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Multifragment Decay of Hot Nuclei: Dynamics or Statistics?

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Abstract

Multifragment events are shown to be associated with specific sources characterized by their mass and excitation energy through the incomplete fusion model. Excitation functions for the different multifragment decay channels are found to be almost independent of the system and the incident energy. Preliminary comparisons of the data with dynamical calculations followed by statistical decay calculations are discussed.

Introduction

Two sources of complex fragments have been identified [1-4] at intermediate energies ($E/A \leq 50$ MeV): a fast, non-equilibrium source producing light fragments at forward angles in normal kinematics, and an equilibrium component, originating from the statistical decay of a compound nucleus and populating the entire range of mass asymmetry in the exit channel. These compound nuclei are formed in complete or incomplete fusion reactions, depending on the incident energy and on the mass asymmetry of the system.

The incomplete fusion model allows one to correlate the mass and excitation energy of the product nucleus with the degree of fusion by means of the source velocity. In reverse kinematics, as the impact parameter decreases, the projectile picks up more and more mass from the target, the velocity of the compound system decreases and its excitation energy increases. This correlation, clearly observed for the 18 MeV/u La+Ni reaction [5], made it possible to study, at one incident energy, the decay properties of hot nuclei over a large excitation energy range.

We have extended this method to ternary, quaternary, etc... events. We have also compared our experimental results to some preliminary results obtained by coupling a Landau-Vlasov calculation [6] describing the dynamical stage of the collision, with a statistical binary decay code [7,8] used to describe the deexcitation process. These results may help us understand the role played by the dynamics and by the statistics in these collisions.

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The experiment

Multifragment emission has been studied in the reactions induced by ^{139}La beams on different targets: ^{12}C,^{27}Al,^{40}Ca,^{51}V,^{nat}Cu, and ^{139}La. Because of the reverse kinematics, even the heaviest fragments have velocities large enough to be identified easily with simple ΔE-E telescopes. Furthermore the reaction products are focused in a narrow cone around the beam direction; therefore the detection efficiency is good even with a detection system of modest size.

Beams of 35, 40, 45 and 55 MeV/u ^{139}La were provided by the Lawrence Berkeley Laboratory BEVALAC. The intensity was 2-3x10^8 particles/pulse. (Some data obtained at GSI at 18 MeV/u and at MSU with ^{129}Xe beams will also be presented). The reaction products were detected in two arrays of 3x3 Si-Si-Plastic telescopes placed at 15° on each side of the beam axis, 37 cm far from the target. This detection system covered the angles between 3° and 28° in the horizontal plane and ±12.5° in the vertical plane. Each telescope had an active area of 4.5x4.5 cm^2 and its total area was 5.5x5.7 cm^2. Au foils (3 mg/cm^2 thick) were placed in front of each telescope for electron suppression. Each telescope had three elements: a 300 µm thick position sensitive ΔE detector, a 5mm thick position sensitive Si-Li E detector and a 7.5 cm thick plastic scintillator with its photomultiplier tube.

Experimental results

The correlation between source velocities and total charge of the fragments gives a useful overview of the reaction mechanism. Fig. 1 presents this correlation for the 2-body events and for six different energies ranging from 18 to 55 MeV/u and four entrance channel asymmetries. The data corresponding to ^{129}Xe beams have been shifted by 3 Z-units to make the comparison easier ($\Delta Z_{La-Xe} = 3$).

The first row corresponds to the most asymmetric system La/Xe + ^{12}C, which has relatively low available energies in the center of mass system, and presents a very simple pattern. At 18 MeV/u, the source velocity distribution peaks at the value expected for complete fusion, which corresponds to the solid line, and the total charge detected is the total charge of the system. In this case, complete fusion has occurred and only neutrons have been evaporated. When the incident energy increases, the distributions move to higher source velocities and lower total detected charge. The same description holds for the ^{27}Al target. The only difference is that, due to the higher excitation energies, the evaporation is more extensive and the detected charge is less than that of the primary compound nucleus, even at 18 MeV/u.

The pattern observed for the heavier targets is more complicated. At 18 MeV/u we observe a very nice illustration of the transition from complete fusion ($Z_1+Z_2 \approx Z_P+Z_T$) to incomplete fusion, with a ridge line going to lower secondary charge when the source velocity increases, which is again what is expected for incomplete fusion in reverse kinematics. As the incident energy increases, and the excitation energy available in the reaction increases, the pattern shifts towards lower Z values because of the evaporation process. At 35 MeV/u the pattern observed is upright, indicating that the system loses by evaporation as many nucleons as it has gained from the fusion with the target. The patterns

