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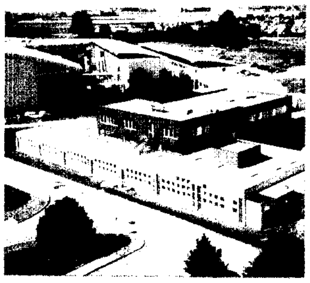

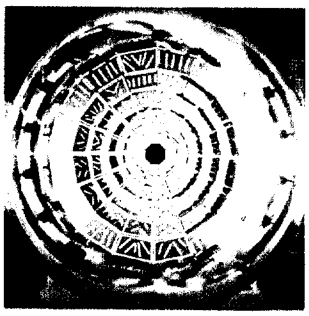

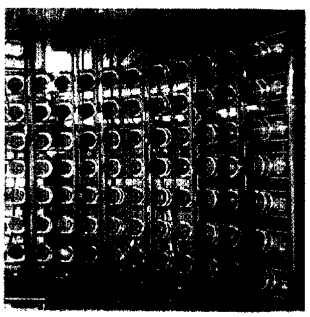

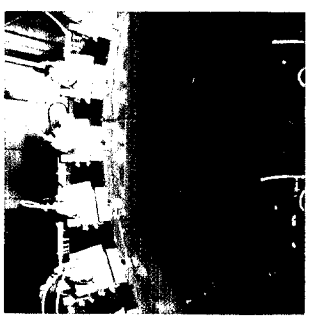

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Dynamical Effects in Nuclear Collisions in the Fermi Energy Range : The Case of Heavy Systems

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Abstract

Recent experimental results concerning heavy systems (Pb+Au, Gd+U, Xe+Sn, ...) obtained at GANIL within the INDRA and NAUTILUS collaborations will be presented. A study of reaction mechanisms has shown the dominant binary and highly dissipative character of the process. The two heavy and excited fragments produced after the first stage of the interaction can experience various decay modes from evaporation to multifragmentation including fission. However, deviations from

this simple picture have been found by analysing angular and velocity distributions of light charged particles, IMF's (Intermediate Mass Fragment) and fragments. Indeed, there is an amount of matter in excess emitted between the two primary sources suggesting either the existence of a mid-rapidity source similar to the one observed in the relativistic regime (participants) or a strong deformation induced by the dynamics of the collision (neck instability). This last possibility has been suggested by analysing in detail the angular distributions of the fragments. More precisely, we observe one isotropic component which is compared with the predictions of a statistical model and a second one aligned on the recoil direction of the projectile like source which should be compared with the predictions of dynamical calculations based on microscopic transport models.

1 Introduction:

The most important challenge for nuclear physics is the understanding of the properties of nuclear matter. To achieve this goal we first have to prepare the nuclei in extreme conditions of excitations energy, spin, isospin, temperature and pressure. In a second step, we try to extract physicals parameters on nuclear matter by using comparisons between data and models. The tool we use to obtain such extreme conditions is heavy ions collisions. These collisions can be described on a time scale. Before the collision, there is only Coulomb interaction between the projectile and the target and during the collision the nuclear interaction takes place. After the collision in the case of heavy systems in the Fermi energy range, mainly two primary fragments are formed: the projectile-like PLF and the target-like TLF which can decay, depending on their excitation energies, in different exit channels like: evaporation of light charges particles, IMF emissions, fission or multifragmentation. We detect all these products in detectors a long time after the interaction (around 10 ns). To obtain physical information about the interaction projectile-target or about the two excited primary fragments PLF and TLF, we compare the characteristics of all detected fragments and particles to those obtained with different models. For example we often use statistical models [1], [2], [3] to describe the decay of the primary fragments. To do that we have first to check whether all degrees of freedom are thermalised (temperature equilibrium, chemical equilibrium, shape equilibrium) or not. It is a required condition to use a statistical model. In this work, we present some results concerning one fixed exit channel: the fission of the projectile-like fragment for which we give evidence for strong deformations, and then non equilibrated shapes.
First of all, we present an experimental method used to estimate the impact parameter of the collision, then an illustration about the binary aspect of the process, then the different angular distributions we study to put in evidence privileged directions corresponding to aligned fissions. Lastly, we give some results about the importance of this effect as a function of the size of the target and the size of the projectile, the incident energy, the violence of the collision and the asymmetry of the fission.

2 Experimental impact parameter:

In Fig. 1, we have plotted the transverse energy of light charged particles $E_{t12} = \sum E_i \sin^2(\theta_i)$ (where E_i is the kinetic energy of the particle i and θ_i its angle relative to the beam direction) for different systems and different incident energies. More precisely this quantity is divided by the available energy in the center of mass of the reaction. The data presented here have been obtained without any condition except to detect at least one light charged particle.Each curve is normalized to the corresponding total number of events.

