Conference Proceedings Vol. 38
«Perspectives in Heavy Ion Physics»
M. Di Toro and E. Migneco (Eds.)
SIF, Bologna, 1993

HIGH ENERGY MULTIFRAGMENTATION(*)

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ABSTRACT

We review our recent results on the fragmentation of Au projectiles after collision with C, Al, Cu, and Pb targets at an incident energy of 600 MeV/u. The measured distributions are given as functions of an impact parameter observable, the total charge of all projectile fragments in an event, Z_{bound}. It is found that the correlation between the mean IMF multiplicity $<M_{IMF}>$ and Z_{bound}, extending from evaporation process to the total disassembly of the projectile, is independent of the target. This universal behaviour may suggest an equilibration of the projectile fragment prior to its decay. Therefore the experimental data are compared to predictions of statistical multifragmentation and sequential evaporation models. The sequential model clearly fails to reproduce the data. The statistical multifragmentation calculations reproduce the behaviour of the $<M_{IMF}>$ vs Z_{bound} correlations but predict too symmetric a break-up. A better agreement is found by using a percolation model.

(*) *Talk given by G.Raciti.*

1. INTRODUCTION.

The study of the nuclear matter under extreme conditions is become one of the major domains of nuclear research. One research topic among the open ones concerns the decay modes of a nuclear system excited up to energies larger than its total binding energy. Since the barrier for multiple emission of intermediate mass fragments (IMF) ($3 \leq Z \leq 30$) can be evaluated around 3-4 MeV/u, it is not surprising that, as predicted [1-3], several IMF have been observed in heavy ion collisions at intermediate [4] and relativistic incident energies [5] . Many scenarios have been suggested for this decay mode called in general "multifragmentation". They range from statistical multifragmentation [1-3] and/or multi-sequential decay [6] to fragment formation due to the exponential growth of the density fluctuations[7] in the spinodal region of instability [8]. In particular the understanding of the multifragmentation process might be crucial to detect the signature of the liquid-gas phase transition expected [9] in nuclear matter around the boiling temperature. In order to distinguish between the different models [1-3,6-9] very specific experimental observables should be found. In this respect we will explore in the present paper correlations between IMF that seem to be sufficiently sensitive [10,11]. The excitation energies around 8 MeV/u where the production of IMF should reach its maximum, can either be reached in central collisions at intermediate energies or in almost peripheral collisions between asymmetric systems at much higher energies. In the latter case the reaction proceeds by the formation of a "fire-ball" and a "heavy" spectator nucleus[12]. The "spectator" is excited by the formation of particle-hole states during the first stage of the collision [13] and by capture of fire-ball nucleons in the attractive mean field . Among these classes of reactions the inverse kinematics ones at high incident energy reveal several advantages, therefore we investigated the reactions Au+ C, Al, Cu, Pb at 600 MeV/u [14]. In fact in these reactions exclusive measurements of IMF, including the heaviest ones, can best be done because of : i)only a relatively small forward solid angle should be completely covered, ii) there is a strong suppression of preequilibrium contributions to the IMF production [15] as well as iii) a very small probability of IMF formation in the "fire-ball" region because of the high reached excitation energy. Both ii) and iii) lead to nearly no ambiguity in the selection of the IMF coming from the decay of the "projectile-spectator". In the following we will first summarize the main features observed [14,16-18] on the IMF correlations and then we will compare our data with the current theoretical calculations.

2. EXPERIMENTAL SET-UP.

The experiment was performed at the SIS accelerator at the GSI - Darmstadt laboratory, where a Au beam bombarded the C,Al,Cu and Pb targets at 600 MeV/u. Since in inverse kinematics the projectile fragments are strongly forward focused, they were detected through the forward spectrometer ALADIN [19] (see fig.1).