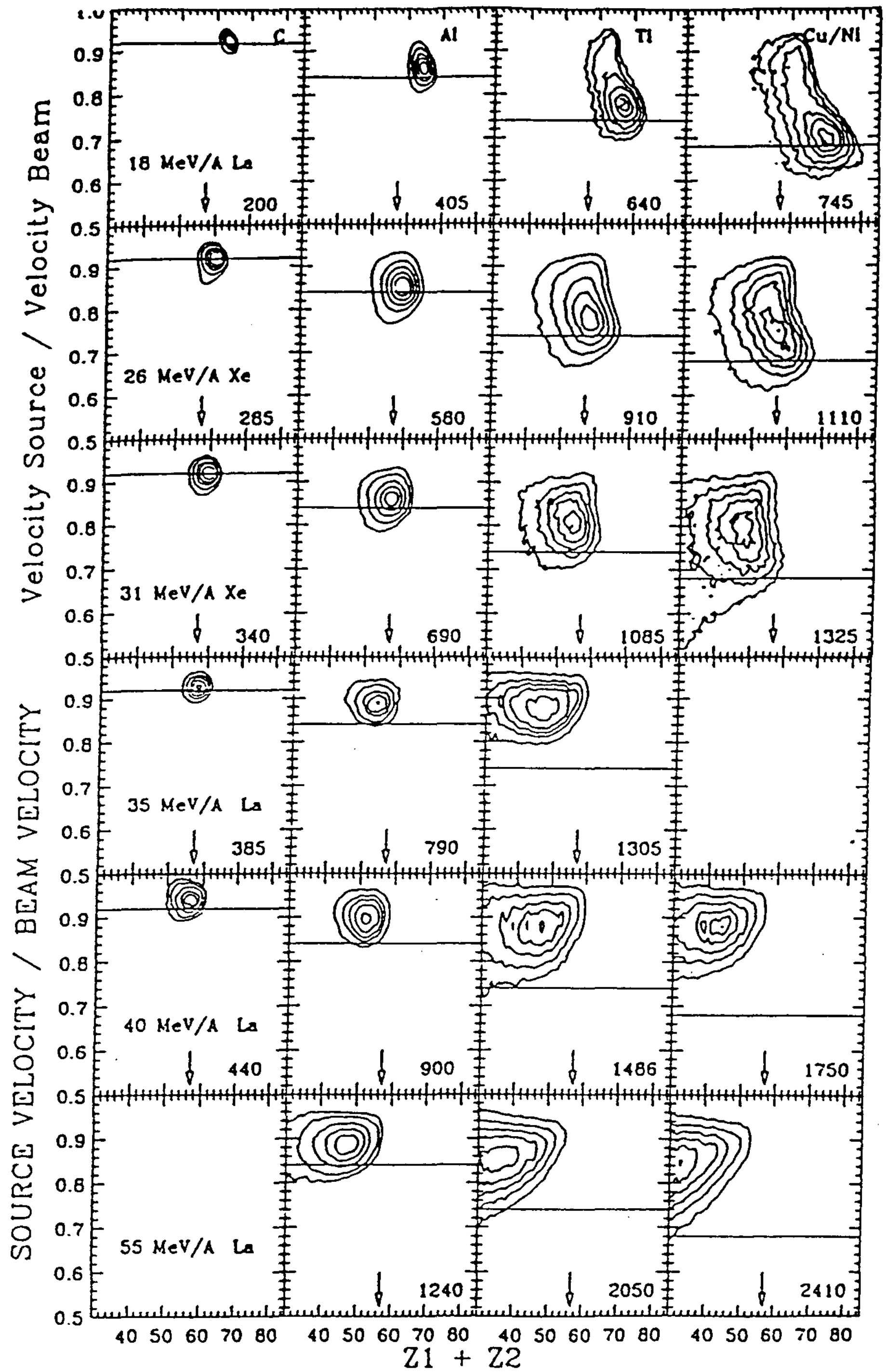

Fig. 1: Linear contour plots of the source velocity versus total detected charge for 2-fold coincidence events, for 6 incident energies and 4 different entrance channel asymmetries. The beam energy and the target are indicated in the first row and column, respectively. The total available energy in the c.m. system is indicated in the lower right of each frame. The horizontal lines and the vertical arrows indicate the complete fusion velocity for each system and the projectile charge, respectively.

observed for ^{51}V and ^{nat}Cu above 35 Mev/u are quite different, with a ridge line going to lower secondary detected charge when the source velocity decreases, which is the opposite to what is observed at lower incident energy.

