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The Systematics of the Deexcitation of Hot Nuclei and the Onset of Multibody Decay

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Abstract

Results from the asymmetric reactions 80 and 100 MeV/u La + C are presented and compared to earlier work with the same system at 18 and 50 MeV/u. Fragment-fragment correlations, cross sections, and distributions in velocity space indicate the continued dominance of a quasi-binary decay mechanism with increased emission of light charged particles. The distributions in velocity also indicate a progression toward a "fireball" type of reaction mechanism. However, the angular distributions of the emitted fragments are incompatible with statistical production mechanisms that have successfully explained the lower energy results, and indicate the dynamical nature of the emission process. Dalitz plots of triple complex fragment coincidences are presented in order to investigate the nature of the multibody decays.

Introduction

Studies of asymmetric projectile-target combinations such as La + C at bombarding energies ≤ 50 MeV/u have investigated the mechanisms of complex fragment ($Z > 2$) emission.[1-5] These studies have shown typically only one or two fragments of $Z > 2$ are produced. The two processes responsible for the emission of these fragments are: 1) The statistical compound nucleus emission of fragments over the entire range of mass asymmetries, characterized by a well-defined source velocity, emission velocities in the source frame that are Coulomb-like, and isotropic angular distributions within this frame; and 2) an anisotropic dynamical binary mechanism relegated to Z-values near those of the target and projectile that is likely related to the low-energy deep-inelastic and quasi-elastic scattering mechanisms.

At 18 MeV/u experimental cross sections from the La + C reaction in the range $Z_{target} < Z < Z_{projectile}$ have been successfully explained by calculations using the statistical model code GEMINI assuming complete fusion and a diffuse l-wave distribution. At 50 MeV/u the fragments near symmetry from the same system have been interpreted in a similar fashion - the statistical decay of an equilibrated compound nucleus, although in this case the velocity of the source indicates that the emission takes place following an incomplete fusion reaction rather than complete fusion. In addition to the degree of fusion of the system, a second difference is that at the lower bombarding energies nearly all the charge of the target-projectile system is detected in binary coincidence events ($\Delta Z < 1$), whereas as the bombarding energy is increased, progressively less charge is contained in the two heavy fragments (see Fig. 1-2). The charge loss of eight at 50 MeV/u has been interpreted as due to three pre-equilibrium protons from the target that remain at rest in the laboratory, thus accounting for the measured source velocity, and five evaporated charges from the compound nucleus or the hot primary fragments.

Gross, in contrast, has chosen to interpret the 50 MeV/u data in terms of a statistical multifragmentation mechanism in which the nucleons rather than being evaporated are instead assumed to be emitted simultaneously with the heavy fragments.[6] In principle one could experimentally distinguish post-scission from pre-scission light charged particle emission by studying light particle-heavy particle correlations, however it would be very difficult to distinguish the sequentiality, or lack thereof, of the light charged particles emitted prior to scission.

In any event, either interpretation assumes the capture of some portion of the target nucleus by the projectile, and the subsequent thermalization and decay of the composite system.

Two natural questions arise that are germane to the extension of these and similar studies to higher energies: 1) What is the maximum amount of excitation energy or excitation energy per nucleon that a nucleus can hold? and 2) What is the maximum relative velocity beyond which there is no longer capture of any portion of the target nucleus by the projectile? That is, when does the incomplete fusion process cease? Since this question concerns the dynamics of the interaction, the maximum relative velocity that can sustain incomplete fusion will depend upon the target-projectile system. Of course, it is expected that above some bombarding energy this process will desist. For instance in the La + C system predictions from a simple geometrical-kinematic model[7] indicate that at 80 MeV/u impact parameters larger than about 4 fm can lead to participant-spectator types of reactions.

In addition, studies of the two above questions can give important information regarding the multifragment decay process. If multifragment decays are governed by a statistical mechanism then it will be the total excitation energy that is the important parameter. If however, the mechanism is dynamic then we expect that the bombarding energy, or relative momentum, may be the quantity of interest. Recent work has indicated that the total excitation energy of the system is more strongly correlated to the complex fragment multiplicity distributions.[8,9]

To answer the first question above it may be best to study the results from symmetric collisions at bombarding energies less than the Fermi energy where the dynamical effects should be smaller, yet the excitation energies can be quite high. To best answer the second question concerning the dynamics of the interaction itself, we have extended our studies of asymmetric systems to larger bombarding energies - 80 and 100 MeV/u. Previous studies have indicated the disappearance of the fusion process by studying evaporation residues[10,11] or coincident fission fragments[8], however it has been shown in lighter systems that complex fragment emission can be a more sensitive probe for fusion products.[12]

Experimental

Beams of ^{139}La ions of 80 and 100 MeV/u were provided by the Lawrence Berkeley Laboratory BEVALAC accelerator complex with intensities of approximately 10^8 particles per spill. Products from reactions with a 3.3 mg/cm^2 ^{12}C target were detected in an 11 element telescope array arranged in a rectangular (3 vertically x 4 horizontally) geometry with one element missing for the beam exit. The detector array subtended 14.4° in-plane, and 10.5° out of plane, which due to the forward focusing of the products from the reverse kinematics reactions provided good solid angle coverage for fragments of $10 \leq Z \leq 30$ and modest coverage for lighter and slightly heavier fragments. Each telescope element of the array consisted of four separate detectors. A 300 μm intrinsic Si ΔE, followed by two 5 mm Si(Li) E1 and E2, and finally a 3" plastic for the lightest ions. Each of the first three detectors was position sensitive in one dimension, and the sensitive dimensions were arranged in an x-y-x configuration to give both the in- and out-of-plane angles of the emitted particles. Inclusive and coincident events were written to tape event-by-event using a VME based data acquistion system interfaced to a VAX 780 computer.

Results

A. Coincidence Events

Figure 1 shows 2-body coincidence events detected with the La + C system at four bombarding energies - 18, 50, 80, and 100 MeV/u. The striking feature of this figure is that at all of the bombarding energies, even up to 100 MeV/u, the products are dominated by events in which there are only 2 heavy fragments. Multibody events with more than two heavy fragments will fall below the dominant band. As expected, as the bombarding energy is increased there is a significant increase in the amount of multibody decay. Although at the lower energies the detector configurations were optimized for events with nearly 2-body kinematics (symmetric configurations), at the higher energies the larger number of detectors and the proximity to the beam (thus fairly large efficiency) allowed the efficient detection of multifragment events as well.

