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Dynamical and statistical aspects in nucleus-nucleus collisions around the Fermi energy.

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Abstract

Nucleus-nucleus collisions at low incident energy are mainly governed by statistical dissipative processes, fusion and deep inelastic reactions being the most important ones. Conversely, in the relativistic energy regime, dynamical effects play a dominant role and one should apply a participant-spectator picture in order to understand the data. In between, the intermediate energy region is a transition one in which it is necessary to disentangle dynamics from statistical effects. Moreover, the Fermi energy region corresponds to available energies comparable with nuclear binding energies and one may expect to observe phase transition effects. Experiments performed recently with 4π devices have given quite new data and a much better insight into involved mechanisms and hot nuclear matter properties. ~~In this contribution, we focus mainly on~~ INDRA data related to reaction mechanisms and multifragmentation are presented.

Most intermediate energy ~~reactions are binary and reminiscent of low energy deep inelastic~~ reactions. Two main bodies are released which may undergo multifragmentation. However, a major difference with mechanisms observed at lower bombarding energies is that particles and light fragments are emitted at intermediate velocity between the two main bodies. They may reflect either the strong deformation of outgoing partners or a third emission zone corresponding to the overlap of both incoming nuclei during the collision as in the participant-spectator picture. Hot nuclei may also be formed in fusion as at lower energies ; however, the corresponding cross section is quite low.

It is possible to study hot nuclei properties either by studying the rare fusion events or by focusing on the decay products of a projectile or target-like partner. It turns out that multifragmentation can take place above an excitation energy threshold of 3 MeV/nucleon. For central collision, it is shown that a detailed study of kinematical properties of outgoing products indicates that expansion occurs during the process. The expansion energy is not purely thermal in nature, but results from a compression phase followed by a lowering of the nuclear matter density. In this context, multifragmentation may be due to a spinodal decomposition of nuclei and may reflect properties of the equation of state of nuclear matter. It is also shown that time sequences are quite different for light charged particle and fragment emission and that multifragmentation exhibits properties which can be described statistically. At last, we discuss INDRA results on the caloric curve, and we understand from calculations why they do not exhibit a clear signature of phase transition.

1 Introduction

The Fermi energy domain is a frontier energy range in which one observes a significant evolution of mechanisms involved in nucleus-nucleus collisions. At low bombarding energies, most inelastic collisions lead either to fusion nuclei (central collisions), or to two excited remnants (semi-peripheral collisions : deep inelastic collisions - DIC) [1-3]. In both cases, the outgoing nuclei undergo a further sequential decay which is rather well explained in statistical theories. On the other side, relativistic collisions are described in the spectator-participant picture [4, 5]. Three pieces of nuclear matter are released : two nuclei (spectators) and a fire-ball. The spectators can be either slightly or significantly excited and undergo mostly a statistical decay. The participant zone is rather excited and expands, leading to final nucleons or light clusters. Nucleon resonances can be excited leading to a significant meson production. Of course, due to the huge amount of available energy and to the small reaction time dynamical effects play a dominant role. In the Fermi energy domain, one evolves from scenarii governed only by statistical features to mechanisms where dynamics is dominant ; from scenarii leading only to final nuclei to mechanisms leading to vaporized nuclear matter ; from scenarii where one (fusion) or two (DIC) nuclei are released to mechanisms leading to three outgoing nuclear "objects".

Another aspect of the Fermi energy domain is that it corresponds to the onset of multifragmentation. It turns out nowadays that multifragmentation is a new decay channel for excited nuclei. However, the question of the respective roles of statistics and dynamics is still open and will be addressed in this contribution. We will see that both statistical and dynamical effects are observed and can be unfolded.

The recent progress in the field have been possible because sophisticated 4π devices have been built, which allows the achievement of a complete kinematical analysis of recorded events [6]. For instance, in the INDRA collaboration , one requires a 80 % "kinematical efficiency", which means that more than 80 % of the available charge [7] and linear momentum has been detected for the selected events [8].