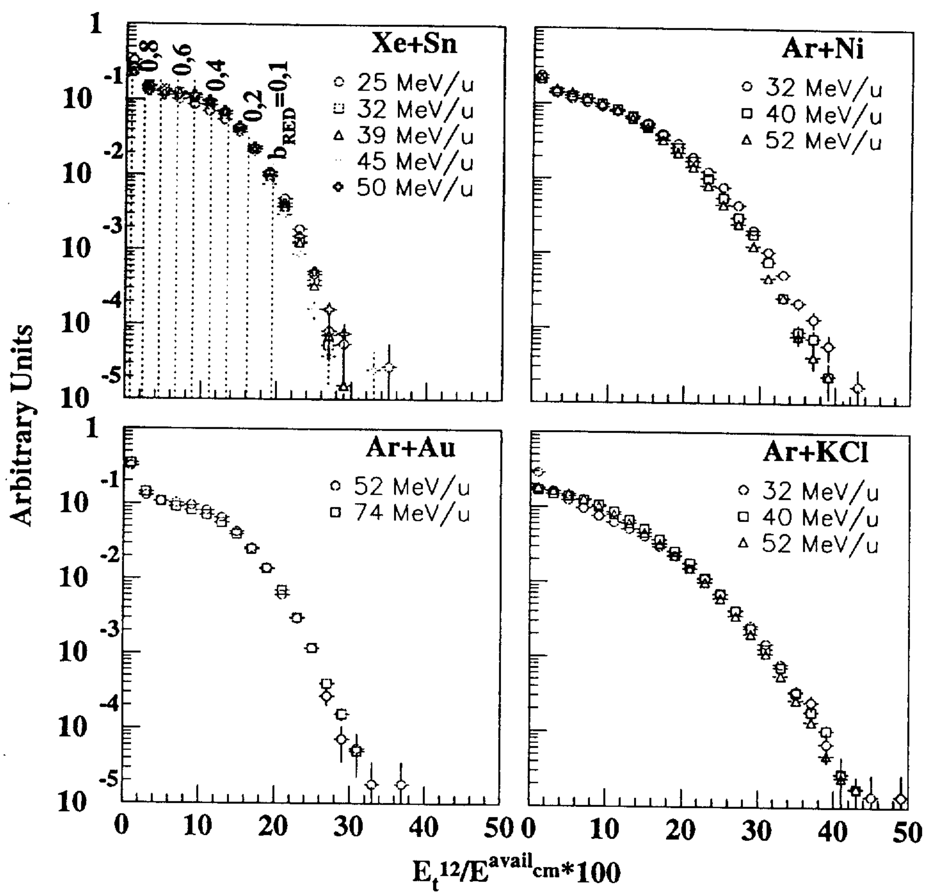

Figure 1: Transverse energy distributions for light charged particles with Z=1,2 divided by the available energy in the center of mass. Different systems are presented in different boxes, the symbols correspond to different incident energies.

We observe that the distributions roughly superimpose for a given system at all the incident energies. We only find differences for the smallest values of the transverse energy, which correspond to the most peripheral collisions and may be attributed to trigger effects. Conversely, on the high energy side associated to the most violent collisions, the same maximum transverse energy value is reached whatever the incident energy is. This suggests that this observable is dominated by the geometry of the collision: we find the same number of events for a given impact parameter independently of the incident energy. So an "experimental" impact parameter can be estimated by using these distributions. We make cuts in the distributions from the highest value to the lowest ones and we count the number of events contained in the different bins. The impact parameter b is determined by assuming a geometrical correspondence between the cross section σ contained in each bin and the impact parameter ($\sigma = \pi b^2$)[4].

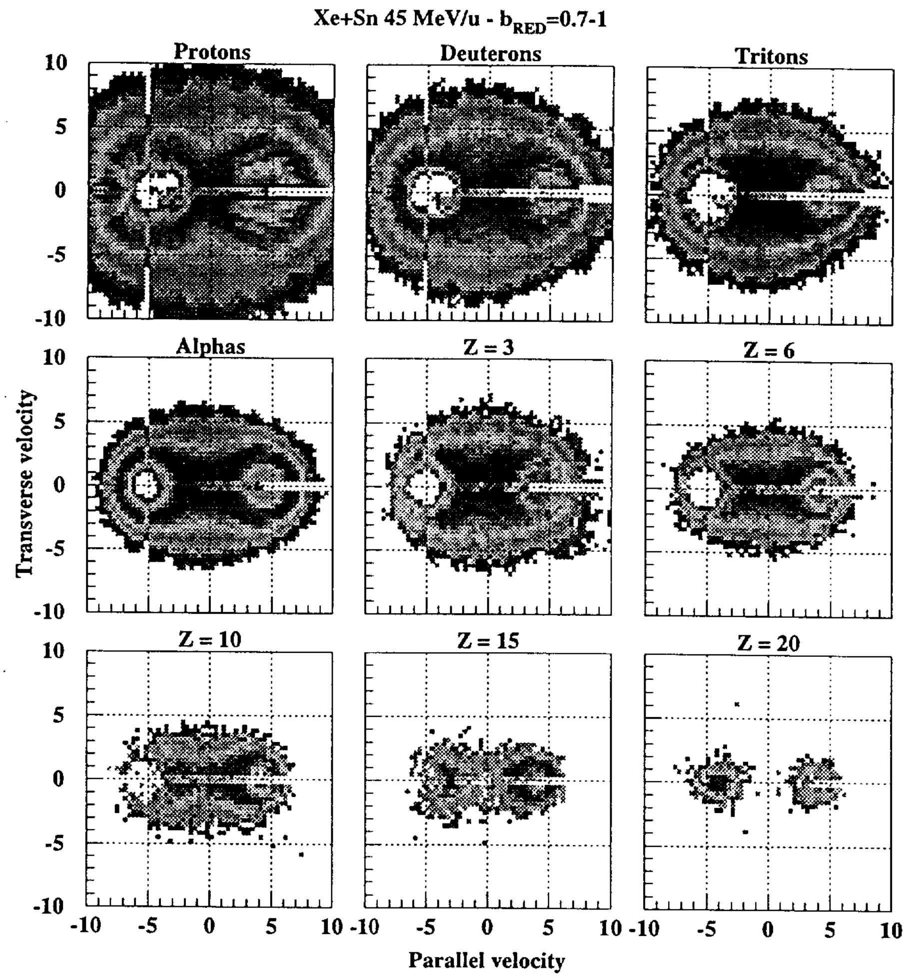

Figure 2: Vpar-Vper velocity plots (cm/ns) for the Xe+Sn system at 45 MeV/u for peripheral collisions. Each panel corresponds to a given charge.

