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Event Shape Analysis of the Reaction ^{40}Ar+^{51}V within a Prompt Multifragmentation Scenario

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Abstract

We present the results of a multifragmentation model incorporating a primordial fragment distribution based on statistical multifragmentation followed by sequential decay of the resulting fragments. The Coulomb trajectories of the fragments are followed. The size of the emitting system and the excitation energy are chosen to reproduce the first order observables of the experimental results for 35 to 85 MeV/nucleon Ar+V collisions measured with the MSU 4π Array. Event-shape analysis in terms of sphericity-coplanarity is carried out and demonstrates that multifragmentation occurs in this system for all energies above 45 MeV/nucleon.

In a recent paper[1] central impact parameter events for the reaction $^{40}Ar +^{51} V$ at incident energies from 35 to 85 MeV/nucleon were selected using the Michigan State University (MSU) 4π Array and the event-shape distributions were analysed. The comparison of the event-shape distributions to a sequential and a simultaneous break-up simulation suggested that a transition from sequential emission toward a more prompt break-up mechanism occurred for incident energies above 45 MeV/nucleon. This interpretation was based upon the failure of the sequential simulation to reproduce the experimental data for the higher energies. The simultaneous simulation did not reproduce the data at any energy studied. The events for this latter simulation were generated by randomizing the emission directions of the outgoing fragments produced from the sequential simulation. However, rather than describing a simultaneous breakup into many large fragments this simulation described an isotropic emission of particles without kinematic correlations. Specifically, this simulation did not include the more plausible situation in which the original system fragmented into three or more large fragments which then decayed by sequential emission.

In the present paper we present a comparison of these data to the results of a multifragmentation model. Our goal is to demonstrate that the failure of the isotropic simulation was due to the inadequacies of the model. A more realistic simultaneous model is able to better reproduce the experimental data above 45 MeV/nucleon, where the sequential model failed. For that aim we use an extended multifragmentation model based on a two-step approach. In the first step the primordial fragment distribution after the prompt break-up is calculated within the statistical multifragmentation model[2] for a given excitation energy. In the spirit of ref.[3] the entropy determining the statistical weight of a partition has been maximized under the constraint that the kinetic temperature, τ, which characterizes the relative motion of the fragments, is given and taken as that extracted from Maxwell-Boltzmann distribution fits to the proton energy spectra. In the second step the dynamical evolution of the most probable partitions (typically of the order of 5000) has been considered. The break-up volume was fixed as $\rho_{break-up} = \rho_0/2$, $\rho_0 = 0.15 fm^{-3}$ being the normal nuclear matter density. The multiplicity of the primordial fragments changes from 5 to 6 as the excitation energies is raised from 8 to 16 MeV per nucleon. For this break-up situation the average distance between the fragments is at least 2.8 fm at which the Coulomb force dominates the fragment-fragment interaction. This has been taken into account by distributing the initial positions of the center of the fragments randomly within the break-up volume. The initial velocities have been chosen according to a Boltzmann distribution given by the kinetic temperature τ. When a particle is evaporated during the expansion, its velocity and the velocity of the recoiling remnant are calculated by assuming a randomly directed emission process in the system of the decaying parent fragment. Particles with $Z \leq 3$ are considered in the evaporation process (for details see refs.[4, 5]).

The results of the multifragmentation model, together with the experimental data, are shown in fig. 1 for the 65 MeV/nucleon case for a set of first order observables. Although the comparisons are not shown for the other energies, the agreement is good in all cases. These observables allow the input parameters for the simulations to be constrained without unduly biasing the multi-particle observables [1].

All of the simulations have used a distribution of source sizes that correlates to the distribution of impact parameters which were selected by the experimental apparatus. The degree to which the MSU 4π array is able to select central collisions has been studied using simulations of reactions and of the detector's response [7]. It has been estimated that for the reaction Ar+V the impact parameters sampled range from 0 to 4 fm. Using geometrical arguments, one can calculate a distribution of initial source sizes for the interaction region from the estimation of the impact parameter distribution. We allowed the shape of the source size distribution to have some freedom, as the impact parameter sampling estimates were based upon simulations and thus not firmly established. The distribution was adjusted to best reproduce the multiplicity observables.

