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FROM EVAPORATION TO MULTIFRAGMENTATION OF HIGHLY EXCITED NUCLEI FORMED AT GANIL ENERGIES

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ABSTRACT

The formation and decay of excited nuclei with masses around A = 200 are studied for excitation energy, ε^* ranging from 0 to 6 MeV/u. For ε^* values up to 6 MeV/n, the various decay channels ending with one (evaporation), two (fission) or more (3, 4, 5) fragments still compete. In case of multifragment emission, we find that :
- the life-time of the excited nucleus before breaking is equal to 100-150 fm/c for ε^* values around 5 MeV/u
- the emission time (i.e. the interval between the emission of two fragments) evolves from a large value ($\tau > 1000$ fm/c, sequential decay) when ε^* equals 2-3 MeV/u to a very small value ($\tau < 50$ fm/c, simultaneous decay) for ε^* values around 5 MeV/u.

1. Introduction

A major objective of the study heavy ion collisions is to probe the static and dynamic properties of nuclear matter out of equilibrium[1,2]. In this paper, we will concentrate on two points : Firstly in our domain of interest where the excitation energy per nucleon ranges between 0 and 7 MeV/u, the emission of massive fragments plays an important role. Beyond the fragment multiplicity , we have measured the characteristics of the emitted fragments and used them to analyze the collision, reconstruct the primary products and extract various physical quantities of interest. Secondly, we have made special efforts to derive the various time-scales which characterize the collisions. They are closely related to the questions of physical interest : limit of stability, lifetime of the excited nuclei, fragment emission timescale and the signatures and characteristics of multifragmentation.

To investigate these points we have used the Nautilus set-up at GANIL. Fragments were detected in the DELF[3] and XYZT[4] detectors. These two detectors constitute an ensemble of 30 position sensitive parallel plate avalanche counters (PPAC), each followed by an ionisation chamber. The angular range covered was 3°-150° with a geometrical acceptance of 55%. Full detection efficiency for atomic numbers equal to or larger than 8 was obtained. The set-up had a low velocity threshold : .5 cm/ns (.13 MeV/u) for DELF and 2 cm/ns (2.07 MeV/u) for XYZT in the forward direction. The measured parameters were the atomic number, Z, the fragment velocity, V, and the angle (with a resolution better than one degree). Light charged particles (not to be discussed here) were also detected with two complex arrays : the Mur and Tonneau. The data presented in this paper concerns the fate of excited nuclei (whose mass are around A = 180-220) produced by a variable impact parameter-dependent transfer of linear momentum, mass and energy from the projectile to the target. The results have been obtained by bombarding Au targets with Ne, Ar, Kr, Xe and Pb projectiles at incident energies ranging from 27 to 60 MeV/u. We will not discuss here the mechanisms but we have observed that, for the lightest systems and the highest energies (Ne at 60 MeV/u, Ar at 30 and 60 MeV/u, Kr at 43 and 60 MeV/u) the collisions end with only one piece of excited nuclear matter which then deexcites, whereas for the largest systems and the lowest energies (Kr+Au at 27 MeV/u, Xe+Au at 44 MeV/u, Pb+Au at 29 MeV/u) the system remains dinuclear at the end of the collision. In the first case, the excitation energy was derived on the basis of the massive transfer hypothesis whereas in the second situation the excitation energy was deduced from the total kinetic energy loss (TKEL) between the two partners.

2. Decay mode probability

The number of massive fragments detected for each collision Pb+Au at 29 MeV/u varied between 2 and 7. When we analysed the multifragment distribution we clearly observed two sources. From the relative velocity between the two sources we deduced the TKEL and the excitation energy per nucleon. We were then able to deduce the fragment multiplicity as a function of the excitation energy. The values for each multiplicity have been corrected for contamination events where at least one fragment has been missed. The resulting distribution is shown in figure 1.

