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NEGATIVE HEAT CAPACITIES IN CENTRAL Xe+Sn REACTIONS[1]

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1 Introduction

The fascinating process, referred as nuclear multifragmentation focuses many experimental and theoretical works [1] since it provides information on properties of excited nuclear matter at subnormal densities and may signal a liquid-gas phase transition in finite nuclear systems. Experimental proofs of a phase transition has been claimed using different techniques : charge distributions [2, 3, 4, 5], slopes of energy spectra [6], or isotopic ratios [7]. This last method is subject to different interpretations about the link between the observed thermometer and the genuine temperature of the source [8]. The energy-spectra slope method is model dependant. Finally the use of global static characteristics of detected events (charge distribution slope) is not free of ambiguities [9].

Recently [10, 11, 12] theoretical works about phase transition has been performed in the framework of microcanonical systems following the pioneering works of [13]. A method based on kinetic energy fluctuations is proposed to measure the heat capacity from which divergences could be observed. This method presents several advantages as compared to a signal based on a "caloric curve". Firstly from an experimental point of view one should realize that a measurement of the excited-source genuine temperature with a good accuracy is far from been achieved for the Fermi-energy domain. Therefore looking for any signal (backbending, plateau) in a (E^*, T)-plot is far to be completed. Secondly, from a pure theoretical point of view, looking for a signal on the "caloric curve" is based on an hypothetic a-priori constant variable (pressure for example) phase transition. This is far to be demonstrated for nuclei and is perhaps irrelevant. For these reasons, microcanonical measurements of the kinetic energy fluctuations has to be prefered for the quest of nuclear phase transition since its status of state variable makes its changes independant on the thermodynamical path. Consequently 4π correlation measurements are needed to perform a valuable step towards the experimental measurement of the Equation Of State of nuclear matter.

M. D'Agostino et al. has applied the proposed fluctuation method to Au Quasi-Projectile sources formed in Au+Au 35 A.MeV reactions [14, 15]. The genuine excited source configuration is reconstructed through a calorimetric analysis of its de-excitation products and the heat capacity shows a negative branch providing a direct evidence of a first order liquid gas phase transition. Two extreme reconstruction methods has been employed in [15], namely the cold and hot fragment hypotheses. For both scenarii which corresponds to two extreme cases (i.e. a lower and upper limit) the phase transition is observed.

We propose to show here the application of the fluctuation method to 32-50 A.MeV Xe+Sn central collisions detected with the INDRA multidetector [16, 17, 18].

2 Framework

Out of 32-50 A.MeV Xe+Sn detected reactions, a fraction of events has been retained using a global variable issued from an event by event shape analysis [19]. Those events are characterized by a multi-production of particles originally created in a unique excited source formed in central collisions. It has been shown that the evolutionary nature of the breaking of the source has to be taken into account [20]. The data characteristics are compatible with the following scenario [22, 21, 23] : (1) formation of an excited compressed source from the projectile and target collision, some light particles do not participate to the pressure build-up and escape in the forward/backward c.m directions, (2) the excited and compressed source expands towards low densities, looses mass (mostly light particles) and excitation energy, (3) at low density the multifragmentation occurs and hot primary fragments are copiously produced, (4) the hot primary fragment decay mechanism takes place. Consequently informations given by fragment behaviour concerns steps (3) and (4) while lcp characteristics are related to the whole evolution of the source. Furthermore by selecting only lcp emitted around 90° in the c.m ($-0.5 \leq \cos\Theta_{cm} \leq 0.5$) it is possible to eliminate most of the pre-equilibrium particules produced during step (1).

From the fragment informations it has been possible to extract the source mean physiognomy with the use of statistical multifragmentation model SMM [24] predictions. They are listed in table 1 for 32 and 50 A.MeV bombarding energies. The presence in SMM of a radial collective flow which varies with the bombarding energy has been necessary to reproduce the fragment mean kinetic energies.