The excitation energy per particle (E^*), which is the essential parameter of the multifragmentation model, is determined by the energy of the incident beam. Note that there is some ambiguity in defining source size and E^*, because the size of the overlap region between the target and the projectile, which corresponds to the source for energetic fragments, is only approximately known according to the experimental selection for central collisions. The kinetic temperature τ is determined in such a way to reproduce the kinetic energy spectra for protons and helium particles (see also ref. [3]).

We see that the multiplicity distributions are well described by the model and that the mass distributions for the light particles are reproduced satisfactorily. For fragments heavier than α-particles the agreement between theory and experiment is not as good. Concerning the energy spectra, we are able to describe those for the protons and the helium nuclei very well. These spectra contain components from the initial thermal emission from the source and from evaporative emission from decaying hot fragments. The energies of the emitted particles are then affected by the Coulomb fields from the surrounding fragments.

In fig. 2 we display contour plots of the event shape distributions of the experimental data, the sequential simulation [1], the isotropic simulation, and the multifragmentation model for the 65 MeV/nucleon case. The average sphericity values for the experimental data and for the three models are small compared to the spherical limit (S = 1.0). This is due to the small size of the system which undergoes fragmentation. At most, 16 fragments are observed in a single event. These low multiplicities limit the observed sphericity[6]. The mean values of these distributions are, however, statistically well separated. In fig. 3 we show the mean of the sphericity distribution as a function of the beam energy. In the figure, the experiment values are compared to values predicted by the three simulations. We have attempted to estimate the potential systematic errors that could be introduced by rotation of the interaction region, collective recoil effects, and distortions due to detection of fragments that have originated from either the target or projectile remnant. All of these effects will tend to reduce the measured sphericity value. They are, however, also most important for more peripheral collisions. At the impact parameters that have been selected, these effects are expected to induce elongations that are significantly smaller than that attributed to the major axis defined by the initial decay in a sequential fission chain [1].

We observe as a general trend, that the theoretical multifragmentation model predicts less sphericity of the event shapes than the isotropic simulation and seems to reproduce better the experimental data. The reason that the average sphericity values from the multifragmentation model are smaller than those for isotropic emission is that, for the cases under consideration, typically only 5-6 intermediate mass fragments are created during the prompt fragmentation stage. The extracted sphericity value for a given event is dominated by the momentum vectors of these primordial fragments. The smaller fragments that are detected result primarily from the decay of these initial fragments, and contribute little to the final event shape. The isotropic simulation of ref.[1] uses the final fragment multiplicity not the intial multiplicity and thus overpredicts the mean of the sphericity distribution. It is a model that contains no dynamics and therefore provides a statistical limit for the observed sphericity from a given multiplicity. Thus, our simulations provide event shape distributions which are dominated by either 2 (sequential decay), 5-6 (multifragmentation), or 6-10 (isotropic emission) intial fragments.

We have also studied the higher order moments of the sphericity distribution. These data are summarized in table 1 for the 65 MeV/nucleon case. One observes that the trends indicated by the mean value of the sphericity distribution are still apparent in the higher order moments. The sequential simulation displays the least variance, as the events lie predominantly along the two-dimensional axis, this also causes it to overpredict the skew. The isotropic simulation overpredicts the variance and underpredicts the skew as it produces a broad and overly uniform distribution. The multifragmentation model reproduces the observed variance and the skew very well.

Therefore, we conclude that if one analyses the moments of the event shape distributions as a function of the beam energy, one could from the gradual change in the shapes of the sphericity distributions get some information on the onset of multifragmentation. This onset occurs between 45 and 65 MeV/nucleon as is illustrated by the mean sphericity as a function of beam energy. The present conclusions are mainly based on the yield of the light particles. In principle, one should go to heavier systems, in order to see a much more pronounced rise of the sphericity when the multifragmentation sets in.

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Table 1: The three moments of the Sphericity distributions for the 65 MeV/nucleon case.