The "complete" detection is also necessary in order to be able to sort properly the events. For instance, it turns out from INDRA data, that fusion (i.e a process in which most nucleons of the initial nuclei merge in a single source) still exists at 50 MeV/u or above, but only with a very small cross section (few tens of millibarns, i.e. about 1% of the reaction cross-section) [8]. Such a sorting can be achieved only if a complete kinematical analysis can be performed on an event by event basis by using global kinematical variables such as the eccentricity, or orientation of the momentum tensor or the proportion of relaxed energy, i.e. a quantity which "measures" to which extent the initial directed kinetic energy has been shared between many degrees of freedom.

In the data which are summarized below, all these steps have been carefully considered.

2 A general overview

The dominance of two main source reactions may be easily recognized in $V_{//}$ - Z plots. Figure 1 is an example for the $Xe + Sn$ system at 50 MeV/u. For each event, one has diagonalized the momentum tensor in order to extract the main axis ;$V_{//}$ is the velocity component on this main axis for each IMF ($Z \geq 3$) of the event. Z is the corresponding charge. In figure 1-a, all IMF have been considered.In figure 1-b only the two heaviest ones have been retained. It turns out that

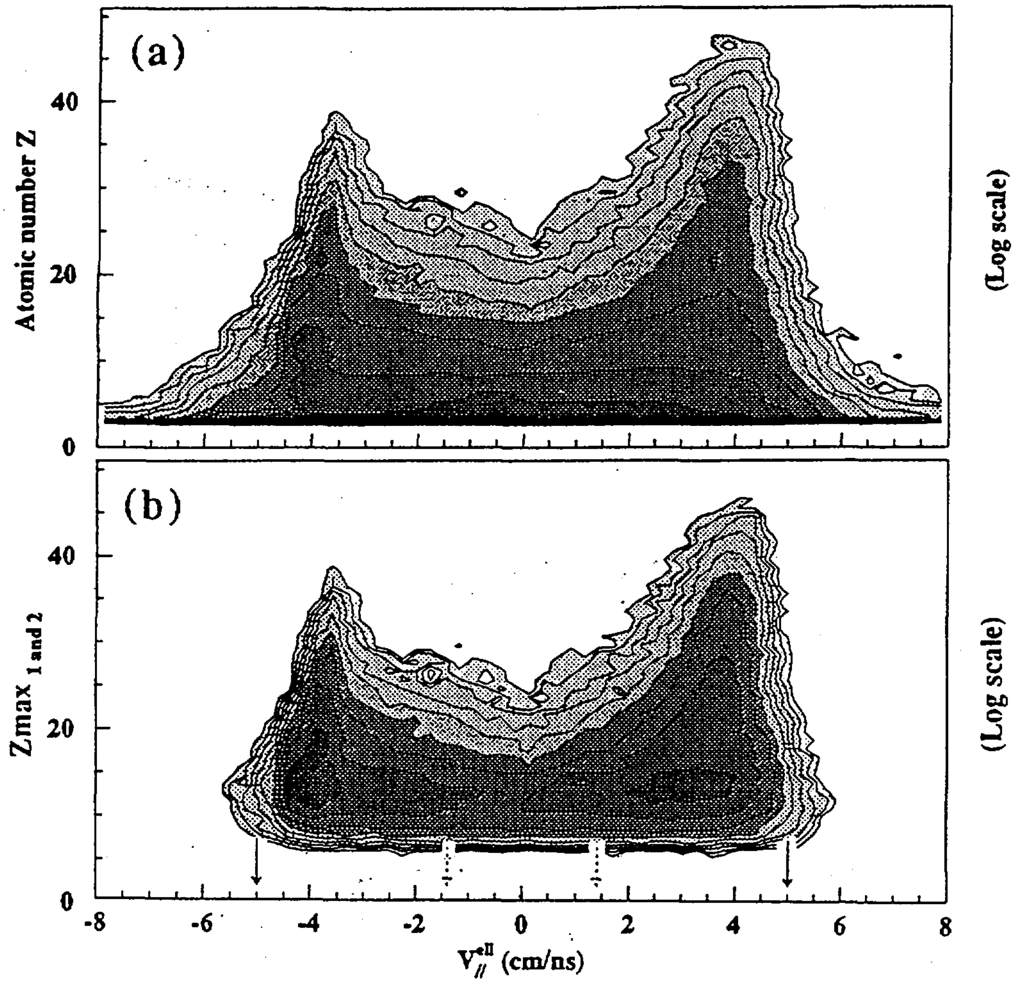

Figure 1: IMF $V_{//} - Z$ plots for the $Xe + Sn$ system at 50 MeV/u. In part (a) of the figure all IMF have been retained. In part (b), only the two heaviest of a given event are retained. Most events exhibit a two source behaviour and only few of them can be attributed to fusion. Extracted from ref 9.

most of the considered products can be attributed to one forward source (projectile-like fragment : PLF) and a backward one (target-like fragment : TLF). The two arrows indicate the initial projectile and target velocities in the center of mass frame. The relative velocities between the selected projectile-like and target-like sources correspond to some dissipation because most peripheral collisions have been eliminated by the "complete event" requirement explained in the introduction. However, they are generally much larger than the expected values for coulomb repulsion (about 2.5-3 cm/ns) and only few events can result from a fusion nucleus decay [9].