From the projections along Z total (Z1 + Z2) (Figure 2) we see that the distribution of total detected charge gets smaller and the width increases as the bombarding energy is increased. A natural question to ask is the nature of this missing charge. Is it due to missing a third complex fragment or due instead to larger multiplicities of protons and alpha particles? We can answer this question by looking at the total charge in coincidence events where there are two or more fragments detected (Figure 3). We find that the total detected charge does not depend upon the number of coincident complex fragments and thus that there is a similar loss of light charged particles independent of the heavy fragment multiplicity. It would be very interesting to determine the nature of the lost light charged particles, whether they are pre-equilibrium or evaporated. The number of evaporated particles would, of course, give a good indication of the amount of (thermalized) excitation energy in the system. Unfortunately, it is impossible in the present study to make a determination of the relative amounts of pre-equilibrium and equilibrium emission of light charged particles.

B. Cross Sections

Figure 4 shows the angle integrated cross sections for the La + C system at the four bombarding energies. The results at 18 MeV/u are consistent with the statistical emission from a system beyond the Businaro-Gallone transition point. There is a maximum in the yield due to a minimum in the potential energy surface at symmetry. These results are described in some detail in reference 4. As the bombarding energy is increased to 50 MeV/u the cross sections near symmetry decrease and become flat. As stated above, we have interpreted these results as statistical compound nucleus emission following incomplete fusion of the target and projectile. The flattening of the cross sections can be explained by the increased temperature of the emitting system, which tends to make all of the decay channels more equally probable. It is likely that at 50 MeV/u a smaller geometric cross section leads to equilibrated products than at 18 MeV/u. This would explain the decrease in the absolute magnitude of the cross sections, and is supported by the large increase in the cross sections for the anisotropic mechanism between 18 and 50 MeV/u.[13]

At the larger incident energies the cross sections evolve into U-shapes. Although this is incompatible with statistical emission from a system beyond the Businaro-Gallone point, it is not inconsistent with statistical emission from a system that has lost a large amount of charge, or angular momentum, or both, prior to the emission process. Thus we can draw no conclusions about the equilibrium or non-equilibrium nature of the process from the shape of the cross section distributions themselves. The symmetric shape of the cross section distribution at 80 MeV/u is more evidence of the predominantly binary nature of the decay process. A large amount of multifragment emission would generate monotonically decreasing distributions, or distributions that remain flat with increasing Z-value.

C. Source of the Fragments

Figure 5 shows the invariant cross sections in Z - rapidity space for the 80 MeV/u La + C reaction. This distribution is similar to "lambda" plots for the same system at lower bombarding energies in that one sees two kinematic solutions for the emission of particles, one forward in the source frame, and one backward, that meet at the heaviest detected fragments which have a nearly constant laboratory velocity. The separation between the legs of the distributions is trivially due to momentum conservation and the Coulomb repulsion energy in the decay, as the lighter fragments receive a larger velocity. The distribution indicates that the two body kinematics are fairly well preserved in these reactions. There is no filling of the area between the legs as would be expected for events with large multiplicities of heavy fragments.

The major difference between the distribution at 80 MeV/u and those at the lower energies is that for the former energy the bulk of the products of $Z > 4$ lie upon the legs of the distribution. There is little of the tailing to lower velocities for Z-values near the target mass as is seen at lower energy. Figure 6 illustrates the disappearance of this intermediate rapidity component at backward angles for $Z = 5$ fragments. The $d\sigma/dv$ spectra are gated on several angles in the source frame for the 18 and 80 MeV/u La + C reactions. It is clear that the shapes of the velocity distributions at 80 MeV/u are quite independent of the angle in the source frame. All of the observed fragments of $Z \geq 5$ appear to be emitted with Coulomb-like velocities from a projectile-like source.

Results from the 50 MeV/u La + C reaction indicate an incomplete fusion mechanism in which mass is transferred from the target to the projectile. The disappearance of fragments in the intermediate rapidity regime at larger bombarding energy is an indication of the onset of the "fireball" picture of nucleus-nucleus interactions.[14] In the fireball model the reaction is divided into three regions - the projectile spectator, the target spectator, and the fireball or the region in which the nucleons in the target and spectator overlap. For the 80 MeV/u La + C reaction the estimated thermal energy per nucleon in the fireball is approximately 20 MeV,which is much larger than the nucleon binding energy. It is likely that at excitation energies this high the participants in the fireball region would be emitted entirely as nucleons. However, if the bombarding energy is not large enough for the fireball to completely decouple from the spectator fragments then the region of high excitation can expand and cool. In the limit of complete equilibration we have the incomplete fusion process seen at lower energies.

The fireball region will have progressively higher temperatures and smaller masses as it is able to decouple more and more quickly at larger bombarding energy. The intermediate rapidity fragments are observed to be less massive as the bombarding energy is increased, as expected from this effect.

D. Angular Distributions

Figure 7 shows the cross sections in rapidity vs. transverse momentum space gated on particular Z-values. In this representation the distributions are invariant to transformations in rapidity. As illustrated in Fig. 7, the bulk of the cross section is distributed along the Coulomb circles, the radii of these circles being determined by the Coulomb velocity with which the fragments are emitted. The fact that the distributions are fairly narrow, and nearly circular, again indicates that the majority of the reactions leading to these products are "quasi-binary", the two-body kinematics are approximately preserved. As stated and explained above, there is little of the backward tailing into the intermediate rapidity region for $Z = 6$ fragments as is seen at lower energy.

At 18 MeV/u the angular distributions $d\sigma/d\theta$ for products from the La + C reaction were isotropic for a wide range of Z-values (see Fig. 8). For those light Z-values contaminated by the deep-inelastic and quasi-elastic components at backward angles, the distributions at forward angles were constant as required by statistical emission from a source with a large amount of angular momentum. In contrast, at 80 MeV/u the distributions change smoothly from backward- to slightly side- and finally forward-peaked with increasing Z-value. For the lighter fragments there is no region of constant $d\sigma/d\theta$ at forward angles as seen at lower energy. Although the fragments appear to be projectile related by the fact that they are emitted with Coulomb-like velocities relative to a projectile-like source, these angular distributions are incompatible with statistical emission from the projectile-like fragment. We see evidence for the predominance of a dynamical mechanism leading to the bulk of the cross-sections for all Z-values, except perhaps those near symmetry which are only very slightly side-peaked.