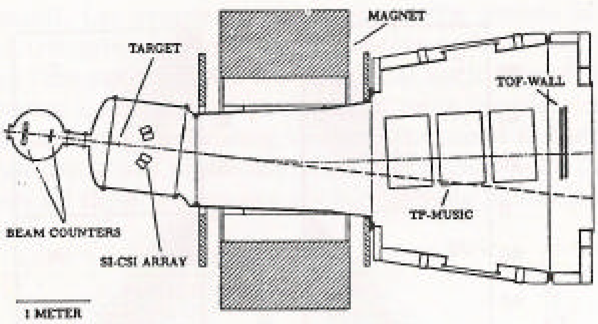

Figure 1 . *The ALADIN apparatus. See text for details.*

The charge and multiplicity of nuclear fragments were determined by means of the time-of-light (TOF) wall, with unit charge resolution for $Z \leq 8$ fragments and $\Delta Z=2$ for the heavier fragments. Fragments with $Z \geq 10$ were identified by the Time Projection - Multiple Sampling Ionization Chamber (TP-MUSIC). Light particles, predominantly originating from the "fire-ball" region, were detected by a 64 element Si-CsI hodoscope in the angular region between 7 ° and 40 ° . For more details see ref.[14] .

3. EXPERIMENTAL RESULTS.

Since the occurrence of multifragmentation is expected [1-3] to depend on the energy deposition in heavy ion collisions and then on the violence of the collision, this process will strongly depend on the impact parameter. In order to characterize this parameter, that in general is derived from the multiplicity of light particles M_{lp}, we introduced [14,16] the quantity Z_{bound}, defined as the sum of the charges of all fragments belonging to the same "event",with $Z \geq 2$ and that have the projectile velocity Z_{bound} is the best estimate of the size of the projectile spectator and will also depend on the excitation energy deposited in the spectator. The correlation between the impact parameter and Z_{bound} was checked in the framework of different model calculations [14]. We use this quantity to explore the evolution of the multi-fragment emission by studying the maximum charge Z_{max} in each event. Fig.2-a shows a scatter plot of the correlation between Z_{max} and Z_{bound} . Fig.2-b shows the correlation between M_{lp} and Z_{bound}.

By definition, Z_{bound} is always bigger than or equal to Z_{max}, therefore all events are located on or below the diagonal. Points on the diagonal correspond to events where only one fragment has been detected, points near the diagonal are typical evaporation events (or very asymmetric fission), where at least two fragments have been observed but most of the charge is concentrated in one of them.

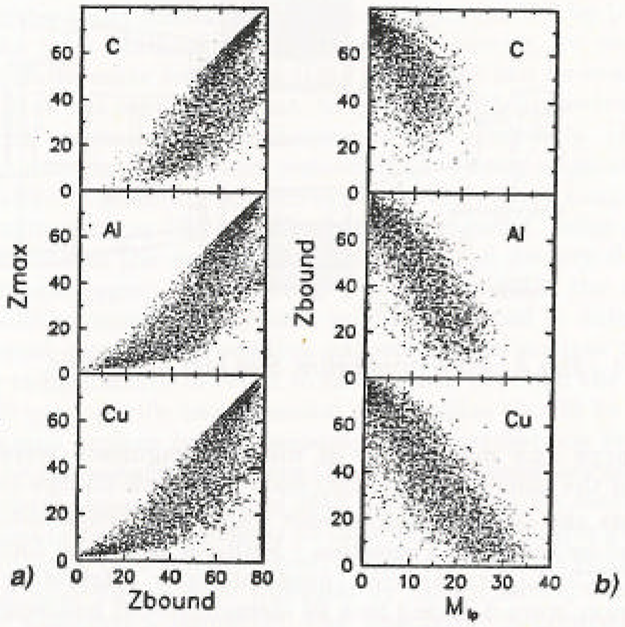

Figure 2 : *a) Z_{max}-Z_{bound} correlation for the fragments detected in each event for the C,Al,Cu targets.*

b) M_{lp}-Z_{bound} correlation for the same reactions.

