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Multifragmentation: New Dynamics or Old Statistics?

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Abstract

The understanding of the fission process as it has developed over the last fifty years has been applied to multifragmentation. Two salient aspects have been discovered: 1) a strong decoupling of the entrance and exit channels with the formation of well-characterized sources: 2) a statistical competition between two-, three-, four-, five-, ... n-body decays.

What is multifragmentation? After many years, many experiments, and many millions of dollars, I am not sure that we can give a good answer. Why? Certainly not for want of data or theories. In fact, one might argue that we are still lacking an answer: 1) because experiments, in their attempt to measure everything, have become unfocussed and their questions vague and 2) because theories, in their attempt to predict everything, have lost their sagacity and become simulations. To paraphrase the gospel, what good is the fitting of the smallest experimental detail with BUU or another theory, if in the process we lose the soul of understanding?

To this day we still do not know whether multifragmentation is a homogeneous or heterogeneous process, namely whether it has an identity of its own, or is a collage of processes brought together by compression either in time or in perspective. We also do not know the respective roles of statistics and dynamics. We do not know whether the fit of the charge distribution and of its moments by percolation models (and by all other models, for that matter) is trivial or significant, and, if it is significant, what is its significance.

One could go on with this litany, and I would, if I did not have something better to suggest. However, I think that I have an idea, on how to go about it, that came to me by thinking about the historical development of what we might call multifragmentation's little brother: namely fission.

It occurred to me that fission could be taken as a paradigm for multifragmentation, pointing to those problems that can be expected to be worked out in short order, and to those which might be open almost two generations after the pioneering studies.

So, let us see how we have managed to understand fission. The most important step is to identify the relevant stages of the reaction. Here is a classification, on which most people would probably agree (see Figure 1).