The two effects mentioned above, the onset of the fireball, and the demise of the statistical emission process are related to the dominance of dynamical effects in this energy region. At larger bombarding energies in the "classical" fireball regime with larger relative velocities and faster projectile-target interactions, products from asymmetric reactions are emitted very nearly isotropically.[15-17] This has been explained as resulting from a nearly two-step reaction mechanism, where the decay of the target remnant is separate from the projectile-target interaction.[18] At these lower incident energies, although the velocity of the detected fragments identifies them as projectile-like in origin, the angular distributions of the fragments carry the dynamics of the interaction process in that the lighter fragments are preferentially emitted backwards toward the lighter reaction partner. Our explanation for this effect is that at these lower energies the decoupling of the fireball may occur on the same time scale as the fragment emission process, whereas at larger energies the interaction is much faster and influences the decay products to a much smaller extent.

E. Multibody Events

Due mainly to the forward focusing of the reverse kinematic technique we have observed a large number of events with three detected fragments of $Z > 2$. To investigate how nuclei disintegrate we present these events as Dalitz plots (Figure 9). The Dalitz plots show the correlations in the detected Z-values, where for each event the three ratios Z_1/Z_{total}, Z_2/Z_{total}, and Z_3/Z_{total} are plotted relative to the three sides of the triangle. Each side of the triangle represents an axis where one of the above ratios is zero and the distances from the axes indicate the values of the three ratios. Each point is uniquely located since $Z_1/Z_{total} + Z_2/Z_{total} + Z_3/Z_{total} = 1$. The figures have been symmetrized by ordering the three detected Z-values in each of the six possible ways as Z_1 , Z_2 , and Z_3 . A gate has also been set on the value of Z_{total} to insure that only events in which the bulk of the charge is detected are analyzed.

The linear contour plots for the 80 and 100 MeV/u La + C systems show that in both reactions we detect mainly events in which there are one heavy and two light fragments. There is a weak maximum for detecting one light fragment and two medium mass fragments, and a deep minimum for detecting three equal mass fragments. Qualitatively, it appears that the charge split is slightly more symmetric at the larger energy, since the minimum in the center of the distribution is not as broad. Preliminary Monte Carlo studies indicate that the detection efficiency is optimized to detect the more symmetric events rather that the asymmetric ones, thus the maxima observed in detecting one heavy and two light fragments correspond to the true experimental distributions of events.

The total number of events in which there are 3 fragments heavier than alpha particles is found to increase by approximately a factor of 3 between 80 and 100 MeV/u. The Monte Carlo simulations have indicated that the efficiency for detecting 3 coincident fragments is relatively insensitive to the change of the velocity of the emitting system between these two bombarding energies. Other observables such as centroids and widths of the velocity distributions, and the angular distribution of the fragments in the source frame are not very different between the 80 and 100 MeV/u systems. This indicates that the factor of three increase in the number of three body events is not seriously biased by the detection efficiency, and that for this system the 80 - 100 MeV/u energy range may be near the threshold for the multifragment emission process, where the probabilities for such events would be expected to rise dramatically.

Conclusion

We have shown that for the La + C system at 80 and 100 MeV/u the products of $Z > 2$ are predominantly produced in events in which there are two heavy fragments. The amount of 3-body decay ($Z > 2$) increases by about a factor of three between these two energies. The centroids of the total charge detected in coincidence events decrease and the widths increase with increasing bombarding energy. This is a continuation of the trend seen from 18 to 50 MeV/u with the same system. The charge loss in these events is shown to be in the form of light particles as the total detected charge is not sensitive to the multiplicity of heavy fragments.

Our major conclusions identify the 80 - 100 MeV/u regime as a very interesting region for studying the dynamics of asymmetric nucleus-nucleus collisions. The reaction products are emitted with nearly two-body kinematics thus simplifying the event reconstruction. The relative momentum between target and projectile is large enough such that the light reaction partner cannot be thermalized in complete or incomplete fusion reactions, yet the time scale of the target-projectile interaction is long enough that the memory of the entrance channel is preserved in the fragment angular distributions. It will be interesting to determine if dynamical models such as Laudau-Vlasov or Quantum Molecular Dynamics are able to reproduce the features of these reactions.

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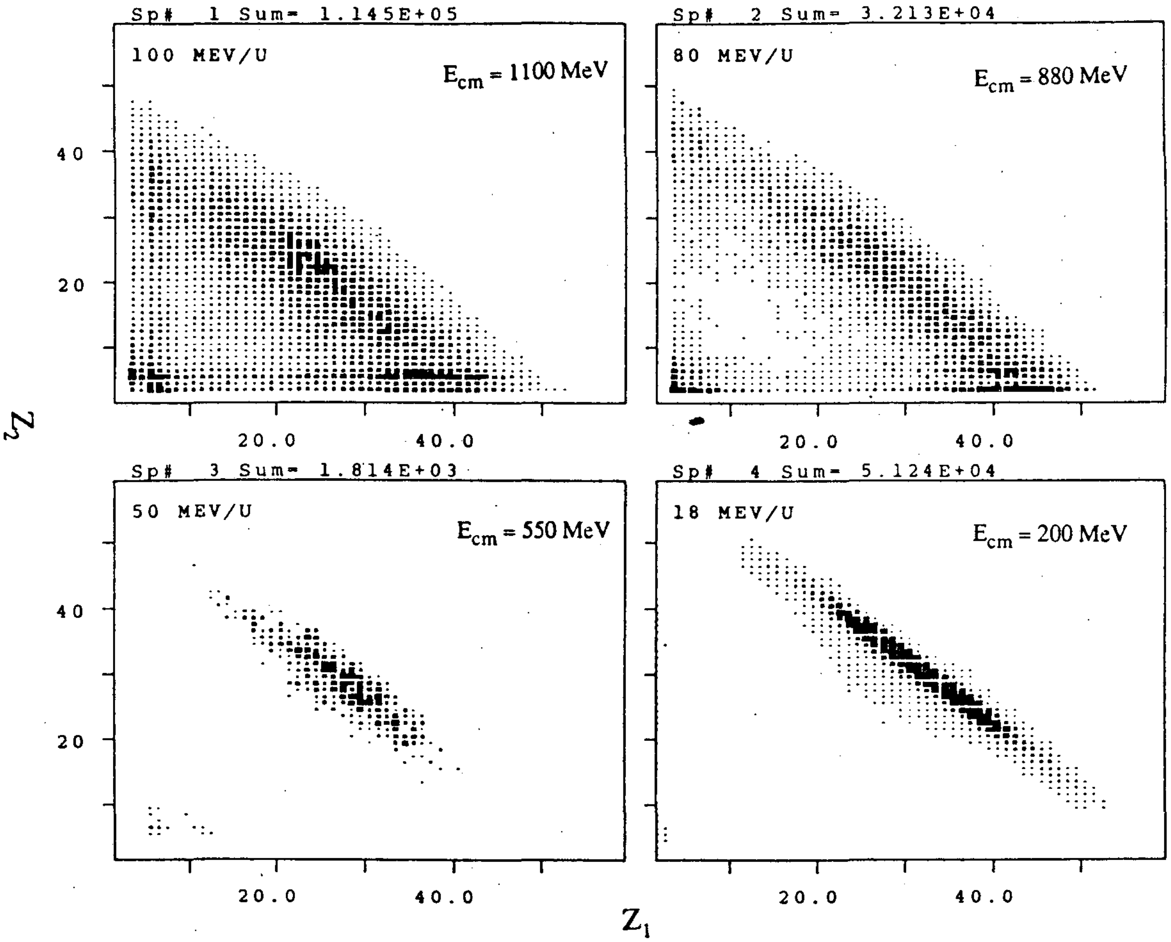

