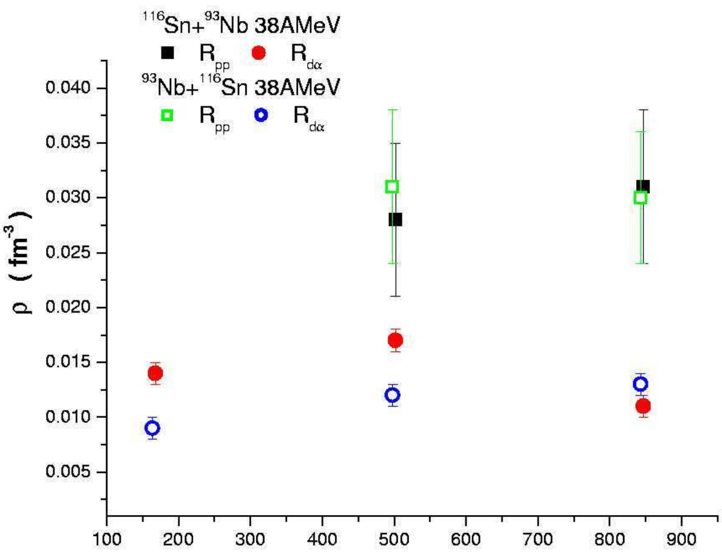

Figure 6. Obtained neck densities as a function of TKEL for the asymmetric systems.

It should be noted that even though the absolute values might be affected by masses underestimations, their order of magnitude and the relative variation could be not. The obtained very low densities are characteristics of a gas, in agreement with BNV calculations.

The observed difference between the densities extracted from p-p and d-α correlation functions respectively, reflects only the measured radii difference (figure 6), being the system mass constant.

How this difference can be connected to an emission time ordering, is presently still under investigation also through IMF-IMF correlation function analysis.

Similar results were found in previous analysis [11] investigating both projectile spectator fragmentation at relativistic energies and mid-rapidity emission in central collisions at intermediate energies [17]. Meanwhile, it is however interesting to note that BNV calculations also predict for the neck density a variation in time as depicted in figure 7. The deduced time interval corresponding to the experimental densities remains constant by varying interacting system and TKEL bin.

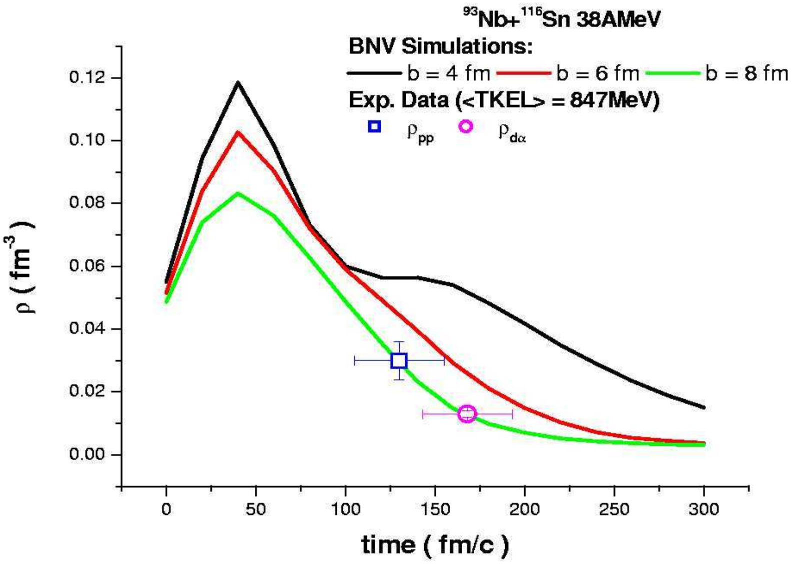

Figure 7. Cross comparison between the experimental densities and the theoretical ones as a function of the reaction times. The time error bars reflect the impact parameter indetermination for the chosen TKEL bin.