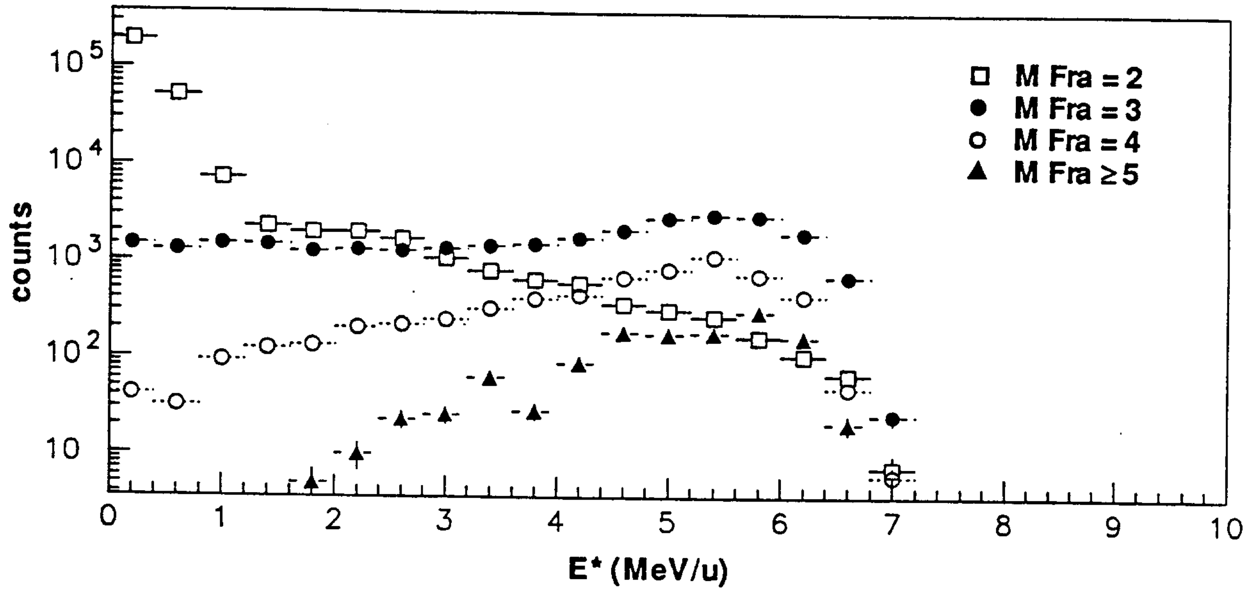


Fig. 1 : Fragment multiplicity , M Fra,as a function of the excitation energy per nucleon ,ε.*

The two body decay channel is still present for excitation energy as high as 6 MeV/u, indicating that the two excited primary partners evaporate only light particles and that the nuclei can sustain without disassembling excitation energies up to 6 MeV/u. This is a value larger than that given by nuclear matter calculations[5]. The five-body final state corresponds to a situation where one of the primary partner disassemblies into at least 3 fragments. This occurs for excitation energies between 2 and 3 MeV/u.

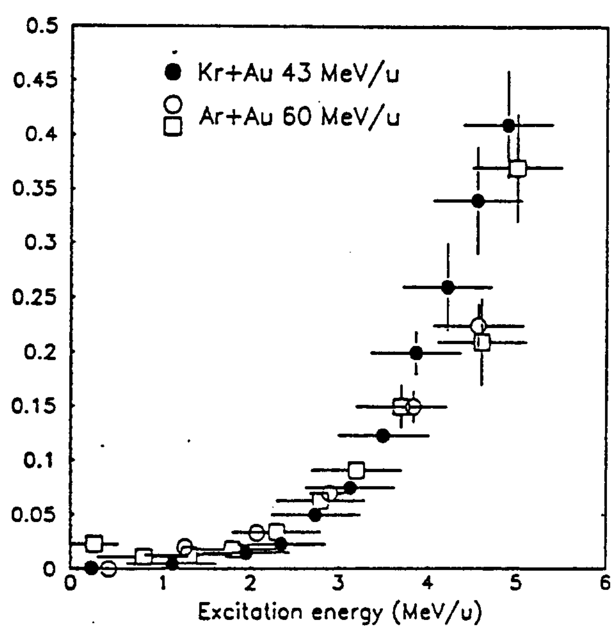


Fig. 2 : Evolution of the two-fold versus three-fold fragment production as a function of the excitation energy per nucleon E. Symbols correspond to different methods for estimating E* and to the two systems studied .*

