# BINARY AND MULTIFRAGMENT DECAY OF VERY HOT NUCLEI

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Compound binary emission of complex fragments is illustrated for a variety reactions. Complex fragment emission from 35 and 40 MeV/N $^{139}$La + $^{12}$C, $^{27}$Al, $^{40}$Ca and $^{51}$V reactions has been studied. Multifragment events from these reactions were assigned to sources characterized by their energy and mass through the incomplete-fusion-model kinematics. Excitation functions for the various multifragment channels appear to be nearly independent of the system and bombarding energy. Preliminary comparisons of the data with sequential-statistical-decay calculations are discussed.

## 1. INTRODUCTION

Heavy ion projectiles are able to impart to nuclear systems important amounts of excitation energy distributed over a large number of nucleons. Thus, heavy ion collisions allow one to study both the formation and decay of hot nuclei[1]. At low energies, compound nucleus decay through binary complex fragment emission has been observed[2] with a cross section which, although very small, is in excellent agreement with statistical model calculations using the transition state formalism[3]. In order to approach the limits of stability of nuclei, higher beam energies must be used. This is not without complications, because the reaction mechanisms become less clear-cut, and it is no longer straightforward to characterize the intermediate hot system under study.

Recently, it has been shown that the incomplete fusion mechanism persists up to rather high energies, producing a large range of nuclei with different masses and excitation energies. For the 18 MeV/N $^{139}$La + $^{64}$Ni reaction a strong correlation was established between the degree of fusion (source velocity) and the mass and excitation energy of the product nucleus[4]. By relating the center-of-mass velocity of binary events to the mass and excitation energy of the product nucleus, it was possible

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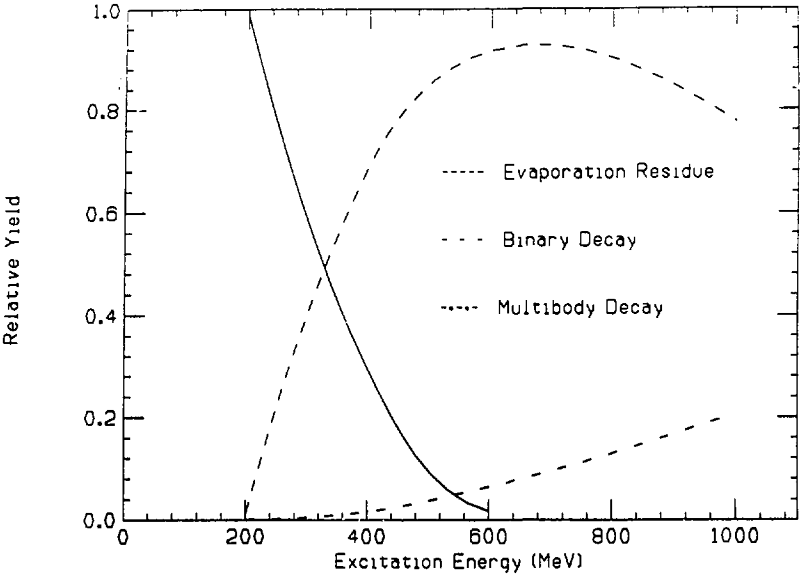

Figure 1
Relative proportions of evaporation residues, binary decays and multibody decays calculated by the code GEMINI for a nucleus of mass A ~160 as a function of excitation energy.

to study at one bombarding energy the decay properties of hot nuclei over an excitation energy range extending up to 4 MeV/N.

At even higher excitation energies, nuclei decay with a high probability by complex fragment emission. The sequential evaporation of several complex fragments gives rise to multibody final states, and contributes to the measured cross sections. Figure 1 shows the relative proportions of evaporation residues, binary decays, and multifragment events predicted by the code GEMINI[5] which treats the sequential statistical decay of a hot compound nucleus in the framework of the transition state formalism[3]. A smooth increase of the multibody probability with excitation energy is observed, but binary decays dominate up to at least 1000 MeV excitation energy. Other models also indicate that above certain excitation energies prompt multifragmentation should begin to occur. For example, in the prompt multifragment decay model of Gross et al.[6] a phase transition towards "nuclear cracking" is present at ~5 MeV/N and, above this energy multifragment decay becomes the dominant exit channel. Thus, experimental excitation functions for the various channels may provide the interpretative key to understanding the underlying decay mechanism.