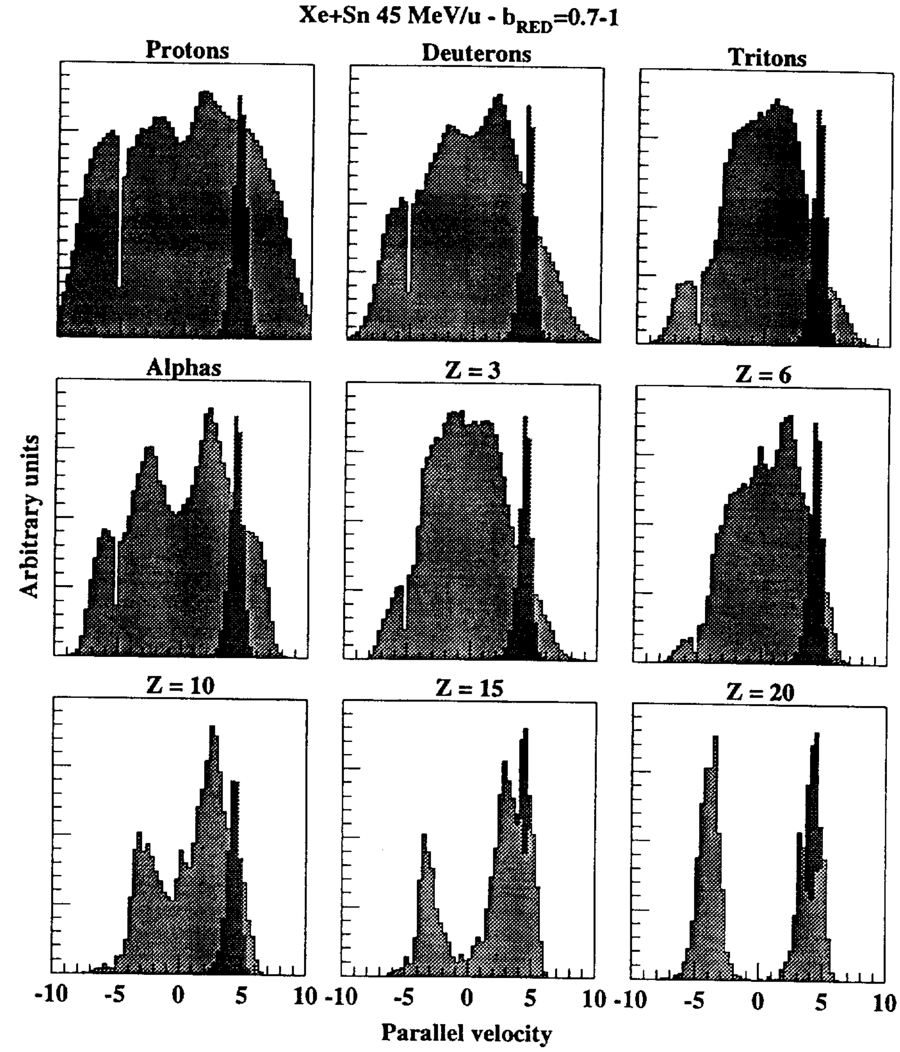

Figure 3: Xe+Sn system at 45 MeV/u, peripheral collisions: parallel velocity distribution (cm/ns) for a given charge (light grey area), parallel velocity distribution (cm/ns) for the heaviest fragment detected in coincidence (dark grey area) .

3 Reaction mechanisms:

For heavy systems at incident energies close to 30 MeV/u, most of the collisions correspond to binary processes [5], [6]. This aspect is illustrated on Fig.2 where transverse velocity versus parallel velocity plots (Vpar-Vper plots) for peripheral collisions are shown for protons, deuterons, tritons, alpha particles, Intermediate Mass Fragments (IMF) with here charge 3, 6 and fragments with charge 10, 15, 20.

These particles, IMF's and fragments are detected in coincidence with a projectile-like fragment whose velocity distribution is indicated by the dark grey area in fig.3.

First it appears clearly that most of the collisions correspond to binary processes. We observe two nice circles around the projectile-like fragment and target-like fragment (except for fragments emitted by the target due to threshold effects). But we can also see an amount of matter in excess between the two primary fragments. To go into detail, we have plotted on Fig.3 the parallel velocity distributions. We observe that the velocity distributions are not symmetrical with respect to the PLF velocity. Particles and fragments are mainly emitted in the backward direction with respect to the PLF velocity and almost all IMF's are emitted between the two primary fragments. The mid-rapidity particles and IMF's have been studied in different works [7],[8],[9], [6], [10], [11] and in this contribution we focus our studies on projectile-like products which correspond to the plots of the lower rows in Fig.2 and Fig.3. To detail these first observations, we study different types of angular distributions.