Bombarding Energy	Mean Size (Z)	Mean Total E^*	Mean $E_{collective}$
32 A.MeV	82	5.6 A.MeV	0.8 A.MeV
50 A.MeV	80	8.8 A.MeV	2.1 A.MeV

Table 1: Mean values of multifragmenting source variables.

The good adequacy between SMM predictions and the observed characteristics of selected data gives an answer to the problem of equilibrium for the multifragmenting source since this dialectical question can only be addressed by comparing data and models. The equilibrium is reached and the (small) collective energy acts as a superimposed motion, decoupled from the thermal degree of freedom, which drives the system towards low densities.

In fig. 1, the lcp c.m kinetic energy spectra and their mean values are presented for 50 A.MeV Xe+Sn. The predictions of the multifragmentation model SMM are also shown in both pictures (dashed lines) and apart for alpha-particles the SMM-calculation which reproduces the fragment mean characteristics is unable to describe properly the lcp features.

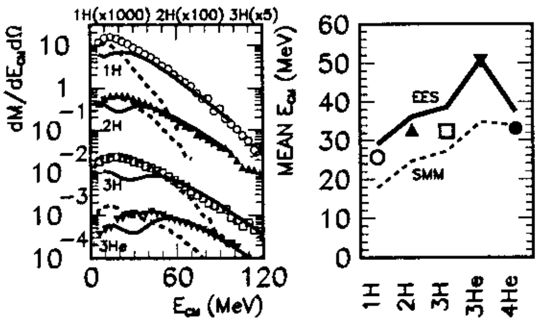

Figure 1: **50 A.MeV** : $-0.5 \leq cos\Theta_{cm} \leq 0.5$ *light charged particle energy characteristics for data (markers), SMM (dashed-lines), and EES (solid-lines).*

This is not surprising since in the SMM-model lcp's originate from the freeze-out configuration and from secondary decays of primary excited clusters only. The source expansion phase which includes light particle production is not described. To go further, we have made use of the equilibrated Expanding Emitting Source model EES [26] : an excited source expands isentropically with particle surface emissions then reach a low density "no-return" point where nuclear bulk properties are simulated by particle volume emissions. In this context, most of the Z≥3-fragments are produced during the volume emission process while lcp's originate from the two phases : surface and volume emission. EES-calculation was done for the 50 A.MeV case. The input parameters of the model correspond to measured values : size and excitation energy of the source calculated with all detected particles (fragments and lcp) except the anisotropic lcp part (i.e. source before expansion). Two points have to be highlighted : (i) a genuine collective energy was required in order to reproduce the fragment mean kinetic energies which confirms compression effects, (ii) the high energy part of lcp c.m kinetic energy spectra is now explained as seen in fig. 1 (full lines). The EES-spectra for lcp's can be divided in two parts which correspond to surface (high energy) and volume (low energy) emissions. The dip for EES-calculation at low kinetic energy is the result of the sharp switch from surface to volume emission and lack of secondary recoils. Also in EES-model the calculation is limited in time and therefore one does not expect to fully explain the very low energy part of lcp's.

Therefore when considering that the high energy part of lcp production is governed by emission during the expansion phase we can explain both lcp and fragment characteristics within an equilibrated time dependant scenario for the source breaking process.

A backtracing procedure [25] has been employed to show that there exists a distribution of sizes and excitation energies for each set of events (32-50 A.MeV) when the source breaks into fragments (step 3) : the number and the energy of pre-equilibrium and surface emitted particules differ from event to event.

