Title

Experimental Signature for Statistical Multifragmentation

Journal

Physical Review Letters, 71(24)

Authors

Moretto, L.G.
Delis, D.N.
Wozniak, G.J.

Publication Date

1992-09-01

LBL-32948
UC-413
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physical Review Letters

A Strong Experimental Signature for Statistical Multifragmentation

L.G. Moretto, D.N. Nelis, and G.J. Wozniak

September 1992

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-32948
UC-413

A Strong Experimental Signature for Statistical Multifragmentation

L.G. Moretto, D.N. Delis, and G.J. Wozniak

Nuclear Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

September 1992

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

A Strong Experimental Signature for Statistical Multifragmentation

L.G. Moretto, D.N. Delis, and G.J. Wozniak

Nuclear Science Division, Lawrence Berkeley Laboratory

1 Cyclotron Road, Berkeley, CA 94720

Abstract

Multifragment production was measured for the 60 MeV/A ^{197}Au + ^{27}Al, ^{51}V, ^{nat}Cu and ^{197}Au reactions. The branching ratios for binary, ternary, quaternary, and quinary decays expressed as a function of the extracted excitation energies E are independent of the reaction. The logarithms of these branching ratios when plotted vs $E^{-1/2}$ show a linear dependence that strongly suggests a statistical competition between the various multifragmentation channels. This behavior seems to relegate the role of dynamics to the formation of the sources, which then proceed to decay in an apparently statistical manner.

PACS numbers: 25.70.Np, 25.70.Gh, 25.70.Jj

Multifragment production[1-12], a most interesting feature of intermediate-energy heavy-ion reactions, still remains elusive in its interpretation. For instance, it is still unclear whether there exists a homogeneous mechanism that may be labeled multifragmentation, or whether the process is simply a collage of weakly correlated features occurring at various stages of the reaction. An example of the latter possibility would be quasi or deep inelastic scattering[9] (or incomplete fusion[2,11,13]) followed by additional binary decays, statistical or otherwise.

Recently, some experimental progress has been made, by isolating and characterizing what appear to be true multifragmentation sources formed in reverse kinematic reactions[2,11]. 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. Kinematically, it is possible to determine how much mass has been picked up and the excitation energy associated with the fused object. 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]. Similar features of target independence suggesting the formation of a source decaying independently of the formation process have been observed by other groups[4,5,7].

The next 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[14-18], or by statistics[19-31]?

The role of statistics in these reactions has been expounded in a variety of models, such as the liquid-gas phase transition[24-26], chemical equilibrium models[20,26,27] or hybrid approaches, such as evaporation occurring simultaneously with dynamical expansion[28], dynamics followed by statistical decay[29-31], etc.. While these models, or approaches, may be well justified a priori, inevitable limitations may make their application to actual data somewhat problematic. 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.

An alternative way of searching for statistical effects would be to 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. 32 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 that has been verified with well understood fission reactions (see figure 1). In this Letter 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. This is, of course, the case for binary decay. However, it is not clear that a similar "barrier" exists for higher order decays. At least, we are not familiar with ternary or quaternary saddle points in the nuclear potential energy surface as described by the liquid drop model. However, deviations from constant density, well within reach of the present energy domain, might introduce such saddles. 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 this picture, 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 $B_2, B_3, \ldots B_n$ 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:

$$P_n(E) \propto \rho(E - B_n). \tag{1}$$

For a Fermi gas level density, we have

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

where a is the level density parameter.

For $E >> B_n$ one obtains:

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

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

$$\ln(P_n/P_2) \propto -\sqrt{a/E}\,(B_n-B_2) . \tag{4}$$

Thus, a plot of

$$\ln(P_n/P_2) \quad \text{vs.} \quad E^{-1/2} \tag{5}$$

should give a straight a line.

As mentioned above, this simple theoretical prediction has been empirically tested in ref. 32 for the overall fission probabilities in the Pb region, and used to prove that the rapid rise in fission cross section in e^- induced fission of similar nuclei is due to statistics. In figure 1a 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. In figure 1b a similar plot is shownt 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.