4 Angular distributions:

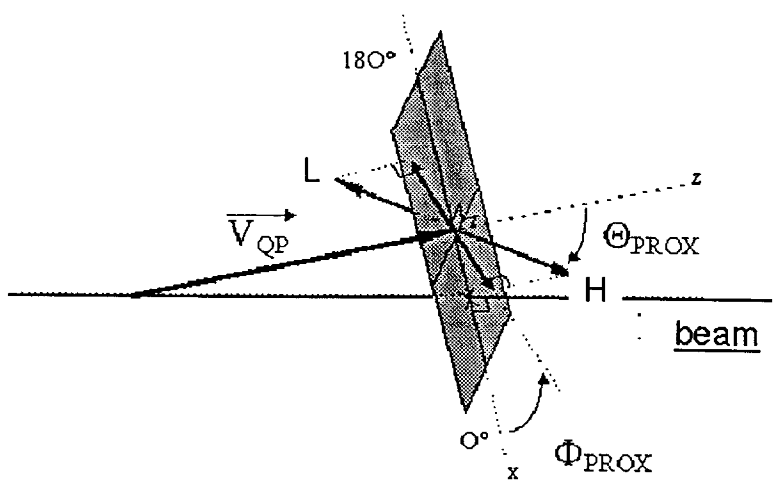

Figure 4: θ_{prox} angle definition: it is defined as the angle between the fission axis oriented towards the heaviest fission fragment H and the recoil velocity of the projectile like fragment (noted here V_{QP}) reconstructed with the two fission fragments. The lightest one is labelled L and the heaviest one H .

The simplest angle to measure is the angle between the fission axis and the PLF recoil direction (Fig.4). It is obtained with the following procedure: we select the events with two heavy fragments in the forward direction in the center of mass; with these two fragments we reconstruct the fissioning nucleus, its velocity and the fission axis (the axis between the two detected fragments).

The "proximity angle" θ_{prox} is defined as the angle between the direction of the recoil velocity and the fission axis (see Fig.4). In the case of a "standard" fission, all directions are allowed and a flat dN/dcos θ_{prox} distribution is expected . The spin effect, which favours the reaction plane, just increases a little bit the distribution for $\cos(\theta_{prox})$ equal 1 or -1 because for these values the fission axis is on the recoil axis, thus in the reaction plane. In Fig.5 we present the experimental $\cos(\theta_{prox})$ distributions associated with the fission of a PLF for a Pb projectile and for different targets (Al, Ag and Au) and for different asymmetries for the fission process. The asymmetry η is defined as the ratio between the difference of the charges of the two fission fragments and the sum of the charges of the two fission fragments.

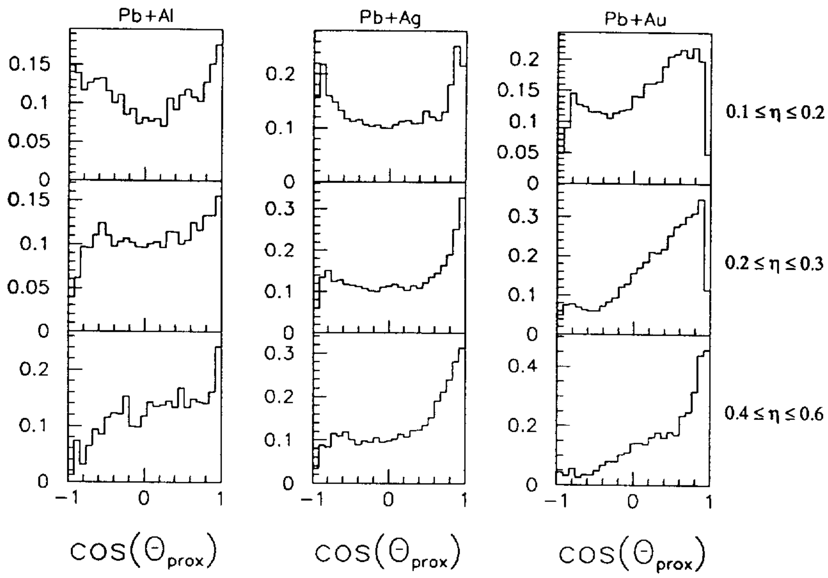

Figure 5: Pb + "X" at 29 MeV/u for peripheral collisions (NAUTILUS). $\cos(\theta_{prox})$ distributions associated with the fission of a PLF for a Pb projectile and for different "X" targets and for different asymmetries of the fission fragments. The columns correspond repectively to Al, Ag, Au targets, and the lines to different asymmetries of the fission fragments.

We observe that for the lightest target (Al), the distributions obtained are symmetrical with respect to zero, so they correspond to what is expected in "standard" fission. The holes seen for $\cos(\theta_{prox})$ equal -1 are due to detector effects, and are non physical. This angle would correspond to the detection of two fission fragments in the recoil direction and thus to the detection of the two fission fragments in the same detector. We can neither detect nor correct from detector effects such configurations. For the silver target, in symmetrical fission the distribution is also compatible with a "standard" fission. But for asymmetrical fission with (η >0.2) , we observe that the forward direction is favoured.

For the Au target this effect is clearly seen even for the more symmetrical fission. To test the effects of the experimental set-up, and of the projectile mass we present in Fig.6 the same observables for the fission of Gd impinging on two different targets: a light target (C) and a heavy one (U).