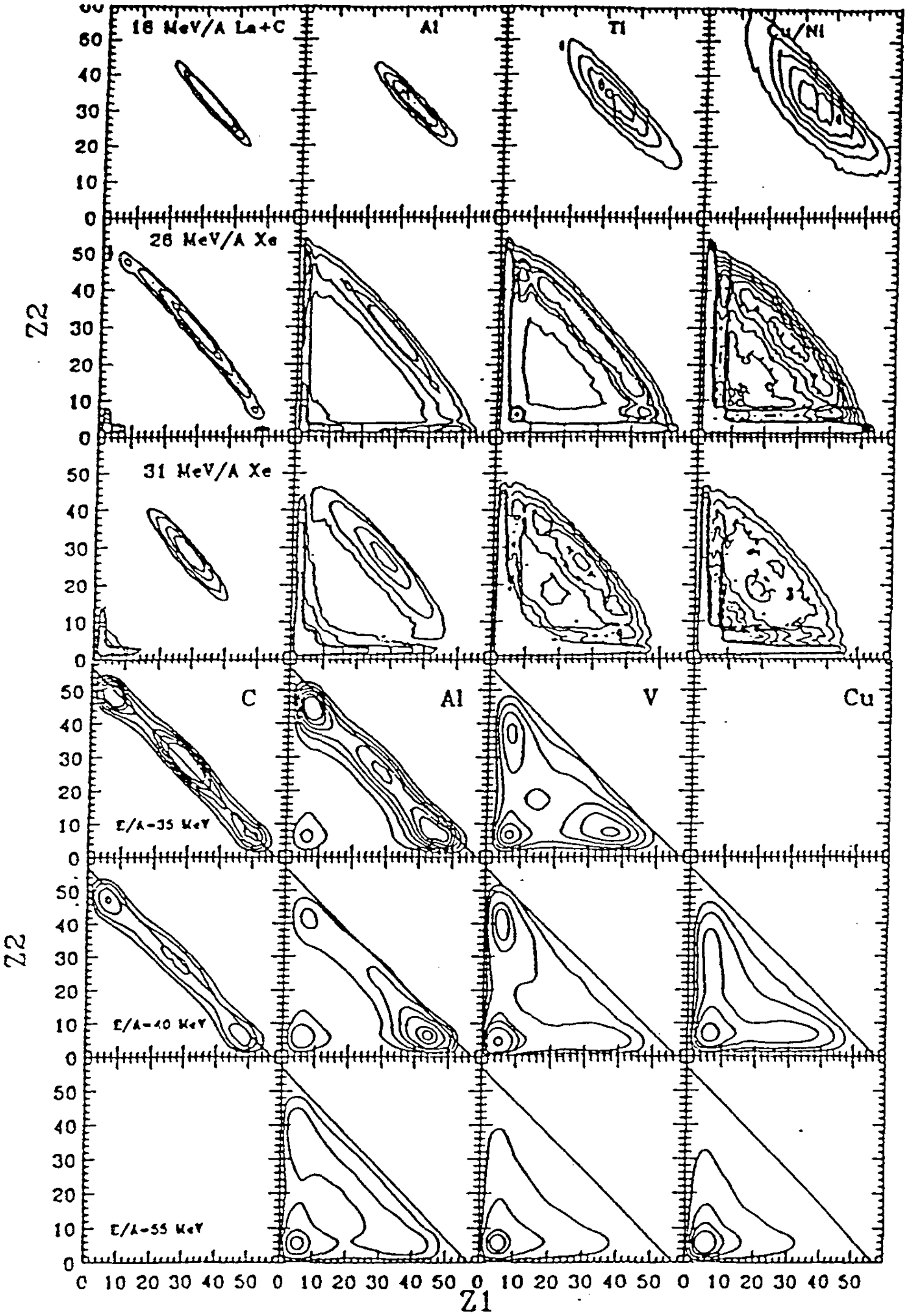

Fig. 2: Linear contour plots of Z_1 versus Z_2 for 2-fold coincidence events. On some of the plots the diagonal line indicate the charge of the projectile (Z_p=57).

Complementary information is provided by the correlation between the measured charge for the two fragments. This plot allows one to determine whether there are only two main fragments or more in the final state of the reaction. If the final state is really binary, the contour plots should be dominated by a band of events peaking at $Z_1+Z_2 = Z_P+Z_T$. If the exit channel is actually multibody with one or several fragments not detected, the events should be distributed everywhere under the line.

The pattern observed on Fig. 2 is very clear for La/Xe + ^{12}C where the contour plots peak at values near the total charge of the system, thus illustrating the binary nature of the process. The band broadens and shifts towards smaller total charge as the incident energy increases, because of evaporation. In the case of the ^{27}Al target, evaporation becomes more important and at the highest incident energy a large fraction of the events are multibody with only two fragments detected. This is even more true for the heavier targets where the band at high Z_1+Z_2 disappears completely above 35 MeV/u.

We shall now consider n-fold events, i.e. events where n fragments are detected in coincidence, with n = 2, 3, 4 and even 5 at 55 MeV/u. Fig.3 presents the Z distributions for n-fold events for all the systems measured at 40 MeV/u. The plots obtained for 2-body events are the projections of the distributions shown in Fig.2 on the principal diagonal. For the ^{12}C target a narrow peak is observed, but as the mass of target increases, this peak broadens and shifts to lower detected charge. These effects arise from the larger range of

