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M.F. RIVET[1], B. BORDERIE[1], J.D. FRANKLAND[1], Ch.O. BACRI[1], M. PÂRLOG[2], M. SQUALLI[1], G. TABACARU[2], M. COLONNA[4], A. GUARNERA[3] and P. CHOMAZ[3]

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INDRA Collaboration

[1] *Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France.*
[2] *National Institute for Physics and Nuclear Engineering, RO-76900 Bucharest-Măgurele, Romania.*
[3] *GANIL, CEA et IN2P3-CNRS, B.P. 5027, F-14076 Caen Cedex, France.*
[4] *Laboratorio Nazionale del Sud, Viale Andrea Doria, I-95129 Catania, Italy.*
[5] *LPC, IN2P3-CNRS, ISMRA et Université, F-14050 Caen Cedex, France.*
[6] *DAPNIA/SPhN, CEA/Saclay, F-91191 Gif sur Yvette Cedex, France.*
[7] *Institut de Physique Nucléaire, IN2P3-CNRS et Université, F-69622 Villeurbanne Cedex, France.*
[8] *Dipartimento di Scienze Fisiche e Sezione INFN, Università di Napoli "Federico II", I80126 Napoli, Italy.*

Abstract

The multifragmentation of "fused systems" was evidenced for central very heavy ion collisions between 30 and 50 MeV/u. Most of the resulting charged products were identified thanks to the high performances of the INDRA 4π array. The measured fragment kinetic energies indicate that the multifragmenting system is radially expanding. The threshold for radial expansion is found around $E_{inc} \sim$ 25-30 MeV/u ($\varepsilon^* \sim$ 5-6 MeV) for systems with total masses larger than 200. Dynamical calculations including fluctuations, in which multifragmentation results from the spinodal decomposition of a finite piece of nuclear matter were performed and give excellent agreement with the experimental data.

1 Introduction

Central collisions between heavy ions around the Fermi energy lead to hot and compressed pieces of nuclear matter. An expansion phase generally follows, and the system may either present a monopolar density oscillation and recover normal density, or indefinitely expand and eventually multifragment: the fate of the system ("to multifragment or not") is governed by the nuclear EOS (incompressibility parameter) and the residual interaction (viscosity). Radial expansion energy appeared already measurable in collisions at 30-50 MeV/u. Its determination is however not obvious because, even for heavy systems, the stopping is not very strong and transparency effects cause most of the collisions to keep a binary character. Only for very heavy systems a careful selection allows one to isolate rare compact shape events for which the concept of radially expanding matter is justified. We will here present data obtained with the INDRA 4π array, showing the event selection, how the collective energy is evidenced, and quantified. A systematics of radial expansion energy measured for heavy systems between 30 and 100 MeV/u will be shown, and compared with results for light systems. In a second part, experimental evidence for volume instabilities as a cause of multifragmentation will be offered, and a full comparison with a dynamical model taking into account fluctuations will suggest that multifragmentation may originate from the spinodal decomposition of finite systems, at least around 30-40 MeV/u.

2 Radial expansion energy below 50 MeV/u.

2.1 Selection of central and isotropic events

Radial expansion can only be properly determined when a well defined multifragmenting source, with radial symmetry in momentum space, has been formed in the course of the collision [1, 2]. When averaging over a sufficiently large number of events, it is then expected that the fragments resulting from the break-up of this system will be isotropically emitted. Multiplicity cuts or completeness criteria are often used to achieve central collision selection, and "single-source" events and "central" events are assumed to be identical ensembles. However it has been shown from the INDRA data that in most cases multiplicity cuts select events with a large variety of shapes, essentially spanning "binary" collisions (associated with multifragment emission [3]), or very deformed multifragmenting systems [4]. Compact shape events were shown to be best isolated by using the angle θ_f between the event main axis [5] and the beam axis. This angle remains small while maximum dissipation is not reached; then all θ_f are populated, but in a strongly non-isotropic way. Collisions in which two main fragments retained a memory of the entrance channel velocity, or alternatively in which the multifragmenting system is highly deformed are dominant. Only for large θ_f angles compact shape events could be isolated, for which the concept of isotropic fragment emission, and thus radial symmetry makes sense. We want to stress that this kind of selection, if compared to the most popular "impact parameter selectors" (multiplicities, transverse energies), does not isolate the very most central collisions; instead it spans the same impact parameter range as the selection of complete events does, namely reduced impact parameters lower than 0.3. This confirms our idea that, due to large fluctuations in both the entrance channel and the de-excitation phase, there is no univocal relation between an impact parameter and the scenario of the collision.

