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Compound Nuclei, Binary Decay, and Multifragmentation in Intermediate-Energy Heavy-Ion Reactions

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COMPOUND NUCLEI, BINARY DECAY, AND MULTIFRAGMENTATION IN INTERMEDIATE-ENERGY HEAVY-ION REACTIONS

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Abstract: Hot compound nuclei, frequently produced in intermediate-energy reactions through a variety of processes, are shown to be an important and at times dominant source of complex fragments.

1. INTRODUCTION

The classification of reaction mechanisms at low energies is rather simple. At one extreme we have direct reactions, involving a narrow subset of nuclear modes, typically single particle degrees of freedom. In between we have quasi-elastic and deep-inelastic reactions involving a much larger number of modes, both single particle and collective, and associated with a much more profound degree of relaxation. At the other extreme we have compound-nucleus (CN) processes, in which there is full relaxation of all the modes, and which are characterized by a complete decoupling between entrance and exit channels.

At intermediate energies this simple picture seems to disappear, and the new complexity creates irresistible images of new and exotic processes. For example, the variety and abundance of complex fragments produced in these reactions suggested mechanisms like the shattering of glass-like nuclei,[1] or the condensation of droplets out of a saturated nuclear vapor,[2] or the somewhat equivalent picture of a nuclear soup curding simultaneously into many fragments.[3,4] The word "multifragmentation" became very popular despite the perplexing lack of evidence for truly multi-fragment exit channels.

But complexity is not synonymous with novelty and it would be prudent to verify that the complexity of the reactions under study is not due to the proliferation and overlapping of conventional processes made possible by the large available energy. More than ever, it is necessary to assess the "background" of conventional processes before a new theory is declared proven or a new mechanism prematurely discovered. In particular, one would be well advised to check how large is the CN contribution to the production of complex fragments. Specifically, it is important to assess the role of compound nuclei in the production of complex fragments even when more than two of them are present in the exit channel.

From a technical point of view due to the complex and confusing experimental environment characteristic of intermediate energies, it is profitable and often necessary to choose the reactions judiciously. A little ingenuity in such a choice may emphasize the process one intends to study and minimize the disturbing noise arising from "irrelevant" features of the reactions. For instance efforts to limit the number of sources of complex fragments or to make their identification easier has been quite beneficial to us.

2. COMPOUND NUCLEI AT INTERMEDIATE ENERGIES

The degree of energy relaxation that can be achieved in nuclear reactions is extraordinary indeed! Even the rather commonplace CN produced by bombarding a medium mass nucleus with 80 - 100 MeV alpha particles is in a way already surprising, but the amount of energy deposited into internal degrees of freedom by heavy-ion reactions is, at times staggering. In the symmetric reaction ^{100}Mo + ^{100}Mo at 23.4 MeV/u as much as 800 MeV or ~4 MeV/nucleon is deposited as excitation energy.[5,6] The use of neutron multiplicity detectors has allowed one to determine with a fair degree of accuracy the extent of energy thermalization.[7] The conclusion, from this and similar charged particle measurements is that, at intermediate energies, the energy relaxation is pervasive and profound. This, by itself does not mean that a CN has been formed, since energy relaxation is only a necessary but not a sufficient condition for its formation.

In the same way, the presence of evaporation-like particle spectra or a fission-like binary decay are not by themselves sufficient critieria. The presence of a CN can be tested by verifying the statistical competition of all the decay channels, or at least the statistical competition of a rather improbable channel (like the emission of a moderate mass complex fragment or the emission of an energetic gamma ray or pion) against a dominant channel like neutron or proton emission. Because of these considerations, the determination of absolute cross sections or, even better, of excitation functions is essential.

How can CN be formed at intermediate energies?

At low energies we are used to preparing CN by means of fusion reactions; after all, it is not an accident that CN are called compound. However, what Bohr had in mind when he introduced this new concept was not the particular way in which the CN was formed, as through fusion. To the contrary he stressed that, due to the complete equilibration of the system, all the dynamical information associated with the entrance channel was forgotten, and that the decay could only depend upon the statistical features of the available exit channels. In order to prove that it does not matter how the CN is formed, the early and not so early literature is rich with examples of different "fusion" channels leading to the same CN - which does indeed decay always in the same way. So, the essence of the compound nucleus is **not** in the fusion of target and projectile but in the **decoupling** of the Entrance and Exit Channels.

Having accepted this, we realize that CN may be more common than previously thought. For instance:

1) The residue product after a CN evaporates a particle is still a CN.
2) The two fragments produced in fission relax and eventually evaporate neutrons as CN.
3) Quasi-elastic and deep-inelastic heavy ion reactions produce fragments which also relax into CN and decay as such.
4) In the process of incomplete fusion both the incomplete fusion product and the spectator do eventually relax into CN.
5) In the fireball production mechanism, the two spectator fragments are expected to relax into CN, and even the fireball may not be far from a CN, either.