Figure 1. Coincidence events plotted as Z_1 vs. Z_2 for the La + C system at four bombarding energies - 18, 50, 80, and 100 MeV/u. The energies in the center-of-mass system for each bombarding energy are indicated. The dominance of the band corresponding to two heavy ($Z > 2$) fragments containing the bulk of the charge is clearly seen in all cases. The distribution of events along the intense band is due to the different detection geometries, symmetric in the cases of 18 and 50 MeV/u, and asymmetric at the higher energies.

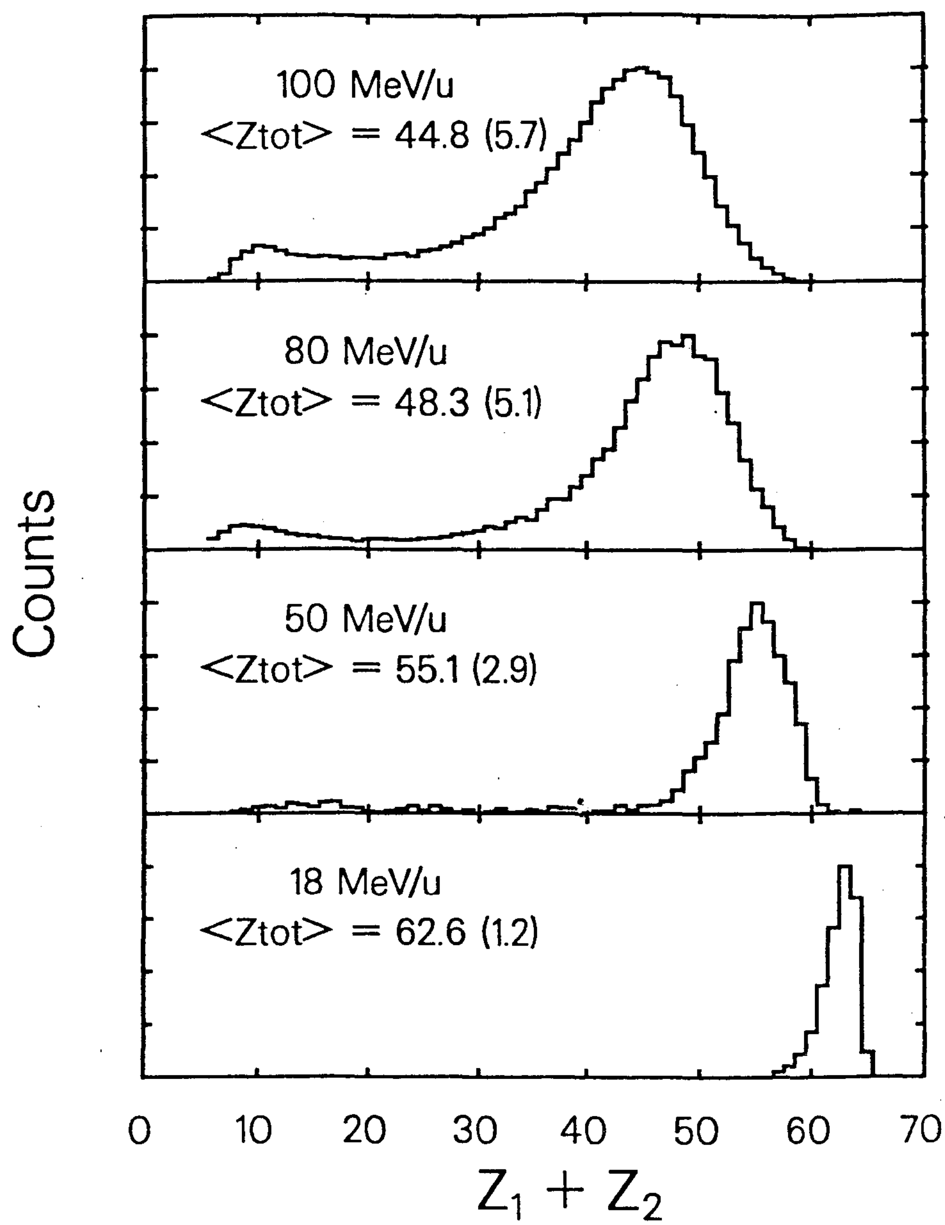

Figure 2. The total charge detected in coincidence events shown for the La + C system at four bombarding energies. The distributions have been normalized to the same number of counts in the most probable bin. In each case a peak is seen corresponding to the majority of the charge being detected with the two heavy coincident fragments. The centriods and widths of the peaks are indicated. The centroid shifts to lower total charges and the width increases with increasing bombarding energy.