2.2 Evidence for extra collective energy

Compact shape events were isolated for the heavy systems studied with the INDRA array (Xe+Sn 32-50 MeV/u; Gd+U 36 MeV/u). Their partition properties as well as kinetic properties were closely examined; for all systems, the fragment average c.m. kinetic energy first increases with the fragment atomic number, and then levels off, or even decreases. If however one removes the heaviest fragment of each partition, a constant increase is observed. It appeared that statistical multifragmentation models (SMM [6], MMMC [7]) or event generators (SIMON [8]) could account for the different experimental fragment multiplicity and charge distributions, providing a tuning of the parameters defining the multifragmenting object (mass, excitation energy, volume). But the fragment kinetic energies, which in these models arise from thermal motion and Coulomb repulsion at the freeze-out, underestimate the measured values. Clearly the high measured energy values call for the occurrence of some extra collective energy. As the incident energies remain moderate, a form of "rotational" flow may be considered [9]. This was tested for two systems, using two different simulations: 50 MeV/u Xe+Sn with MMMC [10], and 36 MeV/u Gd+U with SIMON [4]. A single initial angular momentum value is shared between the fragments (without giving them intrinsic spin). A tremendous amount of angular momentum would be needed in both cases to approach the measured kinetic energies, corresponding to average reduced impact parameters of 0.6; this is clearly incompatible with the central collision selection that we have performed, and also with the reproduction of several other experimental characteristics [4].

We are then led to assume that the extra collective energy is an expansion energy. In the Fermi energy region, the maximum densities reached by the systems in the course of the collisions are not expected to be very large (see next section), while rather high excitation energies may be available (from 7 to 12 MeV/u when the incident energy increases from 30 to 50 MeV/u). Therefore the relative role of thermal and compressional pressure in the expansion has to be investigated. Indeed at much higher energies thermal pressure is shown to take over compression effects [2]. For the 50 MeV/u Xe+Sn system, the role of the temperature of the system was explored through the EES model [11], where a hot system at normal density is followed during its cooling phase: the system first expands while evaporating mainly light particles, before a sudden and quasi-simultaneous emission of fragments occurs. But the radial expansion energy generated by thermal pressure does not exceed 0.5 MeV/u, which cannot explain the large fragment kinetic energies measured [12]. The role of compression must then be dominant [1, 13].

To quantify the expansion energy one generally includes a self-similar radial expansion in the statistical models, assuming that the effects of excitation and of compression are fully decoupled, thermal energy acting on the partition, and expansion energy only increasing the fragment kinetic energy. This approximation may not be too drastic while the expansion energy remains small. The assumption of self-similar expansion is supported by semi-classical dynamical simulations, where the radial velocity is linearly dependent on the distance of the particle from the center of mass, at least up to the time where the system first returns to normal density [14]. Which such a further assumption, one is able to reproduce not only the average kinetic energy of the fragments, but also their energy spectra [12]. The values of the expansion energy so determined are not exempt from ambiguity, as one of the parameter of the statistical models is the freeze-out volume of the multifragmenting source, which in turns influences the Coulomb repulsion between fragments. As the Coulomb energy and the expansion energy are here of the same order of magnitude, the effect of the chosen volume on the expansion energy is important, and the larger the volume, the higher is the "measured" expansion energy.

