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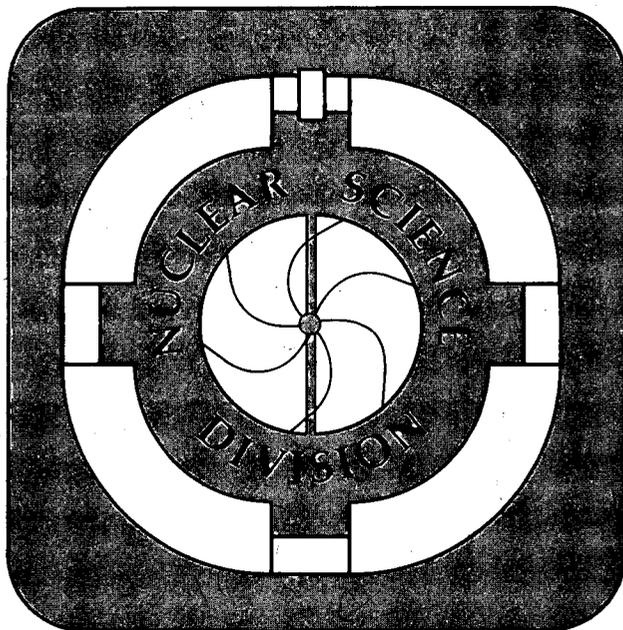
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L.G. Moretto, Th. Rubehn, L. Phair, K. Tso, N. Colonna,  
G.J. Wozniak, D.R. Bowman, G.F. Peaslee, N. Carlin,  
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L.G. Moretto, Th. Rubehn, L. Phair, K. Tso, N. Colonna\*, and  
G.J. Wozniak

*Nuclear Science Division, Lawrence Berkeley National Laboratory  
University of California, Berkeley, CA 94720, USA*

D.R. Bowman, G.F. Peaslee, N. Carlin, R.T. de Souza, C.K. Gelbke, W.G.  
Gong, Y.D. Kim, M.A. Lisa, W.G. Lynch, and C. Williams

*National Superconducting Cyclotron Laboratory and Department of Physics and  
Astronomy, Michigan State University, East Lansing, MI 48824-1321, USA*

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# Charge correlations and dynamical instabilities in the multifragment emission process

L.G. Moretto, Th. Rubehn, L. Phair, N. Colonna,\* and G.J. Wozniak

*Nuclear Science Division, Lawrence Berkeley National Laboratory,*

*University of California, Berkeley, California 94720*

D.R. Bowman,<sup>†</sup> G.F. Peaslee,<sup>‡</sup> N. Carlin,<sup>§</sup> R.T. de Souza,<sup>||</sup> C.K. Gelbke, W.G. Gong,<sup>¶</sup>

Y.D. Kim,<sup>\*\*</sup> M.A. Lisa,<sup>††</sup> W.G. Lynch, and C. Williams

*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy,*

*Michigan State University, East Lansing, MI 48824*

## Abstract

A new, sensitive method allows one to search for the enhancement of events with nearly equal-sized fragments as predicted by theoretical calculations based on volume or surface instabilities. Simulations have been performed to investigate the sensitivity of the procedure. Experimentally, charge correlations of intermediate mass fragments emitted from heavy ion reactions at intermediate energies have been studied. No evidence for a preferred breakup into equal-sized fragments has been found.

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In recent years, multifragmentation of nuclear systems has been extensively studied, and many efforts have been made to clarify the underlying physics [1]. It has been suggested that fragment production can be related to the occurrence of instabilities in the intermediate system produced by heavy ion collisions [2–13]. In particular, two kinds of instabilities are extensively discussed in the literature: volume instabilities of a spinodal type (see e.g. Ref. [12]) and surface instabilities [3]. Spinodal instabilities are associated with the transit of a homogeneous fluid across a domain of negative pressure, where the homogeneous fluid becomes unstable and breaks up into droplets of denser liquid. Surface instabilities can be subdivided into Rayleigh or cylinder instabilities which are responsible for the decay of shapes like long necks or toroids [2], and sheet instabilities which cause the decay of bubbles or disklike structures [3]. A variety of models have predicted the formation of these exotic geometries which may develop after the initial compression of nuclei in the early stage of the collision for both symmetric and asymmetric systems [3,4,6,7,10–13]. Although the scenarios and the models vary, breakup into several *nearly equal-sized* fragments has been predicted for both kinds of instabilities. Thus it would be interesting to search model-independently for this signal. In this paper, we examine the signatures of a breakup configuration which would decay into a number of nearly equal-sized fragments by investigating charge correlations from both experimental data and simulations.