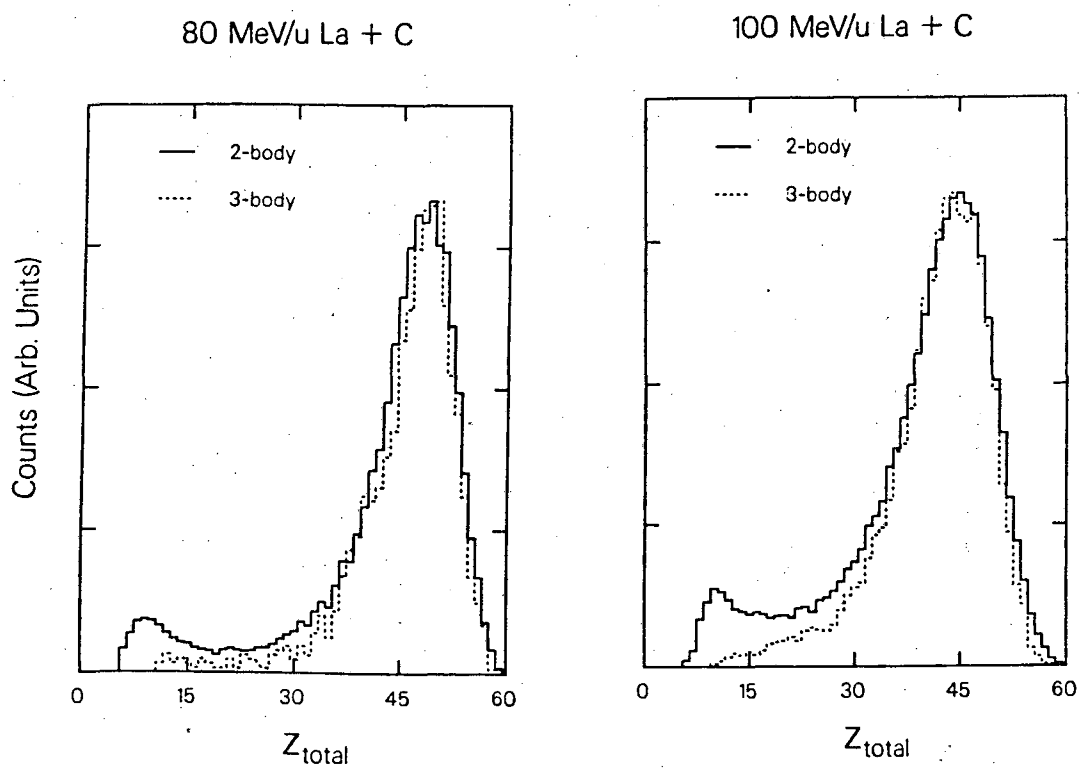

Figure 3. The total charge detected in two- and three-body coincidence events for the 80 and 100 MeV/u La + C reactions. The distributions have been normalized to the same number of counts in the most probable bin. It is apparent that the distributions are virtually identical for two and three coincident heavy fragments.

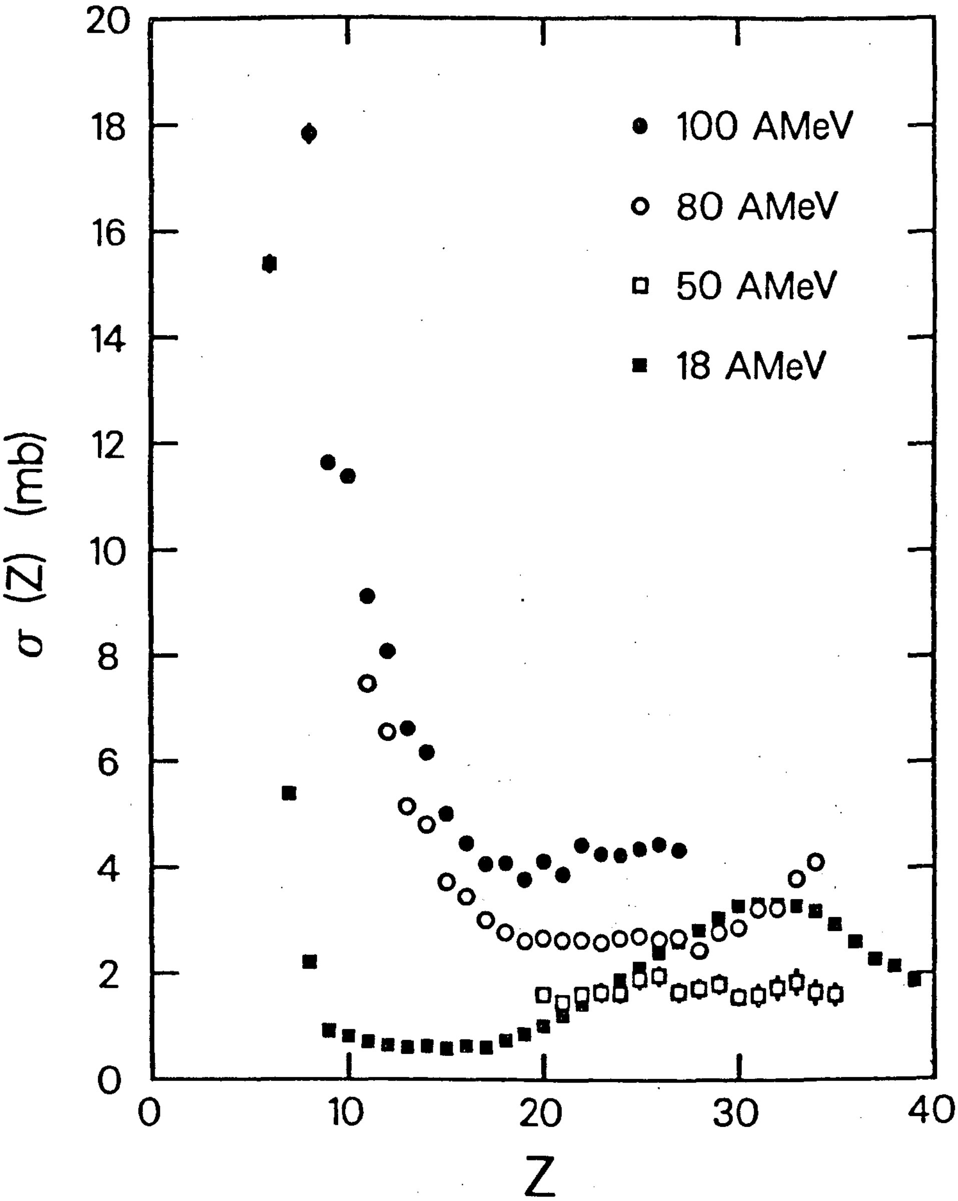

Figure 4. The cross sections as a function of fragment charge for the La + C system at the four bombarding energies (see text).