In this talk we shall present evidence of binary compound nucleus decay at low energies leading to complex fragment production, and we shall show how, at higher energies, multifragment emission can be characterized in terms of excitation functions associated with binary, ternary and quaternary decay.

## 2. COMPOUND NUCLEUS DECAY AND COMPLEX FRAGMENT EMISSION

Much has been theorized about the limits of stability of very hot nuclei. The existence of a critical temperature above which the liquid and the vapor phases of the nuclear fluid lose their identity has been postulated on the basis of the standard theory of classical fluids[7]. The fact that nuclei are at best tiny drops of this fluid, and are affected very much by long range forces, like the Coulomb force, may change the picture drastically, both quantitatively (e.g. regarding the exact value of the critical temperatures) and qualitatively (e.g. regarding the existence or not of a relatively sharp second-order transition).

Furthermore, should the loss of stability turn out to be of the nature described above, it is not clear how this instability should manifest itself, especially in view of the fact that nucleonic and complex fragment emission does already occur well below the expected onset of this instability. The evidence available at present indicates that extended, highly thermalized sources are produced in most collisions. Neutron multiplicities and temperature determinations lead to the confirmation of excitation energies as high as 4-5 MeV/A. Long lived intermediate systems have been characterized in terms of their mass, charge, excitation energy and, to a more limited extent, angular momentum from their binary decay into complex fragments. In many instances it turns out that this complex fragment emission follows the statistical branching ratios expected for compound nucleus decay. This makes these intermediate systems honest-to-goodness compound nuclei, with excitation energies quite near the expected maximum[5,7]. On the other hand, the observation of compound nucleus emission of complex fragments at low energy[2,8] implies the abundant emission at higher energies[7].

Part of the initial confusion about complex fragment emission at intermediate energies may have been due to the broad range of compound and non compound nucleus sources associated with the onset and establishment of incomplete fusion. This problem can be minimized to some extent by the choice of rather asymmetric systems. In such systems, the range of impact parameters is geometrically limited by the nuclear sizes of the reaction partners. Furthermore, the projectile-like spectator, if any, is confined to very small masses, and does not obscure other sources of complex fragments. Many reactions have been studied in reverse kinematics to facilitate the detection of most of the fragments over a large center-of-mass angular range[4,5,7,9].

Representative examples of the invariant cross sections in the $v_{\parallel}$ - $v_{\perp}$ plane for a range of atomic numbers are shown in Fig. 2.[9] For this and other reactions studied so

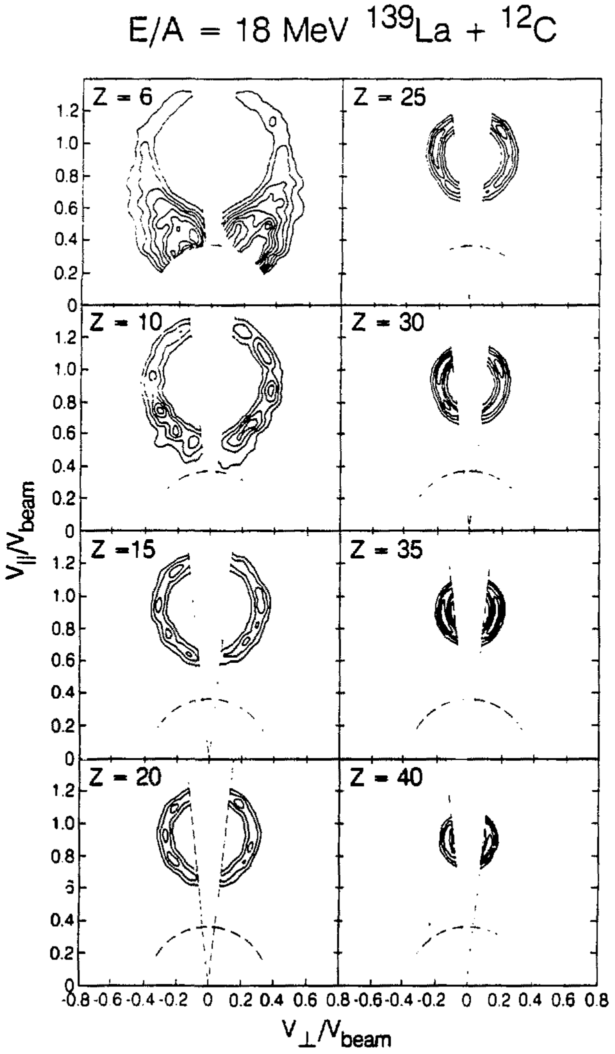

Figure 2

Contours of the experimental cross section $\partial^2\sigma/\partial V_{\|}\partial V_{\perp}$ in the $V_{\|}$ - $V_{\perp}$ plane for representative fragments detected in the reaction 18 MeV/N $^{139}$La + $^{12}$C. The beam direction is vertical towards the top of the figure. The dashed lines show the maximum and minimum angular thresholds and the low velocity threshold of the detectors. The magnitude of the contour levels indicated are relative[9].