3. COMPLEX FRAGMENT PRODUCTION

With the advent of intermediate energy heavy-ion beams, complex fragments have become a very pervasive presence. Where could they possibly come from? Not from CN, since conventional wisdom held that CN decay solely by n, p, and alpha-particle emission or by fission. As a consequence, complex fragments could only come from some other novel mechanism, like liquid-vapor equilibrium, multifragmentation, etc.[8] However, at low energy it has been shown that CN can emit complex fragments.[9] In fact, it is possible to consider light fragment emission and fission as the two extremes of a single mode of decay, connected by the mass asymmetry degree of freedom.[10] *This process allows for complex fragment emission and the rarity of its occurence is due to the important but accidental fact of the high barriers associated with such emissions.*

Let us consider the potential-energy surface of a nucleus as a function of a suitable set of deformation coordinates. This surface is characterized by the ground state minimum and by the fission saddle point. We can cut this surface with a line passing through the fission saddle point along the mass-asymmetry coordinate in such a way that each of its points is a saddle point if one freezes the mass-asymmetry coordinate. The locus of all these conditional saddle points we call the "ridge line".[10] Fig.1 shows two examples of this line (solid curves), one for a light system below the Businaro-Gallone point and the other for a heavier system above the Businaro-Gallone point. The same figure shows the expected

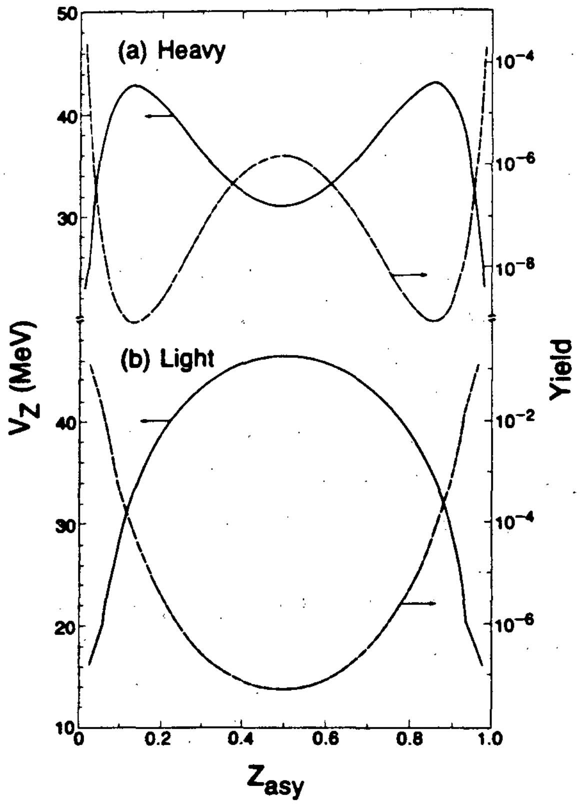

FIGURE 1
Schematic ridge line potentials (solid curve) and calculated yields (dashed curve) for: a) a heavy CN above the Businaro-Gallone point; and b) a light CN below the Businaro-Gallone point as a function of the mass-asymmetry coordinate (Z_{asy}).

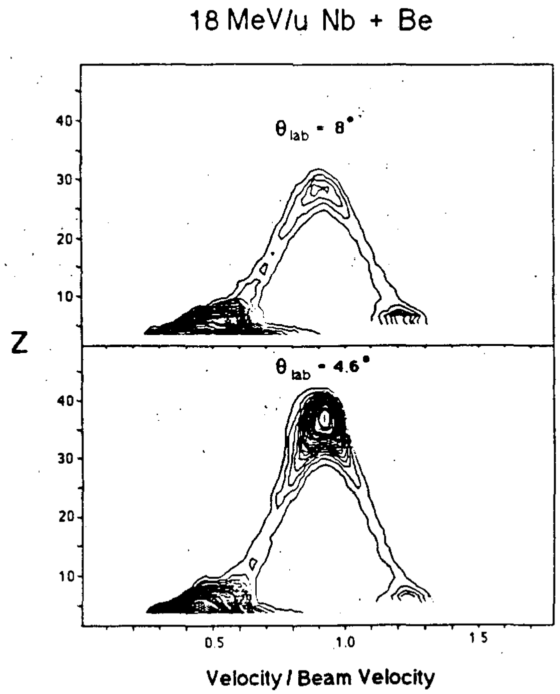

FIGURE 2
Contours of the invariant cross section in the Z - velocity plane for complex fragments emitted from the 18 MeV/u ^{93}Nb + ^{9}Be reaction at θ_{lab} = 4.6° and 8°. The "big foot" visible at low velocities for Z < 10 is attributed to quasi-elastic and deep-inelastic products.

particle yield (dashed curves) following the statistical prediction: $Y(Z) \propto \exp[-V(Z)/T]$. One can make three observations:

1) Systems below the Businaro-Gallone point give rise to a U-shaped mass or charge distribution with a minimum at symmetry.
2) Systems above the Businaro-Gallone point give rise to a similar distribution but with a maximum (fission peak) growing in at symmetry.
3) The yield increases with temperature and increases fastest for the highest barriers.

Consequently complex fragments, although very rare at low energy, become rapidly abundant at high energies. The existence of this CN mechanism at low energies has been proven in detail.[9] Could the fragments observed at higher bombarding energies arise from the same mechanism?

In experiments up to 100 MeV/u,[11] we have been able to identify three kinds of sources of complex fragments, which turn out to be rather conventional. The three sources are:

1) Quasi-elastic/deep-inelastic scattering.
2) Spectators in incomplete-fusion processes.
3) Hot compound nuclei.

The first two sources produce fragments which are target and/or projectile related. The third is just the high energy version of the low energy CN decay.

How can these three sources be distinguished? We have found that reverse kinematics and very asymmetric target-projectile combinations are particularly useful for a series of reasons. The principal reasons are: 1) the quasi-elastic/deep-inelastic processes are confined to both low and high Z-values, whereas the incomplete-fusion spectators are confined to low Z-values leaving uncontaminated the intermediate Z-range for CN products; 2) The associated limited range of impact parameters leads to a corresponding narrow range of momentum transfers and consequently to a small range of source velocities; 3) Reverse kinematics brings all the fragments into a relatively narrow forward cone and boosts their energy, thus greatly simplifying their detection and identification.