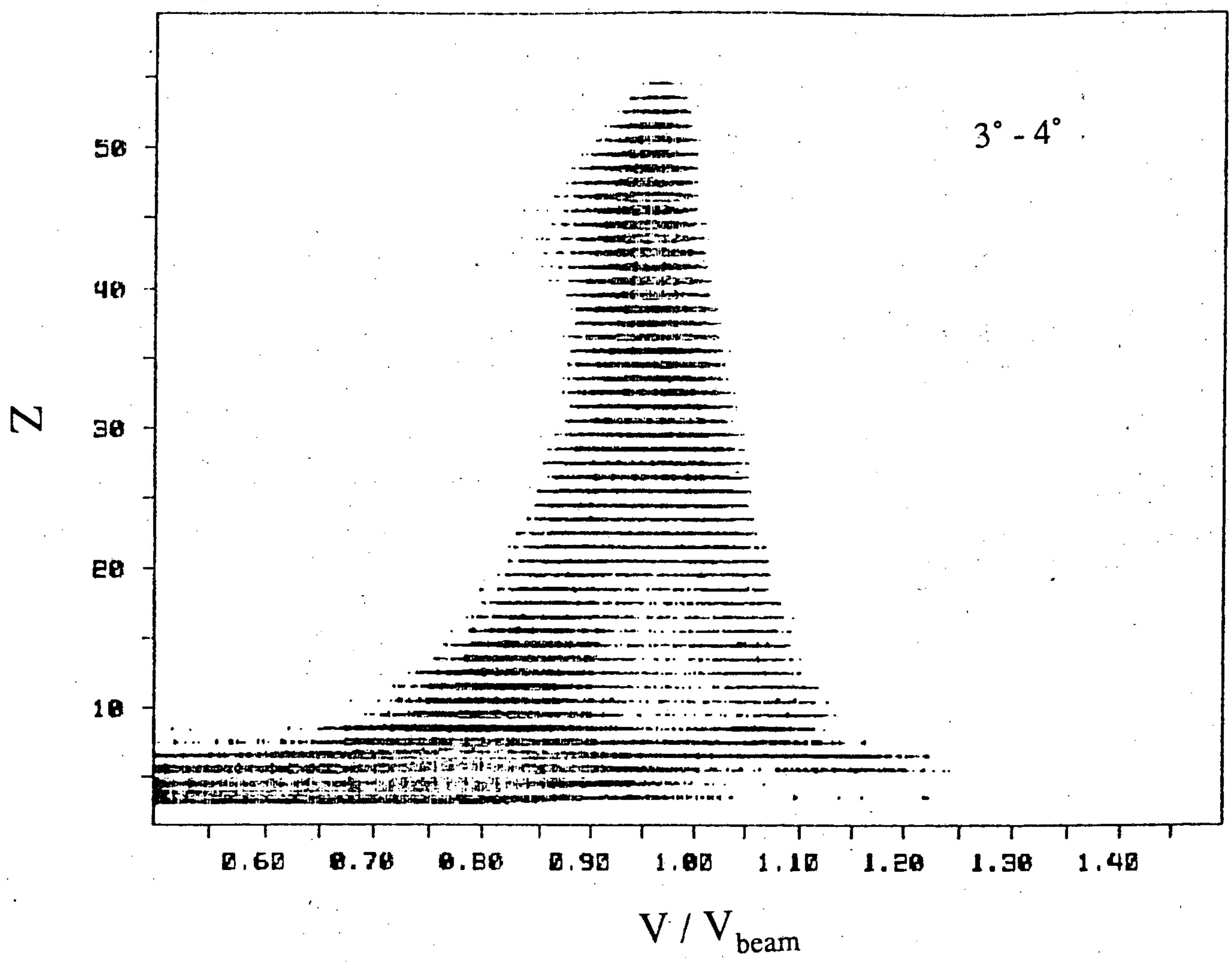

Figure 5. The Gallilean invariant cross section $d^2\sigma(Z)/v^2dvd\Omega$ for the 80 MeV/u La + C reaction gated on laboratory angle from 3° - 4°. The "lambda" distribution characteristic of Coulombic emission is apparent and is the only source of fragments for the majority of Z-values.

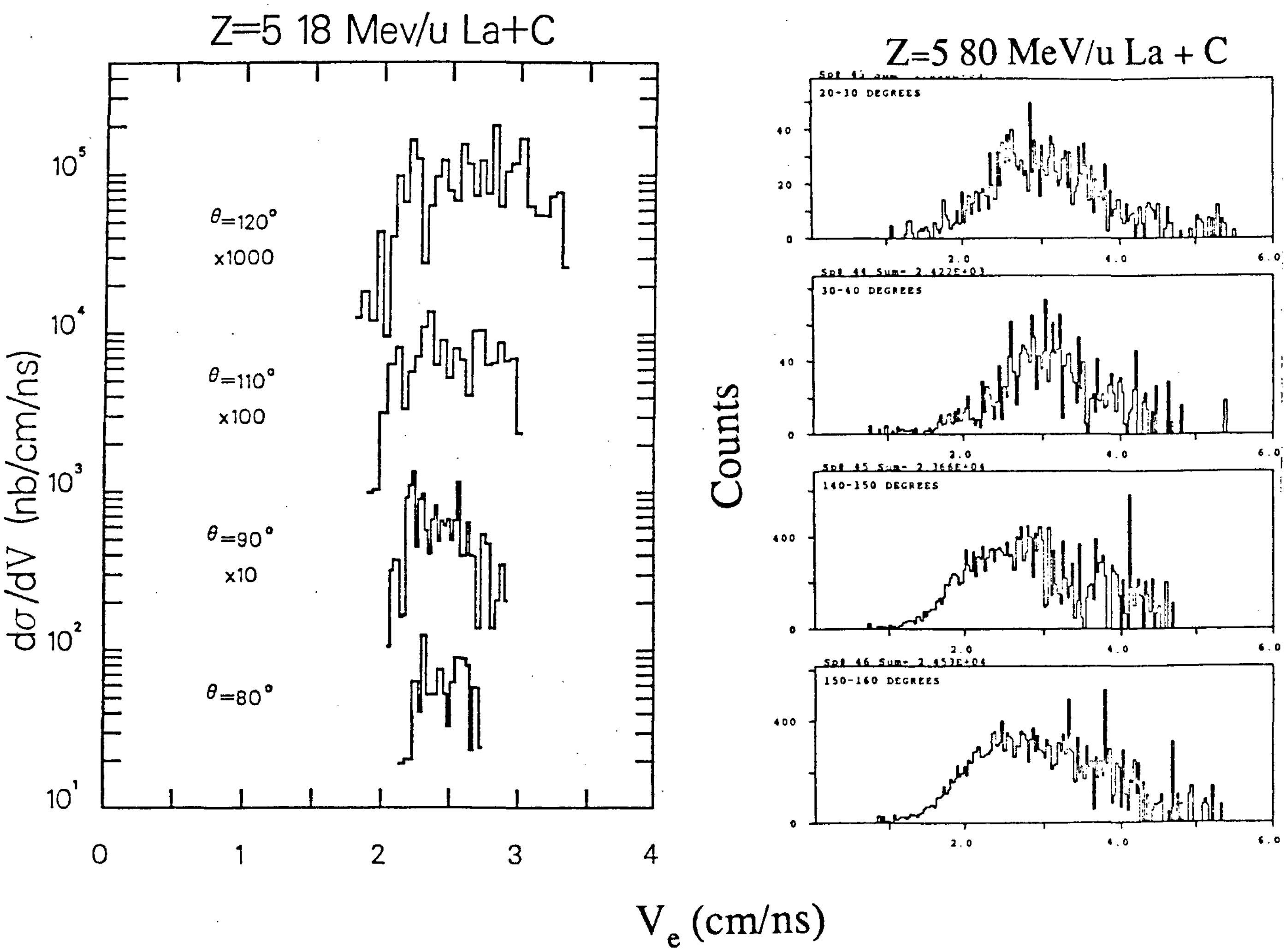

Figure 6. dσ/dv distributions gated on Z = 5 fragments at various angles in the source frame. The tailing to larger velocities is apparent at backward angles in the lower energy data, but at 80 MeV/u all of the distributions are Coulomb-like and quite independent of angle.