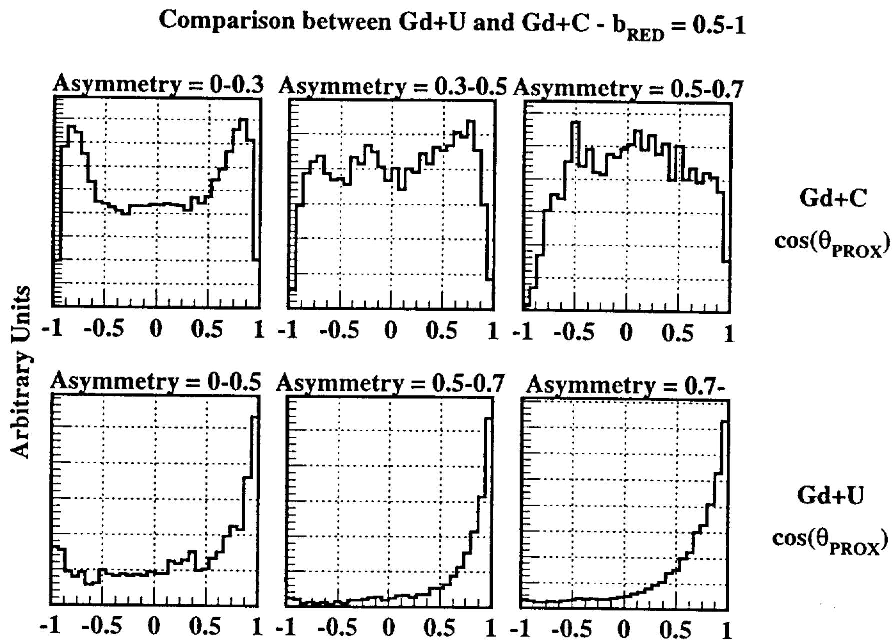

Figure 6: Gd + "X" at 36 MeV/u for peripheral collisions (INDRA). cos(θ_{prox}) distributions associated with the fission of a PLF for a Gd projectile and for different "X" targets and for different asymmetries of the fission. The columns correspond to different asymmetries of the fission-fragments, the lines respectively to C and U targets.

The observations are exactly the same and then depend neither on the detector (NAUTILUS or INDRA) nor on the fissioning nuclei (Pb or Gd). So we can say that after collisions between heavy projectiles and different targets we observe the fission of the projectile-like fragment; however when the target is heavy, the fission axis is preferentially aligned on the direction between the two primary fragments (PLF and TLF). This effect increases with the mass of the target and with the asymmetry of the fission. Such a behaviour can not be understood in a classical approach with a "standard" fission because no fission axis direction should be favoured whatever the charges of the fission fragments are. We evidence here a target effect on the fission of the projectile-like fragment or in other words an effect of the entrance channel on a given exit channel. This is not compatible with the assumption of the thermalisation of all degrees of freedom in a statistical model. The distributions plotted on Fig.5, suggest us that they are the result of two components: a component symmetric with respect to 0, and a second one aligned on the recoil axis of the PLF (peaked at 1). The relative weights of these two components depend on the target size and on the fission asymmetry. We build the symmetrical contribution with the backward part ($\cos(\theta_{prox}) < 0$) which is symmetrised around $\cos(\theta_{prox}) = 0$. The aligned contribution is then obtained by subtracting this reconstructed "standard" fission distribution from the total experimental distribution. The result of this procedure is shown in the right column of Fig.7 for different fission asymmetries from the Pb+Ag system.

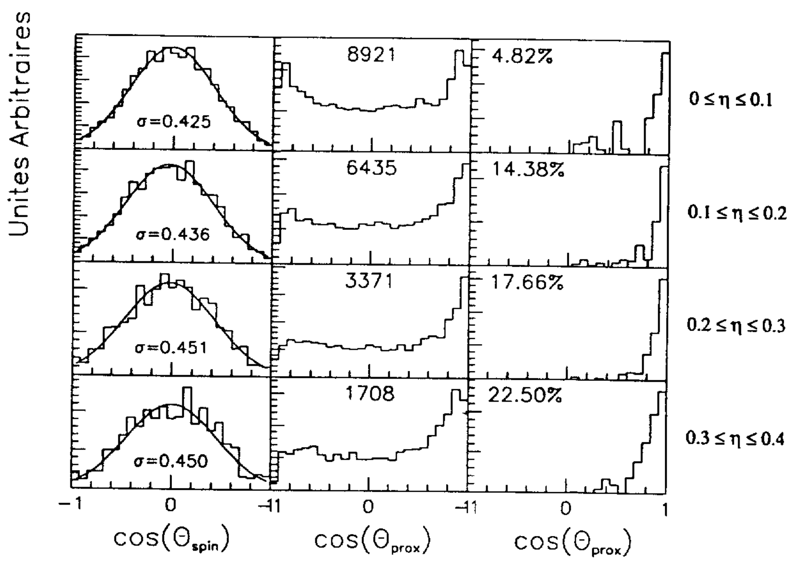

Figure 7: Pb + Ag at 29 MeV/u for peripheral collisions (NAUTILUS). Left panel: $\cos(\theta_{spin})$ distributions associated with different fission asymmetries (see text for the definition). Central panel: $\cos(\theta_{prox})$ distributions associated with different fission asymmetries. The number of experimental events is indicated in each case. Right panel: $\cos(\theta_{prox})$ distributions obtained after subtraction of the reconstructed "standard" fission distribution from the total distribution. The percentage of aligned fission relative to the total events for the same asymmetry is given on each panel. (see text for details).

On the left column, we have plotted the out of plane angle $\cos(\theta_{spin})$ distributions. This angle is defined as the angle between the fission axis and the aligned spin axis(Fig.8). The higher the value of the spin of the fissioning nucleus is, the most the fission fragments are emitted in the reaction plane (with $\cos\theta_{spin}$ value close to 0).