far, one observes beautifully developed Coulomb rings whose isotropy suggests that, up to 50 MeV/u, the fragments may in fact arise from binary compound nucleus decay[7]. Only the fragments in the neighborhood of the target atomic number show the presence of an additional component at backward angles (big foot), that can be attributed to quasi-elastic and deep-inelastic processes, and/or to the spectator target-like fragment in the incomplete-fusion reactions prevailing at higher bombarding energies.

The center of each ring provides the source velocity for each Z value. For all bombarding energies, the extracted source velocities are independent of the fragments' Z value. The radii of the Coulomb rings give the emission velocities in the center of mass. The almost linear dependence of these velocities upon fragment Z value is a clear indication of their Coulomb origin. This is also supported by their independence of bombarding energy. The Coulomb calculations reproduce the data, further illustrating the degree of relaxation of the c.m. kinetic energy. The variances of the velocities arise from a variety of causes, among which the inherent Coulomb energy fluctuation due to the shape fluctuations of the "scission point", and the fragment recoil due to sequential evaporation of light particles.

All of the evidence presented so far for the intermediate energy complex fragment emission points rather convincingly towards a compound nucleus process. However, the most compelling evidence for this compound mechanism lies in the statistical competition between complex fragment emission and the major decay channels, like n, p, and $^4$He emission. The simplest and most direct quantity testing this hypothesis is the absolute cross section.

Absolute cross sections as a function of Z value are shown in Figs. 3 & 4. At first glance one can observe a qualitative difference between the charge distributions from the $^{93}$Nb-induced[5] and the $^{139}$La-induced[9] reactions. The former distributions portray a broad minimum at symmetry, whereas the latter show a broad central fission-like peak that is absent in the former distributions. This difference can be traced to the fact that the former systems are below or near the Businaro-Gallone point, while the latter systems are well above it.

In general, for a given system, the cross sections associated with the charge distributions increase in magnitude rapidly at low energies, and very slowly at high energy, in a manner consistent with compound nucleus predictions. The most important information associated with these cross sections is their absolute value and their energy dependence. Through them, the competition of complex fragment emission with the major decay channels, like n, p, and a decay is manifested. This is why we attribute a great deal of significance to the ability to fit such data. Examples of these fits are shown in Figs. 3 & 4. The calculations were performed with the evaporation code GEMINI[5] extended to incorporate complex fragment emission. Angular-momentum-dependent finite-range barriers were used. All the fragments produced were allowed to decay in turn both by light particle emission or by complex fragment emission. In this way higher chance emission, as well as sequential binary emission, was accounted for[5,9]. The cross section was integrated over $\ell$ waves up to a maximum value that provided the best fit to the experimental charge distributions. In the case of the $^{93}$Nb + $^{9}$Be & $^{12}$C, as well $^{139}$La + $^{12}$C for bombarding energies up to 18 MeV/u, the quality of the fits is exceptionally good and the fitted values of $\ell_{max}$ correspond very closely to those predicted by the Bass model or by the extra-push model[5].