The evidence of the CN origin of these fragments can be seen in Fig. 2, where the cross section in the Z - velocity plane is shown for the reaction 18 MeV/u ^{93}Nb + ^{9}Be at two different angles. The two legs of the lambda pattern represent the upper and lower solutions in reverse kinematics associated with the binary decay of the source, and correspond to the Coulomb circles visible in the $v_{\parallel}$ - $v_{\perp}$ plane for each Z value in Fig. 3 for the 18 MeV/u ^{139}La + ^{12}C reaction. The telltale signature of a binary decay is not only the

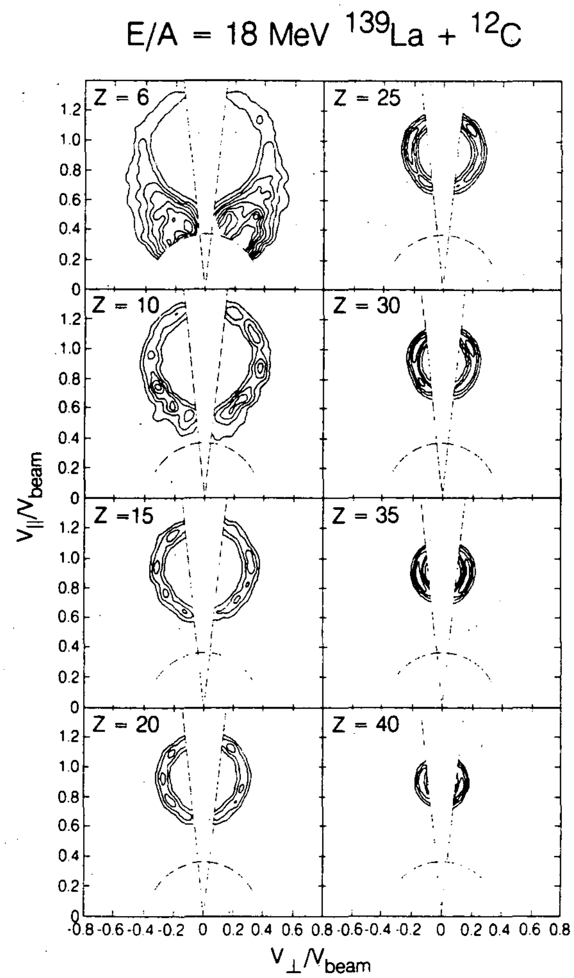

FIGURE 3
Contours of the experimental cross section $\partial^2\sigma/\partial V_{\parallel}\partial V_{\perp}$ in the $V_{\parallel} - V_{\perp}$ plane for representative fragment Z-values detected in the reaction 18.0 MeV/u ^{139}La + ^{12}C. The beam direction is vertical. The dashed lines show the maximum and minimum angular thresholds and the low velocity threshold of the detectors. The magnitudes of the contour levels indicated are relative.

presence of a sharp Coulomb circle, but the fact that its radius decreases with increasing Z value as required by momentum conservation. The large cross sections observed at low Z values and attached to the low velocity branch (see Fig. 2) are associated with quasi-elastic and deep-inelastic products. The choice of very asymmetric target-projectile combinations shows here its wisdom. The more symmetric the target-projectile combination is, the more extensive the obscuration of the CN component by quasi-elastic & deep-inelastic fragments is expected to be.

The centers of the circles give the source velocities which are remarkably independent of the fragment Z value[8,11] and correspond to either complete or incomplete fusion of the light target with the heavy projectile. The nearly linear dependence of the radii of the circles on the fragment Z-value demonstrates their Coulomb origin.[8,11]

The cross sections and their dependence upon energy and fragment Z-value are of particular importance to demonstrate their CN origin. When a CN is about to decay, it is offered many channels which will be chosen proportionally to their associated phase space.

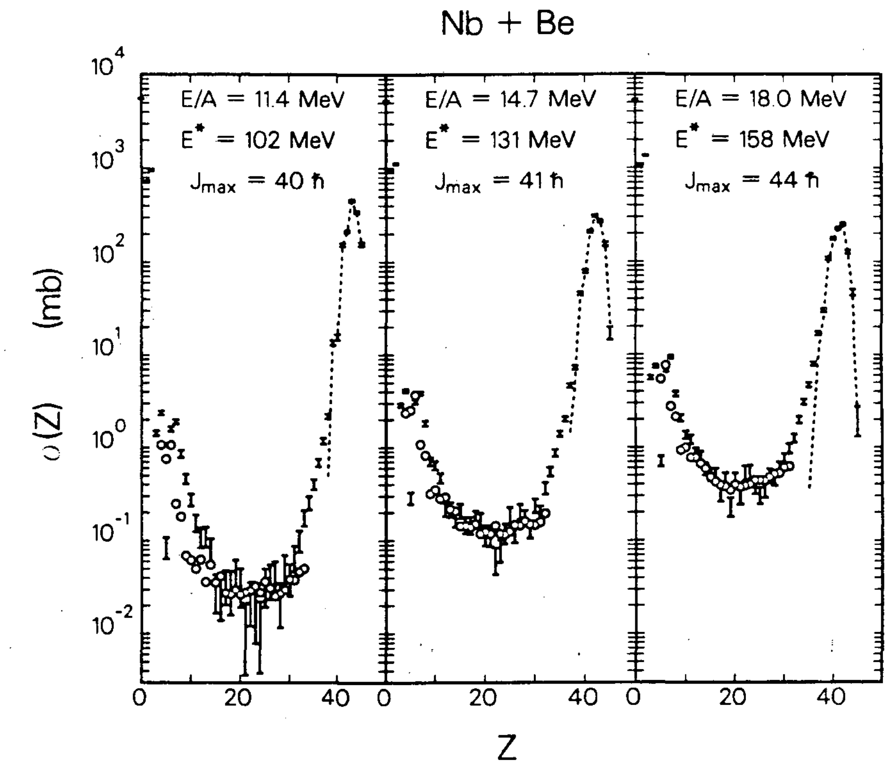

FIGURE 4a
Comparison of experimental and calculated charge distributions for the ^{93}Nb + ^{9}Be reaction at E/A = 11.4, 14.7, and 18.0. The experimental data are indicated by the hollow circles and the values calculated with the code GEMINI are shown by the error bars. The dashed curve indicates the cross sections associated with classical evaporation residues which decay only by the emission 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.