The farther a point is displaced from the diagonal, and more equally the charge of the remaining projectile spectator is distributed among different fragments. The correlations for all the targets are qualitatively very similar: for large Z_{bound} (very peripheral collisions) most of the cross section is found on or close to the diagonal, indicating spallation or evaporation processes, with one heavy projectile remnant. With decreasing values of Z_{bound} up to around 50 (for smaller impact parameters) these events are strongly reduced and a rapid decrease of Z_{max} is observed, indicating that a multifragment emission becomes the dominant process. This occurrence is at about the same value of Z_{bound} for all the targets. In the reaction on the C target the cross section rapidly decreases going to smaller values of Z_{bound}. For the heavier targets an appreciable part of the cross section is found in the region where both Z_{bound} and Z_{max} are small but where the M_{lp} is large (Fig.2-b), indicating that very excited projectile spectators proceed towards a total disassembly into mostly nucleons and a few light IMF.

In order to show the charge-charge correlations among the three largest fragments in each event, a charge-Dalitz plot [17,20] is reported in fig.3. In this plot the distance of a point from each vertex is a measure of the charge of each of the three detected IMF. For the largest values of Z_{bound} we observe events where the charge of one is large and the ones of the other fragments are small, i.e. evaporation processes (the events lie at one of the apexes of the triangle) or two large fragments and a third small, i.e. symmetric fission (the events lie in the middle of each side of the triangle). As Z_{bound} decreases, i.e. the reaction becomes more central, the events populate the diagonal spokes indicating that one fragment is dominating and the other two fragments are of similar size. The region near the center of the triangle where all three fragments are comparable is dominant for the most central collisions.

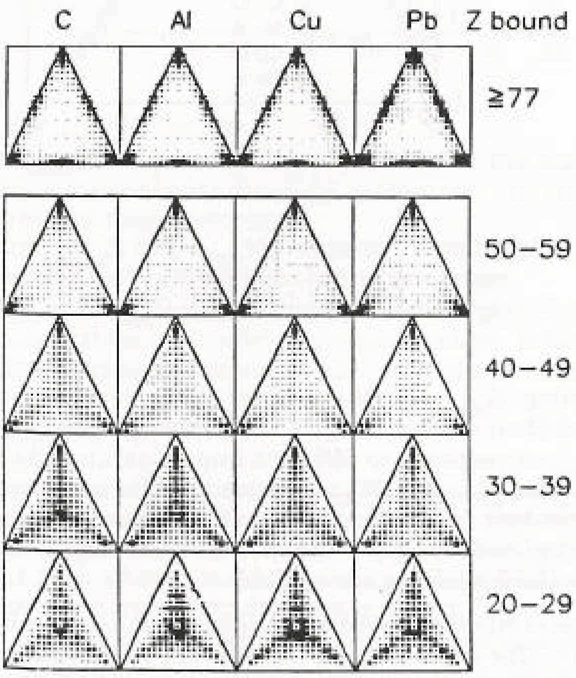

Figure 3: ***Charge-Dalitz plot for different cuts in Z_{bound}. The charge of each fragment is represented by the distance from one of the three vertexes.***

The quantity which is intimately related to the multifragmentation processes is the multiplicity of IMF. The correlation between the mean IMF multiplicity $<M_{IMF}>$ and the magnitude of Z_{bound} is illustrated in fig.4.

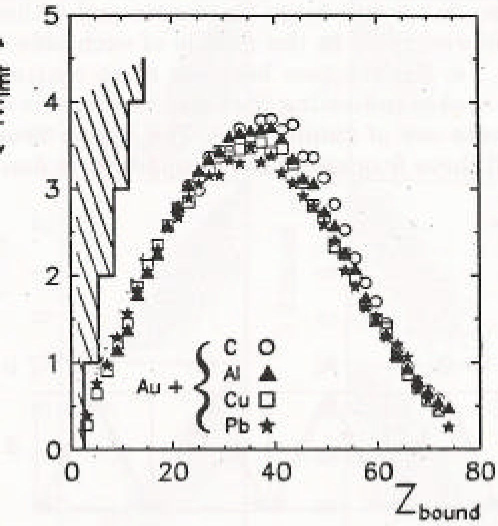

Figure 4 : *Correlation between $<M_{IMF}>$ and Z_{bound} for Au+C,Al,Cu,Pb reactions at E/A=600 MeV/u.(The hatched area marks the region excluded by the limits $Z_{IMF} \leq 3$)*

With decreasing Z_{bound}, $< M_{IMF}>$ first rises, reaches a maximum near Z_{bound}=40 and then decreases again. Since for the different targets a given value of Z_{bound} corresponds to different impact parameters, it is remarkable that the rise and fall of $< M_{IMF}>$ appears to be an universal function of Z_{bound}, independent of the target [16]. The reason for this behaviour remains to be explored; it may indicate that some degree of equilibration is reached when the fragments are emitted.