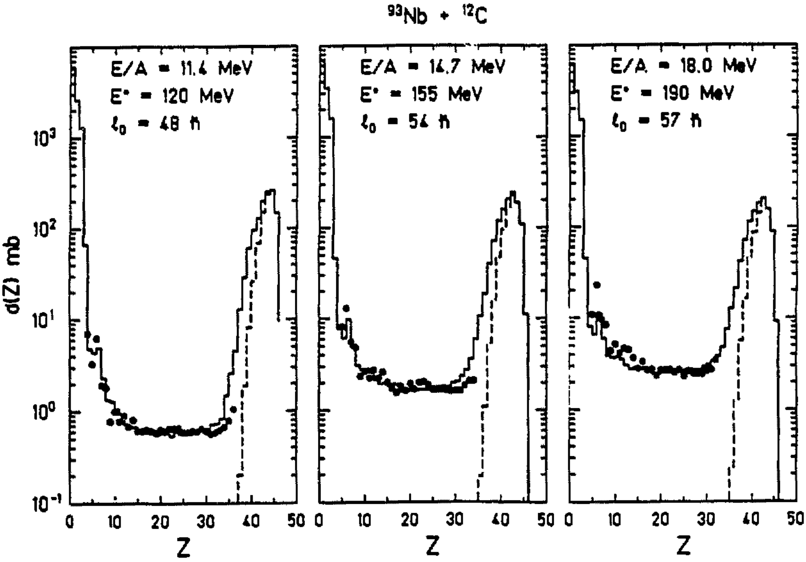

Figure 3
Angle-integrated cross sections (solid circles) plotted as a function of the fragment Z-value for the $^{93}$Nb + $^{12}$C reaction at 11.4, 14.7 and 18.0 MeV/N. The histograms represent calculations with the statistical code GEMINI[9]. The dashed curves indicate the cross sections of light particles ($Z \leq 2$). Note the value of the excitation energy ($E^*$) corresponding to complete fusion and the value of $J_{max}$ assumed to fit the data[5].

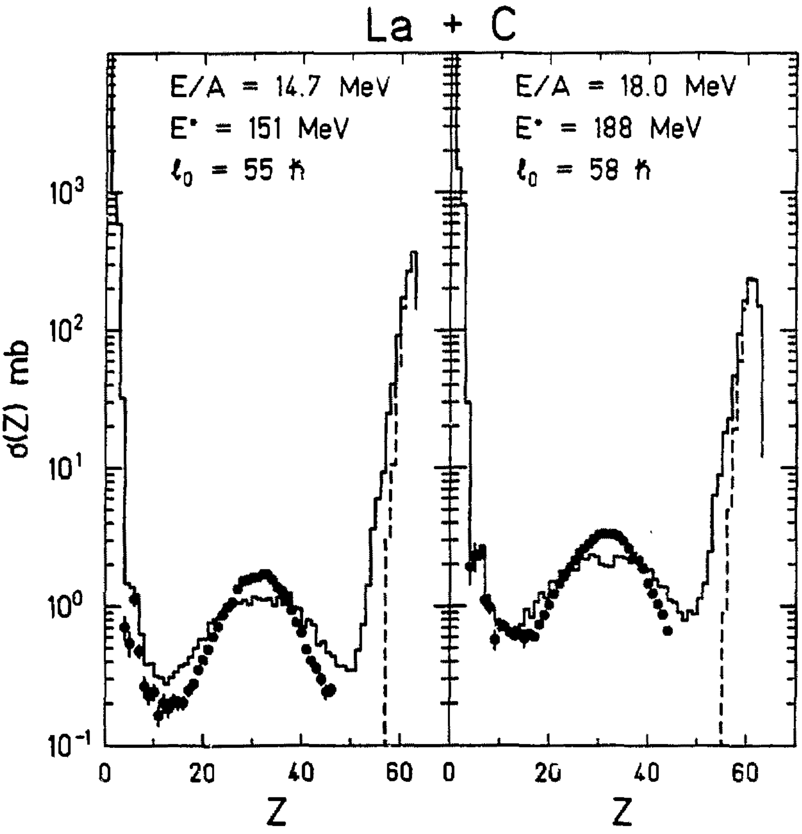

Figure 4
Same as Figure 3 for the 14 & 18 MeV/N $^{139}$La + $^{12}$C reactions.

## 3. MULTIFRAGMENT DECAY

$^{139}$La beams from the Lawrence Berkeley Laboratory Bevalac were used to study reactions on $^{12}$C, $^{27}$Al, $^{40}$Ca, and $^{51}$V targets at an incident energy of 35 MeV/N, and on $^{40}$Ca and $^{51}$V at 40 MeV/N. The beam energies were chosen in order to produce systems with high excitation energies while remaining in a domain where the incomplete fusion model should retain its validity.