In order 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 experiment[33] was performed at the Lawrence Berkeley Laboratory Bevalac. Beams of ^{197}Au ions impinged on targets of ^{27}Al, ^{51}V, ^{nat}Cu and ^{197}Au at 60 MeV/A. The reaction products were detected in an array of 20 Si(0.3mm)-Si(5mm) telescopes. The 20 telescopes were arranged in a 5x5 configuration closely packed around the beam with the central and corner array elements missing. The maximum angular coverage was approximately $\pm 17^0$ in the horizontal and vertical planes. Since in reverse kinematics, the fragments have high kinetic energies and are emitted within a narrow cone around the beam direction, a detection efficiency of about 60% was obtained for inclusive events. The detection efficiency was calculated via Monte Carlo simulations that included the geometry of our detector setup. Since the determination of the detector efficiency for coincidence events requires knowledge of the precise kinematical nature of the events, such an attempt has not been undertaken here. The following analysis is restricted to events where the total measured charge is at least 35 in order to insure a reasonable representation of the kinematical skeleton of the reaction, and to keep the contamination arising from incompletely detected events at an acceptable level[11].

The decay of the hot nuclear systems formed in these 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[34], the excitation energy is approximately related to the parallel component $V_s^{\parallel}$ of the source velocity V_s by $E = E_b\,(1 - V_s^{\parallel}/V_b)$ 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.

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 the 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 with a ^{139}La projectile. Typically, they consist of a broad peak whose width increases with increasing target mass. It has been shown[2,11] 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 ratio of the n-fold to the 2-fold events was determined for different bins of the parallel source velocity and thus of the excitation energy of the source. By this procedure, we were able to obtain the probabilities for binary, ternary, and n-body decays as a function of the calculated excitation energy. The measured probabilities are not corrected for the detection efficiency. However, this efficiency has been shown to be insensitive to modest variations of the source velocity. Thus the uncorrected experimental probabilities P^* differ from those of eqn. 4 only by a term with a weak logarithmic dependence on energy. It follows that

$$\ln\ (P_n^*/P_2^*) = \ln[K(E)] - \sqrt{(a/E)}\ \ (B_n - B_2)\,. \qquad (6)$$

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

Multifragmentation data for the Au-induced reactions plotted in this manner are shown in fig. 2a. The first striking observation is that the data from all the reactions fall on the same curves. This is a strong confirmation of the results obtained for the La-induced reactions presented in Ref. 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 is very suggestive of a "statistical" kind of decay. This statistical feature is brought forth by the $E^{-1/2}$ plot, that indeed generates beautiful straight lines. In fig. 2b the data from 55 MeV/A La induced reactions[2,11] are also plotted in the same fashion, to illustrate the generality of these results.

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.

Can this signature differentiate between the various statistical models? Eq. 6 has been derived for a statistical multifragmentation process. It is immaterial whether we refer to a transition-state model[19] or a "freeze-out" equilibrium model[20,21]. 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 $b_1, b_2, b_3, \dots b_n$ for the successive binary decays. The probability to obtain n fragments is:

$$P_n(E) \propto K(n)\, e^{-b_1/T_1}\, e^{-b_2/T_2 \dots} \propto K(n)\, e^{-(b_1+b_2 \dots)/T} \propto K(n)\, e^{-B_n/T}$$
$$\propto K(n)\, e^{-B_n\sqrt{(a/E)}} \qquad (7)$$

where K(n) is a combinatorial factor and $B_n = b_1 + b_2 + \dots\dots$. 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, which is given by:

$$\frac{d}{dE^{-1/2}} \left(\ln \frac{P_n}{P_2}\right) = -\sqrt{a}\,(B_n - B_2). \qquad (8)$$

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.

An interesting sensitivity of these slopes to the total charge (Z_t) of the event seems to be present. By requiring that the maximum Z_t be progressively larger, we notice a corresponding increase of the slopes (fig. 3). This effect can be understood qualitatively in terms of a barrier that increases with the total mass of the source. Perhaps a quantitative interpretation might be obtained from some of the current multifragmentation models. 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 the mode of its 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.