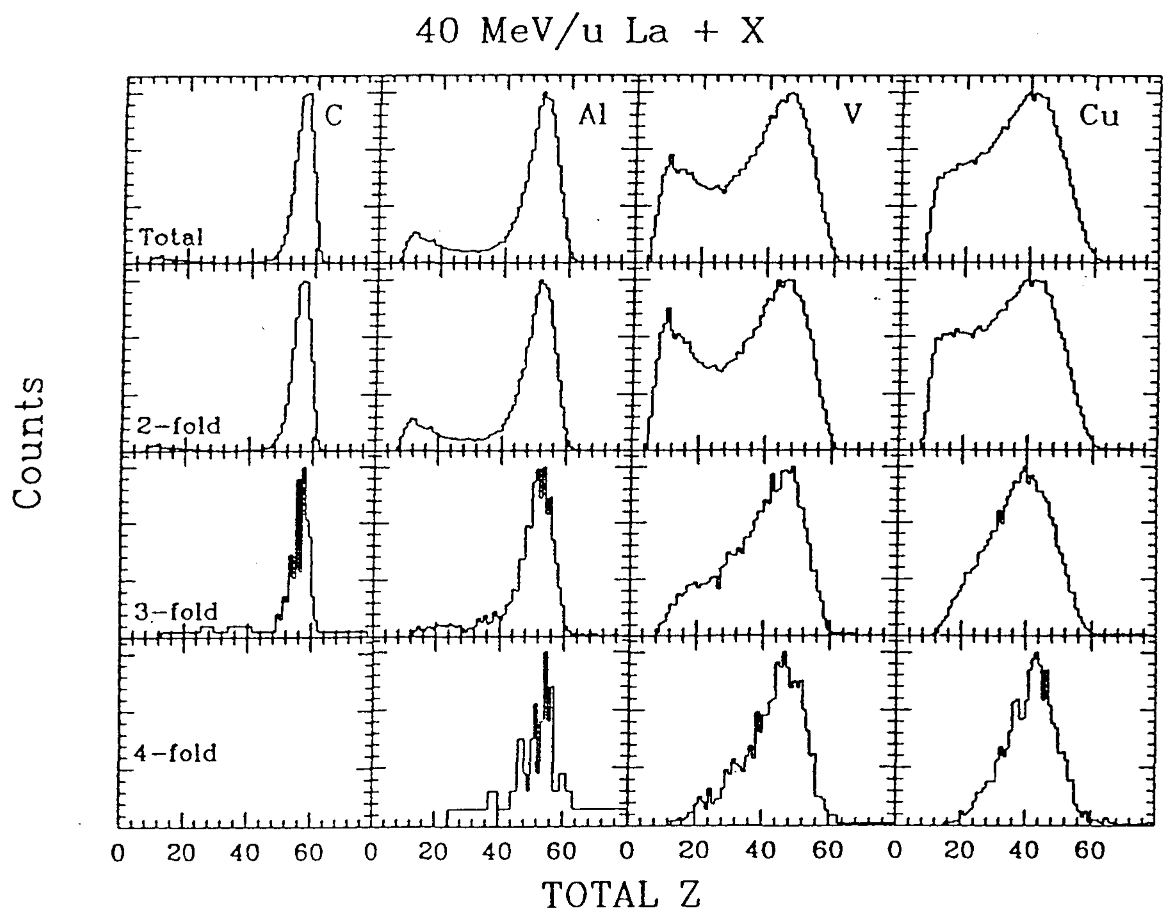

Fig. 3: Total detected charge for some of the systems measured at 40 MeV/u as a function of the multiplicity in the exit channel.

mass transfers and from the increase of light particle evaporation due to the larger range of excitation energies available. The tail at low total detected charges also increases with the mass of the target, and this is related to the increase of higher n-fold events where only 2 fragments are detected. The same Z_{total} distribution plotted for 3-fold and 4-fold events presents a peak centered at approximately the same value, but with a reduced tail to low Z_{total}, indicating that most of these events are complete.

In the following we will restrict ourselves to events where the total measured charge is higher than 30, in order to exclude those events where one fragment is clearly missing and to avoid biassing our kinematical reconstructions. Fig. 4 presents the source velocity distributions obtained at 40 MeV/u for all the targets and for the different fragment multiplicities. The observed peak broadens significantly when the mass of the target increases. This width has two different origins: incomplete fusion processes and the broadening from evaporation. This contribution has been estimated with the statistical code Gemini[9]. In the case of the ^{12}C target, the width can be explained almost entirely by light particle evaporation, but in the case of the heavier targets, a wide range of excitation energies contributes effectively to complex fragment emission. For a given target, the requirement of larger multiplicity of complex fragments selects out events with lower source velocities and therefore higher excitation energies. The same trend has been observed with Ne+Au at 60 MeV/u [10].