A key question is whether thermal equilibrium is reached before the excited system decays. One signature for equilibrium is that the emission of fragments is isotropic. In fig.5 we plot the mean parallel velocity of fragments as a function of Z_{bound} for Au+Cu at 600 MeV/u. In the bottom panel of this figure we plot the ratio of the velocity widths in the transverse and beam directions. Within 20% the ratio is unity for fragments with $Z \geq 8$ and for all values of Z_{bound}. Hence to this level of accuracy, the emission of heavy fragments is isotropic.

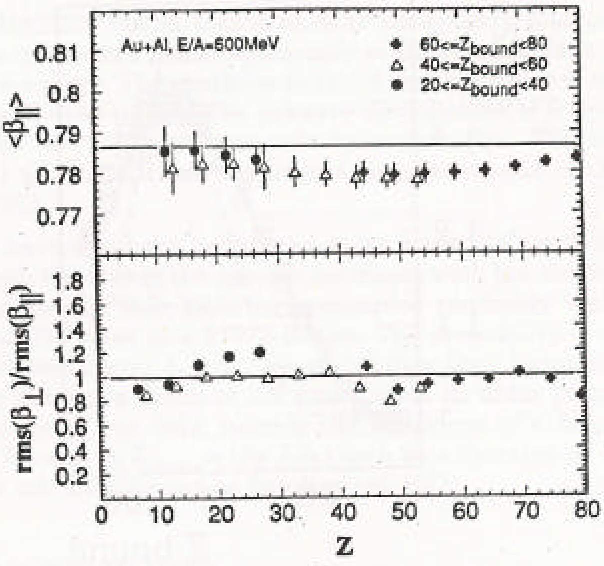

Figure 5: *Mean longitudinal velocity (top) and ratio of the transverse and longitudinal rms velocity (bottom) vs Zbound. The horizontal line (top) marks the beam velocity.*

The number of IMF is only one way to characterize the exit channel of each collision. Other observables can provide complementary information. For example a quantity of special interest is the normalized charge variance [21] :

$$\gamma_2 = \sigma_e^{\,2}/(\langle Z\rangle_e^{\,2}) + 1$$

where $\sigma_e^{\,2}$ is the variance of the charge distribution in the event e and $\langle Z\rangle_e$ is the mean charge. The lowest value of γ_2=1, indicating that all the charges in the event are the same size, will be reached either when only light particles are evaporated from a heavy residue or when a total disassembly of the system into particles and very light fragments occurs. A large value of γ_2 indicates that the charges in the event are widely distributed. A measure of this distribution, i.e. the size of the charge fluctuations, is the mean value of γ_2 . In fig.6 we plot $< \gamma_2 >$ versus Z_{bound}. For values of $Z_{bound} \sim 50$, we observe a peak in the $< \gamma_2 >$ distribution. This indicates that the charges emitted in events with Z_{bound} ~50 have the largest normalized charge variance. This peak occurs during the rise of multi-fragment emission, and again the data show similar behaviour for all four targets.