Moreover, in the same time interval, the model predicts larger neutron enrichment for the ^{116}Sn target system with respect to the ^{96}Nb target system as experimentally observed (figure 4).

This time interval, between 100 and 200 fm/c, has been already indicated, by analyzing IMF-IMF correlation functions [18], as the IMF emission time. The subsequent saturation in the observed time scale by increasing incident energy has been moreover interpreted as a signal of the liquid-gas phase transition at around 5AMeV excitation energy.

In this respect, however, disentangling the partition of the dissipated energy between PLF, TLF and neck and consequently the excitation energy corresponding to the neck emission is at present an hard task.

5. TEMPERATURE IN CENTRAL COLLISIONS AND SIZE EFFECT

Central collisions at intermediate energies are also a suitable tool to produce hot and dense nuclear systems and, in particular, the study of the dependences on the system size can be achieved by varying the incident energy. For this latter purpose we have performed a calorimetric analysis of the studied systems by sorting events belonging to the most central collisions. For this class of events, clear indication of incomplete fused system formation are deduced from the rapidity plot. The isotopic temperature [19] was measured from the ratio between integrated yields of isotopes differing by one nucleons. The excitation energy of the system was evaluated considering the complete transfer of the available kinetic energy to an incomplete fused system, as suggested by the center-of-mass velocity spectra.

Recently, it has been shown [20] that the mass of the fragmenting system has an influence on the observed shape of the caloric curve. In particular, the temperature of the observed plateau decreases with the mass of the fragmenting system. The wide range of masses of the systems explored in this experiment, allowed us to perform the same analysis on our data. The limiting temperature obtained (Fig. 8) confirm the monotonously decrease of the temperature with increasing system mass.

This behavior has been explained [20] by considering Coulomb instabilities and assuming surface emissions.

The same indication has been also extracted from a latent heat analysis [17]. In particular latent heats were deduced from the caloric curves present in literature by integrating the gaussian shapes of the $\delta E / \delta T$ functions around the transition temperature [17]. In figure 9 the correlation between the obtained latent heat per particle and the system size is shown: the size error bars take into account for a systematic indetermination on the total number of nucleons inside the system for which temperatures and excitation energies have been measured, whereas the latent heats error bars account for numerical indetermination on the integral results.

For comparison, in the same figure 9, it is shown the binding energy per nucleon deduced from the “volume term” of the Weiszacker formula (full curve) that disagree with the monotonic increase of the latent heat as a function of the system mass. The same disagreement is found by using the full Weiszacker formula. However recent calculation taking into account an isospin dependence of the surface term [21] looks promising.

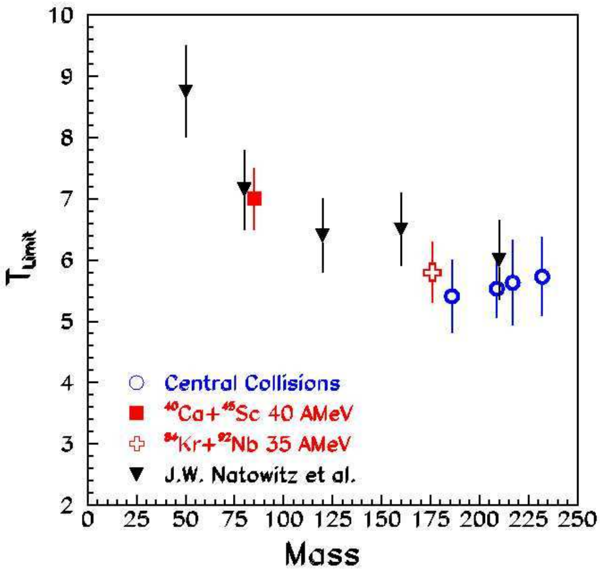

Figure 8. Obtained limiting temperature as a function of the system mass in central collisions.