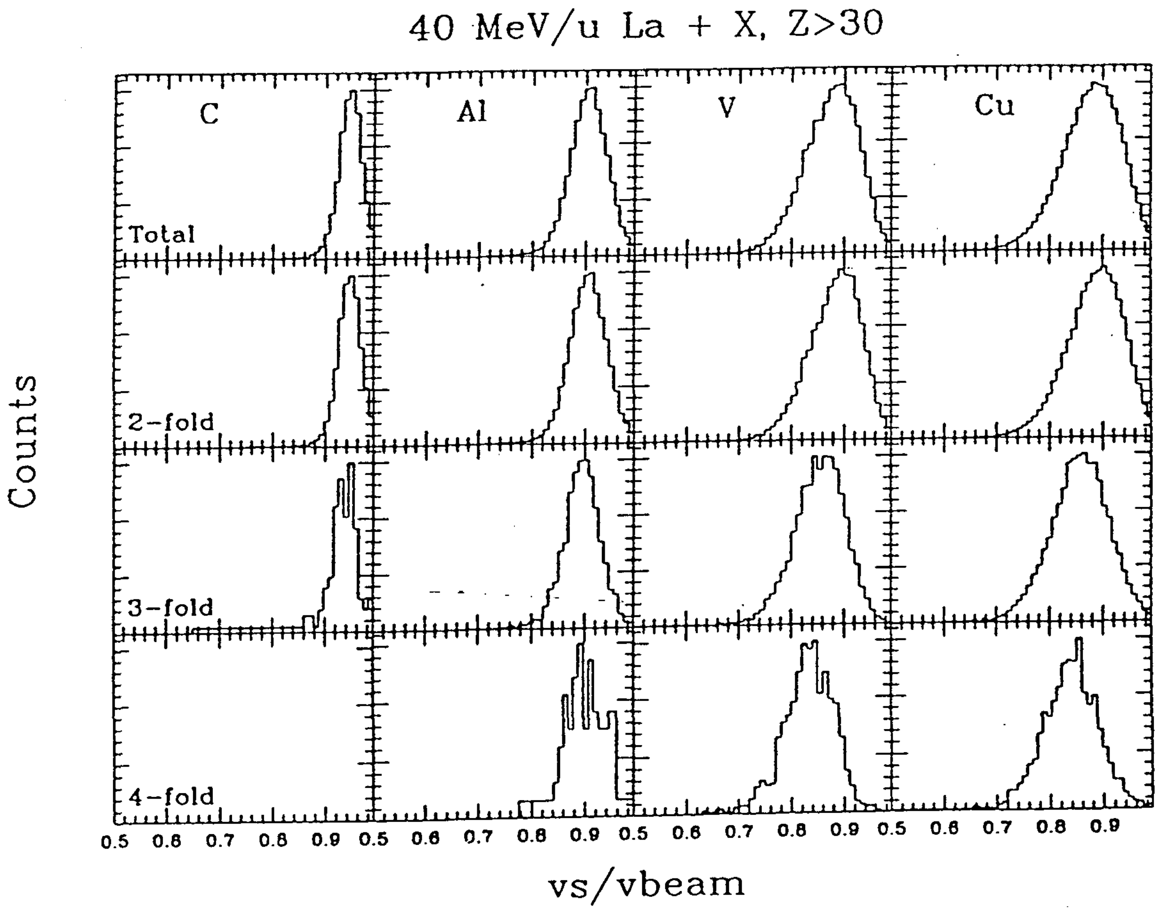

Fig. 4: Same as Fig. 3 for the source velocities expressed as the ratio of the source to the beam velocity.

To study the behavior of hot nuclear systems as their excitation energy increases, excitation functions for the binary, ternary, etc. decay channels have been constructed. More precisely, Fig. 5 presents the evolution of the proportion of n-fold events with respect to the total number of coincidence events as a function of the excitation energy inferred from the source velocity through the incomplete fusion model, for four incident energies. The picture obtained is quite striking. First, at all energies the 3-fold and 4-fold event probabilities (and 5-fold at 55 MeV/u) increase significantly up to excitation energies as high as 8 MeV/u. This energy dependence is a good indication that the relation between E^* and the source velocity is approximately valid and also confirms that the width of the source velocity distribution is only partly due to light particle evaporation (if it were only particle evaporation, the excitation functions would be flat). Second, the increase observed in these excitation functions is smooth. We see no evidence for a phase transition towards nuclear cracking[11,12], and the data suggest that the decay of the hot nuclei under study is governed by the same mechanism up to an excitation energy approaching the total binding energy of these nuclei.

A closer look at Fig.5 shows some minor discrepancies for the lightest targets, for which the points are low. In the case of ^{12}C this can probably be explained by the light particle evaporation which is a major contribution to the width of the source velocity distribution. This can also explain why, in the case of ^{27}Al, the multi-fold probabilities at the highest excitation energies, which correspond to the tail of the source velocity distribu-

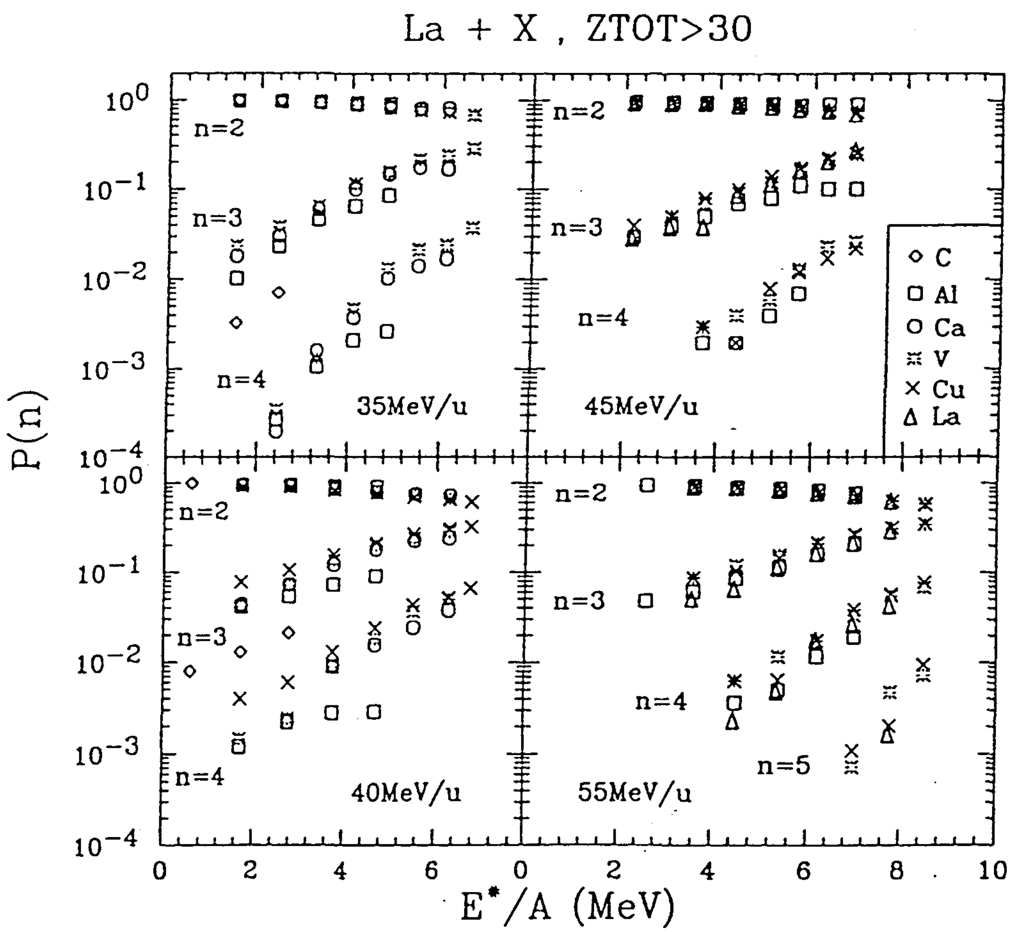

Fig. 5: Proportion of 2-3-4-5 fold events as a function of the excitation energy per nucleon for the systems studied at 4 different energies.

tion, fall slightly below those for the heavier targets. We have checked for the 35 MeV/u La + Ca data that these excitation functions were not skewed by our detection efficiency [9]. However, it has to be pointed out that, due to preequilibrium processes not taken into account here, the excitation energy scale may be wrong by up to 30%, but these effects should only compress smoothly the energy scale.