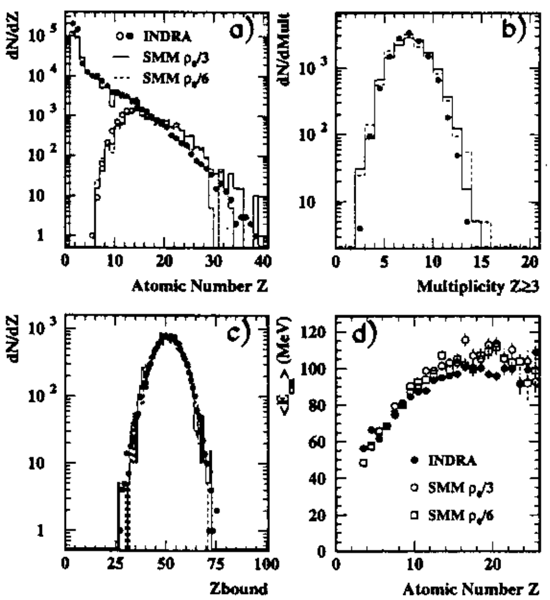

Figure 2: **Backtracing $\rho_0/3$ and $\rho_0/6$ SMM versus 50 A.MeV data :** *charge distribution and the biggest fragment distribution (a), fragment multiplicity (b), sum of Z≥3 (c), mean fragment kinetic energies (d).*

For each bombarding energy, the backtracing procedure was performed for a given SMM freeze-out density (see fig. 2) and it has not been possible to select a "best" volume because of the interplay between the superimposed collective energy and the Coulomb interaction energy of SMM with the used observables.

As a first conclusion, we can say the following : (i) the lcp's and fragments characteristics are compatible with the thermodynamical equilibrium, (ii) collective energy is present, acts as a superimposed perturbation which does not influence the equilibrium concept, (iii) the source at the breaking can be reconstructed experimentally with the fragments and a part of lcp's, the high energy part of lcp's reflect the expansion phase. The framework is now settled for the fluctuation method analysis keeping in mind the presence of collective energy and light particle emission during the expansion.

3 Fluctuation method

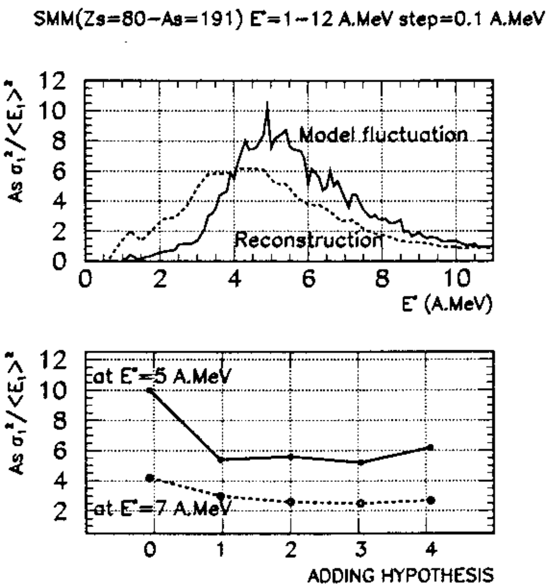

Figure 3: **SMM** : *normalized kinetic energy fluctuation as a function of excitation energy (top). Bottom see text.*

The excited configuration is reconstructed through a calorimetric analysis of its de-excitation products. Two types of reconstruction were performed in [15]. For the present analysis we will concentrate only on the "hot fragment" method since for the studied system it has been shown [22, 23] experimentally that the primary products of the breaking of the source were hot.