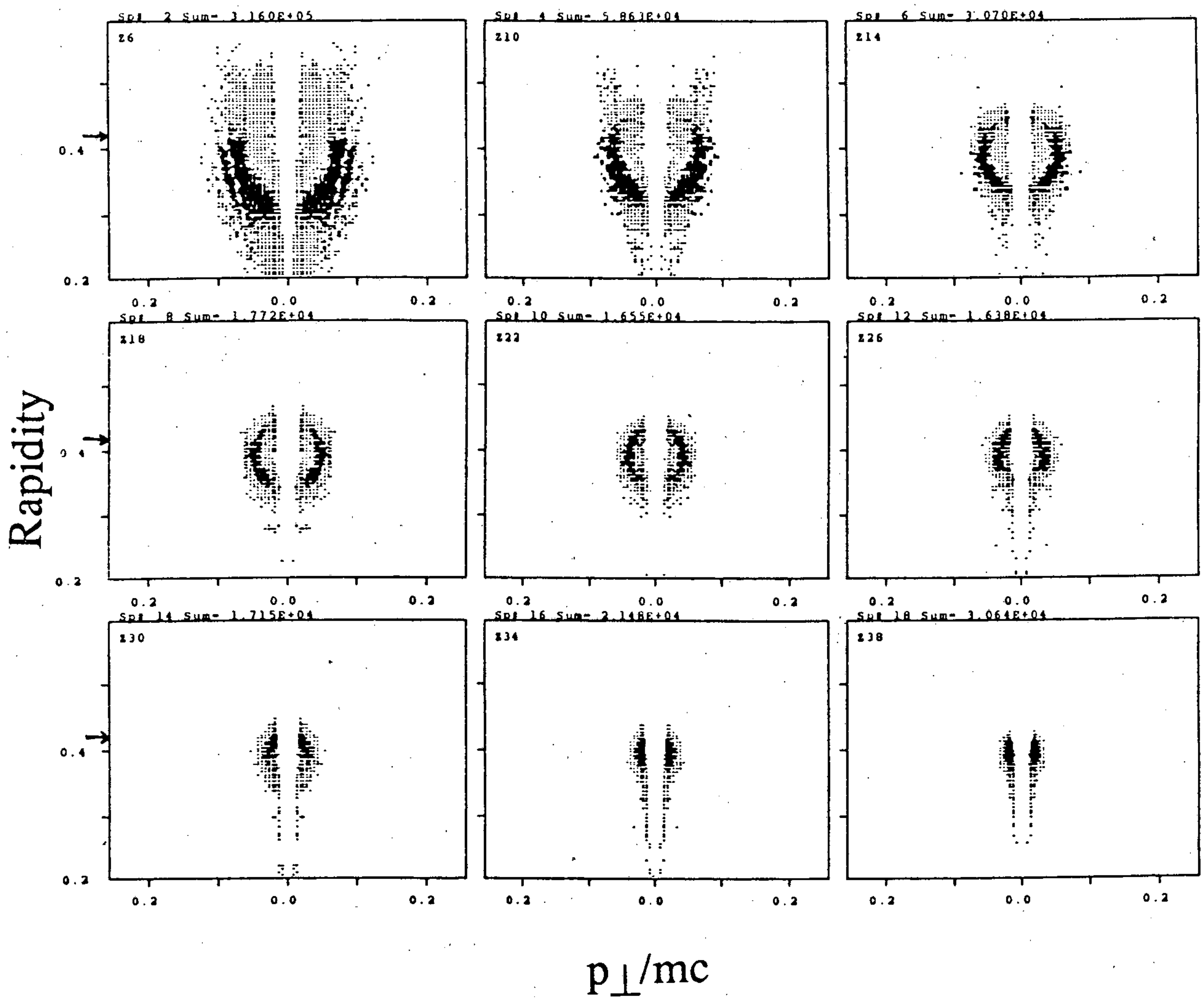

Figure 7. The cross sections in rapidity vs. transverse momentum space $d^2\sigma / dyd(p_\perp/mc)$ for the 80 MeV/u La + C reaction gated on the indicated Z-values. These distributions are invariant to transformations in rapidity. The distibutions are centered near the beam rapidity (arrows). The population of events mainly on the Coulomb rings indicates the disappearance of the intermediate rapidity source for all of these Z-values. The fragment angular distributions in the source frame evolve from backward- to slightly side- and then forward-peaked with increasing Z-value.