The spin effect explains the "bell shape" curve obtained in the left column in Fig.7 and the corresponding "U shape" curve obtained for $\cos(\theta_{prox})$. In this case, for symmetric fission we found only 5% of aligned fission (upper row Fig.7). For more asymmetric fission, the percentage is higher and reach 22% for an asymmetry of 0.35 which corresponds to a charge of 54 for the heaviest fission fragment and 26 for the lightest one. For the other systems and higher asymmetries it is not easy to disentangle the two contributions with

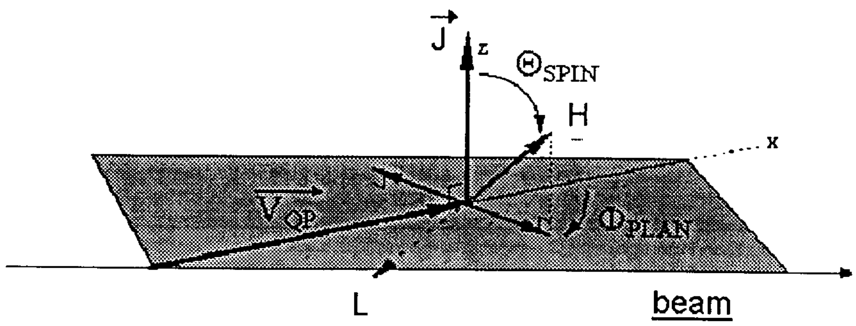

Figure 8: θ_{spin} angle definition: it is defined as the angle between the fission axis oriented towards the heaviest fission fragment H and the reaction plane deduced from the recoil velocity of the projectile like fragment (labelled here V_{QP}) and the beam velocity. ϕ_{plane} angle definition: is is defined as the angle between the fission axis projected on the reaction plane and the recoil velocity of the projectile like fragment .

this method (see Fig.5 for Au target) and we have used another angle ϕ_{plane} defined as the angle between the fission axis projected in the reaction plane and the recoil velocity of the fissioning nucleus (see Fig.8). For a "standard" fission, this ϕ_{plane} distribution is expected to be flat. Spin effects have no influence on these distributions. This is illustrated on Fig.9 for Xe+Sn system at 25MeV/u for two bins of impact parameter. For the most peripheral events in symmetrical fission (upper left plot on Fig.9), the ϕ_{plane} distribution is roughly flat in agreement with the expectations of a "standard" fission. But for asymmetrical fissions, we see a large contribution associated with low values of ϕ_{plane}, then for aligned fissions. The same effect has been observed previously [12], and also for lower incident energies [13], [14], [15].

So we can use this angle to disentangle "standard" fission from aligned one. This is done on Fig.10 for Xe+Sn system for various incident energies and several impact parameters as a function of the fission asymmetry. We first observe that the probabilities of both types of fission as a function of the asymmetry does not depend on the incident energy. For this system, the "standard" fission represents only 25% of the total number of events whatever the incident energy and the impact parameter are. Most fission events correspond to aligned fission and can not be compared to statistical models. The results we would obtain by using such models to extract physical information like fission probabilities or spin would be wrong [16]. So it is very important to study not only the global observables like charge distributions but also to study in detail the reaction mechanisms which lead to fission by looking at the angular distributions and relative velocity distributions.

The characteristics of selected events corresponding to a "standard" fission have been compared to a calculation using "transitional state method" [17], [18] with the fission barrier values given in Ref.[19]. This calculation gives us the probability to observe a

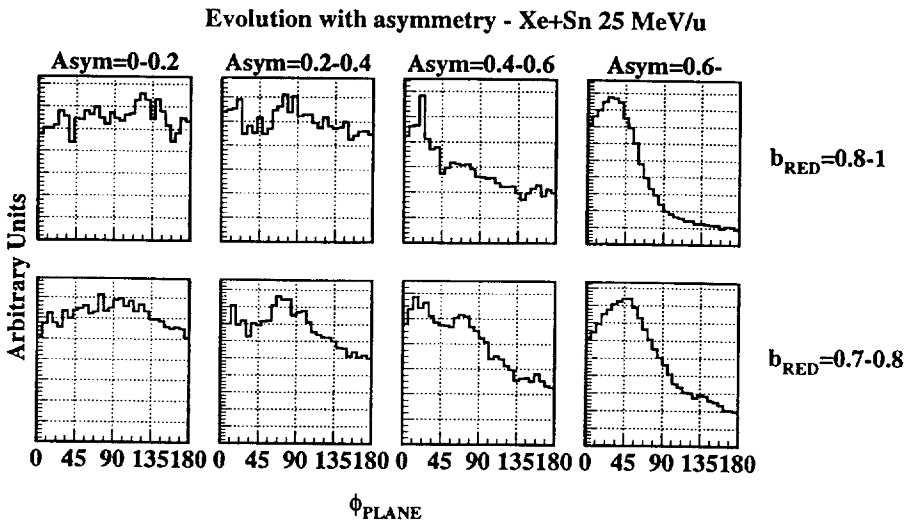

Figure 9: Xe+Sn system at 25 MeV/u. ϕ_{plane} angle distributions for different values of the fission asymmetry. Each row correspond to an impact parameter bin (upper row: b_{RED}=0.8-1, lower row: b_{RED}=0.7-0.8) .

given fission asymmetry for a fixed charge of the fissioning nucleus, a fixed temperature and a fixed spin. It is applied for different systems Gd and Xe and compared to the data (Fig.11).

The variations of the fission probabilities with asymmetry are very different for the different systems but they are reproduced by our calculation with reasonable values of charge, temperature and spin of the fissioning nuclei. For the Gd+U system, the shape of the curve is very sensitive to the "free" parameters (charge, temperature and spin of the fissioning nuclei). For example we can see a large difference when the temperature is increased from 2 to 3 MeV (fig.11a).
In fact, we have some more constraints on the "free" parameters. The $\cos(\theta_{spin})$ distributions presented in Fig.7, give us a constraint on the ratio $J/\sqrt{T}$ and this has been used in another work [20] to extract spin values. The charge of the fissioning nucleus is necessarily greater than or equal to the sum of the charges of the two fission fragments. With this procedure, we find that fission takes place at the end of the decay process. We measure the characteristics in charge, temperature and spin for the fissioning nucleus just at the saddle point, for example charge 54, temperature 3 MeV and spin $24\hbar$ for the fissioning Gd on U target.