In particular, neutron, proton, and alpha-particle decay, because of their small associated barriers, are the dominant decay channels with which complex fragments must compete. Thus, the cross section associated with the emission of any given fragment reflects this competition. In Figs. 4a & 4b examples of the absolute charge distributions are given, together with calculations performed with the CN decay code (GEMINI)[11] which follows the decay of the CN through all the channels including complex fragment emission. The code accurately reproduces the shape, magnitude, charge and energy dependence of the absolute cross sections, thus confirming CN decay as the dominant mechanism in this energy range.

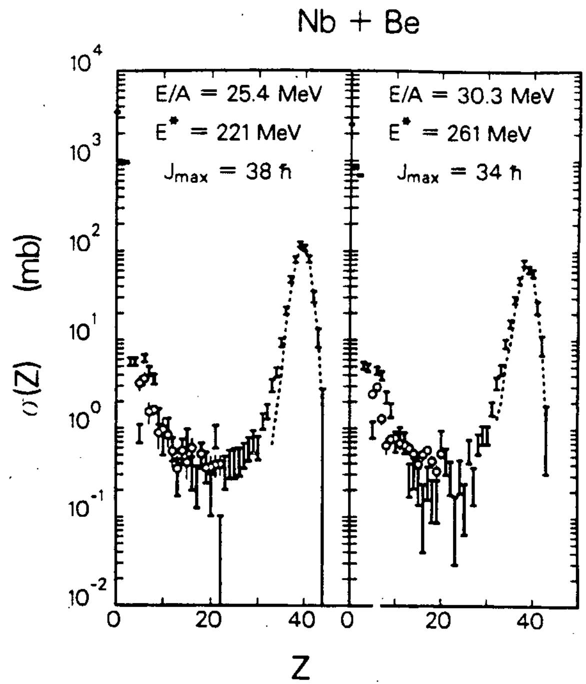

FIGURE 4b
Same as Fig. 4a except for E/A = 25.4 and 30.3 MeV.

Coincidence data confirm the binary nature of the decay. The Z_1 - Z_2 scatter plots (see Fig. 5) show the diagonal band characteristic of binary decay. The hatched area is the predicted locus of events after correcting for sequential evaporation from the primary fragments. The spectrum associated with the sum $Z_1 + Z_2$ shows a rather sharp peak very near the value of Z_{total} indicating that there is only a small charge loss and that most of the total charge available in the entrance channel is found in the two exit-channel partners.

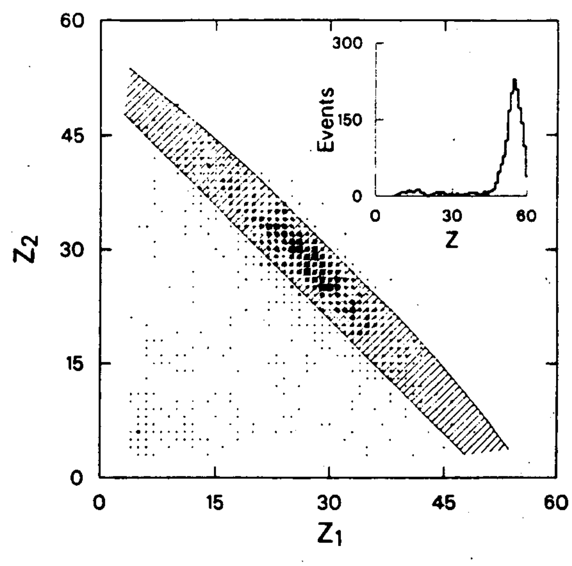

FIGURE 5
Scatter plots of the coincidence events, Z_1 - Z_2, detected in two telescopes on opposite sides of the beam, for the $^{139}La + ^{12}C$ reaction at 50 A MeV. The hatched area is the predicted locus of events after correcting for sequential evaporation from the primary fragments. The distribution of the sum of the charges ($Z_1 + Z_2$) is shown in the inset.

In more recent experiments[12], we have been able to follow the evolution of complex fragment emission up to 100 MeV/u in the reactions $^{139}La + ^{12}C, ^{27}Al$. The Z_1 - Z_2

correlation diagrams for the two targets at 18, 50, 80 & 100 MeV/u are shown in Figs. 6 and 7, respectively, while the corresponding sum ($Z_1 + Z_2$) spectra are shown in Fig. 8 & 9,