2.3 Systematics of radial expansion energy below 100 MeV/u

Radial expansion energy has been found in a number of systems studied by different groups. In most cases the absolute value of the expansion energy is extracted as explained above; this implies that any effect of the apparatus (thresholds) or of the event selection on the measured energy of the fragments will be attributed to a difference in the extra collective energy. For instance, radial expansion energy is often extracted from the energy measured around 90° c.m. in multiplicity selected central collisions, "to avoid contamination by spectator emission". As shown in [8],

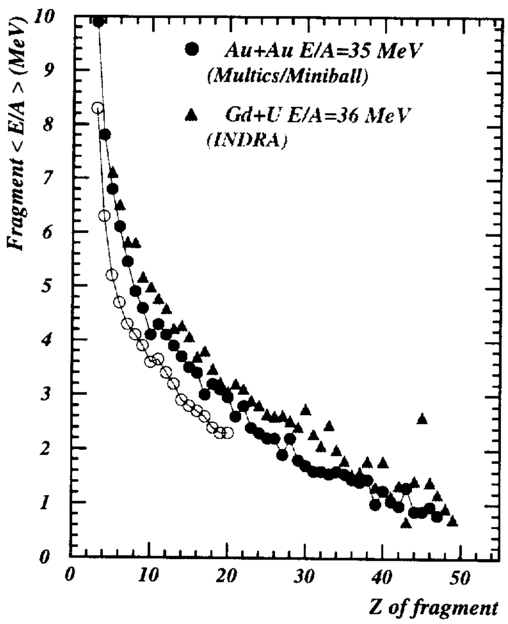

Figure 1: *Measured average fragment kinetic energies for two systems with same total masses, at close incident energies. The 36 MeV Gd+U system (triangles)was studied with INDRA, and compact shape events were isolated at large θ_f. MULTICS/MINIBALL was used for the 35 MeV/u Au+Au system: full points come from the same large θ_f selection [17], while the open points are for 90° c.m. values with a multiplicity cut [18].*

this leads to smaller experimental energies as compared to θ_f selections, and thus to smaller expansion energies. Conversely, with similar event selections, the influence of the apparatus is negligible: fig. 1, which displays the average fragment energy obtained for 2 systems having the same total mass and available energy but measured with different set-up, shows that the role of the selection prevails over that of the apparatus. A systematics of expansion energies published for heavy systems ($A_{tot} >$ 200) is reported in fig. 2; the bars for the INDRA data display the range of values obtained when varying the freeze-out volume between 2.2 and $3V_o$ (the nucleus volume at normal density) [15, 16, 14, 4]; Other authors use $3V_o$ or $6V_o$. Despite the warnings just quoted a general trend emerges, namely an increase of the expansion energy with the c.m. available energy. Expansion energy appears around $\varepsilon^* \sim$5-7 MeV. Clearly the thresholds for multifragmentation and for expansion energy coincide, which means that both phenomena are linked: some compression (even small) is needed to induce multifragmentation.

The situation is not as clear for lighter systems. For the reactions Ar+KCl, Ar+Ni measured with INDRA, some incomplete fusion events were identified below

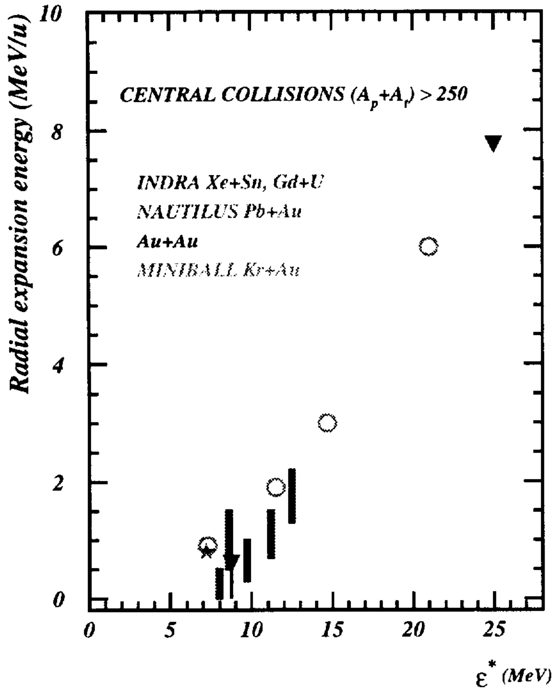

Figure 2: *Systematics of radial expansion energy for heavy systems. ε^* stands for the available c.m. energy. Thick bars are for INDRA data, Xe+Sn and Gd+U (see text). Star: Pb+Au [19]. Inverted triangles: Au+Au [20, 21]; the bar for [20] comes from using two values of freeze-out volume. Open points: Kr+Au [22].*