Source	Mean	Variance	Skew
Experimental data	0.345	0.0343	0.00196
Sequential Simulation	0.306	0.0328	0.00224
Isotropic Simulation	0.360	0.0370	0.00164
Multi-Fragmentation	0.346	0.0347	0.00187

Table

Figure Captions

Figure 1:

A comparison of the predictions of the statistical multifragmentation model with experimental data (crosses) for 65 MeV/nucleon. The excitation energy per nucleon, E^*, is 10 MeV and the kinetic temperature, τ, is 12 MeV. Comparison is made for: (a) multiplicity of identified charged particles, (b) total detected charged-particle multiplicity (includes particles that stop in the ΔE scintillator), (c) mass distribution of light particles, (d) charge distributions, (e) kinetic energy distributions for protons, (f) kinetic energy distributions for helium ions.

Figure 2:

A contour map of the event shape distributions from (a) the experimental data, (b) the sequential simulation, (c) the isotropic simulation, and (d) the multifragmentation model. All are for the 65 MeV/nucleon case. The crosses on each map indicates the mean values.

Figure 3:

The mean value of the sphericity distribution as a function of beam energy for the experimental data (Exp.), sequential simulation (Seq.), isotropic simulation (Iso.), and the multi-fragmentation model (M.F.).

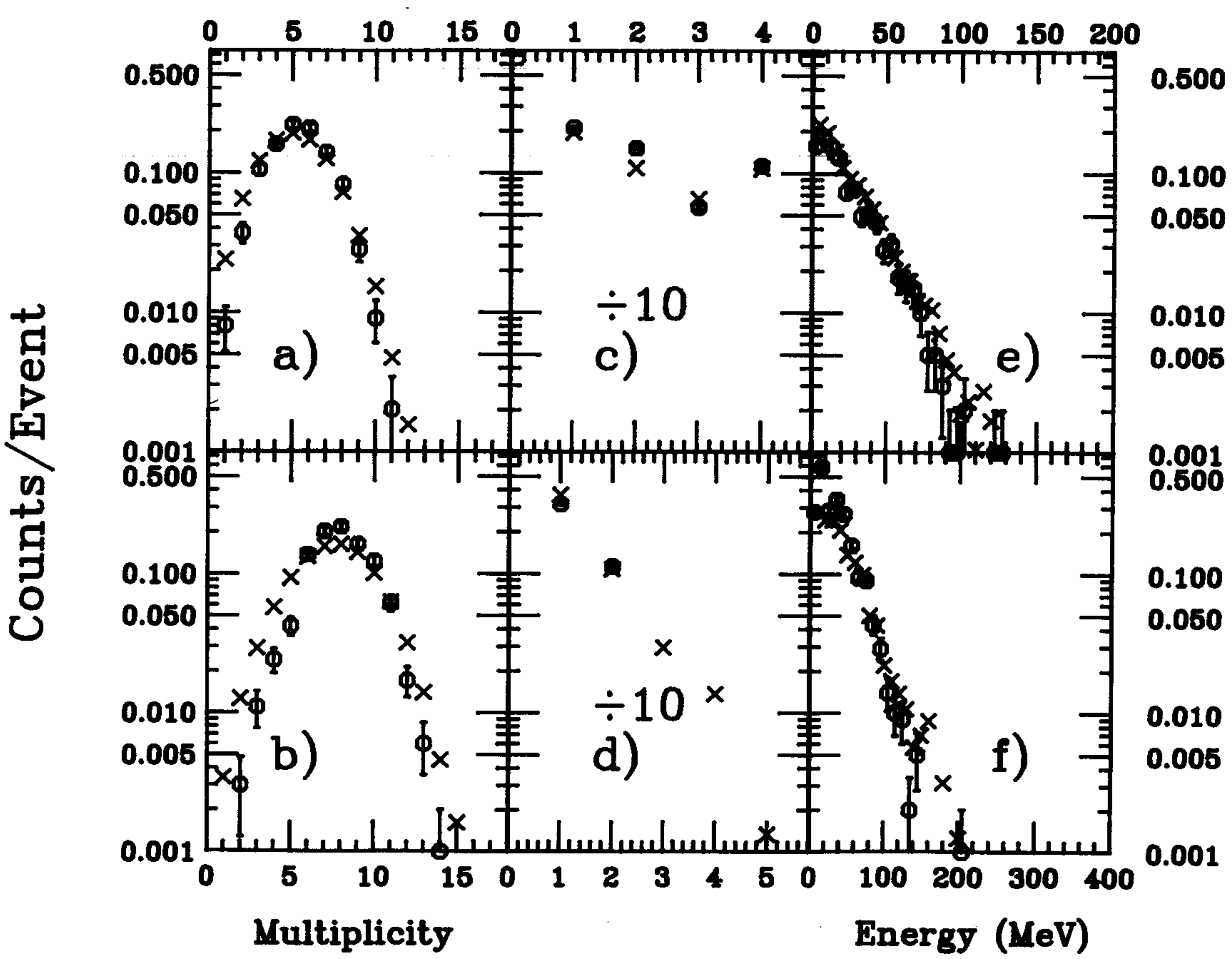
Counts/Event
0.500
0.100
0.050
0.010
0.005
0.001
a)
b)
c)
d)
e)
f)
÷10
÷10
0
5
10
15
0
1
2
3
4
5
0
50
100
150
200
300
400
Multiplicity
Energy (MeV)