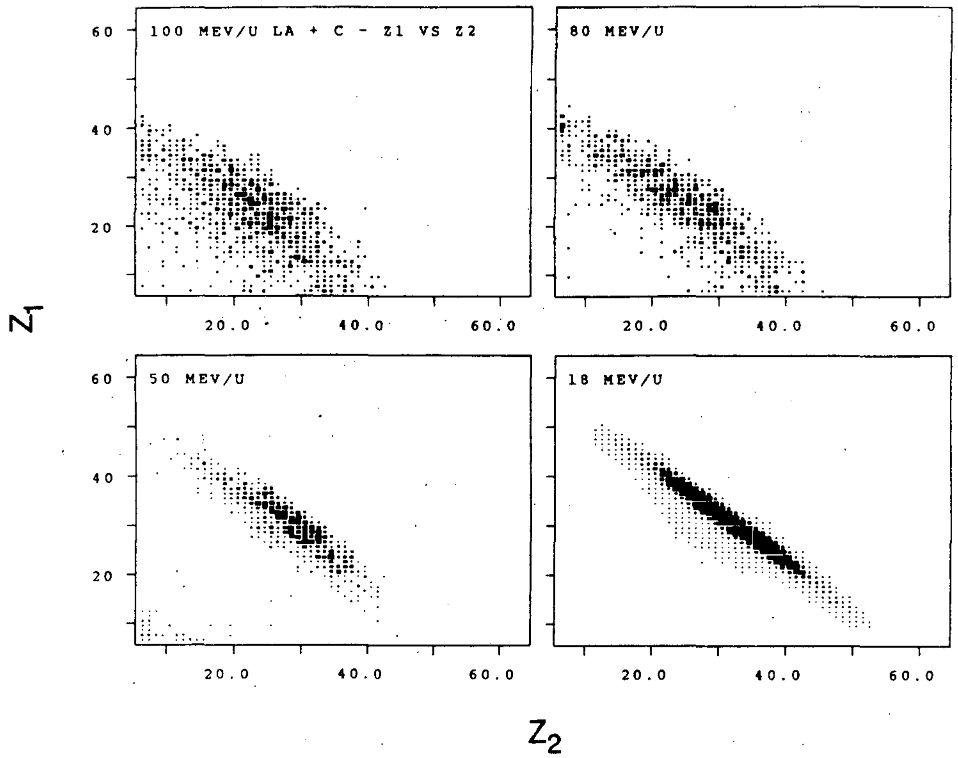

FIGURE 6
Z_1 - Z_2 correlation diagrams for the reaction ^{139}La + ^{12}C from 18 to 100 MeV/u.

respectively. In the case of the ^{139}La + ^{12}C system, the correlation diagrams show the characteristic band of approximately constant $Z_1 + Z_2$ up to 100 MeV/u. This band is very narrow at 18 MeV/u and becomes progressively broader with increasing bombarding energy, but remains still quite distinct even at 100 MeV/u. The corresponding sum spectra (Fig. 8) show a peak that is progressively shifted downward from charge values near that of complete fusion and is correspondingly broadened. Presumably the downshift and the associated broadening arise from both incomplete fusion and sequential evaporation of neutrons and light charged particles. The arrows and excitation energies in parentheses were determined from the Viola systematics.[13]

In the case of the ^{139}La + ^{27}Al system, the correlation diagrams show a distinct binary band up to 50 MeV/u. At 80 and 100 MeV/u, one observes a progressive filling in of the low Z_1, Z_2 area, indicating that the binary correlation is being progressively spoiled. The corresponding sum spectra show a reasonably sharp peak up to 50 MeV/u, which broadens

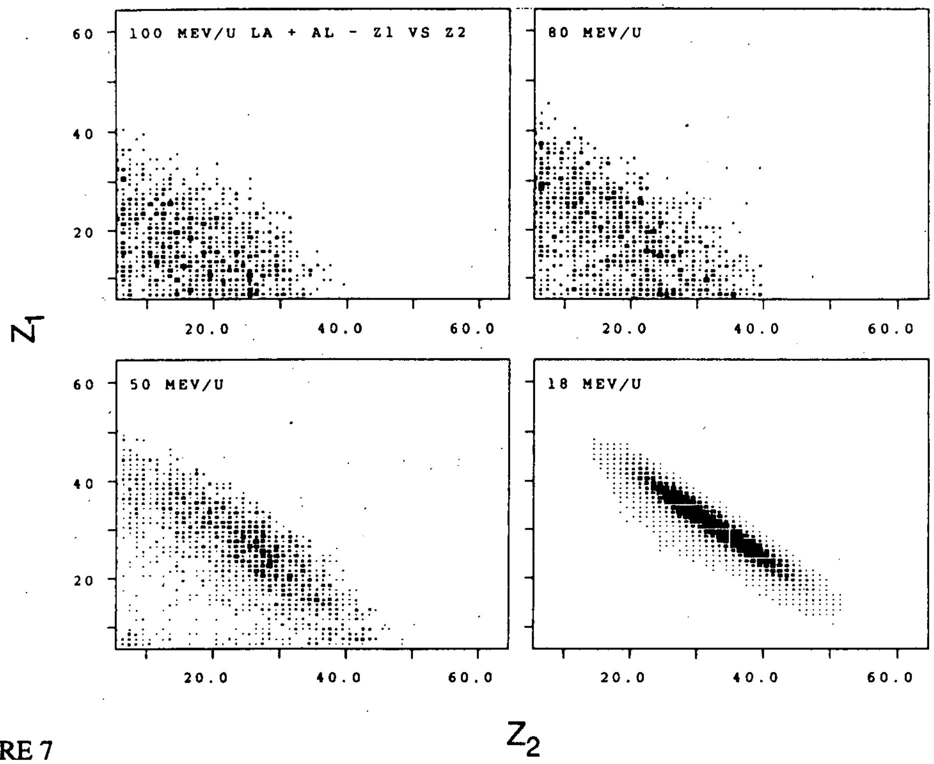

FIGURE 7
Same as in Fig. 6 for the reaction $^{139}La + ^{27}Al$.

and extends towards the low charge region at the highest energies.

The general impression is that a progressively larger amount of excitation energy is brought into the systems with increasing bombarding energy, and that at the same bombarding energy, the energy deposited is larger for the heavier target. At the lower energies, binary decay dominates and is progressively substituted by multifragment decay at the higher energies.

The evidence presented above is but a small sample of the evidence available for CN emission of complex fragments at bombarding energies up to 100 MeV/u.[8,11,12] We have seen that binary decay dominates the picture at the lower energies, while multifragment decay seems to set in at higher energies. Does that mean, automatically, that the role of the CN is over? Most likely not!