Acknowledgments

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the US Department of Energy under contract DE-AC03-76SF00098.

References

1. J. Harris et al., Nucl. Phys. **A471** (1987) 2416.
2. Y. Blumenfeld et al., Phys. Rev. Lett. **66** (1991) 576.
3. E. Piasecki et al., Phys. Rev. Lett. **66** (1991) 1291
4. C. A. Olgilvie et al., Phys. Rev. Lett. **67** (1991) 1214.
5. D.R. Bowman et al., Phys. Rev. Lett. **67** (1991) 1527.
6. R. T. de Souza et al., Phys. Lett. **B268** (1991) 6.
7. J. Hubele et al., Z. Phys. **A340** (1991) 263.
8. K. Hagel et al., Phys. Rev. Lett. **68** (1992) 2141.
9. B. Lott et al., Phys. Rev. Lett. **68** (1992) 3141.
10. J. P. Alard et al., Phys. Rev. Lett. **69** (1992) 889.
11. P. Roussel-Chomaz et al., Nucl. Phys. **A**, accepted, LBL-31310.
12. D.R. Bowman et al., Phys. Rev. **C**, accepted, MSUCL-850.
13. N. Colonna et al., Phys. Rev. Lett. **62** (1989) 1833.
14. J. Aichelin and J. Hufner, Phys. Lett. **136B** (1984) 15.
15. G.F. Bertsch and S. Das Gupta, Phys. Rep. **160** (1988) 190.
16. W. Cassing and U. Mosel, Prog. Part. Nucl. Phys. **25** (1988) 235.
17. G.F. Burgio et al., Phys. Rev. Lett. **69** (1992) 885.
18. L. G. Moretto et al., Phys. Rev. Lett., accepted, LBL-31812.
19. J. Randrup and S.F. Koonin, Nucl. Phys. A356 (1981) 223.
20. D.H.E. Gross et al., Z. Phys. **A309** (1982) 41.
21. J. P. Bondorf et al., Nucl. Phys. **A443** (1985) 321.
22. R. J. Charity et al., Nucl. Phys. **A483** (1987) 371.
23. X. Campi, Phys. Lett. **B208** (1988) 351.
24. P. J. Siemens, Nature **305** (1983) 410.
25. G. Bertsch and P. J. Siemens, Phys. Lett. **126B** (1983) 9.
26. J.A. Lopez and P.J. Siemens, Nucl. Phys. **A431** (1984) 728.
27. A. D. Panagiotou et al., Phys. Rev. **C31**, (1985) 55.
28. W.A. Friedman, Phys. Rev. **C42**, (1990) 667.
29. K. Sneppen and L. Vinet, Nucl. Phys. **A480** (1988) 342.
30. S. Leray et al., Nucl. Phys. **A511** (1990) 414.
31. M. Colonna et al., Phys. Lett. **B283** (1992) 180.
32. L.G. Moretto et al., Phys. Rev. **4** (1969) 1176.
33. D.N. Delis, Q. Sui, N. Colonna, K. Tso, K. Hanold, M. Justice, G.J. Wozniak, L.G. Moretto, B. Libby, A.C. Mignerey, A. Pantaleo, G. D'Erasmo, L. Fiore, E.M. Fiore, I. Iori, and A. Moroni, to be published.
34. D. Guerreau, in Proc. of the Int'l School on Nucl. Phys.: Nuclear Matter and Heavy Ion Collisions, Les Houches, France 1989, [Grand Accelerateur National d'Ions Lourds Report No. GANIL P89-07].

Figure Captions

Figure 1 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. 32).

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

b) Same as in part a) of this figure for the 55 MeV/A ^{139}La + ^{27}Al, ^{51}V, and ^{nat}Cu reactions. (The data are taken from Ref. 2)

Figure 3. Same as in Figure 2 for the 60 MeV/A ^{197}Au + ^{nat}Cu reaction for four different gates on the detected total charge (Z_t).