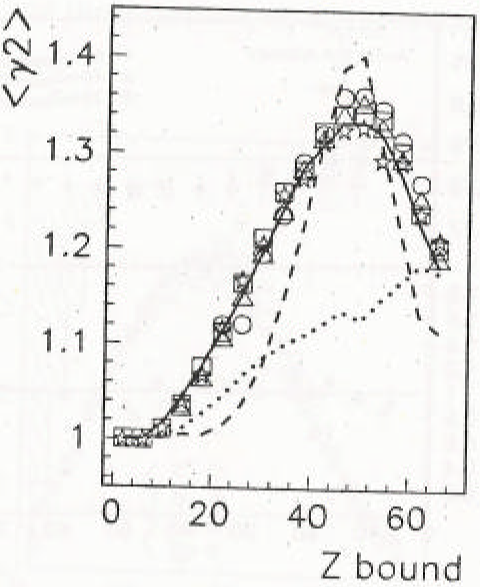

Figure 6: *The average value of γ_2 vs Z_{bound} for Au 600 MeV/u o C(circles), Al(triangles), Cu(squares) and Pb (stars). The line are COPENHAGEN (dashed), GEMINI(dotted) and percolatio (full) predictions.*

4. CALCULATIONS DESCRIPTION.

In the reactions under investigation both the measured velocity distributions of the emitted fragments and the fact that many observables are independent of the target, indicate that some degree of equilibrium is reached Therefore we have explored a set of hybrid calculations where the Boltzmann-Uehling-Uhlenbeak model (BUU) [22] was used to describe the first stage of the collision. For more details about the BUU simulations see ref. [23]. This provided an estimate of the size and the amount of energy deposited into the projectile spectator, which was then used as input to two statistical fragmentation models: the GEMINI model [6] that describes a sequential nuclear decay and the COPENHAGEN model [2-3] that assumes a simultaneous nuclear fragmentation. In order to compare with the data, we exclude all Z=1 fragments from the model predictions. All the calculations are plotted as functions of Z_{bound}. This eliminates to first order any uncertainty in the excitation energy as predicted by the BUU model.

The GEMINI code calculates the decay chain of a compound nucleus as sequential binary decays. The conditional barriers used to calculate the decay-widths for heavy nuclei are taken from the finite-range liquid drop model [24]. The 5.0 version of GEMINI was used in all calculations with its default parameters. The value of the level density parameter was $a=A/8.5$ MeV^{-1} and the decaying system was given zero angular momentum.

The COPENHAGEN model treats nuclear decay as a fast process, i.e. it evaluates the statistical phase space only once for a nucleus of given size and excitation energy. The partition function for this decay is calculated using a hot liquid-drop model. The primary distribution of fragments are allowed to decay on a slower timescale by evaporation. The version of the code is called CRACKER and includes a new treatment of the secondary evaporation [25].

Calculations have also been performed using a percolation model [26] . For our experiment, the size of the system decreases with the violence of the collision. To account for this, sites were occupied randomly within a sphere that contained 197 sites in a 9*9*9 lattice. The probability to occupy a site p_s varied between 0 and 1. For the probability that bonds exist between neighbouring site q_b a value of 0.4 was chosen in order to reproduce two average features of our data, namely the behaviour of $< M_{IMF}>$, which is shown in fig.7-a and $< Z_{max} >$ (fig.7-b) both as a function of Z_{bound}. More details on the calculations can be found in ref. [17].

5. COMPARISON TO DATA.

The observables deduced from our data were compared to the results predicted by the mentioned models. In general the GEMINI predictions are not in agreement with the data.