### 3.1. Summed Charge Distributions

Figure 5 (a-d) presents the distributions of the sum of the measured charges for 2-fold events at $E_{lab}$ = 35 MeV/N. (An n-fold event is defined as an event where n fragments of charge $Z>4$ were detected.) For the $^{12}$C target a narrow peak is observed. This peak broadens for heavier targets, reflecting the wider range of excitation energies resulting from the larger range of mass transfers, which gives rise to increasing amounts of light particle evaporation. With increasing target mass, the tailing to low Z values increases. This tail is due to 3- or 4-body events where only two bodies were detected, and shows the increasing importance of multibody reactions for the heavier targets. The same distributions for 3- and 4-fold events (Figs. 6b,c for $^{139}$La + $^{40}$Ca) exhibit a peak at approximately the same total charge as the 2-fold events, but with a reduced low Z continuum, showing that most of these multi-fold events are essentially complete.

### 3.2. Source Velocities

The following analysis is restricted to events whose total measured charge is at least 30, in order to insure a reasonable representation of the kinematical skeleton of the reaction. If the fragments originate from the decay of a single source, then its velocity is determined by $V_s = \{\Sigma_i m_i V_i\}/\Sigma_i m_i$. In the incomplete fusion picture[1], the excitation energy $E^*$ is approximately related to the parallel source velocity $V_s$ by $E^* = E^b(1-V_s/V_b)$,where $E_b$ is the bombarding energy and $V_b$ the beam velocity. Although this formula does not take into account preequilibrium emission, it remains correct if the preequilibrium particles retain on average the target or projectile velocity. Also, the recoil of the target-like remnant due to the shearing-off of the fusing part is neglected, but calculations[10] show that, by including recoil effects, the excitation energies change by less than 20 MeV, which is much less than the experimental uncertainty.

Source velocity distributions for the $^{12}$C, $^{27}$Al, $^{40}$Ca, and $^{51}$V targets are presented in Fig.5 (e-h) for the 35 MeV/N bombarding energy. The peak of the distribution shifts downwards with increasing target mass showing that, on average, more mass is picked up from the heavier targets. The peak also broadens considerably when going from the $^{12}$C to $^{51}$V target. Part of this width is due to the actual range of source velocities, arising presumably from different impact parameters, and part to the perturbation introduced by light particle evaporation prior and subsequent to heavy fragment emission. This "noise" has been estimated with the statistical decay code

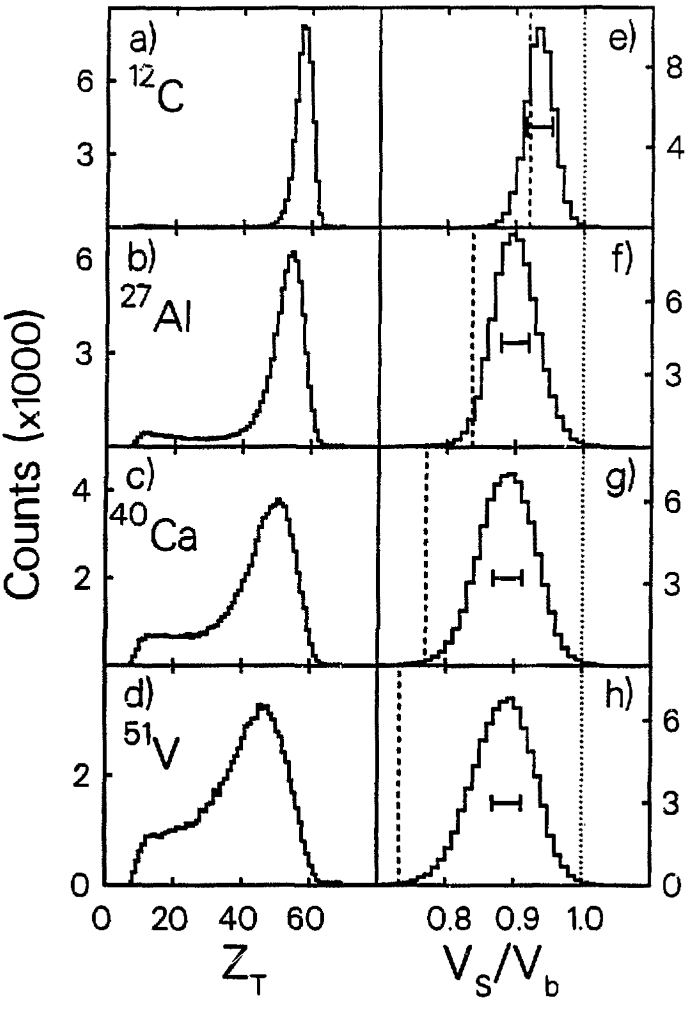

Figure 5

a-d) Distributions of the sum of the measured charges for 2-fold events for the 35 MeV/N $^{139}$La + $^{12}$C, $^{27}$Al, $^{40}$Ca and $^{51}$V reactions. e-h) Distributions of source velocities expressed as the ratio of the source to beam velocity for the same reactions. The dotted line indicates the beam velocity, and the dashed lines the source velocities expected for complete fusion. The horizontal bars indicate the expected broadening of the source velocity distribution due to light particle evaporation for the mean excitation energy.