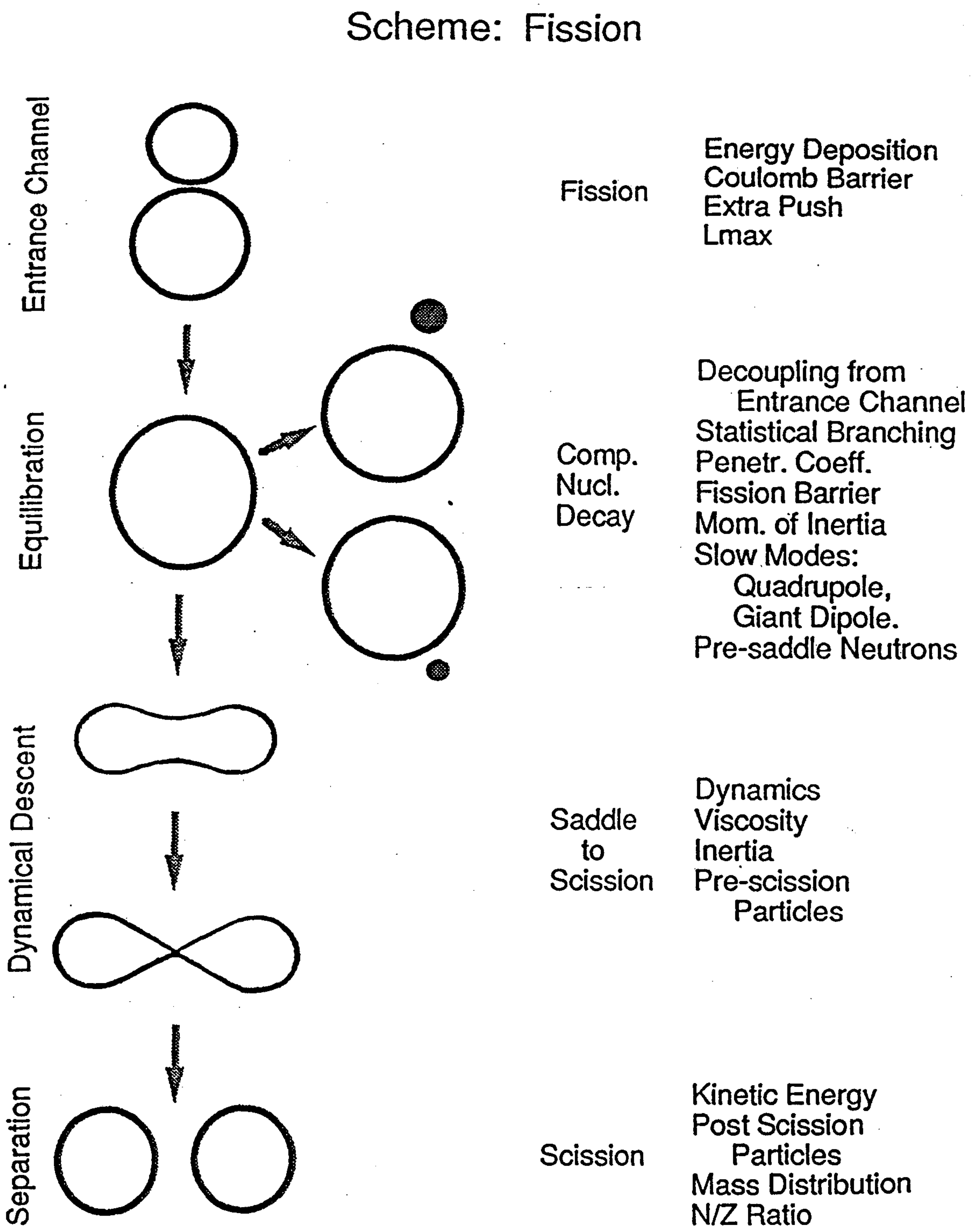


Figure 1 A schematic diagram of the fission process.

Fission

- Entrance channel dynamics
- Decoupling from the entrance channel
- Relaxation to a thermal source (compound nucleus)
- Fission as one of the statistically competing decay channels (branching ratios)
- Dynamical descent from saddle to scission
- Phase space distributions at scission
- Fragment separation

Entrance channel dynamics: in classical low energy fission, it involves the physics of fusion. Fusion barriers, critical angular momentum, extra push, etc., are the parameters that characterize this stage. Fission shares this stage with many other kinds of reactions.

Decoupling from the entrance channel: it implies the formation of a source whose further evolution is independent of the entrance channel.