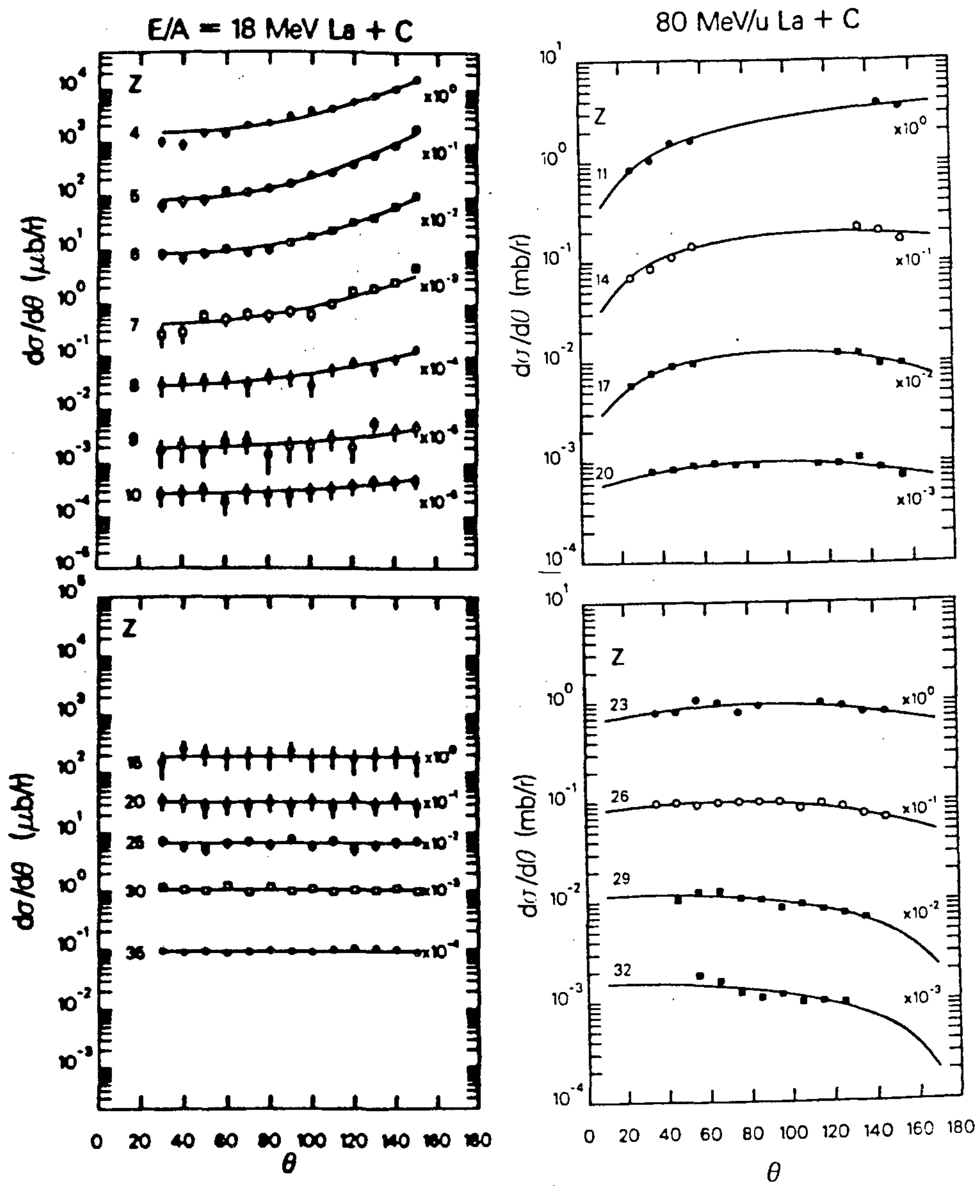

Figure 8. Angular distributions in the source frame dσ/dθ for products from the 18 and 80 MeV/u La + C reactions. There are no regions of constant dσ/dθ at 80 MeV/u as seen at the lower energy and interpreted as the decay products from equilibrated rapidly rotating compound nuclei. Instead the distributions evolve from backward- to forward-peaked with increasing Z-value. The solid lines are the fits to the distributions used to extract the total cross sections.

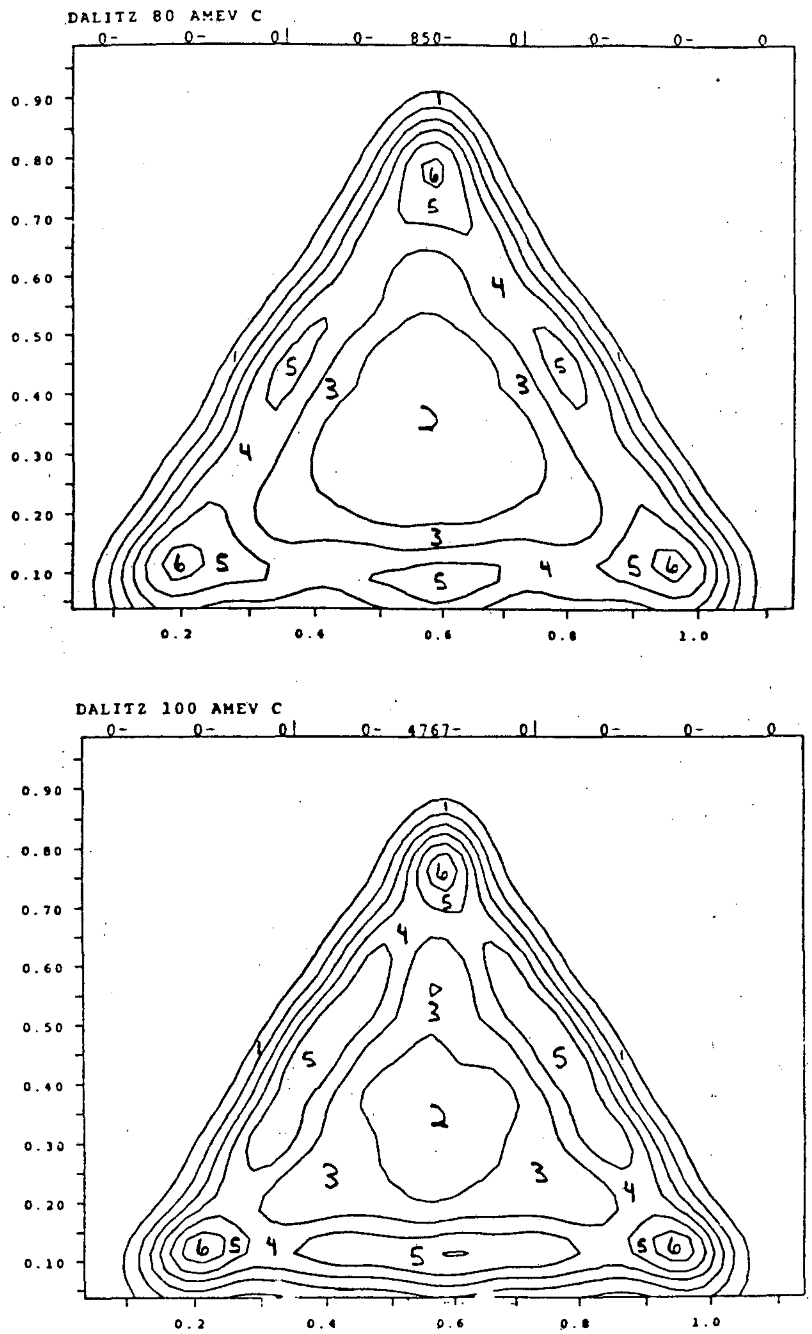

Figure 9. Linear contour Dalitz plots for the three-body events in the 80 and 100 MeV/u La + C reactions. The y-axis is the ratio Z_1/Z_{total}. The x-axis = tan 30° * (Z_2/Z_{total}) + (Z_3/Z_{total}) / sin 60° = 0.577 * (Z_2/Z_{total}) + 1.155 * (Z_3/Z_{total}). The detected fragments have been symmetrized so that there is no preferred ordering of Z_1, Z_2, and Z_3. See text for discussion.

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