FIGURE 1

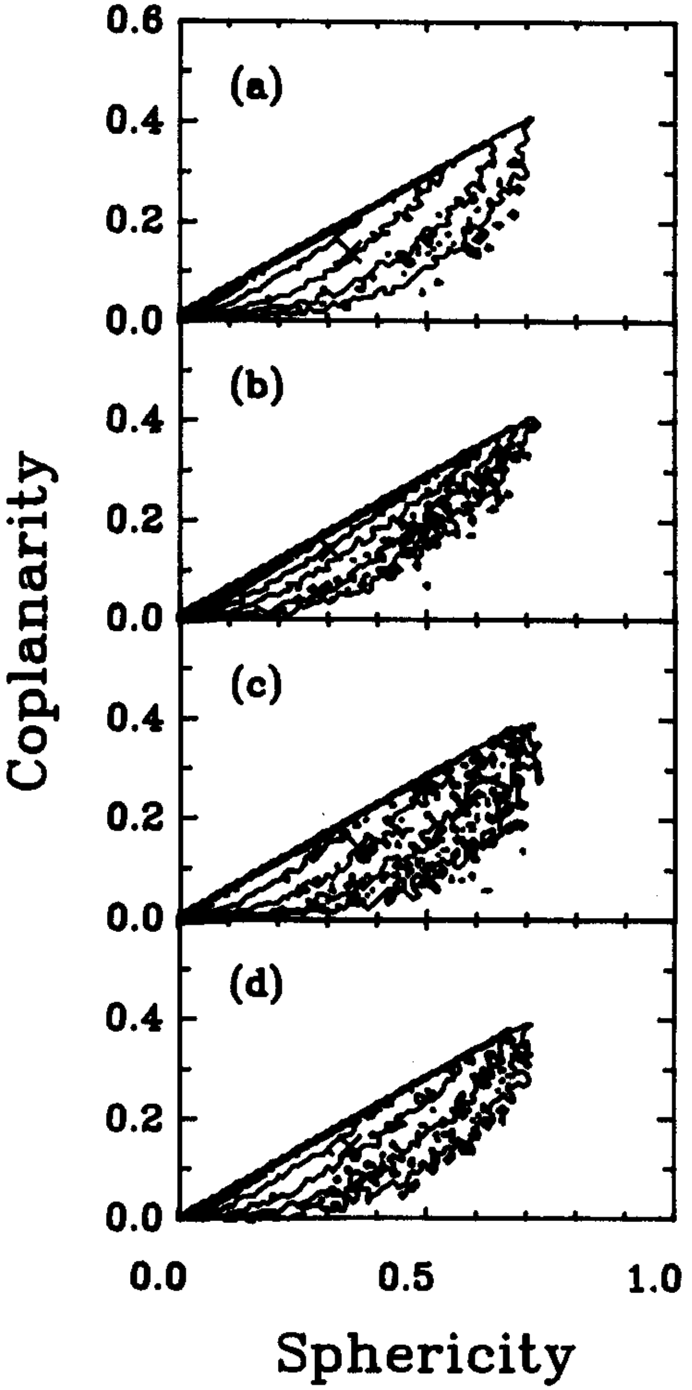
0.6
(a)
0.4
0.2
0.0
(b)
0.4
0.2
0.0
(c)
0.4
0.2
0.0
(d)
0.4
0.2
0.0
0.0
0.5
1.0
Coplanarity
Sphericity