5 Relative velocity distributions:

At last, we study the relative velocity between the two fission fragments. We compare the values obtained for the experimental "standard" fission to the previous calculation and also to the values obtained for the aligned fission in order to extract some quantitative

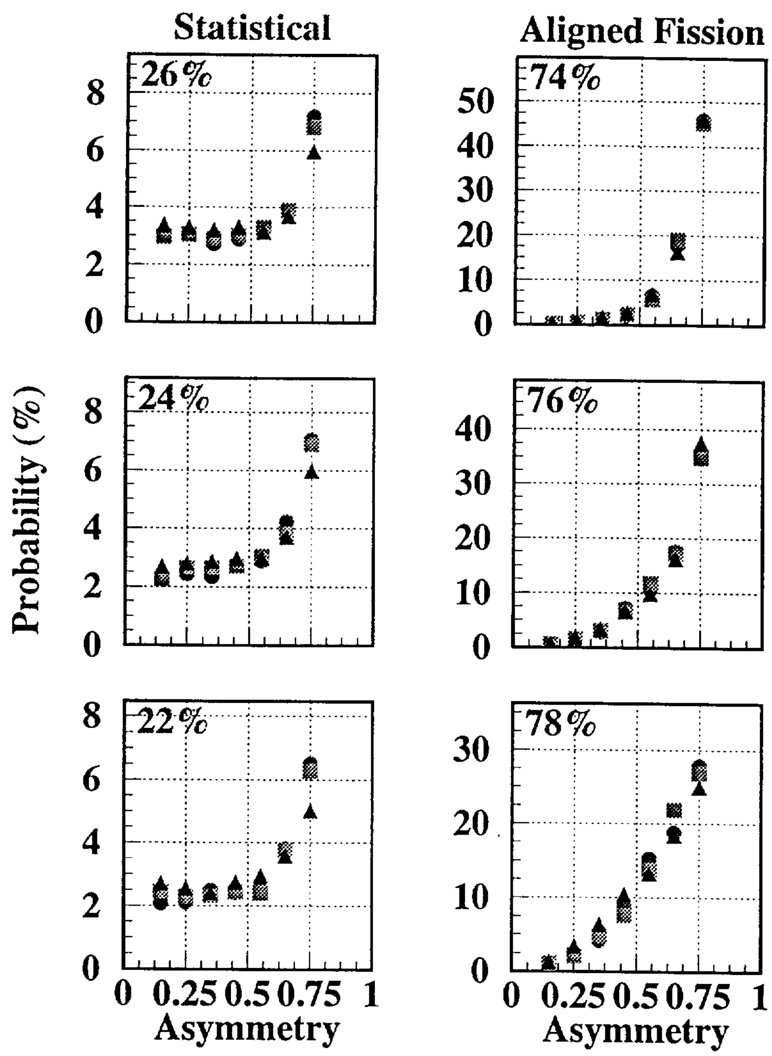

Figure 10: Probability associated to "standard" fission (left column) and to "aligned" fission (right column) for Xe+Sn systems for various incident energies (circles 50 MeV/u, squares 45 MeV/u, triangles 39 MeV/u) and for various impact parameters as a function of the fission asymmetry. The different rows correspond to different impact parameter bins (upper: b_{RED}=0.8-1, middle: b_{RED}=0.7-0.8, lower: b_{RED}=0.5-0.6)

information on this last process (see Fig.12). The contribution of aligned fission to the relative velocity distribution is obtained by subtracting the contribution associated to the "standard" fission from the total relative velocity distribution.

The relative velocities are roughly compatible with the calculation for the "standard" fission component except for the highest asymmetries ($\eta > 0.5$). The impact parameter dependence can be reproduced by an the evolution of the temperature in the calculation,