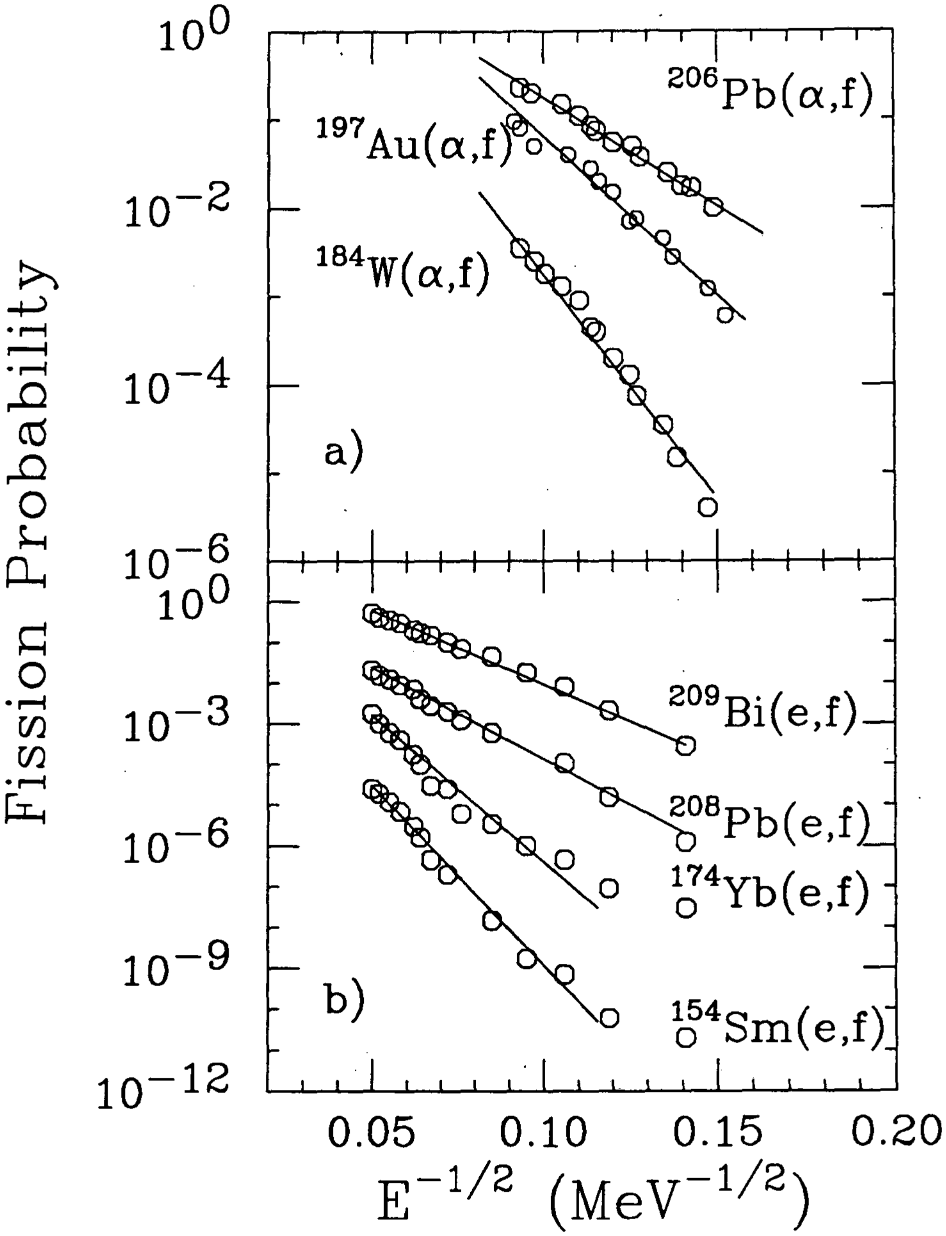
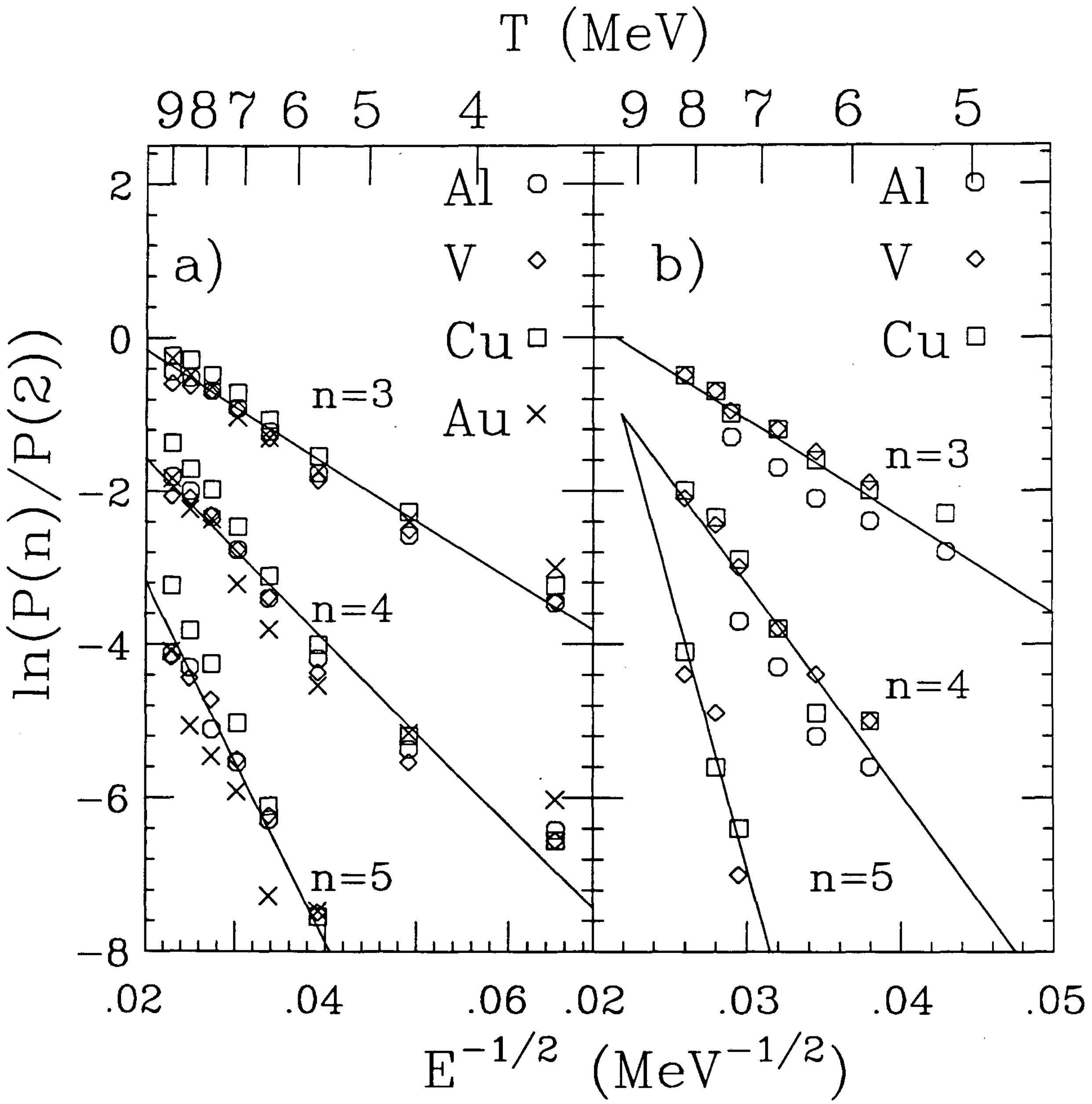
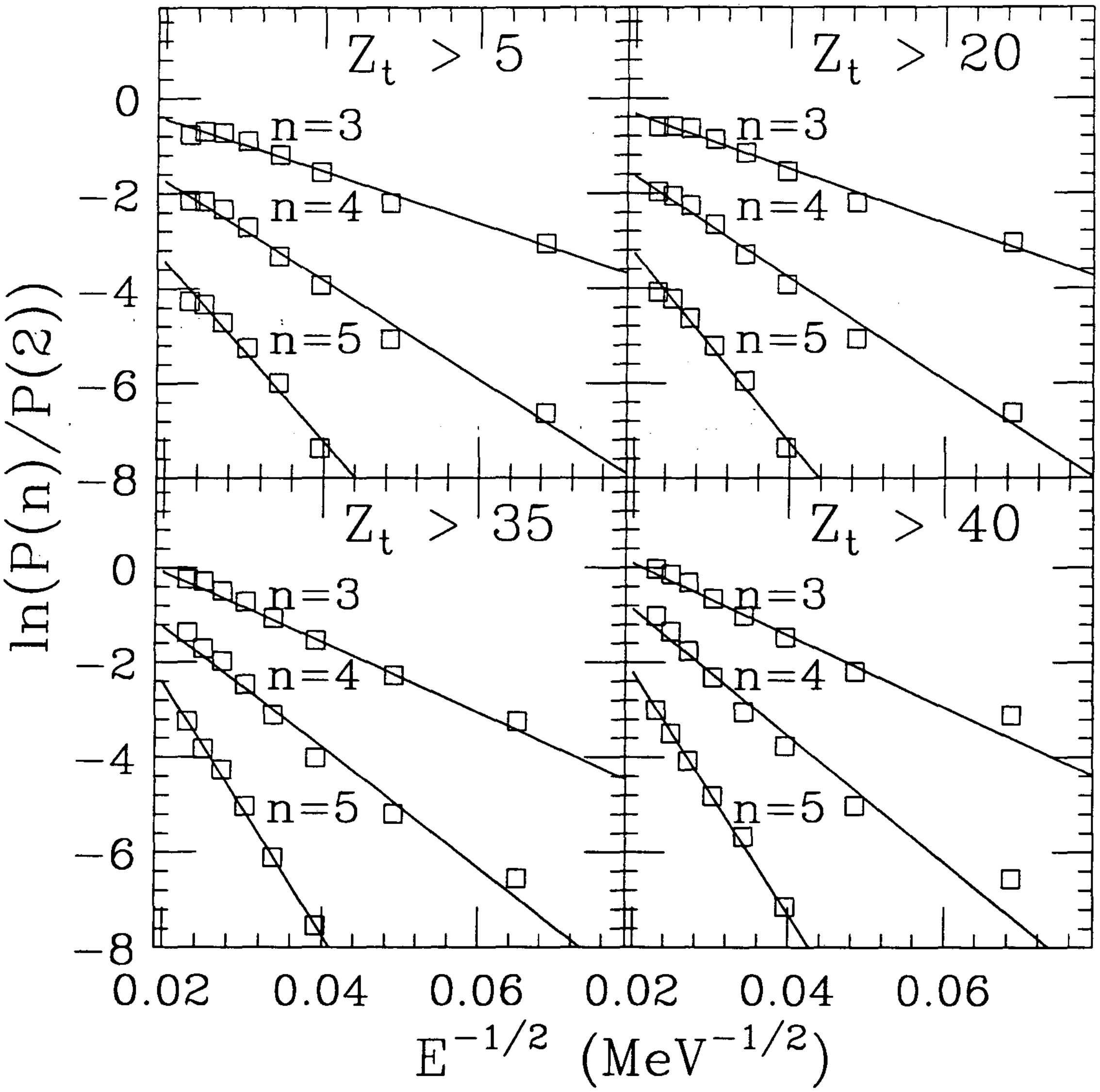

Fission Probability
10^0
10^{-2}
10^{-4}
10^{-6}
^{206}Pb(α,f)
^{197}Au(α,f)
^{184}W(α,f)
a)
10^0
10^{-3}
10^{-6}
10^{-9}
10^{-12}
^{209}Bi(e,f)
^{208}Pb(e,f)
^{174}Yb(e,f)
^{154}Sm(e,f)
b)
0.05
0.10
0.15
0.20
$E^{-1/2}$ (MeV$^{-1/2}$)
XBL 929-1999

Figure 1



XBL 929-2000

Figure 2



XBL 929-2001

Figure 3