One of the crucial variable is the normalized kinetic energy fluctuation (see [15]) calculated with the reconstructed primary products. Using SMM as an event generator with a phase transition, we can appreciate the effects of the differents hypotheses used for the reconstruction method. The true and reconstructed normalized fluctuation of the model are presented in fig. 3-top as a function of excitation energy. In the bottom picture is presented the effect of the different hypotheses involved for two values of excitation energy so to cover the energy domain of 32-50 Xe+Sn central reactions. First we see that for $E^* \geq 4$ A.MeV, the reconstructed kinetic energy fluctuations are lower than the original values. In other words the used reconstruction do not increase the true model fluctuations. Therefore any experimental signal related to fluctuations could be considered as a "minimun" signal in the framework of SMM. Secondly we can give an explanation for this. The normalized fluctuation for E^*=5 and 7 A.MeV for the different hypotheses involved in the reconstruction method are presented in fig. 3-bottom : neutrons not detected, fragments not identified in mass and usable lcp's from the 60-120 degrees domain because of pre-equilibrium (i.e. doubling the lcp's). Those hypotheses concern the calorimetry method to obtain the source excitation energy and the reconstruction method itself : the kinetic energy part of E^* at the multifragmentation-time is deduced from the potential part of the reconstructed primary partitions. In the picture, the label "0" concerns the true model values and "1" concerns the reconstructed fluctuations with all known SMM final products. From this we see that a perfect detector will give a minimum measurement. This is partly due to the fact that in the reconstruction method the fragment multiplicity is the observed final one and the source volume, used for the calculation of the potential part of the energy, is fixed to a constant value for the whole excitation energy range. Therefore in this game a part of the true fluctuations is lost. The label "2" is "1"+assumed number and energy of neutrons. The inclusion of neutrons is performed in our method by assuming a mean number and total energy for each bin in E^*. The label "3" is "1"+"2"+assumed mass of final products. The mass of the fragment is assumed to be a mean value for each Z. Label "4" is "1"+"2"+"3"+doubling lcp detected between 60 and 120 degrees. The forward/backward lcp's are not usable because of mentioned entrance channel effects. The following remarks about "2", "3" and "4" can be addressed. First for each hypothesis which replaces an event by event variation (neutron or mass) by a mean value the effect is either to keep constant the kinetic energy fluctuation or to decrease it.

Secondly the replacement of an event by event variation by doubling a detected one increases the kinetic energy fluctuation but not in a dramatic manner.

Improvements of the method will be done in the future. The questions of the Coulomb interaction volume and the extraction of a mean temperature for the heat capacity measurement will not be traited here and we refer to [15]. Nevertheless it is observed here that the choosen method of replacing unknown event by event variations by a mean value can be considered as a conservative choice against detection lacks.

4 Collective Energy effect

Again with the use of SMM as an event generator, we will appreciate the effect of the collective energy (compression effects) in the reconstruction method.

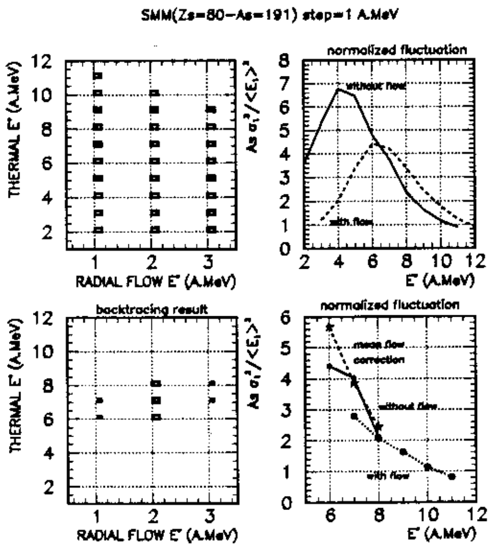

Figure 4: **SMM** : *Collective energy effect on the normalized kinetic energy fluctuation calculation. Two cases : flat distribution of E_{coll} (top) and the result of the SMM-data backtracing for 50 A.MeV Xe+Sn (bottom).*

The method uses the potential and kinetic separation of the total energy. It assumes in the different steps that the kinetic energy is purely thermal so to measure the total heat capacity. The kinetic energy is deduced from the total excitation energy (E*) and the potential energy. If one assumes that the collective energy (E_{coll}) does not affect the event by event partitions, the only measurement which has to be corrected is E^*. This hypothesis of decoupling between thermal and collective motion has been proved to be relevant for 32-50 A.MeV Xe+Sn data (see fig. 2) and it shall be axiomatic in the following.

First we present a "school" case : SMM-calculations are performed between 3 and 12 A.MeV total excitation energy with a flat distribution of E_{coll}=1, 2 and 3 A.MeV (see fig. 4-top left). The result on the fluctuation method without substacting the collective energy (dashed line : with flow) is compared in fig. 4-top right to the result of the fluctuation method with the use of SMM-calculations without flow (full line). From the comparison, one concludes that the inclusion of a collective energy distribution does NOT increase the normalized energy fluctuations. We observe a displacement of the maximun and a reduction of the fluctuations in the SMM-coexistence zone. More generally for a finite system with a phase transition, inside the coexistence zone the biggest fluctuations are of pure thermal origin and any addition of collectivity even in a fluctuate manner will lower them.