4. MULTIFRAGMENTATION AND NUCLEAR COMMINUTION

Most of the evidence presented so far illustrates the emission of complex fragments through binary CN decay. If there is enough excitation energy available, the primary binary-decay products are also very excited and have a significant probability of decaying

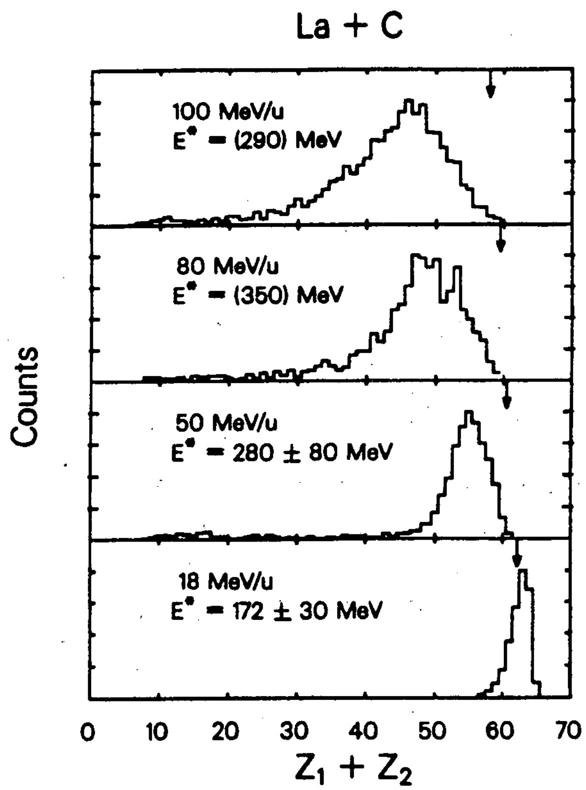

FIGURE 8
$Z_1 + Z_2$ spectra corresponding to the correlation diagrams in Fig. 6. The Z values indicated by the arrows and the excitation energies are obtained from the Viola systematics.[13]

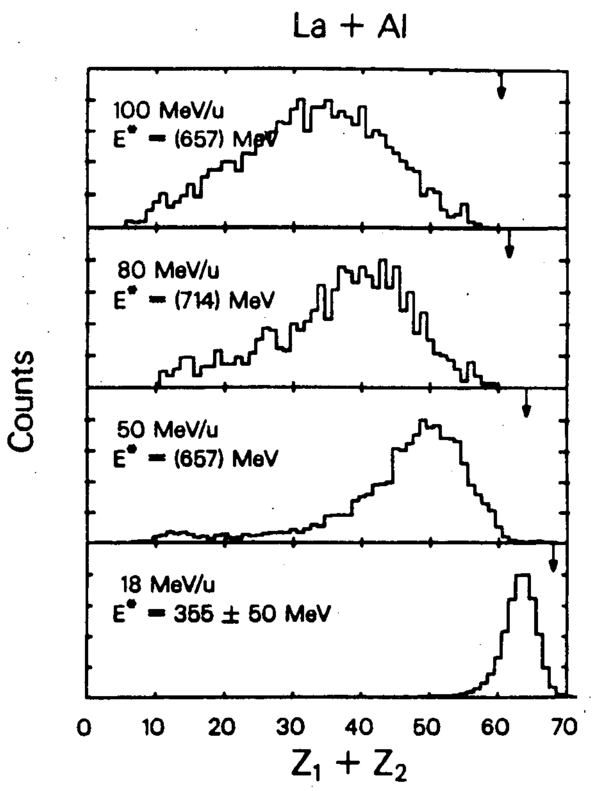

FIGURE 9
$Z_1 + Z_2$ spectra corresponding to the correlation diagrams in Fig. 7.

in turn into two fragments. In this very conventional way, one can foresee one possible explanation for several fragments in the exit channel (multifragmentation), namely several sequential binary decays. At even higher energies, these multifragment events may be responsible for a substantial background to other predicted multifragmentation mechanisms. This process of sequential binary decay, controlled at each stage by the CN branching ratios, we call "nuclear comminution".[8]

The limitations of this process are of two kinds: extrinsic and intrinsic. The most obvious extrinsic limitation is the ability of the system to form a compound nucleus. In other words, the relaxation times associated with the compound nucleus formation are long when compared to the dynamical times leading the system to a different fate. Limitations of this kind are of course shared by all other multifragmentation modes involving an intermediate relaxed system.

The intrinsic limitations are associated with the aspect of sequentiality. Should two sequential binary decays occur too close in space-time, they would interact to an extent incompatible with the definition of sequentiality. In this case one may be led to favor models in which fragments are formed simultaneously. Nonetheless, it may be possible to extend the sequential binary decay model to situations in which the interaction between two successive decays is strong enough to perturb the angular distributions. This is because the decay probabilities are overwhelmingly affected by the level densities of the corresponding final states. These level densities arise almost completely from the intrinsic degrees of freedom. The collective degrees of freedom on which the angular distributions depend hardly contribute to the level densities. Therefore, one can observe a multifragment pattern, whose branching ratios are still clearly binary, while the angular distributions may be substantially perturbed.