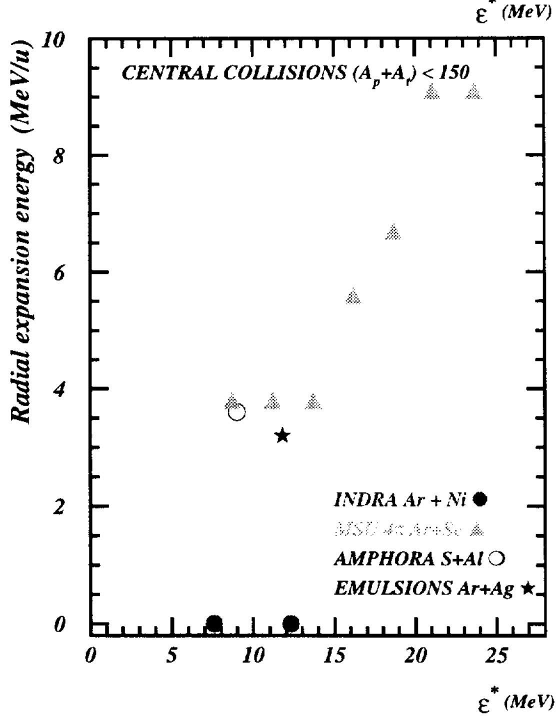

Figure 3: *Systematics of radial expansion energy for light systems. Full points are for Ar+Ni (INDRA data). Star: Ar+Ag(emulsions) [25]. Triangles: Ar+Sc [23]. Open point: S+Al [26].*

52 MeV/u, among which some multi-fragment events appeared; but their characteristics rather resemble those of an evaporative process, with a heavy residue accompanied by lighter companions. In other words there is no expansion energy. Conversely, other published data quote a large amount of radial energy, even larger than for heavy systems at a given excitation energy. But we met here a typical case where the transverse energies measured at 90^o c.m. for the 10% most central collisions are much higher for Ar+Sc [23] than for Ar+Ni [24], both at $\sim$ 75 MeV/u. Then obviously the deduced extra collective energy will be much larger in the first case. Whether this arises from the experimental set-up (thresholds) or from the selection is difficult to disentangle. If we rely on the ensemble of INDRA data, the lack of multifragmentation/expansion for small systems is difficult to impute to a

smaller stopping, as reported at higher energies [2], because fusion sources are indeed formed. It may signify that compression is not sufficient to drive and maintain the system at low densities, eventually because of the smaller Coulomb repulsion which helps the expansion for the heavier systems.

3 Multifragmentation and spinodal decomposition of finite systems

As quoted in the previous section, the properties of single-source events at a freeze-out point are compatible with the assumption that a thermodynamical equilibrium has been reached at that moment. Therefore it may be argued that multifragmentation is just the dominant de-excitation mode for hot systems. But these systems have been produced through violent nuclear collisions, and have lived quite a long history before reaching this point; we have shown above that multifragmentation only becomes an important exit channel when the system has been compressed and then expands towards low densities. This means that fundamental properties of nuclear matter such as incompressibility, viscosity ... must play a role, and that instabilities of different kinds (surface, volume) dynamically generated in the course of the collision may also be contemplated for causing the break-up of the system [27]. Experimentally, an interesting effect was observed in the INDRA data: single-source multifragmentation events from two systems with different masses but the same available energy display the same charge distribution, while the fragment multiplicities scale as the size of the total systems. These results are shown in fig 4. for the two systems Xe+Sn at 32 MeV/u and Gd+U at 36 MeV/u.