To conclude on these excitation functions, their independence with respect to target-projectile combination and to incident energy suggests a competition between the different decay channels independent of the entrance channel and therefore supports the idea of an intermediate system whose decay properties are mainly determined by its excitation energy and angular momentum.

Boltzmann-Nordheim-Vlasov calculations

It seems interesting to compare our experimental data with the predictions obtained for complex fragment emission with a self-consistent transport equation approach (Boltzmann-Nordheim-Vlasov or Landau-Vlasov). The two fundamental ingredients that enter the BNV equation are the self consistent mean field and the in-medium nucleon-nucleon cross section

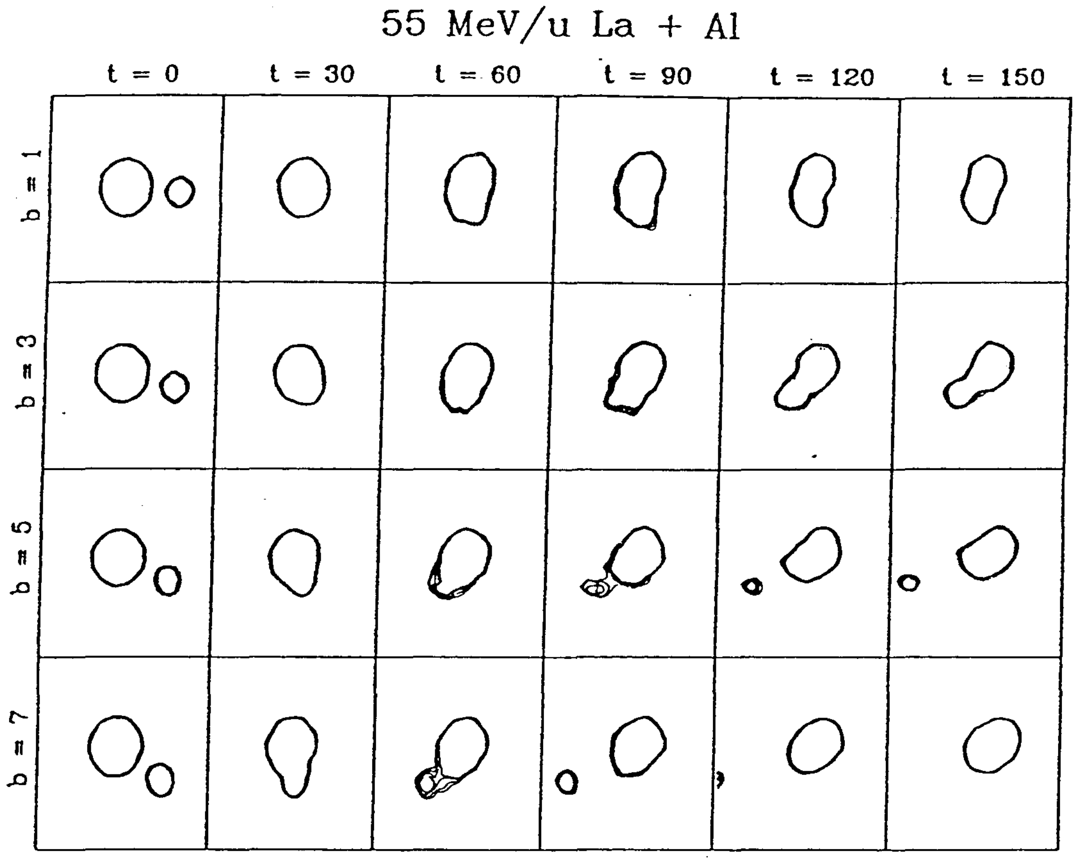

Fig. 6: $^{139}La + ^{27}Al$ collisions at 55 MeV/u calculated with the BNV equation for several impact parameters (expressed in fm). The initial velocity axis (z) is horizontal and the impact parameter axis (x) is vertical. The times are expressed in fm/c. The lines represent equal density level in the (x, z) plane.

σ_{NN}. In the code we used [6], the mean field is given by the Coulomb interaction between protons plus a nuclear density dependent part of Skyrme type with parameters chosen to get a nuclear compressibility value K=200 MeV. The cross section σ_{NN} is assumed to be the free nucleon-nucleon cross section with an energy dependence parametrized from experimental data. An example of the evolution of the collision between ^{139}La and ^{27}Al at 55 MeV/u is presented on Fig. 6 as a function of time for different impact parameters.