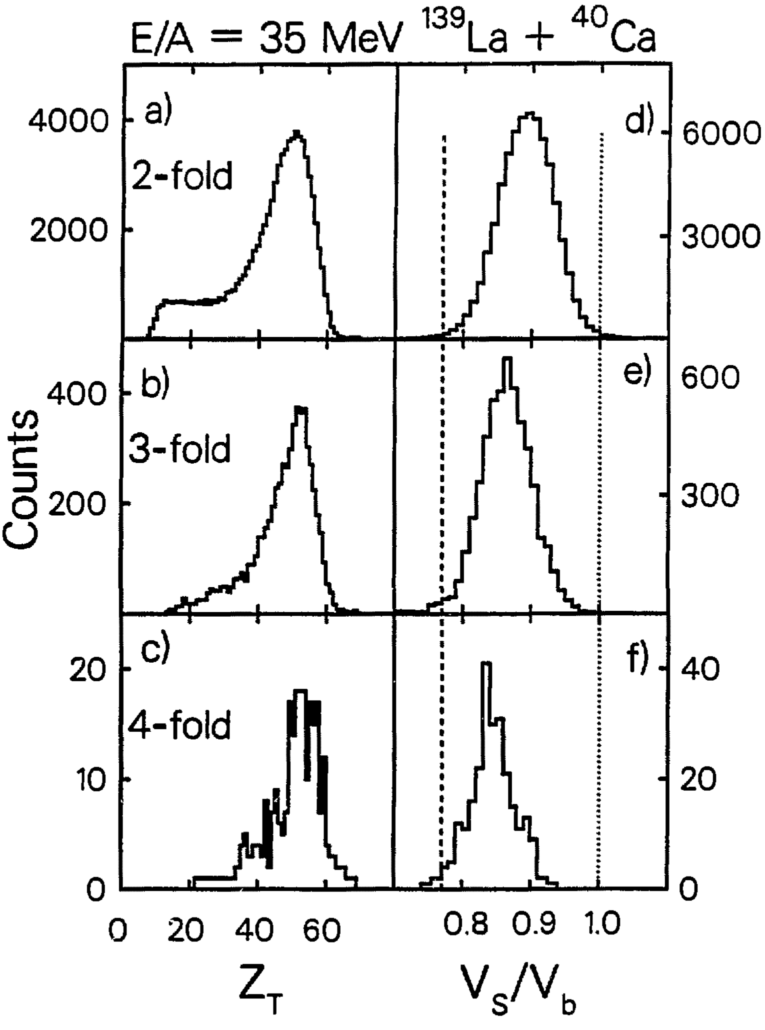

Figure 6

Same as Fig. 5 for 2-, 3- and 4-fold events from the $^{139}$La + $^{40}$Ca reaction at $E_{lab}$ = 35 MeV/N.

GEMINI[5], filtered by the appropriate detector geometry, and is represented by the horizontal bars on Fig.5 (e-h). In the case of $^{12}C$ the width can be explained almost entirely by light particle evaporation, showing that, due to the interplay between the incomplete fusion mechanism and the complex fragment decay probability, a very limited range of excitation energies contributes to complex fragment emission. However, this is no longer the case for the heavier targets, where a large range of excitation energies is indeed observed.

When the events are separated according to the fragment multiplicity (see Fig.6 (d-f)), the requirement of a larger multiplicity of complex fragments selects out events with lower source velocities, i.e. higher excitation energies. For the $^{40}Ca$ target at $E_{lab}$ = 35 MeV/N, the estimated most probable excitation energies are 530, 660, and 750 MeV for 2-, 3-, and 4-fold events, respectively. The same trend is observed for all targets. A similar result was recently observed in the $^{20}Ne$+ $^{197}Au$ reaction at 60 MeV/N, but only for 2- and 3- body final states[11]. To check that this result is not due to some experimental artifact, we have generated with the statistical code GEMINI a set of binary and multibody events resulting from the decay of a nucleus at a given excitation energy. Assuming a fixed source velocity, the results were filtered by the detector acceptance, then the source velocity was reconstructed using the same analysis code as for the experimental data. In this simulation the mean source velocities were the same for different multiplicities, indicating that the experimental detection efficiency is not skewing the multibody results significantly.