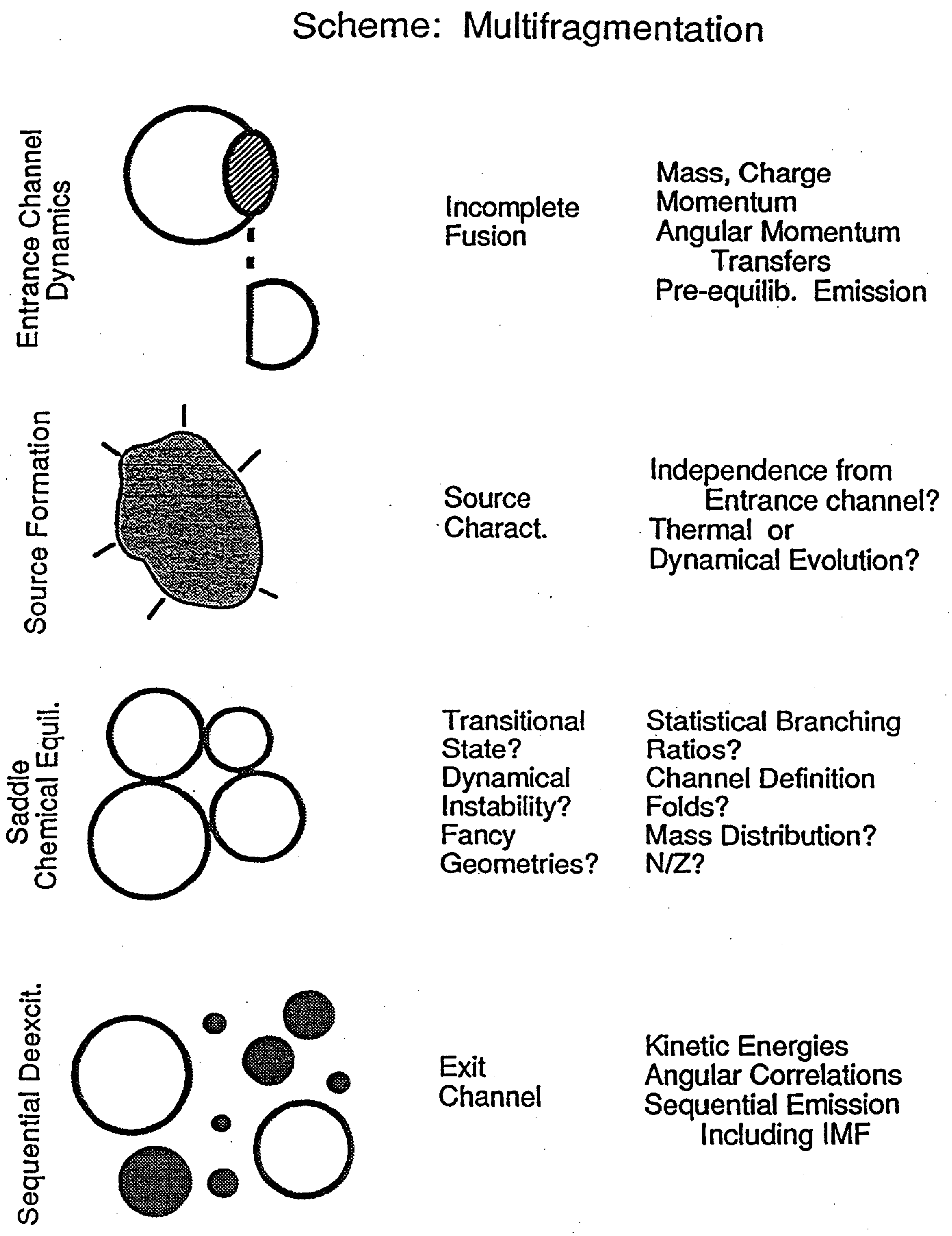
Relaxation to a thermal source: here the decoupling is further guaranteed by thermalization. This path is shared by all compound nucleus reactions.

Statistical branching ratios: the compound nucleus explores all accessible ways to decay, and branches its decay proportionally to their respective phase space volumes. Fission becomes one of the several statistically competing channels.

Dynamical descent from saddle to scission: though the branching ratios are statistical, the fission process also exhibits the delights of dynamics, with its trimmings of viscosity, inertia, prescission particle emission, etc.

Scission: here another miracle happens. Despite all the dynamics, the charge and mass distributions seem to be rather statistical. I say "rather" in order to distinguish from the "very" that refers to the branching ratio (begging perfunctory forgiveness to Kramers and epigones). What is not statistical, is the loose set of scission constraints, which must be obtained from dynamics, the scission configuration not being a stationary point. It is fair to say that the theoretical description of the fission mass distribution is in no better shape today than in Fong's day, over twenty years ago, and this should serve as a lesson.

Fragment separation: now things get easy -- or do they? How about sequential decay? And what if the fragment's sequential decay is another fission, perhaps following very shortly after the first?



Scheme: Multifragmentation

Entrance Channel Dynamics	Incomplete Fusion	Mass, Charge Momentum Angular Momentum Transfers Pre-equilib. Emission
Source Formation	Source Charact.	Independence from Entrance channel? Thermal or Dynamical Evolution?
Saddle Chemical Equil.	Transitional State? Dynamical Instability? Fancy Geometries?	Statistical Branching Ratios? Channel Definition Folds? Mass Distribution? N/Z?
Sequential Deexcit.	Exit Channel	Kinetic Energies Angular Correlations Sequential Emission Including IMF

Figure 2 A schematic diagram of the multifragmentation process.

Multifragmentation

How can this be applied to multifragmentation? Let us take one point at the time, and see how far we can go (see Fig. 2).

Entrance channel dynamics: something has been learned about this. At lower energies the fusion process dominates. At intermediate energies incomplete fusion sets in with its energy and mass asymmetry dependence. At higher energies we enter the fireball regime. It is sensible to assume that as the bombarding energy increases, the incomplete fusion product evolves towards multifragmentation, while, in the fireball regime one or both spectators may do so.