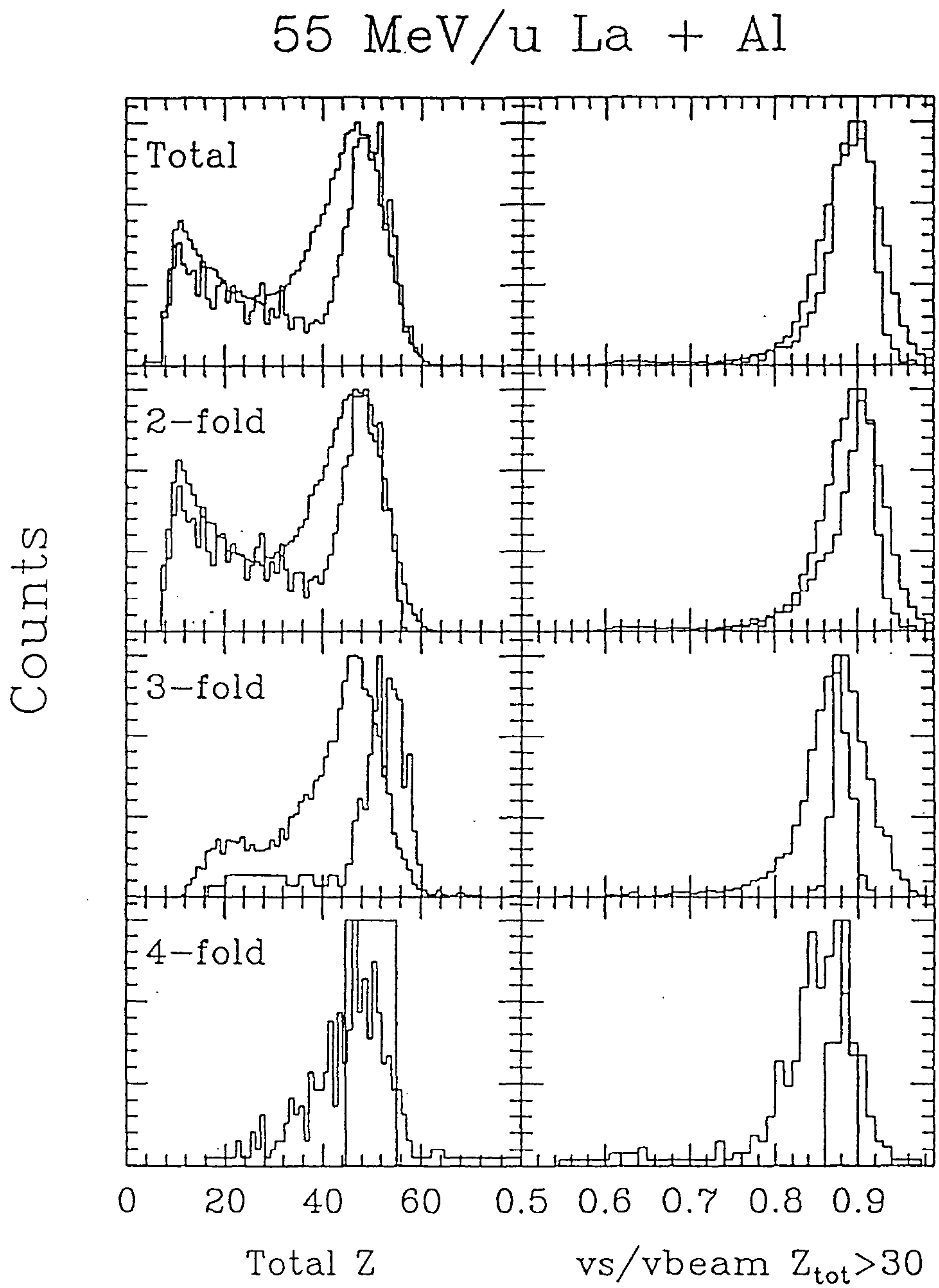

Fig. 7 Experimental and calculated total detected charge and source velocities for 55 MeV/u $^{139}La + ^{27}Al$. The calculations have performed with the BNV model [14] plus the GEMINI evaporation code [7,8].

For the most central collisions, "complete fusion" occurs, accompanied by preequilibrium emission. At the end of the collisions only one heavy residue exists which is very elongated and will probably undergo fission (b = 3 fm). For intermediate impact parameters, incomplete fusion occurs, where the target breaks into two pieces and part of the target is absorbed by the projectile. For larger impact parameters, the two incident nuclei merge together, but two centers can always be distinguished and, after a time depending on the impact parameter, the system separates into two fragments close in mass to the target and the projectile. Although this process is again accompanied by preequilibrium emission, its features are reminiscent of deep inelastic collisions as they are observed at low incident energies. For the heavier systems $^{139}La + ^{51}V$ and $^{139}La + ^{nat}Cu$ at 55 MeV/u, these calculations show the presence of a participant zone in addition to the projectile-like and target-like remnants for impact parameters between 5 and 7 fm, and therefore indicate the occurrence of participant-spectator type reactions.