FIGURE 2

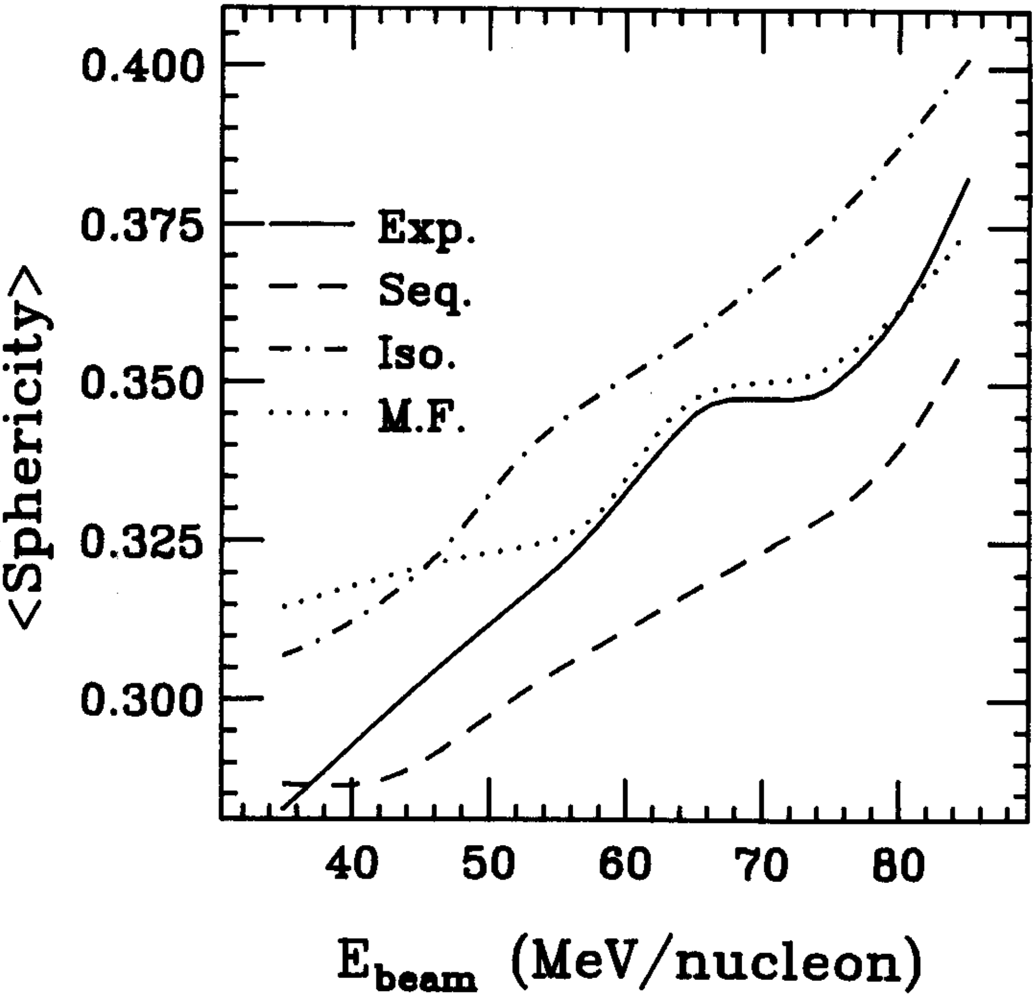
0.400
0.375
0.350
0.325
0.300
<Sphericity>
Exp.
Seq.
Iso.
M.F.
40
50
60
70
80
E_{beam} (MeV/nucleon)

FIGURE 3