The lesson to be learned from these considerations is that the best way to establish the underlying mechanism of a multifragmentation process is to study the excitation functions of binary, ternary, quaternary events, which of course reflect the energy dependence of the branching ratios, and not to be troubled too much, should the angular distributions indicate

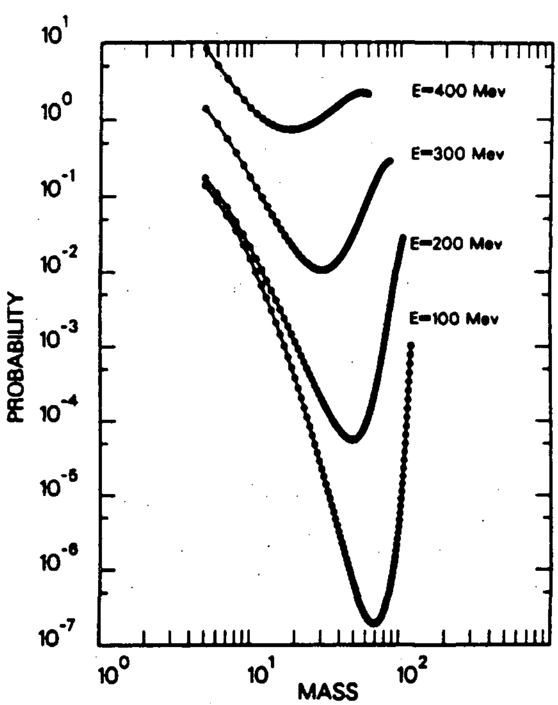

FIGURE 10a
Theoretical mass distributions from comminution calculations of the dexcitation of a CN with mass 150 at several excitation energies. Notice the power-law behavior at small masses.

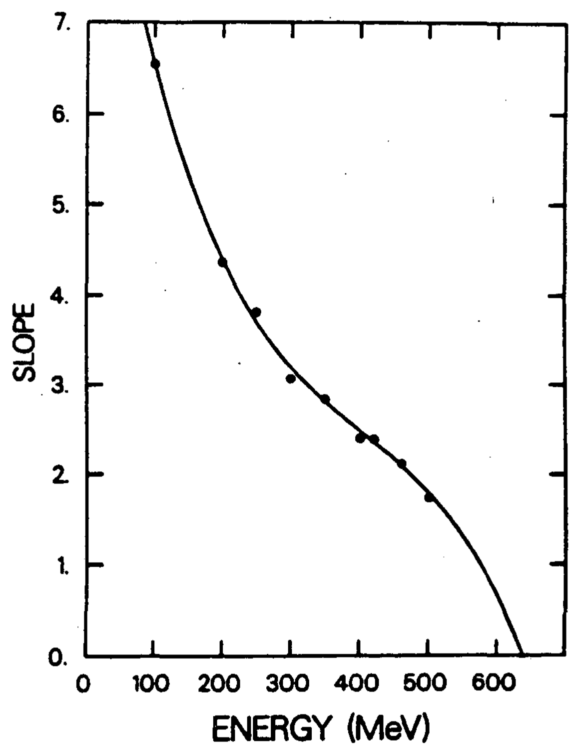

FIGURE 10b
Exponent τ of the power-law dependence as a function of excitation energy.

multifragment interaction.

The calculations of the mass distributions resulting from the sequential binary decay model are trivial although tedious and time consuming. We have tried to simulate the process by assuming a potential energy curve vs mass asymmetry (ridge line) with a maximum value of 40 MeV for symmetry and 8 MeV for the extreme asymmetries. The primary yield curve is taken to be of the form:

$$Y(A) = K \exp[-V(A)/T(A)] . \qquad (1)$$

Each of the resulting fragments is assumed to have a similar ridge line, a properly scaled temperature, and is allowed to decay accordingly, until all the excitation energy is exhausted. For a series of initial excitation energies, the resulting mass distributions are shown in Fig. 10a. The log-log plots show an exquisite power-law dependence for the low mass fragments. At excitation energies of about 400 MeV, the exponents (see Fig. 10b) are around 2.3 - 2.4 which, incidentally, are very close to the value expected for the liquid-vapor phase transition at the critical temperature. This result shows that a power-law dependence