The transition between two-body and three-body breakup has been also studied for the excited nuclei formed in the Ar+Au and Kr+Au collisions using the kinematic coincident method[6]. The excitation energy has been calculated by various methods and the results are given in the figure 2. As seen in the previous figure three-body decay starts to set-in around ε*=2-3 MeV/u and dominates for ε*=5 MeV/u.

3. Fragment emission : from long to short time-scales

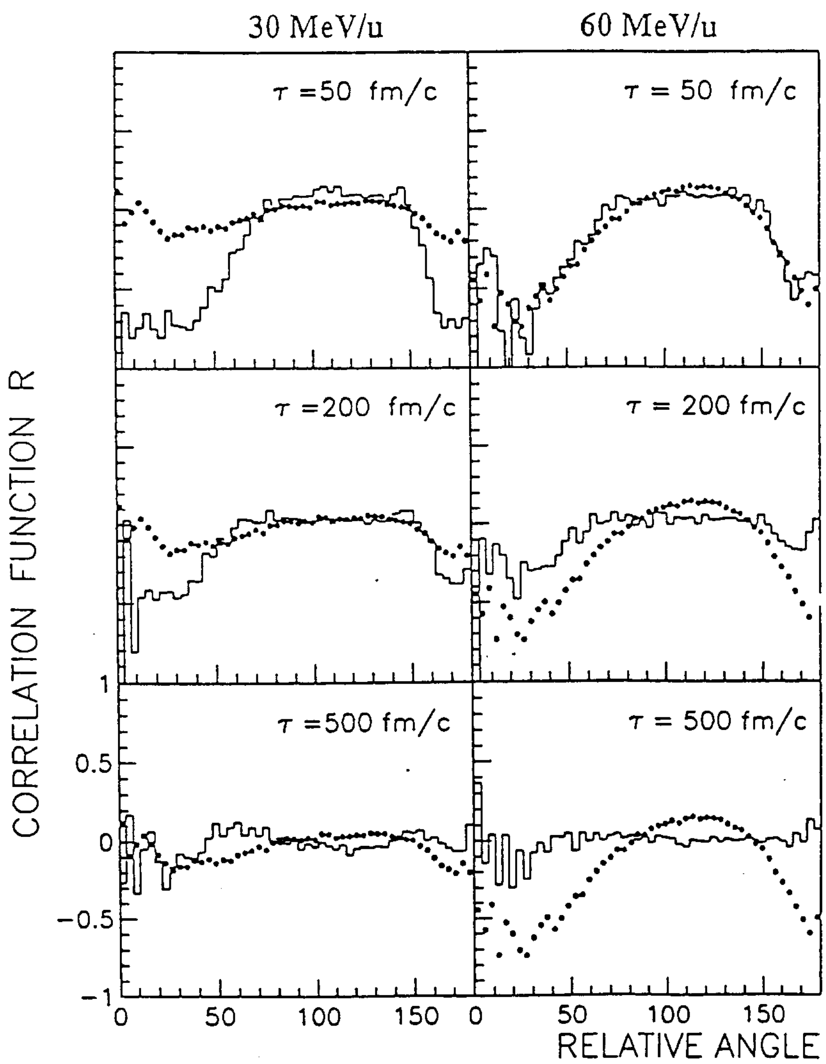


Fig. 3 : Correlation function for the relative angle distributions. The dots are the experimental results and the histograms are the results of the calculations for various spliting times. At 30 MeV/u on the left, the decay is clearly sequential (τ > 500 fm/c) whereas at 60 MeV/u, it is simultaneous (τ ≤ 50 fm/c).