This implies also that we have to correct for the collective energy in our Xe+Sn measurements otherwise the signal could be washed out. As for previous hypotheses (c.f section fluctuation model) our choice was to performed a mean correction so to be conservative. To validate this choice we have made use of the backtracing result SMM-data (see fig. 2 for 50 A.MeV Xe+Sn). In the backtracing procedure the collective energy was included in the source variables and was tagged with the help of a fragment kinetic energy variable. The result is presented in fig. 4-bottom left for the Thermal and Collective part of the total excitation energy for a given freeze-out density of SMM. This can be considered as a realistic energy distribution for SMM as compared to the previous "school" case. The calculations with and without flow are presented in fig. 4-bottom right and the same conclusions as before can be drawn. Furthermore the effect of taking a unique mean correction (E_{coll}=2 A.MeV) for the kinetic energy fluctuation analysis is also presented in fig. 4-bottom right (dashed line) and we see that the "without flow" values are almost recovered.

Bombarding Energy	32 A.MeV	39 A.MeV	45 A.MeV	50 A.MeV
Mean $E_{collective}$	0.8 A.MeV	1.2 A.MeV	1.7 A.MeV	2.1 A.MeV

Table 2: Mean values of the collective energy.

In conclusion, for our data using a backtracing analysis we are able to measure the collective energy part of the total excitation energy. This consists of a picked distribution which is possible to approximate with a single mean value for each bombarding energy without perturbing the kinetic energy fluctuation analysis. In the following, the used mean collective energy corrections are presented in tab. 2 and the source volume was fixed to 3 times the normal volume for the potential Coulomb interaction energy calculation.

5 Flow corrected results

The raw and flow corrected results are presented in this section.

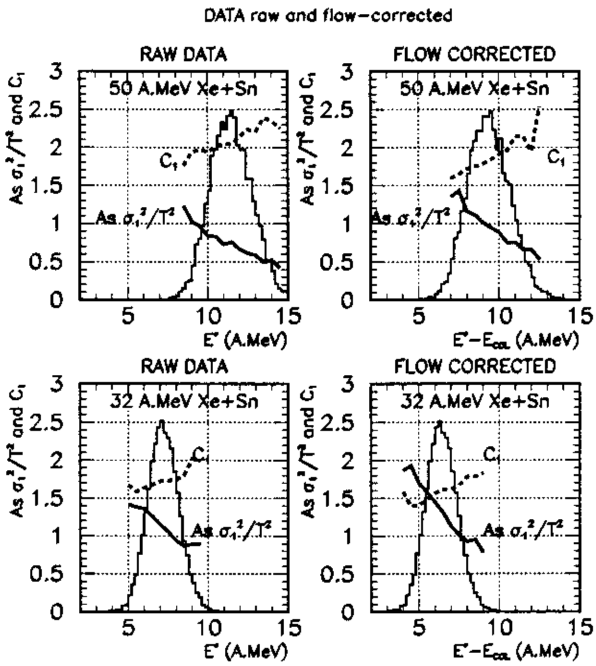

Figure 5: **Data** : *Fluctuation analysis. Excitation energy distribution is superimposed in each picture (arbitrary units).*

For each picture the kinetic heat capacity (C_1) and its conjugate the kinetic energy per nucleon fluctuation normalized to the temperature and multiplied by the source size ($A_S\ \sigma_1^2/T^2$) are plotted as a function of the excitation energy. A negative total heat capacity is observed for $A_S\ \sigma_1^2/T^2 > C_1$ with a divergence for equality of the two reconstructed variables. The formulae for C_1 and T calculations can be found in [14], they are mean values extracted for each considered 0.5 A.MeV bin in excitation energy. Inside each picture, the measured excitation energy distribution is superimposed so to have a hint about significative points. The excitation energy scale is for "raw" data the calorimetry measurement while for "flow corrected" data it is the calorimetry result corrected by a mean collective energy value (c.f tab. 2).

