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MULTIFRAGMENT EVENTS FROM HEAVY ION COLLISIONS : SOURCES AND EXCITATION FUNCTIONS

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Abstract

Multifragment events from 35 and 40 MeV/N ^{139}La + ^{12}C, ^{27}Al, ^{40}Ca and ^{51}V reactions can be 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.

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Intermediate energy heavy ion reactions have focused experimental [1, 2] and theoretical [3, 4] attention on multifragmentation and its possible association with the formation and decay of very hot nuclei [5]. A proper description of multifragment decay of hot nuclei requires the characterization of the source in terms of its size (mass, charge) and excitation energy, as well as of its branching ratios for the binary, ternary, etc. decay channels. Excitation functions for the various channels may provide the interpretative key to understanding whether the underlying decay mechanism is statistical or otherwise. Such functions have been predicted by several theoretical models, such as sequential compound nucleus decay [6] and simultaneous statistical multifragment decay of very excited nuclei [3, 4].

In the incomplete fusion regime, heavy ion beams produce nuclei with a range of masses, velocities and excitation energies. Within the incomplete fusion picture, for heavy projectiles on a light target, large impact parameters result in nuclei slightly heavier than the projectile moving at slightly less than the beam velocity and with small excitation energies. For smaller impact parameters, more mass is picked up from the target, resulting in slower, hotter, and heavier nuclei. For the 18 MeV/N ^{139}La + ^{64}Ni reaction, such a correlation was established between the degree of fusion (source velocity) and the mass and excitation energy of the product nucleus [7]. By relating the center-of-mass velocity of binary events to the mass and excitation energy of the product nucleus, it was possible to study at one bombarding energy the decay properties of hot nuclei over an excitation energy range extending up to 4 MeV/N.

In this paper we show that, in a similar manner, ternary and quaternary events can be associated with specific sources formed through incomplete fusion processes. Source velocity distributions were obtained for 2-, 3- and 4-fold events. The proportions of binary, ternary and quaternary decay were determined for different bins of the velocity and thus of the corresponding mass and excitation energy of the source. In this way, extended excitation functions were obtained for each reaction and bombarding energy. The remarkable result is that these excitation functions are very similar for different target-projectile combinations, and even for two different bombarding energies. This result supports the validity of the incomplete fusion model and a competition between the various multifragment channels independent of the entrance channel.

^{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. In such reverse kinematics reactions, the fragments have high kinetic energies and are emitted within a narrow cone around the beam direction. Thus, a satisfactory detection efficiency ($\sim$ 40% for 1 fragment) was obtained by using two close-packed square arrays of 9 Si(0.3 mm)-Si(5 mm)-plastic telescopes placed on either side of the beam. The angular coverage was 2^o to 26^o in the horizontal and $\pm$ 12^o in the vertical plane. The 25 cm^2 position-sensitive Si devices yielded an angular resolution of 0.4^o. All fragments except the lightest ($Z < 4$), which will not be considered in the present analysis, were stopped in the 5 mm detectors. The ΔE-E measurements yielded unit charge resolution up to $Z = 57$ for most telescopes. The energy calibrations were performed by running several low intensity beams with different atomic numbers directly into all the detectors [8] , and the error on these calibrations is less than 2%. The pulse height defect in the Si detectors was significant for $Z \geq 25$ and a correction was applied [9]. The velocities of the fragments were inferred from their kinetic energy and charge, using the mass parametrization of ref. [10].

Figure 1 (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. 2b,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 a high percentage of these multi-fold events are essentially complete.

The following analysis is restricted to events where the 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 $\mathbf{V_s} = \sum_i m_i \mathbf{V_i} / \sum_i m_i$. In the incomplete fusion picture [5], 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 [11] show that 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.1 (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 GEMINI [10], filtered by the appropriate detector geometry, and is represented by the horizontal bars on fig.1 (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.2 (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 Ne + Au reaction at 60 MeV/N, but only for 2- and 3- body final states [12]. 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.