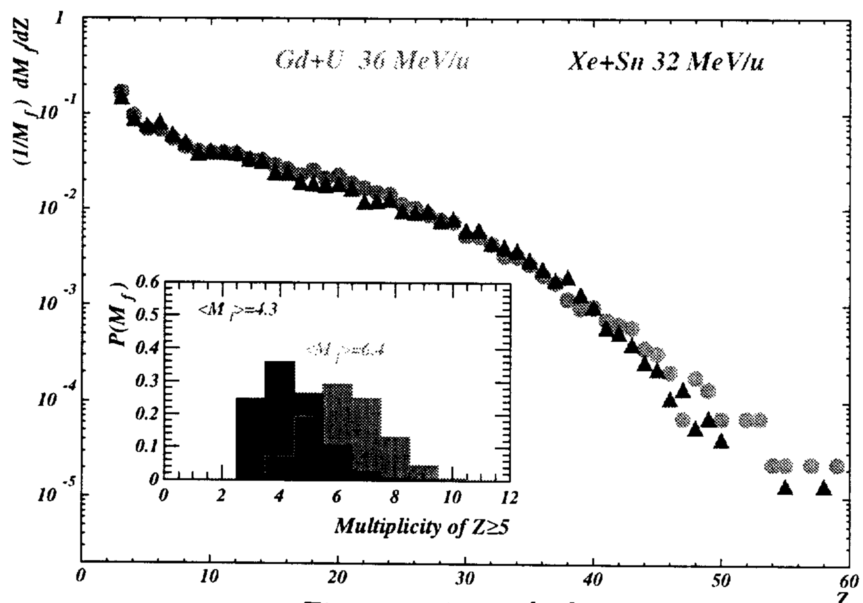

Figure 4: *From [29], see text.*

Although this scaling results from some statistical models [10], for the heavy systems considered (~ 250 and 400 nucleons) it may also sign an effect of bulk instabilities. Moreover it matches the expectations from a spinodal decomposition of finite systems, which predict a scaling effect arising from the production of fragments with a favored size, connected to the wave length of the most unstable mode. Note that this simple picture is blurred by several effects: the beating of different modes, the eventual coalescence of fragments while the nuclear force still acts and the finite size of the system will tend to end-up with a broad, exponentially falling distribution of fragment charges. Thus a test using two different systems appeared more convincing than results arising from a single reaction, and it was worth comparing the experimental findings with a complete simulation of nucleus-nucleus collisions, including fluctuations to allow the formation of fragments [28]. In reference [29], it was shown that the multiplicity and charge distributions for both systems - and thus the scaling- were correctly reproduced, but that the calculated fragment kinetic energies were too low. Since then two major improvements have been implemented in the simulations: firstly quantal fluctuations connected with collisional memory effects [30] are now taken into account with the determinant result of doubling the overall amplitude of fluctuations [31]. Secondly the previous simulation method, which consisted in injecting the correct (classical) fluctuations when the system enters the spinodal region , but continuing with a standard BNV calculation, led to a damping of these fluctuations. The fragment formation time was thus artificially (and incorrectly) increased, leading to smaller kinetic energies due to the decrease with time of the expansion of the system. A better simulation method was proposed [28], which creates the density fluctuations through a stochastic force, and therefore maintains them while the system is unstable. This method, analogous to the Langevin treatment of Brownian motion, is called Brownian One-Body dynamics (BoB). The simulation (for head-on collisions, as fluctuations calculated for infinite matter can be rather safely extrapolated only to systems having a spherical symmetry) thus proceeds as follows [4]: the dynamics is followed through a BNV/BoB simulation, up to the time where the fragments are formed and well separated. The fluctuating force starts acting at the time of maximum compression in order to get the correct amplitude at the entrance in the spinodal region. Characteristics of the Gd+U and Xe+Sn systems at these two times are shown in table 1. The maxi-

	Maximum Compression				Spinodal zone				
	A	Z	ρ/ρ_0	T MeV	A	Z	ρ/ρ_0	T MeV	v_{max}/c
$^{129}Xe+^{nat}Sn$	247	103	1.25	8.3(^{a})	238	100	0.41	4.0	.09
$^{155}Gd+^{238}U$	389	154	1.27	8.3(^{a})	360	142	0.41	4.0	.10