### 3.3. Excitation Functions

To investigate the behavior of nuclei as their excitation energy increases, excitation functions for the multi-fold events have been constructed. The excitation energies were inferred from the source velocities. The cross section for multibody events at a given excitation energy depends on the probability of producing nuclei with this excitation energy via the incomplete fusion process. In order to remove this dependence, we have plotted the proportion of n-fold events with respect to the total number of coincidence events: P(n) = N(n)/(N(2)+N(3)+N(4)+ ....),where N(n) is the number of n-fold events. Evaporation residues (1-body events) were not considered since in reverse kinematics they are confined to a very small angle around the beam direction where our detection efficiency is small. These excitation functions (Fig.7) have not been corrected for the detection efficiency. Such a correction requires knowledge of the precise kinematical nature of the events, such as mass distributions and relative velocities of the fragments, and will not be attempted here. Nevertheless, several remarkable features can be noted.

First, the probabilities for 3- and 4-fold events increase substantially with the excitation energy of the source up to the highest energies observed (~1000 MeV or 6 MeV/N). Such behavior would be expected from any statistical model and is an *a posteriori* verification of the relation between source velocity and excitation energy

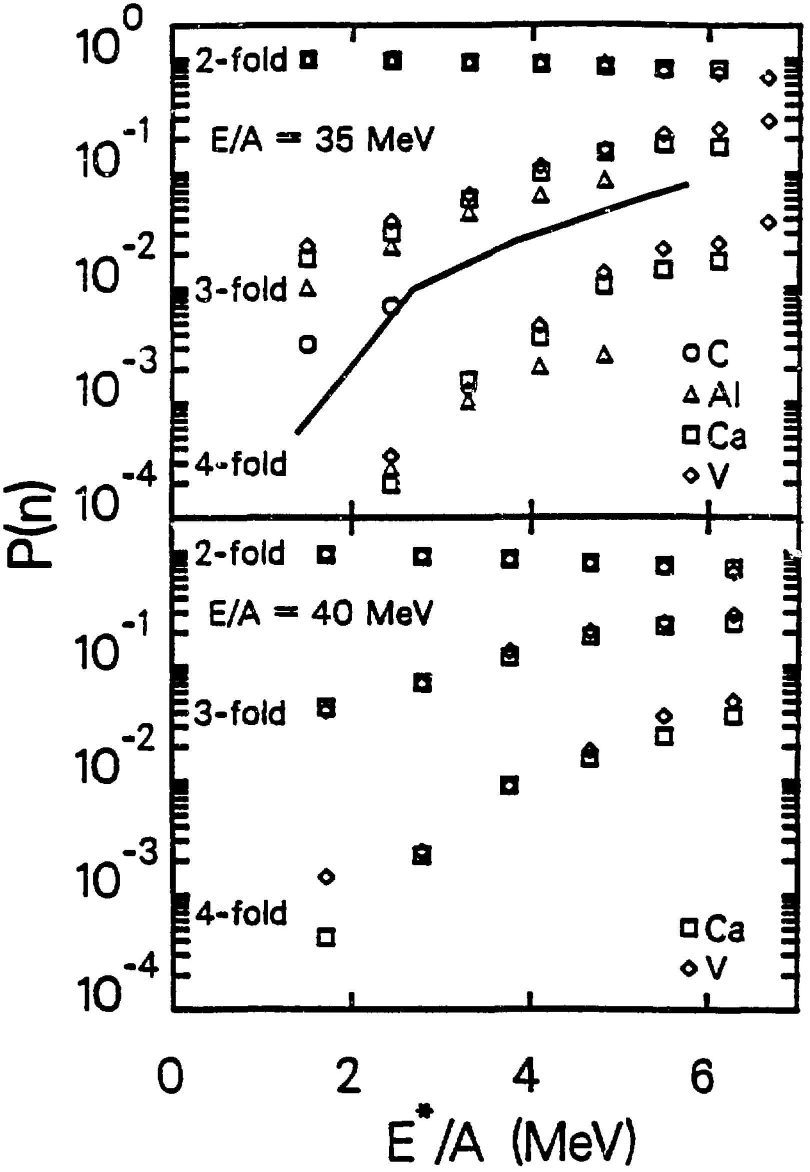

Figure 7

Proportion of 2-, 3-, and 4-fold events as a function of excitation energy per nucleon for the targets studied at $E_{lab}$ = 35 MeV/N (top) and 40 MeV/N (bottom). The estimated masses of the hot nuclei vary from 145 at 2 MeV/N to 175 at 6 MeV/N. The solid line is the result of a statistical calculation with the code GEMINI for 3-fold events (see text).