To investigate the behavior of nuclei as their excitation energy increases, excitation functions for the multi-fold events have been constructed from the results obtained for the various 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: $P(n) = N(n)/(N(2)+N(3)+N(4)+\ldots)$, 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.3) 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 ($\sim$ 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 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.3 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 1). 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 [6] predicts a strong decrease of the complex fragment decay probability with decreasing angular momentum [13]. 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. [3] predict a sudden rise in the multibody probability at $\sim$ 3 MeV/N for a nucleus of mass 100. Gross et al. [4] predict a similar transition towards nuclear cracking at an excitation energy of $\sim$ 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$\sim$160) is governed by the same mechanism up to an excitation energy approaching the total binding energy of these nuclei.

In this letter we have demonstrated a technique which permits the characterization of hot nuclei and of their decay over a wide range of excitation energies using a single bombarding energy. The source velocity technique[7] 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 ($\sim$ 6 MeV/N) no evidence for a phase transition towards nuclear cracking was found.

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Figure Captions

Fig.1 : 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.

Fig.2 : Same as fig. 1 for 2-, 3- and 4-fold events from the ^{139}La + ^{40}Ca reaction at $E_{lab} = 35$ MeV/N.

Fig.3 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.

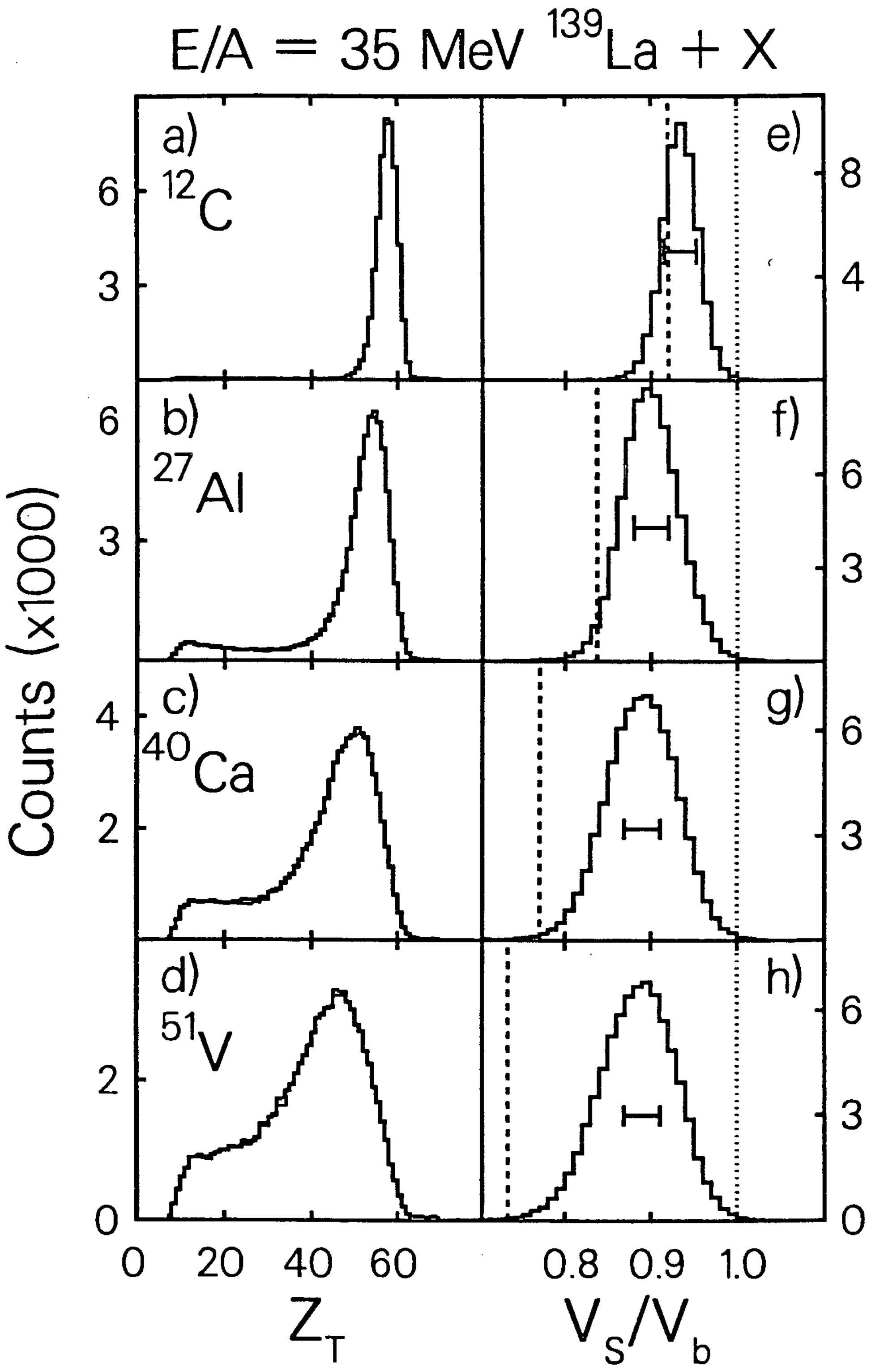

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fig.1

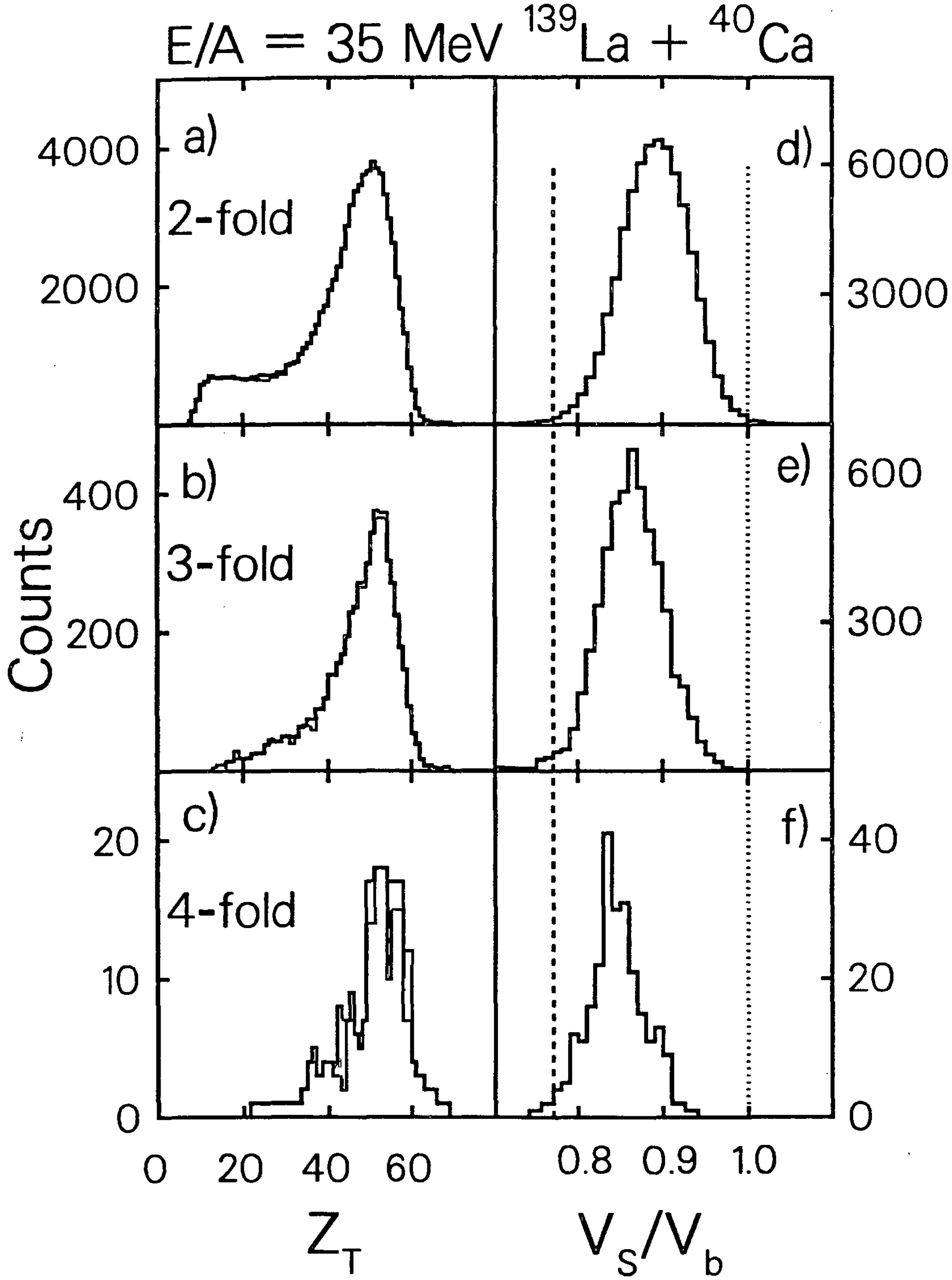

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fig.2

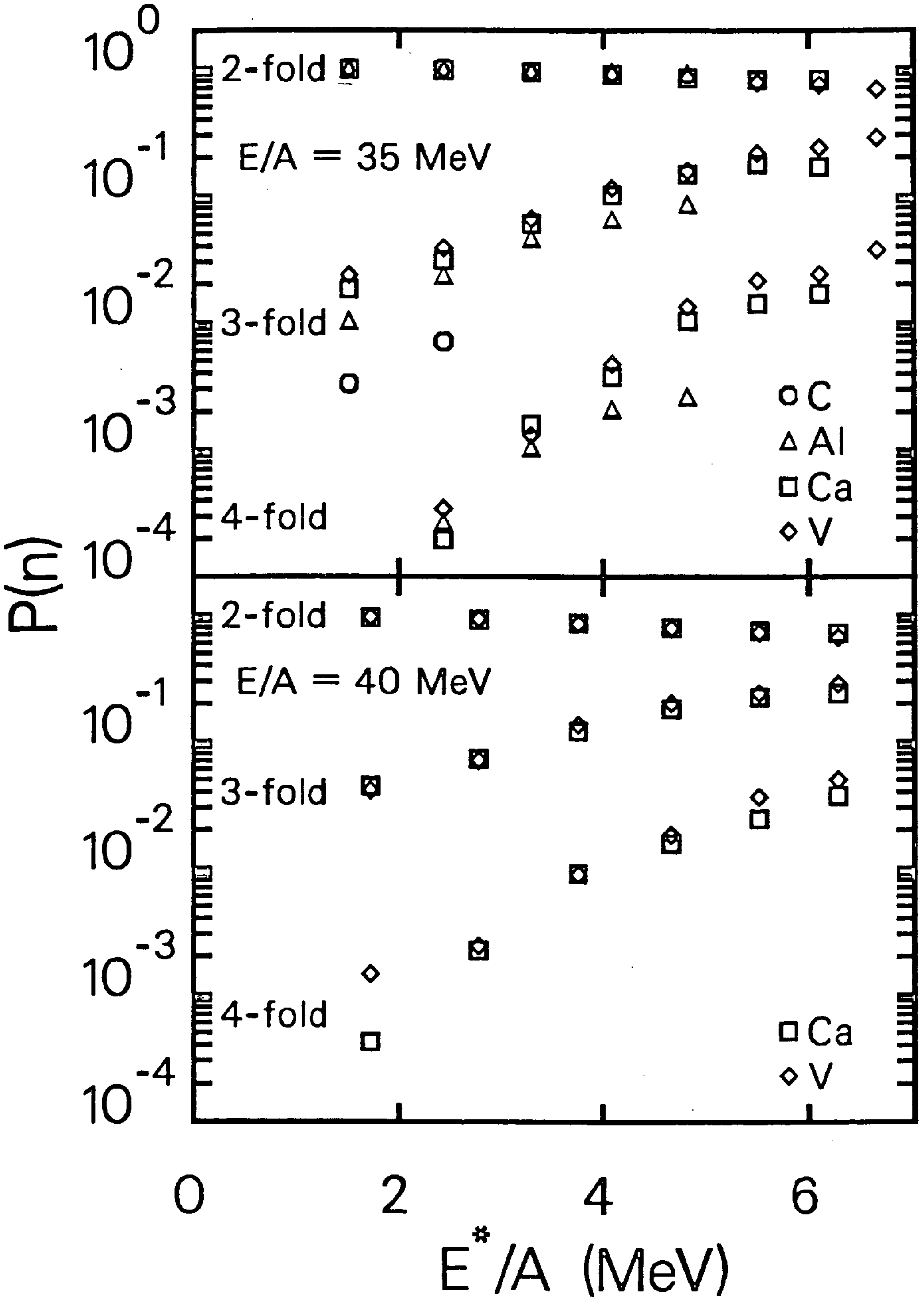

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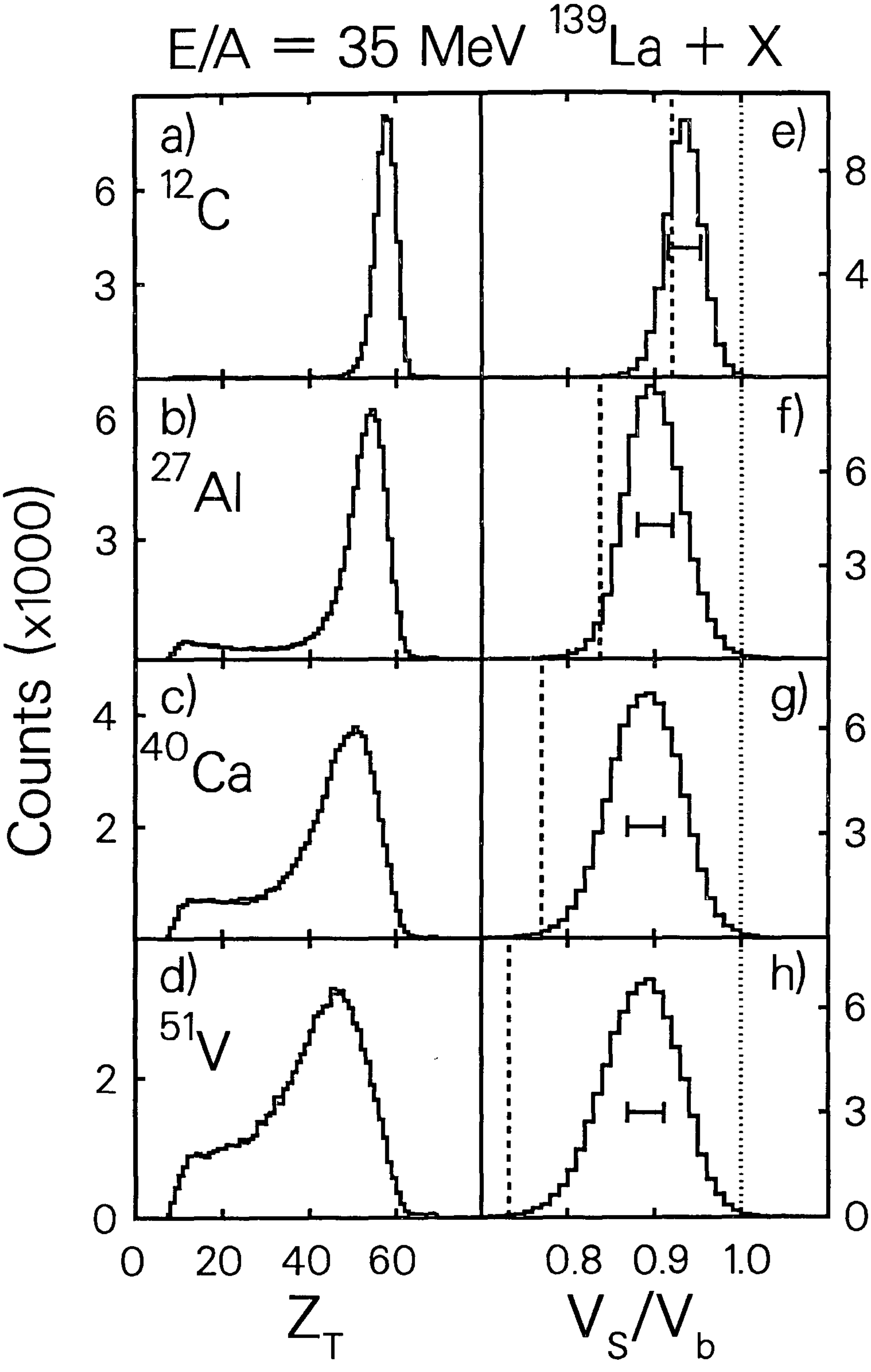
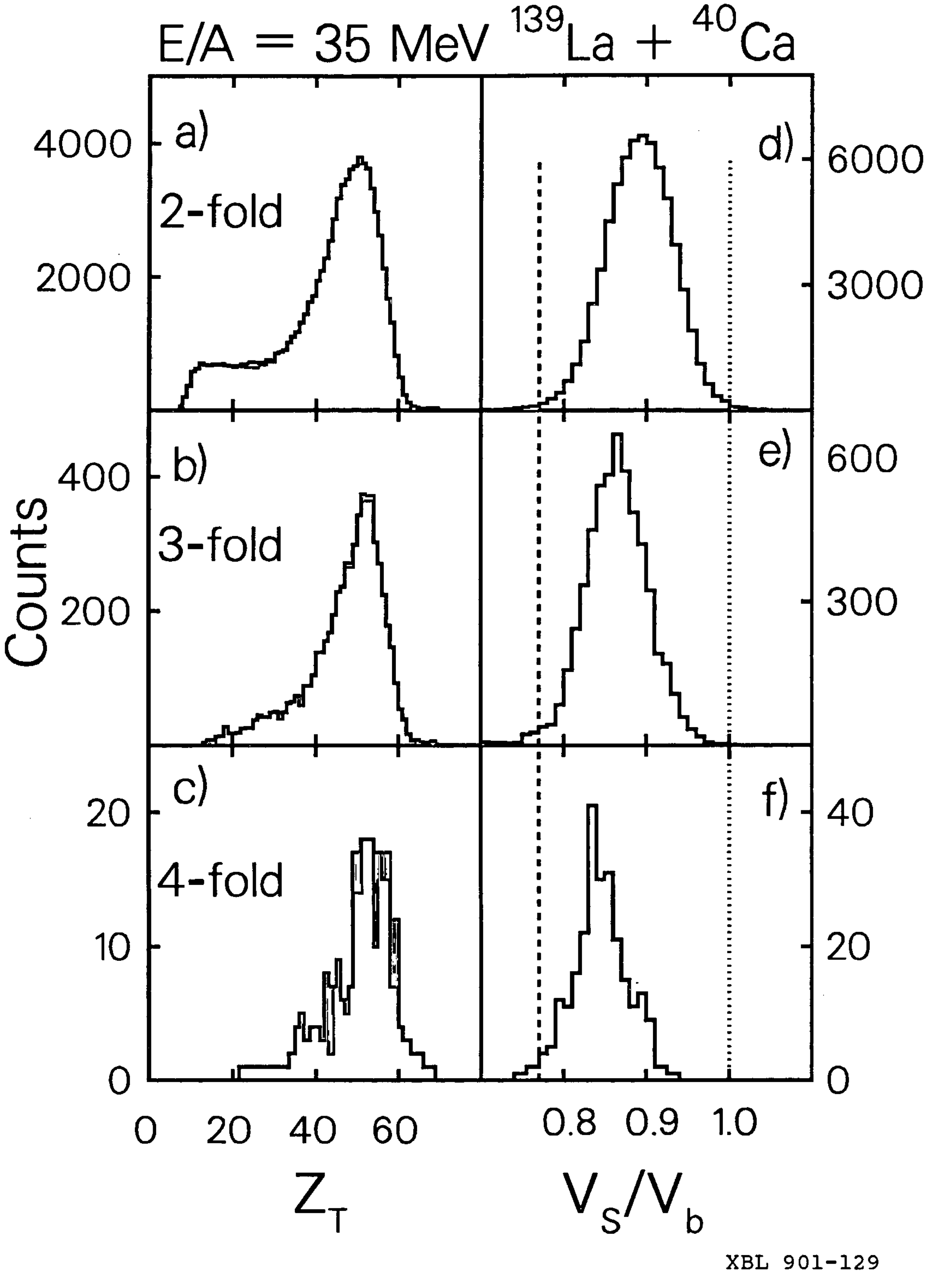
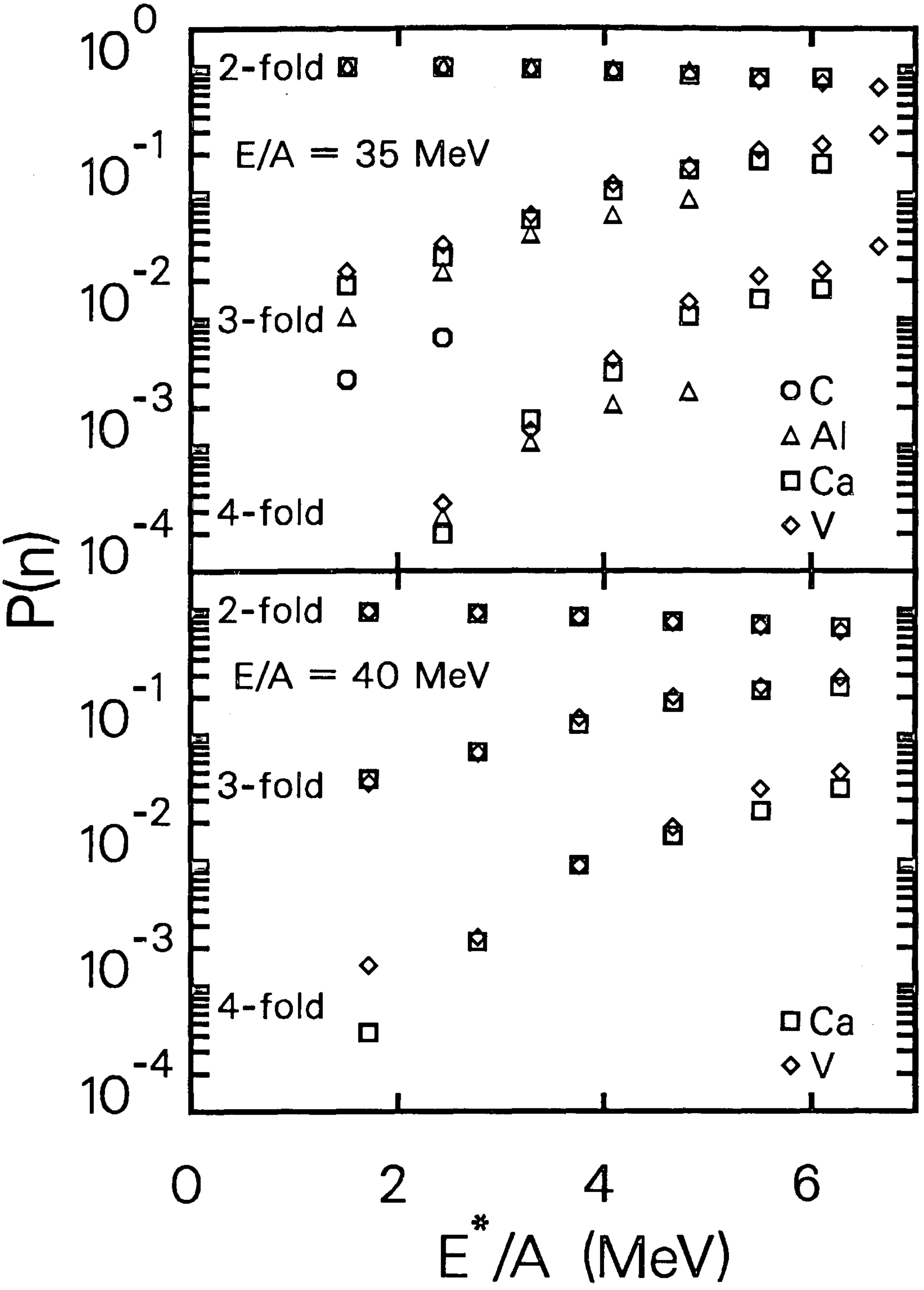
fig.3


E/A = 35 MeV ^{139}La + X
Counts (x1000)
a) ^{12}C
b) ^{27}Al
c) ^{40}Ca
d) ^{51}V
e)
f)
g)
h)
0
3
6
2
4
0 20 40 60
Z_T
0.8 0.9 1.0
V_S/V_b
8

XBL 901-130


E/A = 35 MeV ^{139}La + ^{40}Ca
a)
2-fold
b)
3-fold
c)
4-fold
d)
e)
f)
4000
2000
400
200
20
10
0
6000
3000
600
300
40
20
0
Counts
0
20
40
60
Z_T
0.8
0.9
1.0
V_S/V_b

XBL 901-129



P(n)
E*/A (MeV)
0
2
4
6
10^0
10^-1
10^-2
10^-3
10^-4
2-fold
3-fold
4-fold
E/A = 35 MeV
E/A = 40 MeV
○ C
△ Al
□ Ca
◇ V

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