Table 1: *Left: t=40 fm/c, time of maximum compression;* ^{a} *Local temperature at the center of the non-equilibrated system. Right: t=100 fm/c: thermalised systems inside the spinodal zone.* v_{max}/c *is the radial velocity at the surface.*

mum density is 25-30% higher than normal density, corresponding to a moderate compression. Slightly after entering the spinodal region, the systems are in thermal equilibrium at low density, with a temperature of 4 MeV. The radial velocity at the surface is rather large ~0.1c. When the fragments are well separated, they still bear an excitation energy of ~3.2 MeV/u, as seen in table 2. Figures to remember from this table are the average radial energies, whose values are close to the extra collective energy added to statistical models (fig 2), and similar to the amount of

	A_{tot}	Z_{tot}	N_f	$< Z_f >$	$< \varepsilon^* >$ MeV/u	$< \varepsilon_{rad} >$ MeV/u	E_{coul} MeV
$^{129}Xe +^{nat} Sn$	194.0	76.1	5.1	13.4	3.2	0.81	175.2
$^{155}Gd +^{238} U$	320.0	120.8	8.1	12.6	3.3	1.54	430.0

Table 2: *Characteristics of the systems at the end of the BoB simulations, when starting the de-excitation step. A mass $< A_{tot} >$ and a charge $< Z_{tot} >$ are shared between $< N_f >$ fragments ($Z \geq 5$) of average atomic number $< Z_f >$.*

Coulomb energy. At that time it may well be that the systems populate all phase-space, thus being describable through statistical models. The de-excitation of the hot primary fragments, whose mass accounts for 80% of the total system mass is followed through the evaporation part of the SIMON code. Finally the results are filtered to take into account the experimental set-up.

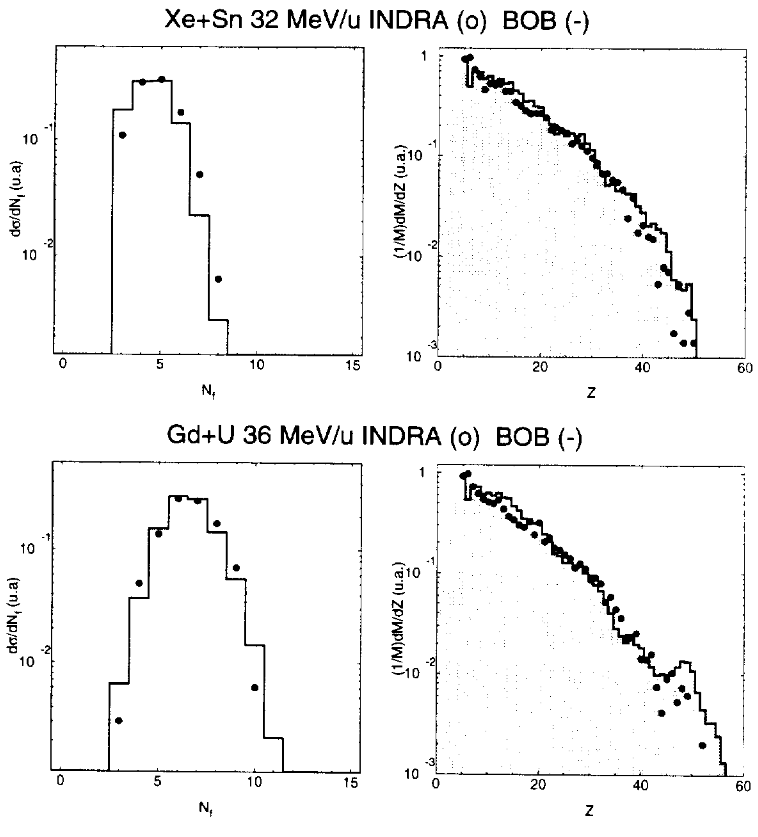

Figure 5: *Experimental (points) and simulated (lines) fragment multiplicity and charge distributions for single multifragmenting sources formed in 32 MeV/u Xe+Sn and 36 MeV/u Gd+U collisions [4]. The grey histograms refer to the hot primary fragments (see table 2).*