We have experimentally studied the reactions Xe+Cu at 50 MeV/nucleon. The measurements were performed at the National Superconducting Cyclotron Laboratory of Michigan State University using the Miniball [14] and a Si-Si(Li)-plastic forward array [15]. Detailed information on the experiment can be found in Ref. [16].

For comparison, and in order to determine the sensitivity of our analysis, Monte Carlo calculations have been performed. The created events obey two conditions: the sum charge of all fragments is conserved within an adjustable accuracy, and a fragment is produced according to the probability resulting from the experimental finding, that the charge distributions for intermediate mass fragments (IMF) are nearly exponential functions [17]:

$$P_n(Z) \propto \exp(-\alpha_n Z). \quad (1)$$

Experimentally, a variation of the parameter  $\alpha_n$  between 0.2 and 0.4 has been reported for extreme cuts on the transverse energy  $E_t$ . In our simulations, we have chosen a fixed value of 0.3. The size of the decaying source was chosen to be equal to the sum charge of xenon and copper,  $Z_{source} = 83$ . Events with equal sized fragments of charge  $Z_{art}$  were randomly added with probability  $P$  to simulate a dynamical breakup of the system into nearly equal-sized pieces. Furthermore, the simulation allows one to smear out the charge distributions of the individual fragments of such an event according to a Gaussian distribution. This smearing of the charge distribution not only accounts for the width of the distribution due to the formation process *per se*, but also for the probable sequential decay of the primary fragments (i.e. the evaporation of light charged particles). In the following, the full width at half-maximum of this distribution is denoted by  $\omega$ . We have demanded that at least 75% of the total available charge is emitted according to Eq. 1; i.e. the production of particles was stopped in the simulation once this percentage had been reached. We note that in this simple approach the transverse energy  $E_t$  has not been simulated.

First, we investigate two particle correlations. Both the experimental and the simulated events have been analyzed according to the following method. The two particle charge correlations are defined by the expression

$$\frac{Y(Z_1, Z_2)}{Y'(Z_1, Z_2)} \Big|_{E_t, N_{IMF}} = C[1 + R(Z_1, Z_2)] \Big|_{E_t, N_{IMF}}. \quad (2)$$

Here,  $Y(Z_1, Z_2)$  is the coincidence yield of two particles of atomic number  $Z_1$  and  $Z_2$  in an event with  $N_{IMF}$  intermediate mass fragments and a transverse energy  $E_t$  (for the definition of the latter, see Ref. [18]). The background yield  $Y'(Z_1, Z_2)$  is constructed by mixing particle yields from different coincidence events selected by the same cuts on  $N_{IMF}$  and  $E_t$ . The normalization constant  $C$  is chosen to equalize the integrated yields of  $Y$  and  $Y'$ .

To demonstrate the sensitivity of our method to breakup configurations producing equal-sized fragments, we show in Fig. 1 the results of simulations for the case  $N_{IMF} = 6$ . Here, 1% of the events consist of fragments which all have the size  $Z_{art} = 6$ . The peak produced