In fig. 5 are presented the 32 and 50 A.MeV mentioned pictures for raw and flow corrected data (see tab. 2). For the left part, without any correction, the data seems overcritical besides the fact that a sketch of crossing for 32 A.MeV is visible. Once the flow correction is applied the signal of crossing is clearly seen for 32 A.MeV data while for 50 A.MeV the general tendancy remains unchanged.

Since it has been demonstrated that the collective energy, if present, has to be removed for the fluctuation analysis, the fig. 5-bottom right shows a divergence in the total heat capacity.

6 Emission during expansion correction

It has been shown previously that particle emission (mostly light particles) occurs during the expansion phase. This phenomenon has an effect on the fluctuation method since for the E^* measurement and the potential energy reconstruction at the breaking time some detected light charged particles should not be taken into account. As a matter of fact the characteristics of the multifragmenting source obtained through SMM-data comparison does not correspond to the values measured with all the isotropic detected information : about 11.5 A.MeV for E^* as compared to 8.8 A.MeV with SMM for the 50 A.MeV case. This is understood in the context of EES-calculations (see fig. 1) and we have made an estimate of this effect by selecting for the event by event fluctuation analysis the low energetic lcp's. The selection is performed by retaining only lcp's with an energy in the c.m lower than a given value. The choosen values, estimated from EES-calculations where the surface emission contribution is clearly visible, are given in tab. 3 for 32 and 50 A.MeV. It is seen that all 4He-particles are retained and all 3He-particles are removed [20].

Bombarding Energy	p	d	t	3He	4He
32 A.MeV cuts	30 MeV	30 MeV	50 MeV	0 MeV	∞
50 A.MeV cuts	30 MeV	40 MeV	60 MeV	0 MeV	∞

Table 3: Light Charged Particule c.m energy cut.

7 Full corrected results

The flow and full corrected results are presented in fig. 6 in a format already explained in section 5. Left-spectra has been presented in fig. 5. Right-spectra concern the full (collective energy + emission during expansion) corrected results and the excitation energy scale is now assumed to represent the thermal excitation energy of the source at the multifragmentation time. For 32 A.MeV the heat capacity divergence is still present and occurs now for the most probable events. For 50 A.MeV the divergence is now observed.

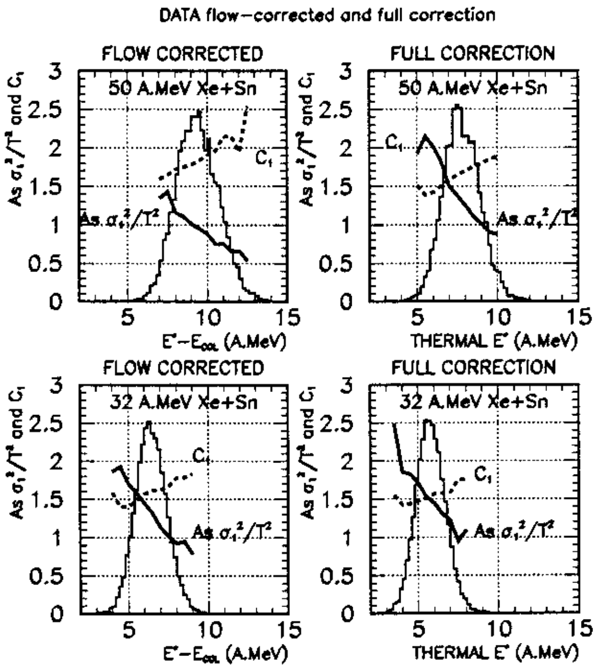

Figure 6: **Data** : *Fluctuation analysis. Excitation energy distribution is superimposed in each picture (arbitrary units).*