The occurence of multi-body decay is, however, not enough to characterize properly the process of multifragmentation. Indeed, one must investigate in detail the fragment emission time-scales since "true" multifragmentation is generally defined as a fast process. This aspect of the process may be studied with the help of the angular correlations between the fragments taken two-by-two[7,8]. In particular, when dealing with all the emitted fragments, the angular correlations are very different depending on whether the emission is simultaneous or sequential. It is even possible to derive, in the case of sequential decay, the time-scales between each splitting by comparing the experimental angular correlations to the results of trajectories calculated using various values of the time. The first value, obtained for the excited nuclei (3 MeV/u) formed in the Ne+Au collisions at 60 MeV/u was 300 fm/c[9].

The method has been and is presently being used for various systems and an illustration is given in figure 3 for Ar+Au collisions at 30 and 60 MeV/u[10,11,12].

The results for the different systems are given as a function of excitation energy in the figure 4.

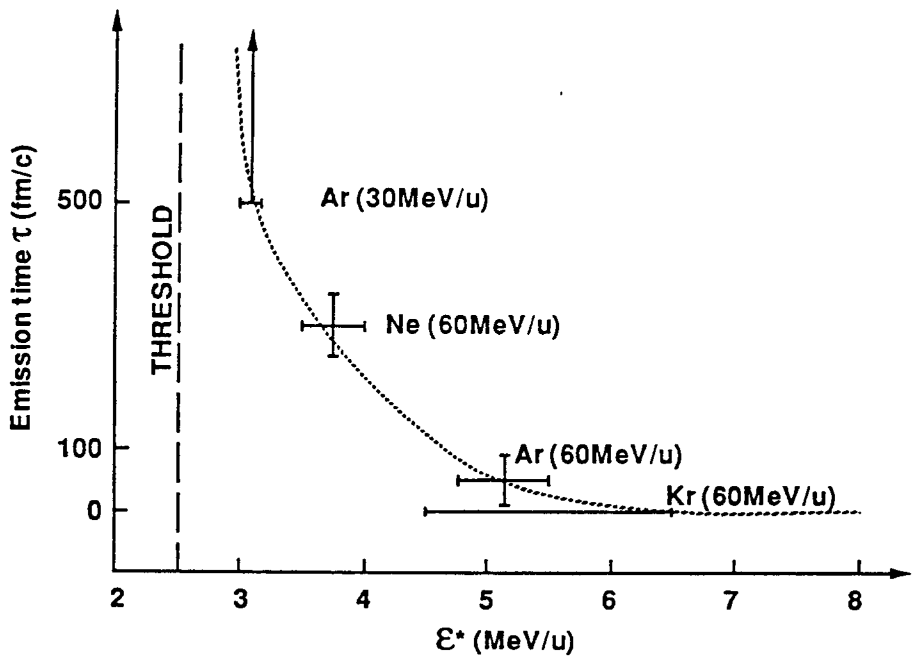


Fig. 4 : Fragment emission time as a function of the excitation energy .

For each system, it is possible to observe a time signature for the multifragmentation which clearly occurs for excitation energy larger than 5 MeV. By studying the charge evolution, in the case of three-body decay by means of Dalitz plots (fig. 5), we observe a clear evolution from fission with an additional light fragment to the multifragmentation where we observe identical charge distributions for each fragment. For the multifragmentation events in the Kr+Au collisions at 60 MeV/u, the average fragment kinetic energy as a function of atomic number is given in figure 6 and compared with the calculations described in reference [13]. There is no need for any expansion energy.