Figure 5 shows that the calculated multiplicity and charge distributions of fragments well match the experimental data. More detailed comparisons on the charge distributions of the three largest fragments display the same excellent agreement [4]. The role of secondary decay in the fragment distribution is negligible, as observed by comparing the grey histograms (primary fragments) and the solid histograms (final fragments). Shape variables, such as the isotropy ratio, with its multiplicity dependence, or the distributions of the relative angles between fragments, are also well accounted for [4]. Finally the most crucial test is on the fragment kinetic energies, displayed in fig. 6. As compared to ref [29], the energy calibration of the INDRA CsI located past 45^o (lab) were improved for fragments with charge larger than 15 [32]. This correction is particularly important when the velocity of the reaction center

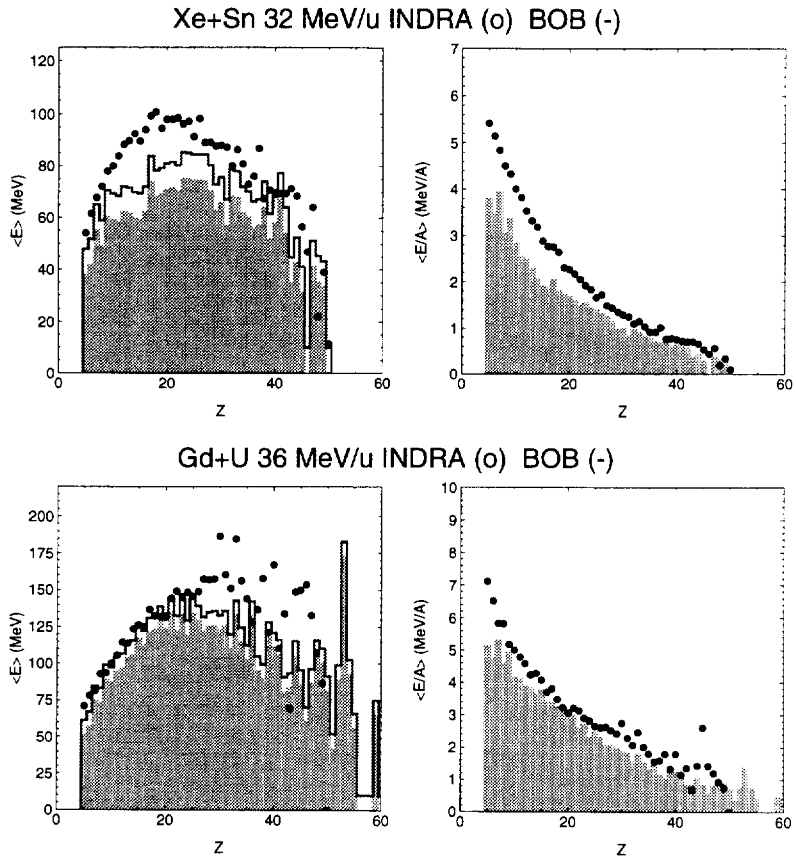

Figure 6: *Experimental (points) and simulated (filled histograms) average fragment kinetic energies. The lines are the calculated values when adding the thermal fluctuations [4]. The results are for total energies on the left, and in MeV/u on the right.*

of mass is small, and the fragment velocities in the c.m. are large. Practically among the heavy systems quoted in this paper, it acts on the energy of fragments with $15 < Z < 35$ produced in the 36 MeV/u Gd+U central collisions. The better simulations now correctly reproduce the fragment energies for the Gd+U system, especially if the thermal energy, minimized because of the number of test particles, is added. For Xe+Sn, the calculated energies fall within 20% of the measured values, which is satisfactory if one remembers that there were no adjustable parameters in the simulation.