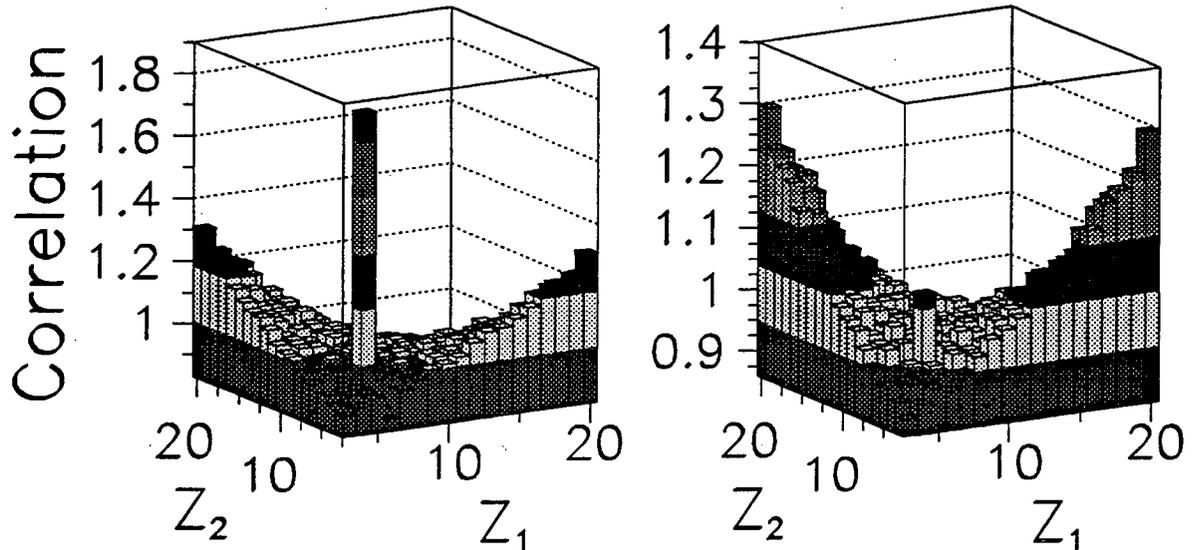


FIG. 1. Two particle charge correlations of intermediate mass fragments from simulations investigating events with  $N_{IMF} = 6$  and a source size of 83. Randomly, 1% (left panel) and 0.1% (right panel) of the events were chosen to have equal sized fragments ( $Z_{art} = 6$ ).

by these fragments is clearly visible, even if we decrease the yield of equal-sized fragments to only 0.1%.

Historically, charge correlations have often been investigated by using Dalitz plots [19,20]. However, this technique does not provide a sensitive tool to search for an *enhanced* breakup into several nearly equal-sized fragments, since the “background” is ignored. The Dalitz analysis is equivalent to studying *only* the numerator of the charge correlation function and will reflect only charge conservation in our search for relatively small enhancements. Thus, the strong signal shown in Fig. 1 does not show up in a Dalitz plot. Furthermore, the Dalitz plots and the charge distributions of the three largest fragments from Ref. [20], which claim to be a signature for an enhanced breakup into nearly equal-sized fragments, can be reproduced trivially by our simple simulation. Thus, these “signals” reflect only the background produced by charge conservation.

The magnitude of the peak shown in Fig. 1 depends not only on the yield, but also on the width of the charge distribution of the nearly equal-sized fragments. In Fig. 2, we show the