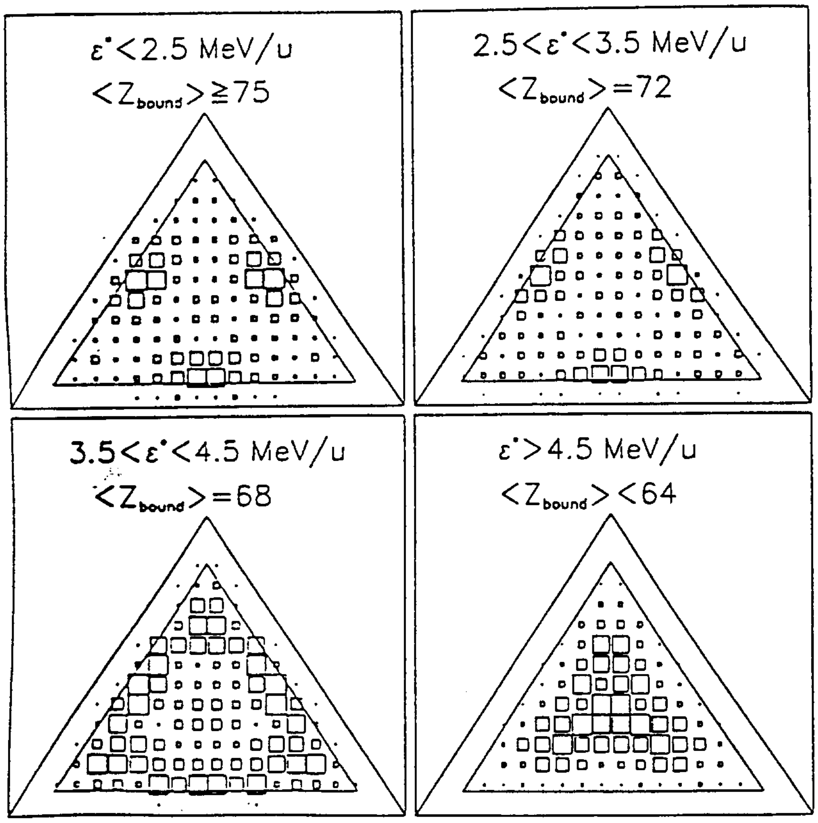


Fig. 5 : Dalitz plots for the three fragments for the Kr+Au system. The events have been sorted according to the excitation energy per nucleon. For each bin, the average Zbound = $Z_1+Z_2+Z_3$ is indicated. The interior triangle shows the limits due to the detection system (lowest detectable charge is 8).