Such a behaviour is quite general and it has been observed for lighter or heavier systems ($Ar+KCl$ [10], $Ar+Al$ [11], $Ar+Ni$ [12], $Zn+Ti$ [13], $Gd+U$ [14], $Pb+Au$ [15]) and by other authors [16-22] over the whole intermediate energy range (15 - 100 MeV/u). From the energy damping, it has been possible to establish in ref 10 and 12 that a considerable amount of energy may be dissipated (up to full damping) which may lead the PLF or TLF to complete vaporization [12].

3 Dynamical effects

A precise observation of figure 1 indicates that the mechanisms observed in the Fermi energy range are not pure deep inelastic collisions. Indeed, many IMF (Z $\geq$ 3) are emitted at mid-rapidity between the projectile and target like fragments. This feature does not concern the heaviest products in an event as it can be seen from a comparison of figures 1a and 1b. It mainly concerns light IMF or particles [52] : it can be for instance recognized in figure 2 for alpha particles (system $Xe+Sn$ at 50 MeV/u [23]). Similar results have been published by many authors (see ref 6 for a review). They are signatures of the so-called neck-emission. They mean that part of the nuclear matter is not emitted from the PLF or TLF after full equilibration but is rather reminiscent of the overlap zone between interacting partners. Two scenarii are possible which both reflect a strong deformation of the system during the primary interaction : i- the overlap zone may be separated from the PLF and TLF ; in this case one is dealing with a third source as the participant zone in the relativistic regime ; ii- the overlap zone (neck) may stick to the PLF (or TLF) after the primary interaction. The PLF (or TLF) is in this second case strongly deformed and may decay before shape relaxation ; it is then expected to observe a coulomb correlation with the PLF (or TLF). Such a correlation has indeed been observed in reference 10 and both scenarii are predicted in dynamical calculations [24]. They reflect the evolution with temperature of nuclear matter viscosity. They may also reflect isospin properties of nuclei [25, 26].