Decoupling from entrance channel: this implies formation of a source. This decoupling has been observed in both the incomplete fusion regime (and we shall show some of our evidence below) and in the fireball regime. This is a great simplification!

Relaxation to a thermal source: there is scattered evidence for this, but this is implied if we observe statistical branching ratios.

Statistical branching ratios between channels: here things get difficult. There is evaporation proceeding at a furious pace. Which channels should we look at? We suggest, and it is the main theme of our talk, to consider binary, ternary, quaternary, and quinary events as possible independent channels. When we do so, and look for their excitation functions, we discover that they are, as far as we can see, statistical. If this is true, we have reached a very important conclusion, and we have attained an understanding of the process comparable to that of fission up to the branching ratios.

Dynamical descent from saddle to scission: unfortunately here we do not know anything, not even whether the system passed through a transition state or not. Certainly there is plenty of room for dynamics of one sort or another, until we reach the equivalent of a scission point or freeze-out point.

Scission point: we have already commented on the statistical looking charge distributions and their moments, so well fitted by percolation theories. But, what about fragment separation and decay?

Fragment separation and sequential decay: sequential fragment emission through conventional compound nucleus decay of the primary fragments must be undoubtely there, and quite abundant. How does one reconcile this with the good fits from all the models that do not consider it?

We, of course, do not have an answer to all of these points. However, here is an attempt along these lines.

Sources of multifragmentation

Recently, some experimental work has succeeded in isolating and characterizing what appear to be true multifragmentation sources formed in reverse kinematics reactions[1,2]. These sources are formed in a process akin to incomplete fusion, whereby one partner of the collision picks up, and fuses with, a variable portion of the other partner. From the kinematics of the event, it is possible to determine how much mass has been picked up and what is the excitation energy associated with the fused object[3]. Surprisingly, these sources, once characterized as described above, undergo multifragment decay in a way that is singularly independent of the formation process. The observed branching ratios for binary, ternary, quaternary, and quinary decays seem to depend almost exclusively upon the excitation energy E of the fused object, and remarkably little upon the target-projectile combination or even the bombarding energy[2].

The obvious question that we want to address is: what is the multi-fragmentation mechanism of these sources? In particular, is this decay controlled by dynamics[4-8], or by statistics[9-21]?

The possible role of statistics in these reactions has been expounded in a variety of models, such as chemical equilibrium models[11,12], the liquid-gas phase transition[14-17], or hybrid approaches, such as evaporation occurring simultaneously with dynamical expansion[18], dynamics followed by statistical decay[19-21], etc. While these models, or approaches, may be well justified a priori, inevitable limitations may make their application to actual data somewhat problematic[22]. In other words, while the models may be sound in their essence, they may be too schematic and thus unable to fit the data satisfactorily.

Alternatively, one can examine the data themselves in order to see whether they contain signatures that may be brought forth without the help, or impediment, of any given model. As an example very much to the point, in ref. 23 the rise of the fission probability P with excitation energy in electron or Bremsstrahlung induced fission was shown to be statistical in origin by demonstrating the presence of a characteristic energy dependence [$\ln(P) \propto E^{-1/2}$]. This dependence is a generic attribute of statistical decay, and it has been verified with well-understood fission reactions (see figure 3). Here we apply a similar approach to intermediate-energy heavy-ion reactions in order to demonstrate the statistical nature of the multifragmentation branching ratios.

Let us suppose that the hot nuclear system formed in the heavy-ion reaction decays statistically, and that a barrier of some sort governs this decay. Alternatively, in the framework of the chemical equilibrium picture, one can consider the potential energy of each configuration as a barrier. It is conceivable that, in these pictures, there might arise a hierarchy of "barriers" such that all the binary configurations would have barriers closer to each other than to those of the ternary configurations, and so on. Thus, let us assume that B_2, B_3, ... B_n are the average "barriers" associated with binary, ternary, and n-body decays. The decay probability for each channel should be proportional to the level density of the system $\rho(E)$ (dominated by the internal degrees of freedom) at an excitation energy equal to the available energy minus the barrier:

$$P_n(E) \propto \rho(E - B_n). \qquad (1)$$

For a Fermi gas level density, we have

$$P_n(E) \propto e^{2\sqrt{a(E-B_n)}}, \qquad (2)$$

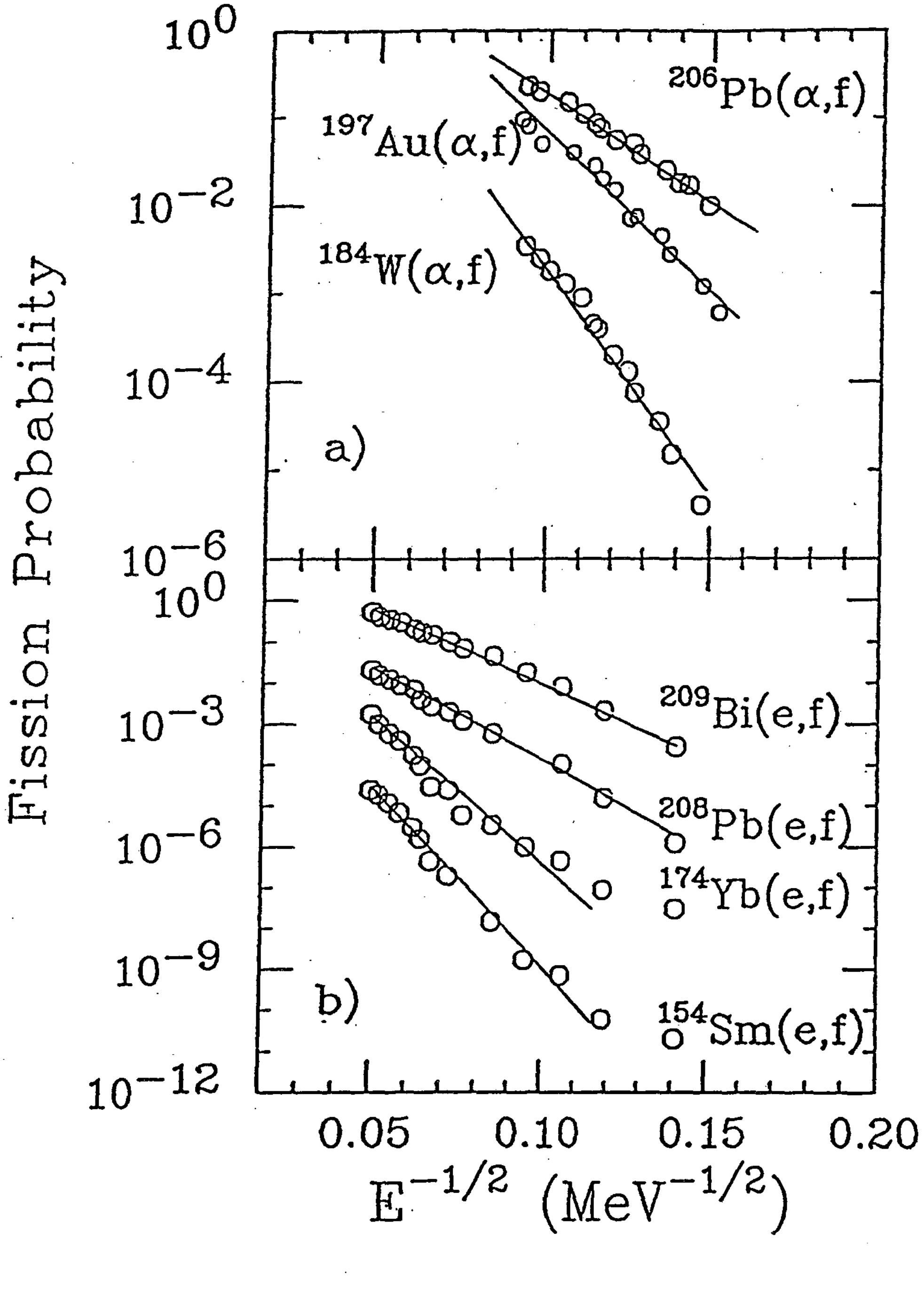


Figure 3 a) The fission probability plotted as a function of $E^{-1/2}$ for the α-induced reactions ^{206}Pb(α, f), ^{197}Au(α, f), and ^{184}W(α, f) and b) for the electron-induced reactions ^{209}Bi(e, f), ^{208}Pb(e, f), ^{174}Yb(e, f), and ^{154}Sm(e, f). (The data are taken from ref. 23).

where a is the level density parameter.