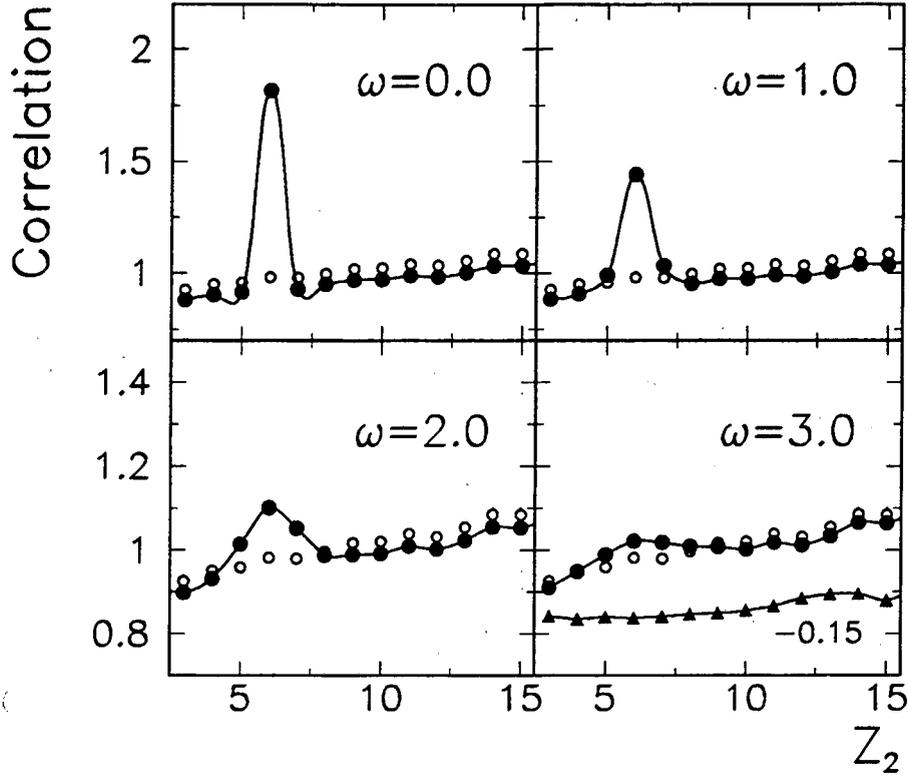


FIG. 2. Two particle charge correlations resulting from simulations for  $Z_1 = 6$  as a function of the fragment charge  $Z_2$  for different values of the width of the charge distribution  $\omega$ . Randomly, 1% of the events were chosen to have nearly equal sized fragments (full circles). For comparison, we have also plotted a calculation where no additional events with equal-sized fragments have been added (open circles). Experimental results for the case  $N_{IMF} = 6$  are shown in the right lower panel (full triangles). For clarity, these values are vertically shifted by a value of  $-0.15$ . The error bars are smaller than the size of the symbols.

correlation functions (solid circles) for different widths  $\omega$  and for  $Z_1 = 6$ . For comparison, we have plotted the results of a calculation (open circles) where no additional events with equal-sized fragments have been added: As expected, a dependence of the size of the peak on the smearing can be observed which limits the sensitivity of the two particle correlation functions to an enhancement of events where the charge distribution is relatively narrow. However, for the narrow widths predicted as e.g. in Ref. [7], a clear signal should be visible in the experimental data. The same analysis used for the simulation has been applied to the

experimental data. In Fig. 3, we show the results for the reaction Xe+Cu at 50 MeV/nucleon for different cuts in the intermediate mass fragment multiplicity  $N_{IMF}$ . A top 5% cut on  $E_t$  has been applied in order to select central events. With higher fragment multiplicity the distribution peaked along the line  $Z_1 + Z_2 \approx 30$  changes into a distribution peaked at values where one fragment is heavy and its partner is light. However, an enhanced signal for breakup into nearly equal-sized fragments (a signal appearing along the diagonal) was not observed in *any* of the  $N_{IMF}$  bins. As an example, we show in Fig. 2 the experimental two particle correlation function vs.  $Z_2$  for  $N_{IMF} = 6$  and  $Z_1 = 6$  (triangles).