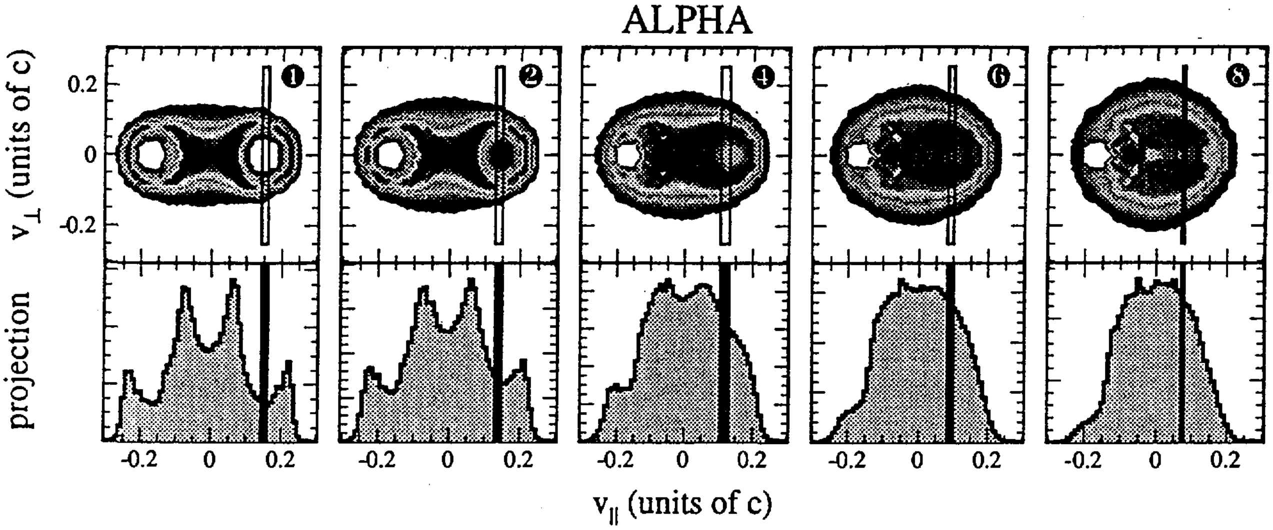

Figure 2 : Invariant c.m velocity plots for alpha particles and various dissipation bins (see ref 23 for details). The accumulation in the mid-rapidity region is also clearly seen on the projection spectra (lower row). From ref 23.

4 Onset of multifragmentation

The Fermi energy domain is very well suited to study the limit of existence of nuclei when their excitation energy is increased. In terms of the equation of state of nuclear matter, one expects to observe a first order phase transition from a liquid to a gas. It is for instance what is looked for when plotting the well- known caloric curve we will discuss below. However, many obstacles exist which are due to the finite size of nuclei and the necessity of assuming thermal equilibrium. The direct observation of a phase transition is hence not so simple and it is easier to look for indirect evidences for such phenomena, i.e. some discontinuity in the nuclei properties as a function of their temperature or excitation energy. The onset of multifragmentation for excitation energies of about 3 MeV/u is such a signal which is expected from theoretical calculations [27, 28] and which has been extracted from data (figure 3). Multifragmentation is a one step break-up of an excited nucleus into at least three fragments.The simultanity has been experimentally established from fragment-fragment correlation studies [30-33]. Nuclei which undergo multifragmentation are always highly excited, and may be formed either in rare fusion reactions or in the dominant two body reactions described in section 2. In the first case the cross section is rather low but the

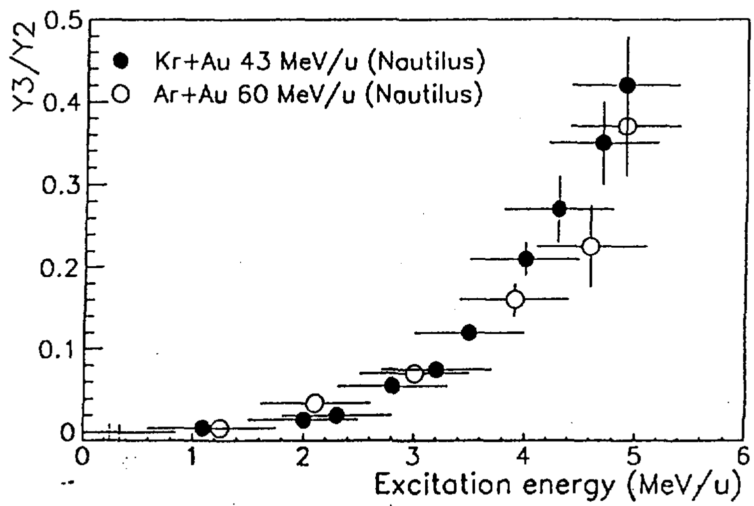

Figure 3 :Evolution of the ratio between three and two fragment decay as a function of excitation energy for $Kr + Au$ and $Ar + Au$ systems. The sharp increase of the three fragment decay above 3 MeV/u corresponds to the onset of multifragmentation. Extracted from ref 29.