For $E >> B_n$ one obtains:

$$P_n(E) \propto e^{2\sqrt{aE}} e^{-B_n\sqrt{a/E}} \propto e^{-B_n/T}. \qquad (3)$$

For convenience, we want the ratio of the n-fold events to the binary events:

$$\ln[P_n / P_2] \propto -\sqrt{a/E}(B_n - B_2). \qquad (4)$$

Thus, a plot of $\ln(P_n/P_2)$ vs. $E^{-1/2}$ should give a straight a line.

As mentioned above, this simple theoretical prediction has been empirically tested in ref. 23 for the overall fission probabilities in the Pb region, and used to prove that the rapid rise of the fission cross section in e^- induced fission of similar nuclei is due to statistics. In figure 3a the total fission probability is plotted vs $E^{-1/2}$ for three α-induced reactions in an energy regime where compound nucleus formation is well established. The expected linear dependence is observed, and the slopes correlate quantitatively with the known fission barriers. It is important to notice that the linear dependence extends even to regions of excitation energy where multiple-chance fission contributes substantially. Thus, one should consider this linear dependence as "empirical" evidence for statistical decay.

In figure 3b a similar plot is shown for four e^- induced fission reactions. The energy dependence of the fission probability was extracted by unfolding the e^- induced fission cross sections from the virtual photon spectrum. The observed linear dependences and the correlation of the slopes with the fission barriers proved that the rise of the fission cross section with increasing e^- energy is a statistical effect arising from the phase spaces associated with the competing decay channels[23].

To see whether a similar dependence exists in the multifragmentation branching ratios, we have performed an experiment with the specific purpose of determining the multifragment branching ratios as a function of the excitation energy of the decaying source. The decay of the hot nuclear systems formed in ^{197}Au-induced reactions was studied, following closely the approach of Ref. 2, by determining the ratio of the n-fold events (n = 3, 4, and 5) with respect to the 2-fold events as a function of the excitation energy E. In the incomplete-fusion model[26], the excitation energy is approximately related to the parallel component $V_s^{//}$ of the source velocity V_s by $E = E_b(1 - V_s^{//}/V_b)$ where E_b is the bombarding energy and V_b is the beam velocity. This formula does not take into account preequilibrium emission, thus the calculated value of the excitation energy should be regarded as an upper limit[22].

The parallel source velocity was calculated from the source velocity V_s of the multifold events which was determined by: $V_s = \Sigma_i m_i V_i / \Sigma_i m_i$ where m_i and V_i are respectively the mass and velocity in the laboratory frame of the i-th fragment and the summation is performed over all the detected fragments. The resulting velocity distributions are very similar to those observed in ref. 2 for a ^{139}La projectile. Typically, they consist of a broad peak whose width increases with increasing target mass. It has been shown[1,2] that most of this width is due to the actual range of source velocities, and only a fraction is due to the perturbation introduced by light particle emission prior and subsequent to heavy-fragment emission.

The number of binary and multibody events was determined for different bins of the source velocity and thus of the excitation energy of the source. By this procedure, we obtained the probabilities for ternary, quaternary, and quinary decays, as a function of the calculated excitation energy, shown figure 4. The measured probabilities were then corrected for the detection efficiency. Sets of 2-, 3-, 4-, and 5-fold events were generated by simulating the reactions following the procedure described in Ref. 21, where the dynamics is given by a Landau-Vlasov calculation[21] and the subsequent statistical decay of the primary fragments is described by the statistical code GEMINI[12]. The simulated events were then filtered through a software replica of our detector to estimate the efficiency and the spill over of higher folds into lower fold coincidences. These efficiencies were then used to correct the experimental data shown in figure 4b.