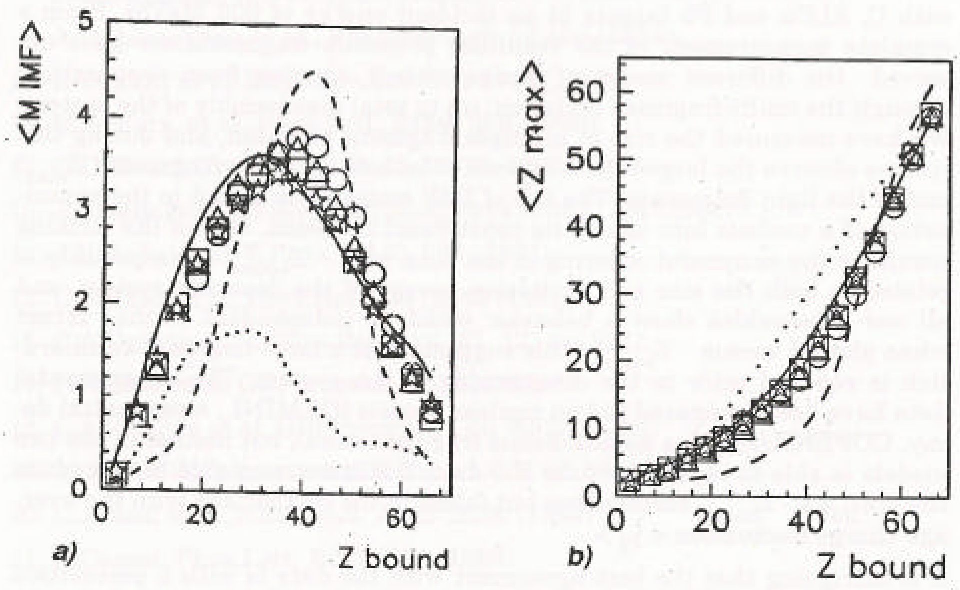

Figure 7: *a) Experimental $<M_{IMF}>$-Z_{bound} correlation compared to the COPENHAGEN(dashed), GEMINI(dotted) and percolation(full) predictions. b)Same as (a) but for <Zmax>-Zbound correlations.*

For example, as shown in fig. 7, GEMINI predicts a large value of $< Z_{max} >$ for most values of Z_{bound}, indicating that the decay sequence leaves a too large residual nucleus.The calculated values for $< \gamma_2 >$ (see fig.6) are significantly too low for most values of Z_{bound}, i.e. the emitted charges show too small a variance within each event. There is also no indication of a peak within the range of Z_{bound} in this distribution.

The COPENHAGEN model, on the other side, underpredicts the maximum charge in an event, and produces too many of the heavier IMF in the mid-peripheral collisions.Nevertless the calculations reproduce almost well the $<M_{IMF}> - Z_{bound}$ correlations. Moreover the Copenhagen model produces a peak in the $< \gamma_2 >$ distribution at the right position but slightly overpredicts the height of this peak(fig.6).The prediction falls rapidly lower than the data as Z_{bound} decreases, probably because the break-up is too symmetric.

In contrast to these two models, the percolation model has considerable success in reproducing most aspects of the charge correlations. As mentioned above,the parameters in the percolation model were adjusted to reproduce the values of $< M_{IMF} >$and $< Z_{max} >$ as a function of Z_{bound}. The predictions for the charge correlations were then compared to data, in particular the predicted values $< \gamma_2 >$ agree well with the measured data (fig.6).

6. CONCLUSION.

We have studied the fragmentation of a gold projectile after its collision with C, Al,Cu and Pb targets at an incident energy of 600 MeV/u. From a complete measurement of the resulting projectile fragments we have observed the different modes of nuclear decay, ranging from evaporation, through the multi-fragment emission, up to total disassembly of the system. We have measured the rise of multiple fragment emission, and during this rise we observe the largest fluctuations of both the heavier fragment (Z_{max}) and of the light fragments. The fall of IMF emission is linked to the vaporization of a nucleus into nearly its constituent nucleons. One of the striking results is the successful ordering of the data with Z_{bound}. This quantity is related to both the size and excitation energy of the decaying system, and all our observables show a behavior which is independent of the target when plotted versus Z_{bound}. This suggests that a large degree of equilibration is reached prior to the disassembly of the system. The experimental data have been compared to two nuclear models (GEMINI , a sequential decay, COPENHAGEN, a simultaneous fragmentation), but neither of the two models is able to reproduce fully the data.The latter was able to reproduce the $<M_{IMF}> - Z_{bound}$ correlations but failed in the comparison with the average charge fluctuation $< \gamma_2 >$.

It is intriguing that the best agreement with the data is with a percolation model, after parameter adjustment. All our measured data, especially the peak in the $< \gamma_2 >$ distribution, are consistent with the observation of a smoothed, percolation-like critical behavior at moderate values of Z_{bound}. Thermodynamically, as we span the region from evaporation to complete vaporization , one might expect to find some evidence of a nuclear liquid-gas phase transition. Up to now, it is, however, not clear what constitutes definitive evidence for such a transition.

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