absence of neck-emission makes conclusions more reliable. On the other hand, two-body-collisions can be used to study multifragmentation over a wide range of energy dissipation, but they suffer from the difficulty of subtracting the neck-emission contribution. In any case, the question of the degree of thermal equilibrium is raised. However, it turns out that multifragmentation is a slow process because fragment production lasts at least 100 fm/c. Such a value is obtained from transport theory calculations [34-38]. This means that when fragments are released, thermal equilibrium of the system is achieved. From this point of view, there is a big difference with the situation observed for light charged particles (Z = 1,2) which may be emitted on a wide time scale during the collision, from preequilibrium (or flow emission) down to evaporation from final nuclei. Such a difference between fragment and particle emission has clearly been established with INDRA data as it will be shown in the next section [44].

5 Multifragmentation properties

The main ingredients which have been considered in order to understand the underlying physics of multifragmentation are the involved excitation energy and temperature, and the kinematical properties of outgoing fragments. The fragment multiplicity or size distributions are not so useful quantities because they are strongly altered by secondary decays, even if the rise and fall of intermediate mass fragment (IMF) production exhibits an interesting universal behavior [39-43].

The main difficulty concerning excitation energy and temperature measurements is that they evolve continuously during the whole process [44]. The excitation energy is generally obtained by calorimetry and one has to select particles and fragments of interest. In the fusion case, the principle consists in asking for an isotropic emission in the fusion nucleus rest frame, in order to eliminate preequilibrium particles. In binary reactions, one considers only particles and fragments emitted in the forward (backward) hemisphere in the PLF (TLF) rest frame in order to eliminate neck contributions and one requires flat particle angular distributions in each source frame. The idea of these methods is to select particles which have been emitted when the source has "forgotten" the beam direction, i.e when relaxation is achieved. There is no ambiguity for the fragment contribution since they are late emitted. There is some ambiguity for light charged particles.

Temperatures can be deduced either from kinetic energy spectra shapes, or from double isotopic yield ratios, or from excited state population ratios. In any case the difficulty lies again in the time scale which is addressed by the method. Kinetic energy spectra lead to values which are averaged all along the decay chain and they are very sensitive to source velocity measurement. Double isotopic or excited state yields are sensitive to secondary decays. It is the reason why these various thermometers do not indicate the same apparent temperatures and simulations are highly necessary to understand the data. This feature is clearly illustrated in figure 4, obtained in ref 45 for a $Z = 16$ nucleus. The full lines are temperature-excitation energy correlations (caloric curve) calculated for various thermometers in a quantum statistical model (QSM) [46]. They are quite different from the initial correlation used as an input in the calculation (dashed line), but they are able to explain qualitatively the experimental results (points). Such comparisons indicate that data may be reproduced in assuming that thermal and chemical equilibrium is achieved during multifragmentation. They also lead to the conclusion [45, 7] that isotopic yield ratios correspond to apparent temperatures that can be strongly biased at high excitation energy due to side feeding. Therefore a quantative interpretation of results simular to the Aladin curve [49] in terms of a first order phase transition is difficult to justify.