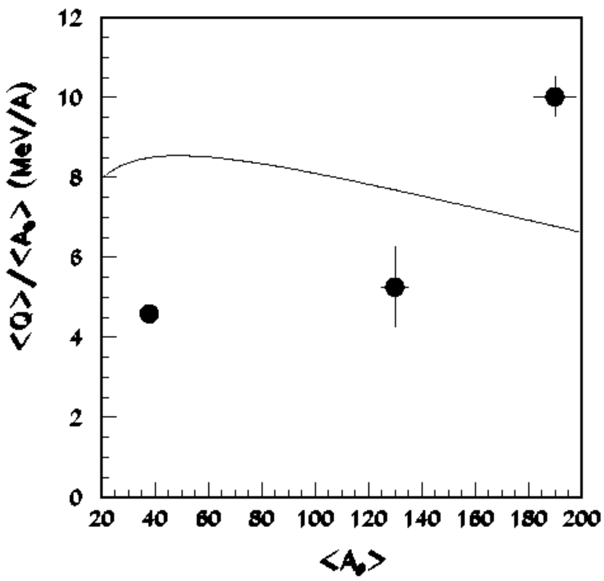

Figure 9. Correlation between latent heat and system mass for projectile fragmentation at high incident energy

6 CONCLUDING REMARKS AND FUTURE PERSPECTIVES

The preliminary results here presented, refer to isospin contents, and density analysis of the neck formed in heavy ion reactions at 38AMeV studied with the multi-detector array FIASCO and the hodoscope HODO-CT at the Laboratori Nazionali del Sud (Catania).

The data have been sorted in bin of total kinetic energy loss (TKEL) which is a measure of the degree of dissipation of the reaction, and hence of the impact parameter. For peripheral and semi-peripheral reactions the clear presence of two sources, one centered at the projectile velocity and the other at the center-of-mass one has been obtained by analyzing the fragment velocities. In the angular range covered by the hodoscope, mainly contribution from the mid-rapidity source have been detected and then analyzed.

Ratios of isotope yields clearly indicate a neutron enrichment of the neck matter, even for relatively small impact parameters, as predicted by BNV calculations. Moreover effects of isospin diffusion through the neck are observed comparing the ratios obtained in the two asymmetric systems $^{116}Sn+^{93}Nb$ and $^{93}Nb+^{116}Sn$.

In order to better highlight such signatures, of course, an increase in the neutron richness in the entrance channel is needed. The possibility of performing experiments with a similar setup but using the radioactive ion beams delivered by the FRIBS Fragment Separator recently successfully tested [22] at the LNS will be ideal.

From particle-particle correlation analysis, the radii of the neck region have been extracted. The radii obtained from p-p correlation, were found always smaller that the one extracted from unlike-particle correlation. The corresponding low densities, even though possibly affected by mass underestimation, strongly corroborate the theoretical prediction, which indicate a neck matter mainly composed by gas. Moreover, from a cross-comparison with the BNV model predictions, the observed difference between the radii (densities) measured via the p-p and d-α correlations could be related to different measurement times. The involved time scales agree well with previous measurements of emission times performed trough IMF-IMF correlation functions and to couple the present setup with a device allowing the detection of both gamma and high energy protons, which have been demonstrated to probe the reaction dynamics in the first stage of the collision [23] may in the future, improve our understating of this emission-time-ordered process.

. Whether the obtained time scales for the neck decay are to be related to the transition from the liquid to the gas phase is still an open question. In particular a better understanding of the partition of the dissipated energy in the reaction is needed in order to deduce the excitation energy deposited in the neck.

Moreover a calorimetric analysis has been performed on incomplete fused systems formed in central collisions and limiting temperatures has been extracted for all the studied systems. The obtained values agree well within the systematic monotonous decreasing with increasing system mass. This observation has lately been explained assuming Coulomb effects accompanied by surface emission. The same kind of mechanism might also explain the observed increase of the latent heats, extracted from the caloric curves, by increasing the system mass.

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