The full corrected method gives the good tendancy for the thermal E^* at the breaking time as compared to SMM-results but is not in full agreement. For 50 and 32 A.MeV the comparison is respectively : 7.8 and 5.8 A.MeV for the experimental mean E^*_{therm} (i.e. full corrected measurement) as compared to 6.7 and 4.8 A.MeV from SMM-results (c.f tab. 1). Improvements will have to be done in the future. Nevertheless because the number of removed lcp's is low as compared to the total isotropic ones, the effect is more visible on the excitation energy scale than on the fluctuation values themselves. This can be explained by the larger dependance of the fluctuation method upon fragment static characteristics as compared to lcp's.

8 As a conclusion

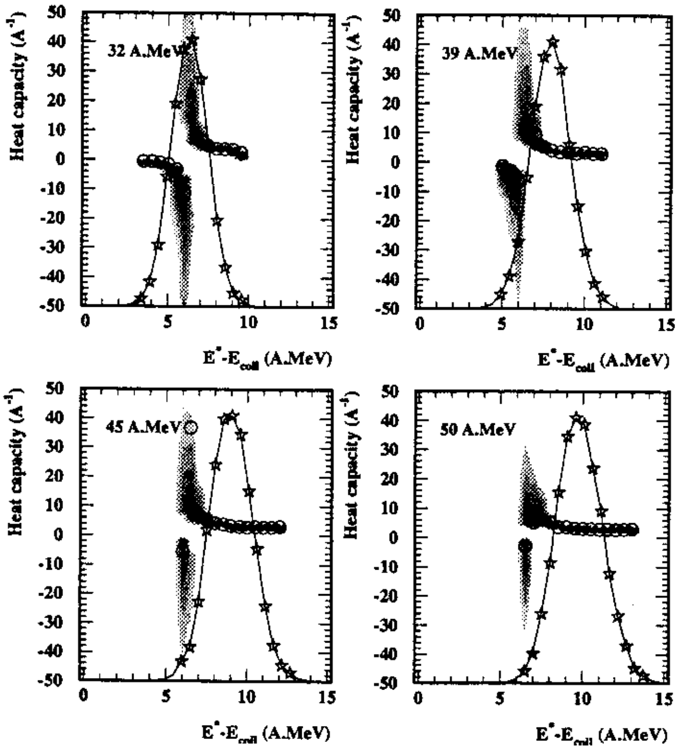

Figure 7: **Data** : *Heat capacity with flow correction and variable multifragmenting volume. Excitation energy distribution corrected by mean collective flow is superimposed in each picture (arbitrary units). All figures are made with a 0.5 A.MeV energy step.*

For Xe+Sn central reactions a divergence in the total heat capacity is observed. A negative heat capacity branch is measured and so tends to confirm the observation of a first order phase transition in heavy-ion collisions [14]. In our case, using central 32-50 A.MeV Xe+Sn collisions, the thermal excitation energy range does not cover the whole coexistence region and one does not expect to sign the transition between the "liquid" and the coexistence zone.

This result was obtained by taking into account the presence of collective flow. This step is fundamental since the fluctuation method is based on thermal measurements. A try of taking into account for particle emission during the expansion phase has been presented. It remains an attemp since up to now we have some difficulties to restore the true thermal excitation energy. Nevertheless it does not perturbe heavilly the kinetic energy fluctuation measurements themselves because the presence of the heat capacity divergence corresponds to large fluctuations on the detected fragment partitions.

About the location of the heat capacity divergence, we can notice that it varies with the bombarding energy (see fig. 6). This could be explained by our calculation method which uses the same volume (i.e. 3 V_0) whatever the bombarding energy is. A more reliable situation is observed when one uses a breaking volume which depends on the fragment multiplicity [24] in an event by event basis. The result is presented in fig. 7 for the flow corrected measurement. It can be observed that the location of the divergence does not depend on the bombarding energy which could tend to prove that the first phase transition is not accomplished at constant volume for central collision reactions.

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