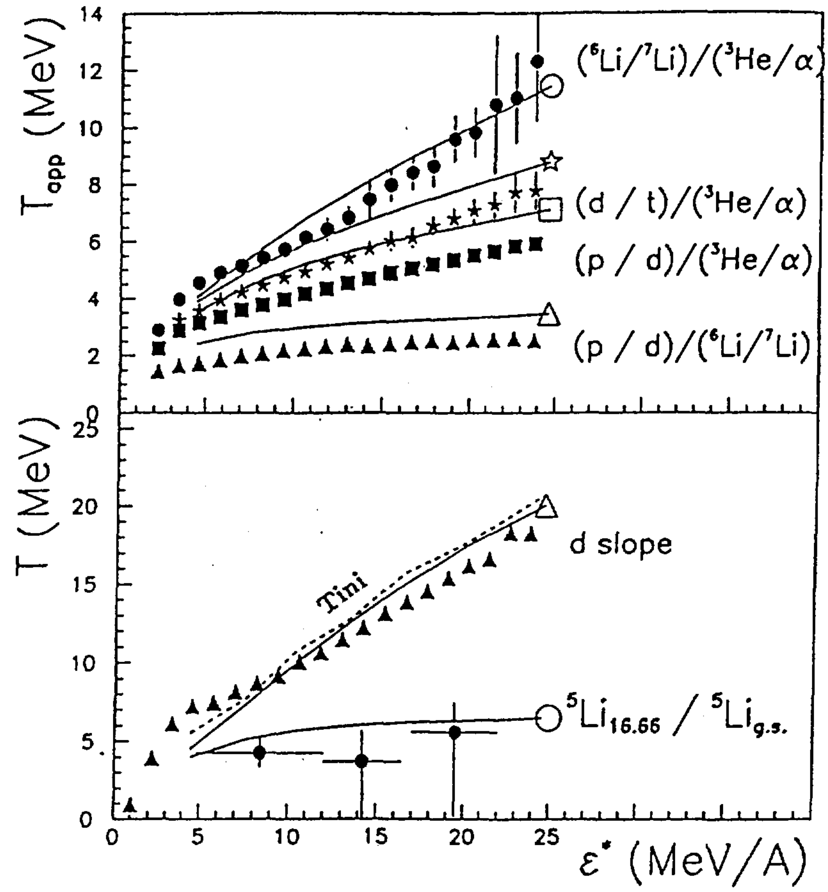

Figure 4 : Apparent temperature obtained from various methods (upper : double isotopic yield ratios ; bottom : slope parameter for deuteron or excited state population ratio) as a function of the excitation energy. Points are experimental [7] and correspond to the PLF decay for the $Ar + Ni$ system. Solid lines and open points are calculated in a quantum statistical model [46]. The dashed curve corresponds to the initial correlation assumed for the calculations. From ref 45.

Further conclusions may be drawn from the dynamical properties of fragments emitted in a multifragmentation. In figure 5 results are shown for single source events observed in $Gd + U$ [14, 48] and $Xe + Sn$ [8] collisions. It has been checked that multifragmentation was isotropic and that only few light charged particles were reminiscent of the projectile direction. Experimental data are well accounted for by a one step statistical process but it is necessary to assume that part of the excitation energy has been converted in expansion energy : 1 MeV/u is necessary for the Gd case and 2 MeV/u for $Xe + Sn$. They can be compared with the total excitation energy