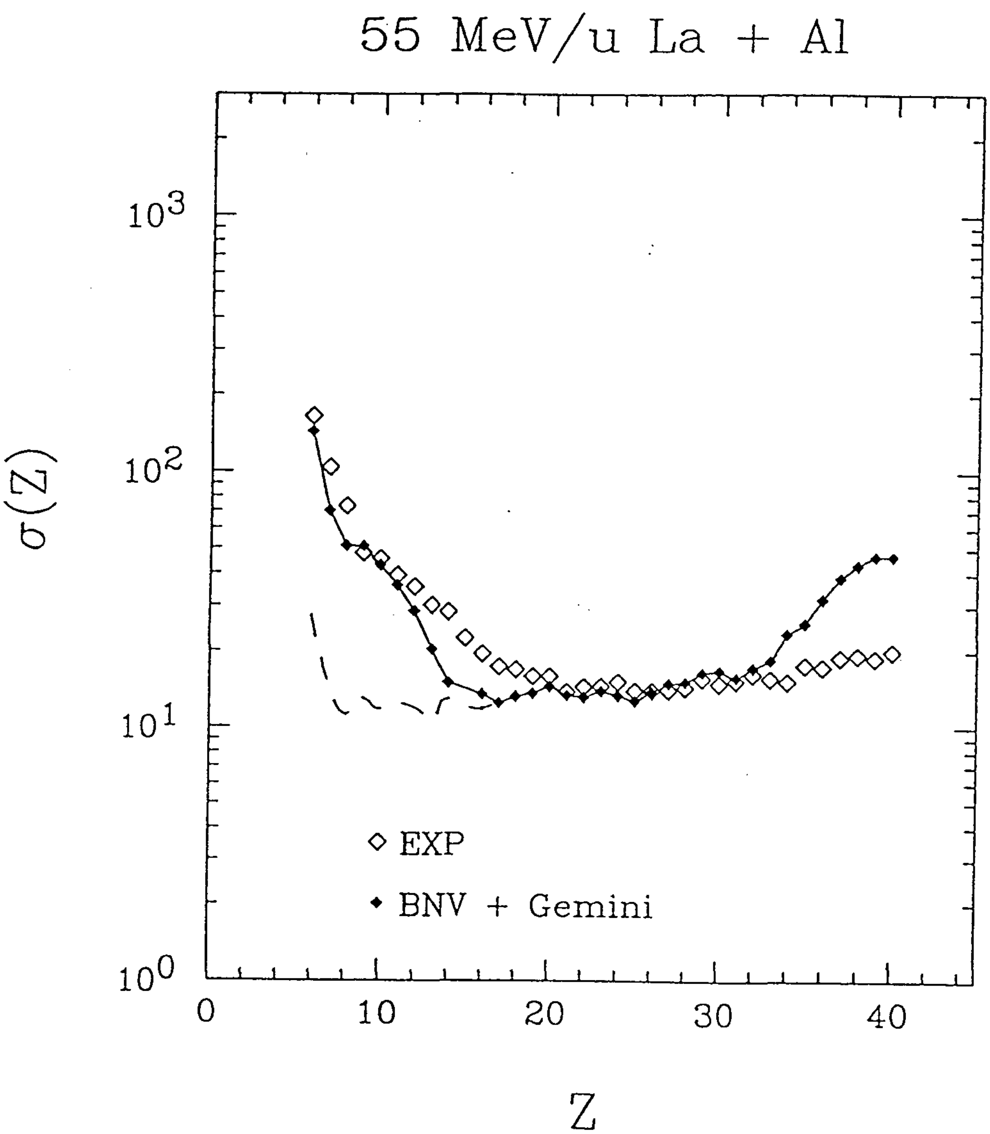

Fig. 8: Comparison of experimental integrated cross sections for ^{139}La + ^{27}Al at 55 MeV/u (diamonds) with the results of BNV+ Gemini calculations (solid line, see text)

Our purpose is now to compare our data where the fragments are detected "cold" with the fragments produced in the reactions predicted by this code. To achieve this, we stop the BNV calculations as soon as the compound system, if it exists, is equilibrated, or as soon as the 2 or 3 fragments produced in the exit channel are separated. Their characteristics (A, Z, E^*, J, velocity, angle) are introduced as input in the statistical decay code Gemini[7].

The calculated and measured total Z and source velocity distributions for the ^{139}La + ^{27}Al reaction at 55 MeV/u are shown in Fig. 7. The overall agreement is quite satisfactory although the experimental distributions are somewhat broader then those predicted by the model.

The charge distribution is compared with the experimental cross sections in Fig. 8. The agreement is excellent in the region between Z = 18 and 45 but the calculation underpredicts the data in the intermediate mass region.

To summarize our preliminary results concerning the BNV calculations, they predict for asymmetric systems at intermediate energies the persistence of the mechanisms known below 10 MeV/u, accompanied by preequilibrium emission: complete or incomplete fusion for the most central impact parameters, and deep-inelastic processes for peripheral impact parameters. The same kind of conclusions have been drawn for the Ar+Ag reaction at 27 MeV/u [13]. For more symmetric systems we observe the onset of the fireball regime for intermediate and large impact parameters around 40 MeV/u.

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References

[1] R.J. Charity et al., *Nucl. Phys.* A511, 59 (1990)
[2] M. Fatyga et al., *Phys. Rev. Lett.* 58, 2527 (1987)
[3] B.Borderie et al., *Phys. Lett.* B205, 26 (1988)
[4] E. Plagnol et al., *PhysLett.* B221, 11 (1989)
[5] N. Colonna et al., *Phys. Rev. Lett.* 62 , 1833 (1989)
[6] A. Bonasera et al., *Phys. Lett.* B244 , 169 (1990)
[7] R.J. Charity et al., *Nucl. Phys.* A483, 371 (1988)
[8] R.J. Charity et al., *Nucl. Phys.* A476, 516 (1988)
[9] Y. Blumenfeld et al.,*Phys. Rev. Lett.* 66, 576 (1991)
[10] R. Bougault et al., *Phys. Lett.* B232, 291 (1989)
[11] J. Bondorf et al., Nucl. Phys. A444, 460 (1985)
[12] D.H.E. Gross et al., Phys. Lett. B200, 397 (1987)
[13] B. Borderie et al., to be published in *Ann. Phys.*
[14] M. Colonna et al., to be published.

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