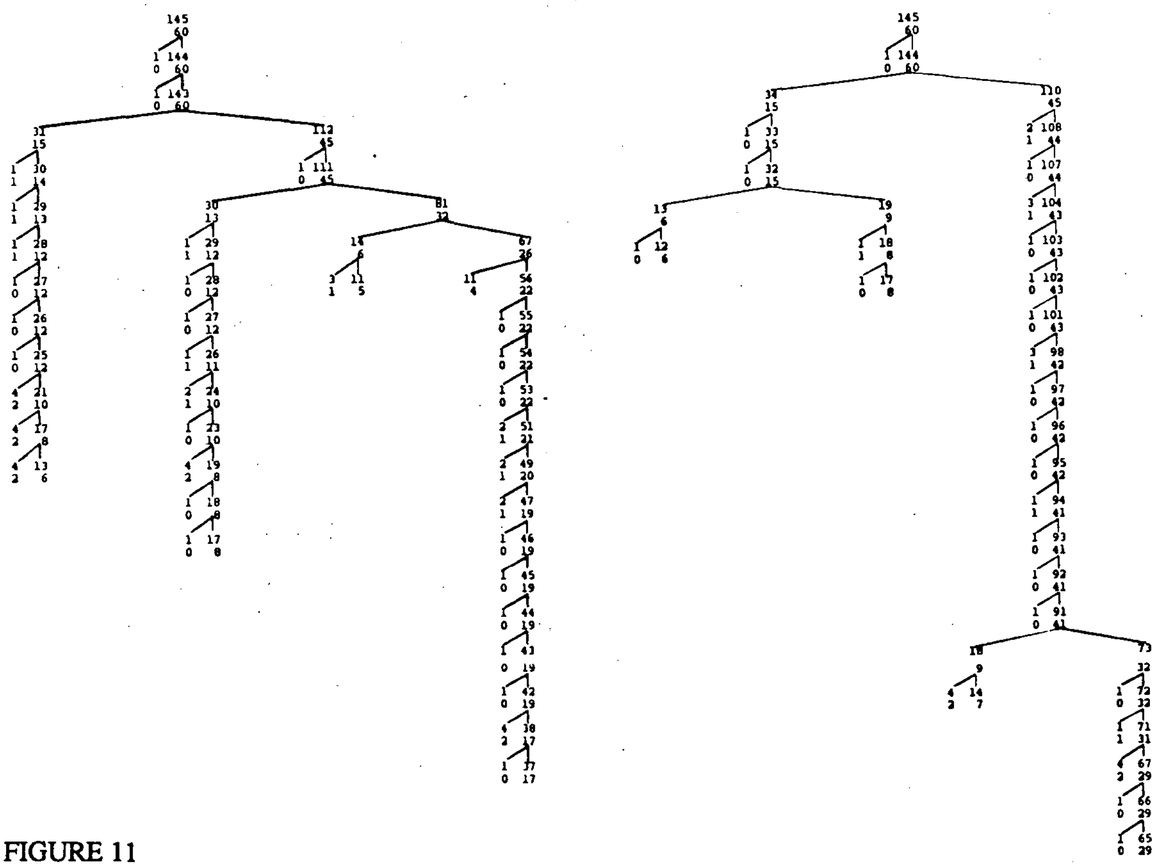

FIGURE 11
Examples of sequential multifragment events from the compound nucleus ^{145}Eu ($\ell_{max} = 60\hbar$) as calculated by the code GEMINI.

is not a unique diagnostic feature of liquid-vapor equilibrium, but rather is an apparently "generic" property arising even from sequential binay decay or comminution. A more realistic calculation with the statistical code GEMINI leads to similar results.[8]

The statistical code GEMINI can be used to generate complete events on the basis of standard compound nucleus branching ratios. Some examples of events with four and five complex fragments plus a multitude of lighter particles are illustrated in Fig. (11). Of course the analysis of individual complete events does not reveal the "statistical" nature of the branching ratios. Little can be said concerning the fact that the first "binary" decay is in one case occuring at the beginning of the cascade and in another quite late in the cascade after the emission of a multitude of light particles. Nor is the selection of these "particular" events among a plethora of ordinary binary decays conducive to an appreciation of the underlying statistical processes. These can be appreciated more directly in the excitation functions for events with one, two, three, etc. fragments in the exit channel, like those plotted in Fig. (12). Here one can get, at a glance, a "qualitative" feeling of the statistical competition beside the direct quantitative predictions. In view of the uncertainties in the barriers used in the

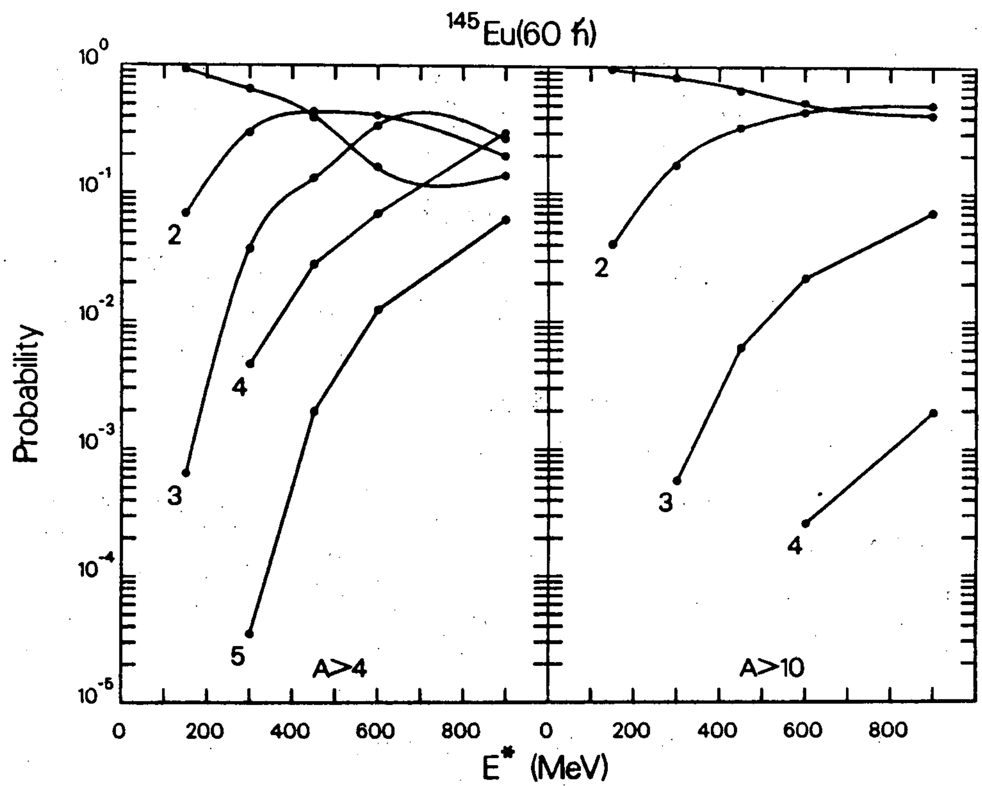

FIGURE 12
Probability of producing exactly one, two, three, etc. fragments a) A > 4, b) A > 10 as a function of excitation energy for the compound nucleus ^{145}Eu (ℓ_{max} = 60ħ).

calculations, plus the fact that the temperature dependence of the barriers themselves has not been included, the qualitative dependence of the branching ratios may be the most important lesson to be derived from this exercise.

7. CONCLUSIONS

From this brief discussion, one can conclude that compound nuclei, which dominate reactions at low energies, still play a big role at intermediate energies. The large increase in excitation energy enhances processes that were very improbable at low energies, like the emission of complex fragments. Also, the larger excitation energy available permits extensive sequential emission of complex fragments, thus simulating true multifragment exit channels.

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