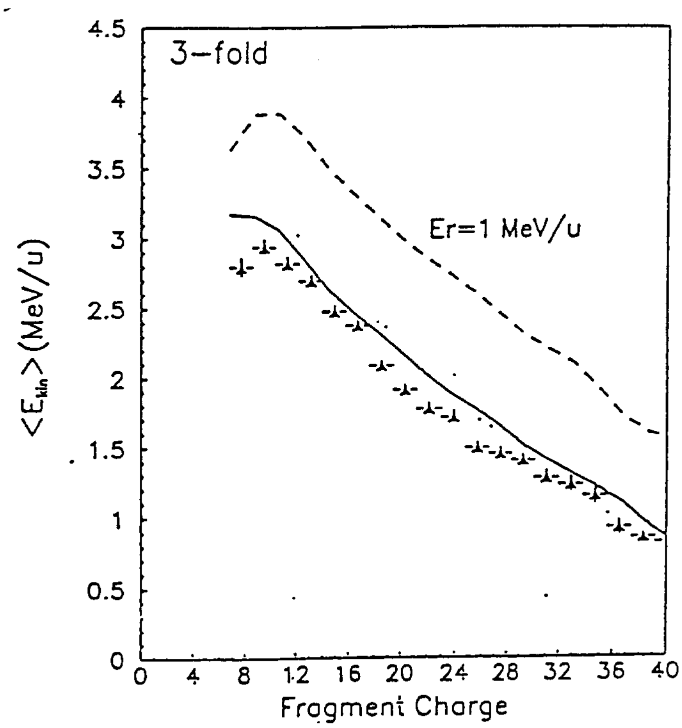
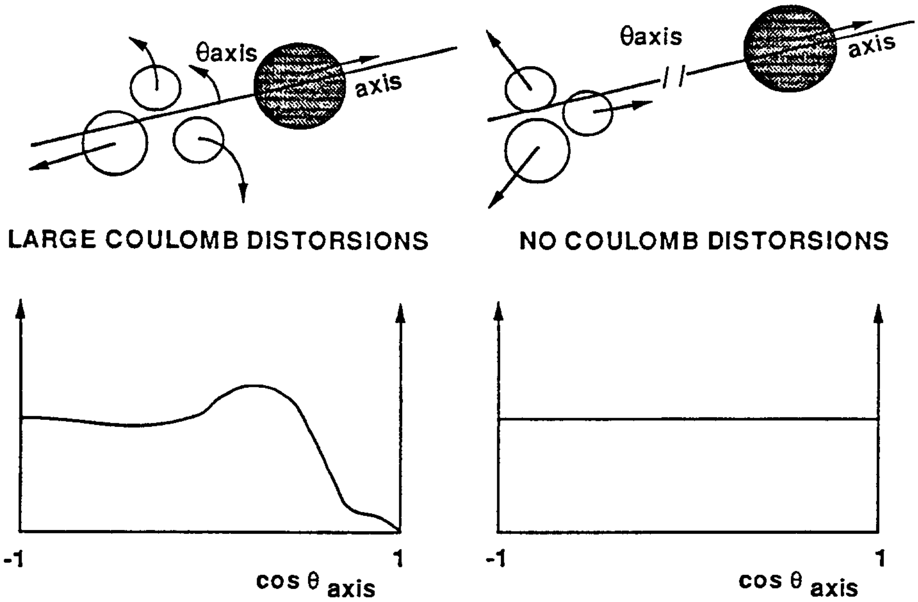


Fig. 6 : Average fragment kinetic energy as a function of atomic number for three target-emitted fragments in the reaction Kr+Au at 60 MeV/u. Black triangles : experimental points. Curves : statistical multifragmentation model [13] with two different initial conditions ; no expansion energy (solid line) and 1 MeV/u radial expansion energy (dashed line).

4. Measurement of lifetimes

Whereas the emission time measurement allows one to obtain a signature of multifragmentation and to study the excited nuclei, the measurement of the lifetime of the excited nuclei between the end of the collision and the beginning of the disassembly is a key parameter for the understanding of the collision mechanisms. Roughly speaking the knowledge of this time provides information on the origin of the disassembly. In case of very short times, as given by semi-classical codes, we are probably dealing with bulk instabilities related to a spinodal decomposition and we would be testing the equation of state at low density. On the other hand, a "long" lifetime would be related to surface and Coulomb instabilities and the system probably evolves with large deformation up to the breakup (simultaneous for high excitation energies and sequential for lower excitation energies). In that case we are measuring the viscosity and its temperature dependance. The measurement of such a lifetime is made possible when the collision fulfills the two following conditions : the primary collision has a deep inelastic character and ends with two excited nuclei which fly away before decay and, secondly, only one of these nuclei disassemblies into fragments. The disassembly products have their trajectories influenced by the large Coulomb field induced by the partner which has not broken up. This point is illustrated in the figure 7 which also displays the trends of the expected angular distributions with respect to the main axis of the collision. The characteristics of the angular distribution of the fragments, especially the dip around zero degree is directly related to the lifetime of the excited nucleus prior to breakup.