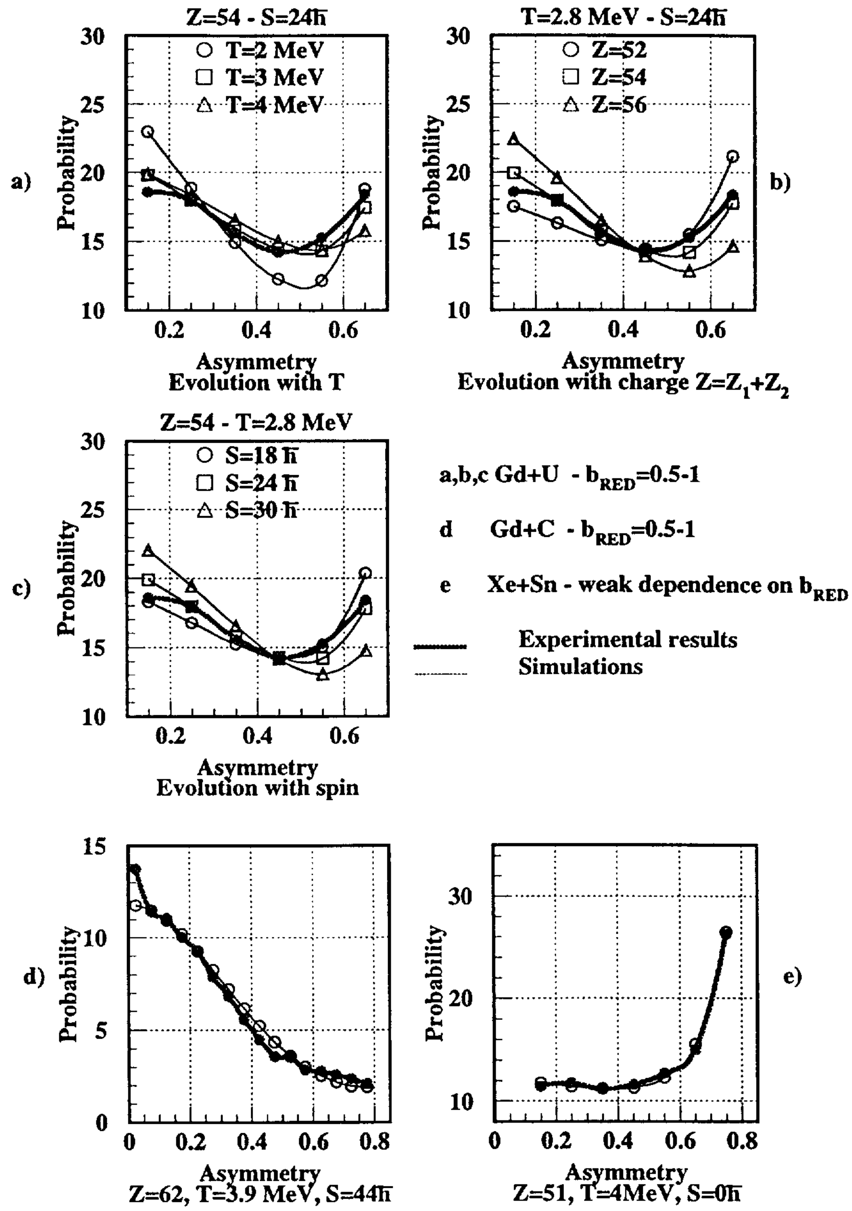

Figure 11: Probability associated with a given fission asymmetry for different systems and different impact parameters from b_{max} (peripheral collisions) to $0.5b_{max}$ for the Gd+U system at 36 MeV/u (a,b,c). a: evolution with the temperature of the fissioning nucleus. b : charge of the fissioning nucleus. c: spin of the fissioning nucleus. d: Gd+C system at 36 MeV/u. e: Xe+Sn system at 45 MeV/u. The full symbols correspond to the data, the open symbols correspond to the calculations.

suggesting that the temperature of the fissioning nucleus depends on the impact parameter. For the aligned component, the relative velocity values are always higher. They

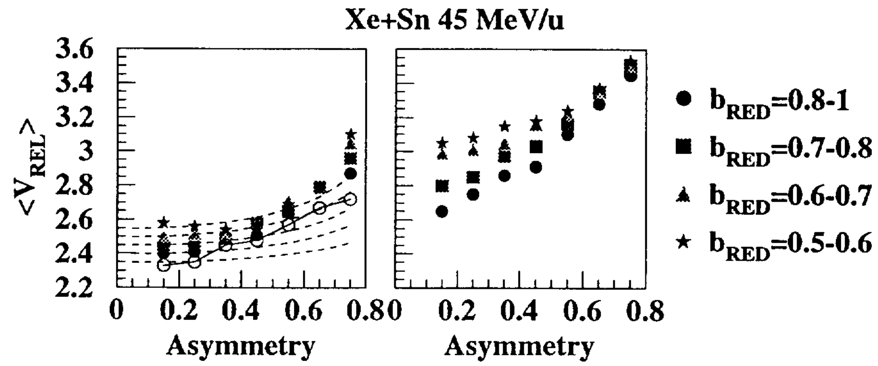

Figure 12: Relative velocity distributions as a function of the fission asymmetry for different impact parameters (full symbols) for the Xe+Sn at 45MeV/u. Left column: distribution associated with the "standard" fission, the open circles concern the most probable value of the relative velocity for b=0.8-1. The dashed lines correspond to different temperatures 2, 4, 6, 8, 10 MeV in the calculation. Right column: distribution associated with the aligned component.

also show a clear evolution with the impact parameter. These values and these evolutions are strong constraints for dynamical models.
All these observations allow us to think that the aligned fission originates from very strong deformations of the projectile during its interaction with the target. Just after the collision the deformation is so great that the projectile-like fragment goes inevitably towards fission. Its deformation is as large (or even more) as the deformation of the same nucleus at the saddle point in a "standard" fission process. The process is continuous, so the relative velocity associated to the deformation corresponding to the saddle point is different from zero. This velocity can be considered as a deformation velocity which is related to the viscosity of nuclear matter. Thus, the measured relative velocity between the fission fragments is higher than in a "standard" fission. This relative velocity is the addition of the coulomb repulsion and the deformation velocity of the nucleus and then puts an experimental constraint on nuclear viscosity. The total probability to observe the decay of the PLF in two fragments is also higher than the "standard" fission probability and can not be reproduced by calculations using only statistical hyphotheses.

6 Summary:

In heavy ions collisions, the reaction mechanisms are really complex. We have given evidences for the binary aspect of the collisions but also for different dynamical origins of particles and fragments. In this work we focused our study on the decay in two fragments of the projectile-like fragment and we compared this process to a "standard" fission. By using all the information obtained with multidetectors, (angular distributions, asymmetry of the fission fragments) two fission components could be extracted. One component is compatible with the "standard" fission. This component has been compared to calculations using statistical hypotheses and all the observables are in a quite good agreement. From this comparison we have derived the characteristics of the fissioning nucleus (charge, temperature and spin) at the saddle point. The second component is aligned on the recoil velocity of the projectile-like fragment. The relative weight of each component depends on the size of the systems and on the asymmetry of the fission fragments, but not on the incident energy. The aligned fission represents for example 75% of the total number of fission events for the Xe+Sn system and can not be reproduced by calculations using statistical hypothesis. The measured relative velocities between the two fission fragments for this component are very high and depend on the impact parameter. The observables associated to aligned fission have to be compared to dynamical calculations.

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