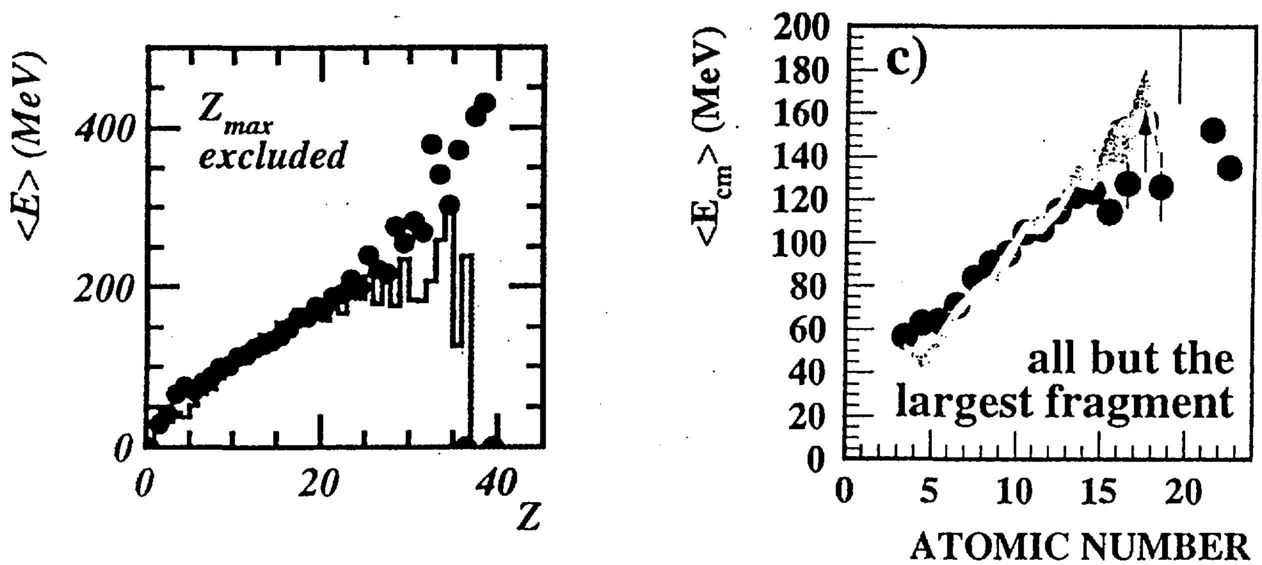

Figure 5 : Correlation mean kinetic energy - atomic number for the fragments (but the heaviest) emitted in multifragmentation of fusion nuclei.
Left : $Gd + U$ System at 36 MeV/u [14, 48] ; Right : $Xe + Sn$ system at 50 MeV/u [8]. The agreement between experimental results (points) and theory (lines) can be obtained only in assuming an expansion energy of 1 MeV/u for the Gd case, and 2 MeV/u for $Xe + Sn$.

of 7 and 12 MeV/u respectively. From a general point of view, it seems that the relevant parameter governing this expansion energy value is the nucleus excitation energy (figure 6). However a steady increase may also be observed as a function of the incident energy (figure 7) and the role of the initial projectile and target mass ratio has not been fully adressed [48].

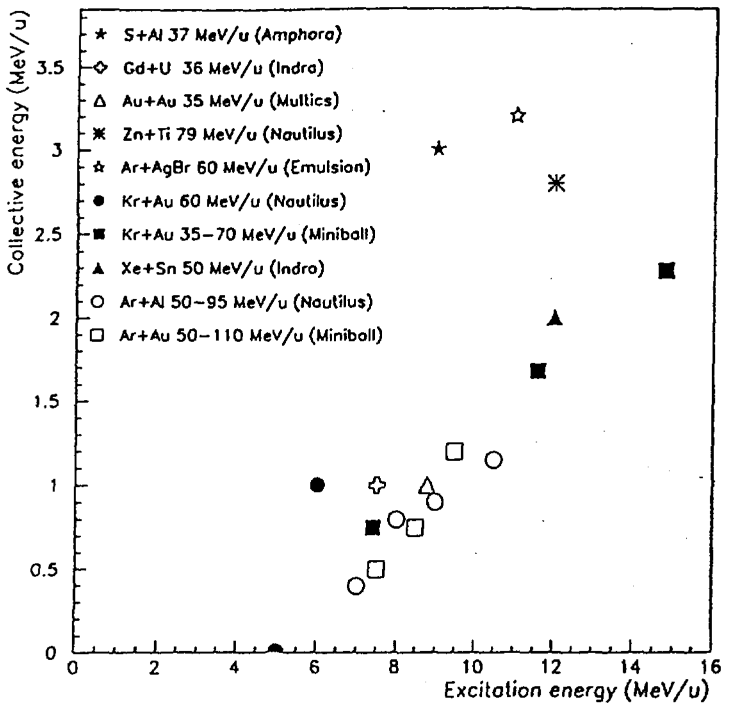

Figure 6 : Evolution of the expansion energy as a function of the excitation energy. Data have been obtained for bombarding energies lower than 100 MeV/u. Results from both semi-peripheral (two sources) and central (one source) collisions are included. Excitation energy seems to be a good scaling parameter for many data. Extracted from ref 6.