Fragment angular distribution

Fig. 7 : Proximity effects between the two partners when only one disassemblies

The experimental distributions for the collisions Pb+Au at 29 MeV/u are displayed in figure 8 for several bins of TKEL. We see a clear evolution from the low excitation energies where we do not see any dip at zero degree and only angular momentum effects, to the highest excitation energies where we can clearly see the dip and thus a sizeable influence of the heavy partner indicating a short separation at the time of breakup.

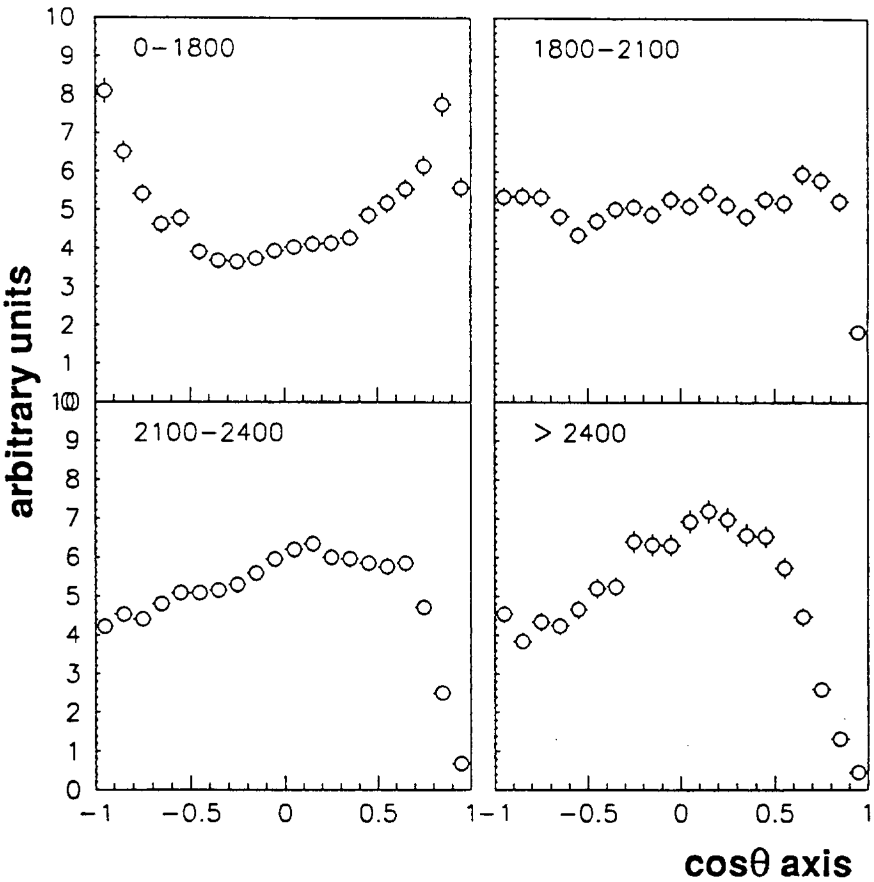


Fig. 8 : Cos θ axis distributions for various TKEL bins. The fragment multiplicity of the selected events is 4, one of them corresponding to one primary fragments and the other to the disassembly of the second primary fragment.

To obtain the lifetime we have to know the separation and the velocity. This can be done by use of a simulation taking into account the collision as described by a simple diffusion model giving the velocities at scission before Coulomb acceleration. The results of the influence of the lifetime on the angular distribution is given on the figure 9 for these different values and compared to the experimental distribution corresponding to the highest excitation energy and thus the shortest life time. The best fit is found for 150 fm/c.

The results are still preliminary and more complete calculations able to reproduce all the characteristics of the collisions are needed before given definitive values and evolution with excitation energies may be given. Nevertheless, we have already observed that for heavy ion collisions at 30 MeV/u, where fusion does not occur even for the highest excitation energies (> 5 MeV/u) the lifetime is larger that the one given by rather dynamical models. Thus seems indicate that we are dealing with statistical decay rather than with dynamical decay. This conclusion is strengthened by the observation of the mixing of the various decay modes over a large range of excitation energy.