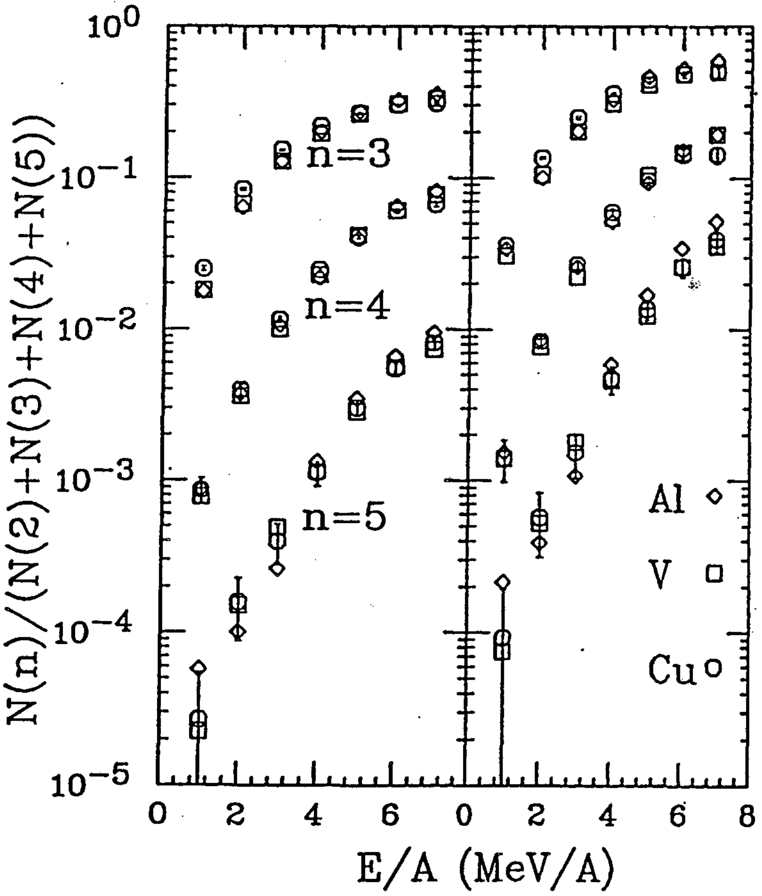


Figure 4 a) Uncorrected relative probabilities for the ternary, quaternary, and quinary decays as a function of the source excitation energy for the 60 MeV/u ^{197}Au + ^{27}Al, ^{51}V, and ^{nat}Cu reactions. b) Same as in a) after efficiency corrections (see text). Statistical errors are shown for the Cu target when they exceed the size of the symbols.

The first striking observation is that the data from all the targets fall on the same curves. This is a strong confirmation of the results obtained for the La-induced reactions[1,2]. More specifically, once the multifragmentation source is characterized in terms of the kinematically determined excitation energy, the branching ratios for the various multifragment channels seem to be fixed and independent of the specific reaction that has produced the source. This decoupling between entrance and exit channel suggests a "statistical" kind of decay.

This statistical feature is brought forth by the $E^{-1/2}$ plot shown in figure 5, that indeed generates straight lines. Similar straight lines are obtained from the La data[22]. We believe that the observed linear dependence for both the Au- and La- induced reactions is a strong signature for processes controlled by phase space. Since this dependence demonstrates statistical equilibrium between "different" channels, it may be deemed more significant evidence for deep equilibration than the thermalization of the kinetic energy spectrum within a given channel.