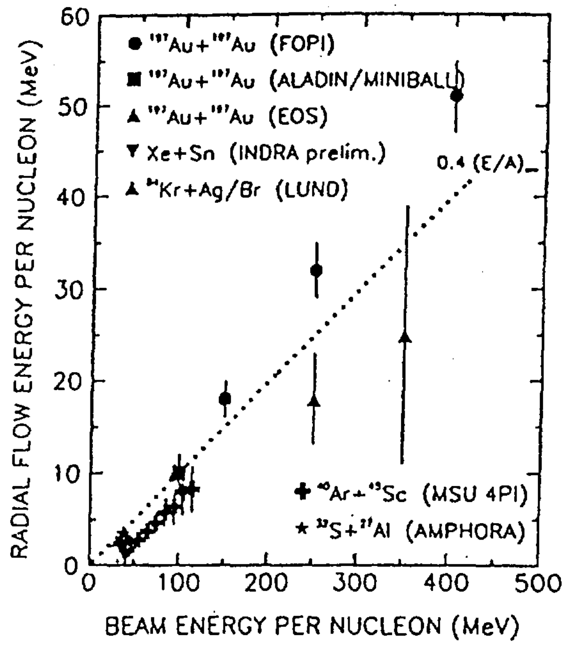

Figure 7 : Evolution of the expansion energy with bombarding energy up to the relativistic energy domain ; from ref 49.

What is the origin of the expansion energy ? Two hypothesis may be performed : thermal and mechanical ones. In the first case, expansion results from the pressure induced by the thermal energy stored in a nucleus [50]. In the second case, it results from an initial compression followed by an expansion driving the system to low density and to the spinodal region of the nuclear matter equation of state. Detailed calculations performed for the system $Xe + Sn$ with the expanding emitting source (EES) model exclude the thermal origin of the 2 MeV/u expansion measured at 50 MeV/u [44]. It hence turns out that the spinodal region properties could be the good candidate to explain the experimental data. This interpretation is supported by BNV calculations performed in ref 44, which indicate a compression energy of about 2.5 MeV/u 60 fm/c after the beginning of the collision. It is then possible to understand the time evolution of the system during these head-on collisions. During the compression stage, the incident energy is relaxed. Excitation energies exceeding 10 MeV/u are reached. The compression stage is followed by an expansion. All along this path, particle emission occurs which cools down the nucleus. 90 fm/c after the beginning of the collision, the system enters the spinodal region. In this low density region, multifragmentation develops mainly on the basis of statistical arguments because reaction time is long enough. Such a statememt is also supported by the fact that statistical SMM calculations [51] are able to reproduce nicely fragment mass distributions provided the excitation energy which is used as an input of the code is reduced to 7 MeV/u. This reduction takes into account the cooling down due to light particle emission in the compression-expansion stage down to the freeze out configuration where the multifragmentation partition is defined from phase space i.e. statistical arguments.

6 Concluding remarks

It then appears that we have today a coherent view of multifragmentation is central collisions in the Fermi energy domain. Multifragmentation seems to result from mechanical instabilities which may correspond to the spinodal region of the nuclear matter equation of state. The system may reach this zone because it is compressed in the early stage of the collision. During the compression-expansion stage, energy dissipation takes place but part of the corresponding excitation energy is removed by fast light charged particles. The expansion energy is of the order of a few MeV/u and the corresponding expansion velocity is small enough to ensure statistical equilibrium at the freeze out stage, when the multifragmentation configuration is decided. For this reason, multifragmentation may be described by statistical models. The validity of such a description seems to hold even for excitation energies largely exceeding the nucleus binding energies since statistical features have also been recognized in vaporization events [12, 53].

In this paper, we have also shown that the general topology of nucleus-nucleus collisions in the Fermi energy domain is now well understood and that a link has been established between low and relativistic energy collisions. The dynamical features observed in the neck region for binary collisions should be used in the near future to understand viscosity properties of strongly excited nuclear matter. It remains also to describe in a coherent way the multifragmentation process when it is induced in fusion and binary type reactions. In a near future, the INDRA group will also extend the analysis performed on light and medium mass systems to higher total masses and entrance channel asymmetries.

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