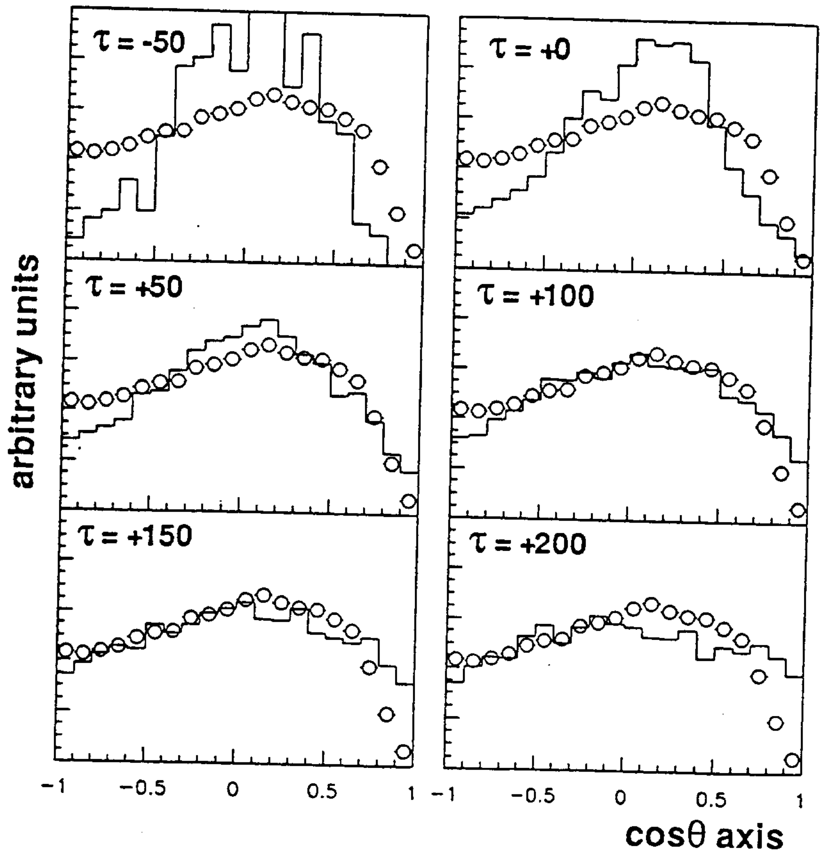


Fig. 9 : Cos θaxis distribution
points : experimental results for the highest TKEL (> 2100 MeV).
Histogram : Results of trajectory calculations under various lifetime conditions.

5. Conclusions

The results presented here are based on an analysis using the characteristics of all the massive fragments produced in heavy -ion collisions. We observe that evaporation processes (only one massive fragment at the end) still exists for excitation energies as large as 6 MeV/u and that the various decay modes are present over the whole range of excitation energies.

By using the Coulomb effects between the various massive fragments, we are also able to measure various characteristic time-scales.

Firstly we have measured the emission time between fragments and for various systems we have observed the evolution from sequential decay, where the fragments are produced by several splitting separated by time intervals larger than 1000 fm/c, to the simultaneous decay, for ε^* larger than 5 MeV/u. We obtain in the latter case a clear signature of multifragmentation, as confirmed by the charge distributions.

Secondly, for collisions retaining a binary character (as observed in the Pb+Au collisions at 29 MeV/u) and by using events where only one of the primary partners disassemblies, we have measured the lifetimes of nuclei with excitation energies larger than 5 MeV/u. The measured value at this excitation energy is 150 fm/c (5 10^{-22} s). This value, obtained for a bombardment energy of 30 MeV/u, is rather long with respect to what is expected from dynamical effects alone and seems to indicate that in this case, we are observing a fast statistical decay.

The same kind of analysis will be used in the future with the results obtained with the INDRA detector for several other systems.

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