over the entire source velocity range studied. This energy dependence also confirms that the width of the velocity distribution originates mostly in the incomplete fusion process, and is only partly due to sequential light particle decay.

Second, the relative proportions of multi-fold events for the three heaviest targets and the two bombarding energies are very similar, suggesting that the sources produced in these reactions depend mainly on how much mass is picked up by the projectile from the target, and relatively little on the actual nature of the target. This is precisely what constitutes the essence of the incomplete fusion model! A closer look at Fig.7 shows a slight decrease of the multi-fold probability for lighter targets, as well as for the lower bombarding energy for a given target. One possible contribution to these minor discrepancies is the effective broadening of the excitation energy bins due to light particle evaporation, which is particularly severe in the case of the lightest targets for which evaporation is a major contribution to the width of the source velocity distribution (Fig 5). In particular this could explain why the multi-fold probabilities for the $^{27}$Al target at the highest excitation energies, which are in the tail of the source velocity distribution, fall significantly below those measured for $^{40}$Ca and $^{51}$V. Moreover, the transition state model of statistical decay[3] predicts a strong decrease of the complex fragment decay probability with decreasing angular momentum[12]. Thus, an additional source of the differences could be that the hot nuclei are formed in the various reactions with slightly different angular momenta.

Finally, the proportion of multi-fold events increases smoothly with excitation energy up to approximately 6 MeV/N. The statistical multifragmentation calculations of Bondorf et al.[13] predict a sudden rise in the multibody probability at ~3 MeV/N for a nucleus of mass 100. Gross et al. [6] predict a similar transition towards nuclear cracking at an excitation energy of ~5 MeV/N for a $^{131}$Xe nucleus. Experimentally we see no evidence for such phase transitions, and the data suggest that the decay of the hot nuclei under study (A~160) is governed by the same mechanism up to an excitation energy approaching the total binding energy of these nuclei.

In order to investigate if this mechanism could be the sequential statistical decay of an equilibrated compound nucleus, calculations were performed using the code GEMINI. Several excitations energies between 200 and 1000 MeV were studied. The initial mass and angular momentum of the compound nucleus corresponding to each excitation energy was calculated with the incomplete fusion model of Moretto and Bowman[10]. Between the two extreme excitation energies considered, the masses range from 145 to 175 and the angular momenta from 40 to 100 ħ. For each event, the code outputs the charge, mass and velocity vector of each fragment. Assuming the source velocity given by the incomplete fusion calculation, the results were filtered by the detector acceptance, taking into account the beam spot size, and the angular divergence of the beam.

The results for 3-fold events is shown as a solid line in the top part of Fig. 7. The trend of the data is nicely reproduced, but the absolute proportion of 3-fold events is underestimated by about a factor of 2. Moreover the proportion of 4-fold events predicted by the calculation is almost a factor of 10 too low. As discussed before, this could be due to an imprecise estimate of the angular momentum in the incomplete fusion model. Another possibility would be the pre-equilibrium emission of at least one of the fragments. Such pre-equilibrium emission of intermediate mass fragments has already been observed[14], and a hint for such a behavior in the present data is given by the inclusive angular distributions of the light fragments which are strongly backward peaked in the source frame.

## 4. CONCLUSIONS

In this talk we have presented evidence for binary compound emission of complex fragments at moderate excitation energies. Furthermore, the source velocity technique[4] was extended to multibody events and employed in conjunction with the incomplete fusion model to estimate the excitation energy on an event-by-event basis. This, in turn, has allowed us to present for the first time excitation functions for multifragment events. These excitation functions are largely independent of target-projectile combination and of bombarding energy, lending support to the incomplete fusion picture and to the idea of an intermediate system whose decay properties depend only on its excitation energy and angular momentum. Up to an excitation energy of 1000 MeV (~6 MeV/N), no evidence for a phase transition towards nuclear cracking was found.

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