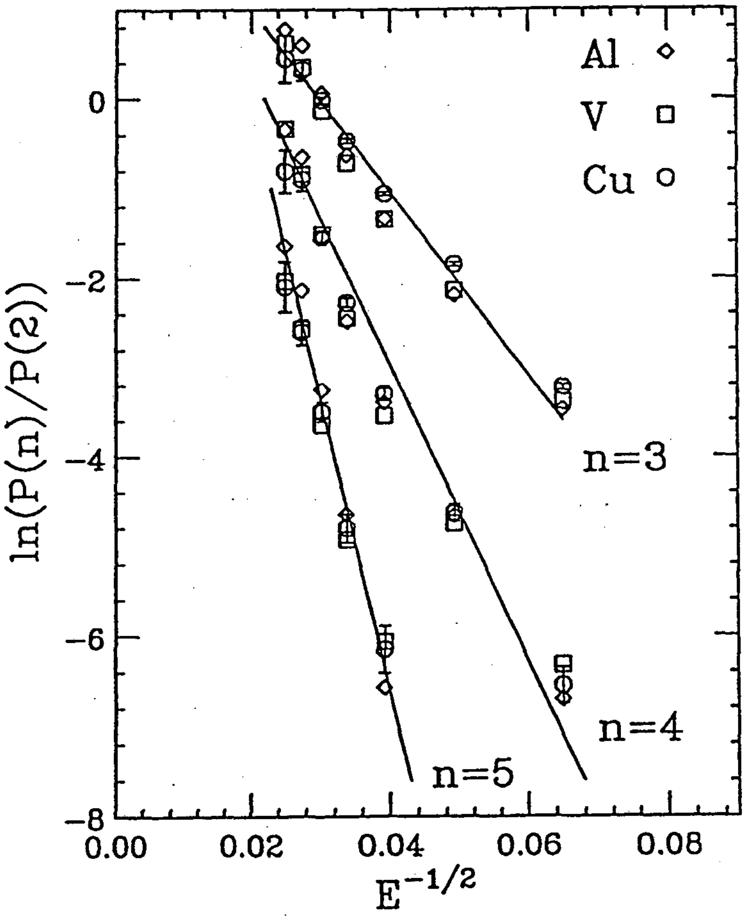


Figure 5. The natural logarithm of the ratio of the corrected 3-, 4-, and 5-fold probabilities to the 2-fold probability(symbols) as a function of $E^{-1/2}$ for the 60 MeV/u ^{197}Au + ^{27}Al, ^{51}V, and ^{nat}Cu reactions. The lines are the best fits to the data. Statistical errors are shown for the Cu target when they exceed the size of the symbols.

Can this signature differentiate between the various statistical models? Equation 4 has been derived for a statistical multifragmentation process. It is immaterial whether we refer to a transition-state model[9] or a "freeze-out" equilibrium model[10,11]. In the former case, B_n is the barrier to be crossed in order to reach an n-body decay configuration. In the latter case B_n is the "potential energy" of the n-body system at the freeze-out configuration. However, the same dependence can be obtained for sequential decay. Let us suppose that the system undergoes sequential decay with probabilities $P(E) << 1$ and with barriers $b_1, b_2, b_3, \ldots b_n$ for the successive binary decays. The probability to obtain n fragments is:

$$\begin{aligned} P_n(E) &\propto K(n)e^{-b_1/T_1}e^{-b_2/T_2}\ldots \propto K(n)e^{-(b_1+b_2 \ldots)/T} \propto K(n)e^{-B_n/T} \\ &\propto K(n)e^{-B_n\sqrt{a/E}} \end{aligned} \tag{5}$$

where $K(n)$ is a combinatorial factor and $B_n = b_1 + b_2 + \ldots\ldots$. Thus, even for multiple sequential binary decay we expect a linear dependence of $\ln P_n$ with $E^{-1/2}$. Therefore, the observed linear dependence, per se does not discriminate between a prompt or sequential multifragmentation mechanism.

In principle however, one can obtain more specific information from the slope of the straight line (see Eq. 4). Since B_n could be very different for simultaneous or sequential decay, a greater experience with both the data and the models might lead to a discrimination between the two possibilities. Still, we have already a strong message, that the role of dynamics may be limited to the process of source formation (incomplete fusion for instance), while phase-space seems to control the ultimate fate of the source.

In conclusion, the evidence presented above strongly suggest the following picture for multifragmentation:

1) The dynamics of the reaction seems to be limited to the formation of a source of a given mass, energy, and angular momentum through a mechanism similar to incomplete fusion.

2) Once this source is formed, its decay is apparently independent of its mode of formation.

3) The branching ratios between the various multifragmentation channels are dictated by the available phase space as shown by the excitation functions.

4) The qualitative features of the excitation functions do not permit distinguishing between a sequential or simultaneous decay mechanism, but the quantitative features may contain relevant information in this regard.

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