To summarize, we have shown firstly that the measured energies of fragments emitted by single (compact) sources indicate that multifragmentation occurs at low densities reached by the system after a compression phase. Near its threshold multifragmentation appears as closely linked to compression/expansion effects. Secondly we have experimentally observed that two heavy systems with the same available energy produce the same fragment charge distributions, while fragment multiplicities scale with the total masses. This scaling naturally emerges in a full dynamical calculation including fluctuations, where multifragmentation arises from the spinodal decomposition of finite systems. The origin of multifragmentation may then be traced back to this phenemenon, at least for central collisions around 30-35 MeV/u, owing to the excellent agreement between static and kinetic variables observed in the experiments and in the calculations.

References

[1] B. Borderie, Int. Symposium on Large-Scale collective motions of Atomic Nuclei, Brolo Italy (1996) (eds G. Giardina, G. Fazio, M. Lattuada) World Scien-

tific (1997) p.1.

[2] W. Reisdorf and H.G. Ritter, Annu. Rev. Nucl. Part. Sci. bf 47 (1997) 663.

[3] B. Tamain et al. (INDRA collaboration), this conference.

[4] J.D. Frankland, thèse, Université Paris XI Orsay, 1998, IPNO-T-98-06.

[5] J. Cugnon and D. L'Hôte, Nucl. Phys. A397 (1983) 519.

[6] J.P. Bondorf et al, Phys. Reports 257 (1995) 133.

[7] D.H.E. Gross, Rep Prog. Phys. 53 (1990) 605 and Phys. Reports 279 (1997) 119.

[8] A.D. Nguyen, thèse, Université de Caen, 1998, LPCC T 98-02.

[9] M.B. Tsang et al., Phys. Rev. Lett. 57 (1986) 59.

[10] A. Le Fèvre, thèse, Université Paris 7-Denis Diderot (1997), GANIL T 97 03.

[11] W.A. Friedman, Phys. Rev. C 42 (1990) 667.

[12] R. Bougault et al. (INDRA collaboration), this conference, and J.P. Wieleczko et al. (INDRA collaboration), to be published.

[13] B. Borderie, B. Remaud, M.F. Rivet and F. Sébille, Phys. Lett B302 (1993) 15.

[14] M.F. Rivet for the INDRA collaboration, Proc. XXXV Int. Winter Meeting on Nuclear Physics, Bormio (I. Iori, eds) (1997) 225.

[15] N. Marie et al. (INDRA collaboration), Phys. Lett B391 (1997) 15.

[16] S. Salou, thèse, Université de Caen (1997), GANIL T 97 06.

[17] M. D'Agostino et al., Proc. XXXV Int. Winter Meeting on Nuclear Physics, Bormio (I. Iori, eds) (1997) 276.

[18] M. D'Agostino et al., Phys. Lett. B 371 (1996) 175.

[19] D. Durand et al., preprint LPCC 96-02.

[20] M. D'Agostino et al., Phys. Lett. B 368 (1996) 259.

[21] W.C. Hsi et al., Phys. Rev. Lett 73 (1994) 3367.

[22] C. Williams et al., Phys. Rev. C 55 (1997) R2132.

[23] R. Pak et al., Phys. Rev. C 54 (1996) 1681.

[24] T. Lefort et al. (INDRA collaboration), submitted to Nucl. Phys. A.

[25] H.W. Barz et al., Nucl. Phys. A531 (1991) 453.

[26] D. Heuer et al., Phys. Rev. C50 (1994) 1943.

[27] L.G. Moretto and G.J. Wozniak, Ann. Rev. of Nuclear and Particle Science Vol 43 (1993) 379.

[28] A. Guarnera et al., Phys. Lett. B373 (1996) 267. A. Guarnera, thèse, Université de Caen (1996). GANIL T 96 01.

[29] M.F. Rivet et al. (INDRA collaboration), Phys. Lett. B 430 (1998) 217.

[30] K. Morawetz, this conference.

[31] S. Ayik and J. Randrup, Phys. Rev. C 50 (1994) 2947.

[32] M. Pârlog et al. (INDRA collaboration), to be published.