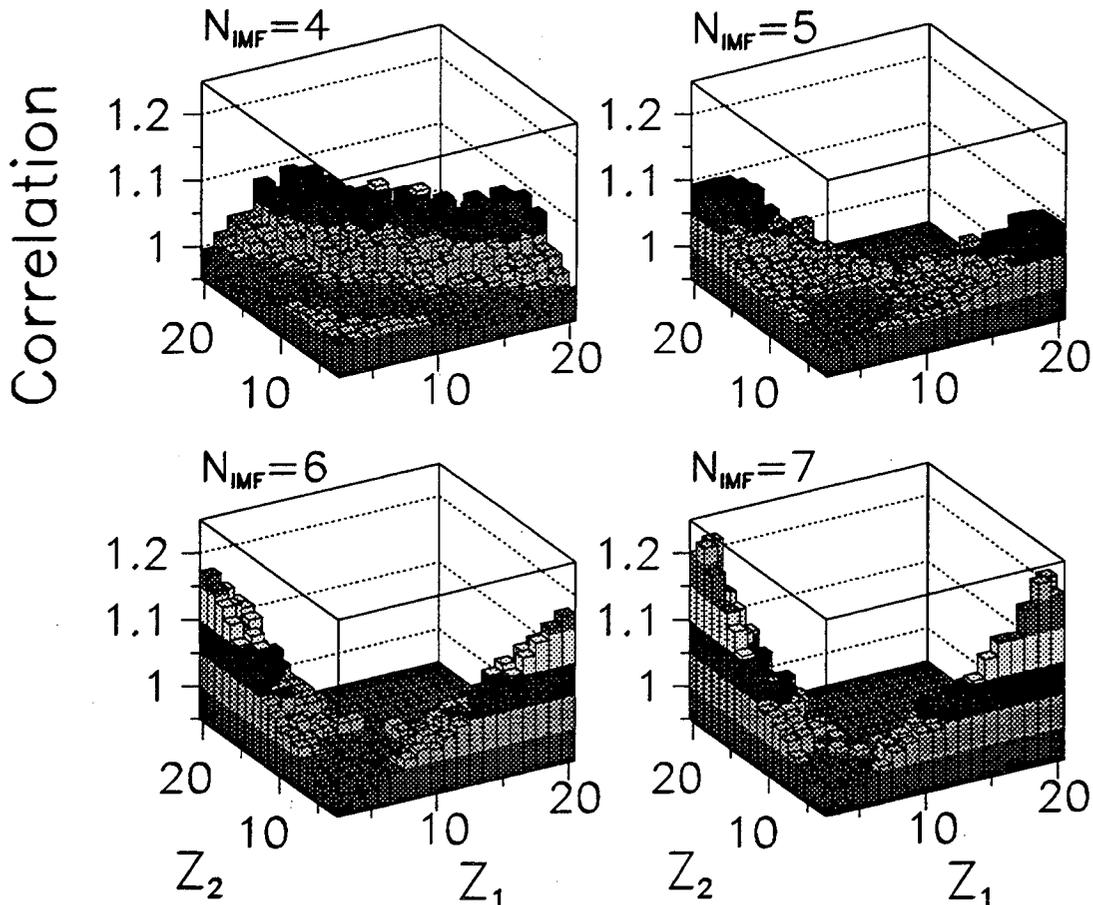


FIG. 3. Experimental two particle charge correlations for the reaction Xe+Cu at 50 MeV/nucleon. The different figures correspond to  $N_{IMF}$  cuts between 4 and 7.

Furthermore, we have investigated the correlation functions obtained by our simulations without enhanced breakup for several intermediate mass fragment multiplicities. The evo-

lution of the shape of the distribution with increasing values of  $N_{IMF}$  is very similar to that observed in the experimental data of Fig. 3. Simulations with different system sizes show that the charge correlations decrease as  $Z_{source}$  increases; this can be attributed to the definition of an IMF ( $3 \leq Z_{IMF} \leq 20$ ) relative to  $Z_{source}$ . We have also performed calculations using a percolation code and have observed a dependence similar to that presented in Fig. 3. In order to study whether the evolution of the distributions' shape with multiplicity is only due to charge conservation, we have investigated the breakup of an integer number  $Z_0$  (chain) into  $n$  pieces. The latter were produced by  $(n - 1)$  random breaks of the bonds. The calculated two particle correlation functions for different multiplicities  $n$  have a similar evolution of the distribution with  $n$  as shown in Fig. 3. These findings indicate that the observed experimental evolution of the shape of the two particle charge correlation distribution with fragment multiplicity is due to the limited number of possibilities to create fragments if both the sum charge and the number of fragments are fixed. A signal of enhanced emission will sit on top of such a background.

To search for weak signals of events with nearly equal-sized fragments, and in the hope of increasing the sensitivity of the method, we have investigated higher order charge correlations [21]. This quantity is defined by the expression:

$$\frac{Y(\Delta Z, \langle Z \rangle)}{Y'(\Delta Z, \langle Z \rangle)} \Big|_{E_t, N_{IMF}} = C[1 + R(\Delta Z, \langle Z \rangle)] \Big|_{E_t, N_{IMF}}. \quad (3)$$

Here,  $\langle Z \rangle$  denotes the average fragment charge of the event,  $\langle Z \rangle = \sum_{i=1}^{N_{IMF}} Z_i / N_{IMF}$ , and  $\Delta Z$  is the standard deviation, defined by  $\Delta Z = \sqrt{(N_{IMF} - 1)^{-1} \sum_{i=1}^{N_{IMF}} (Z_i - \langle Z \rangle)^2}$ . The normalization constant  $C$  and the yields are defined according to Eq. 2. The denominator for the background yield  $Y'(\Delta Z, \langle Z \rangle)$  is obtained by constructing "pseudo events" where one fragment is selected from each of the previous  $N_{IMF}$  events of the same event class (same  $E_t$  range).

In Fig. 4, we show the results of an analysis investigating higher order charge correlations. The same simulation which has already been shown in Fig. 1 was used. Here, only 0.1% of the events were chosen to have fragments with equal size. We show two cases with a

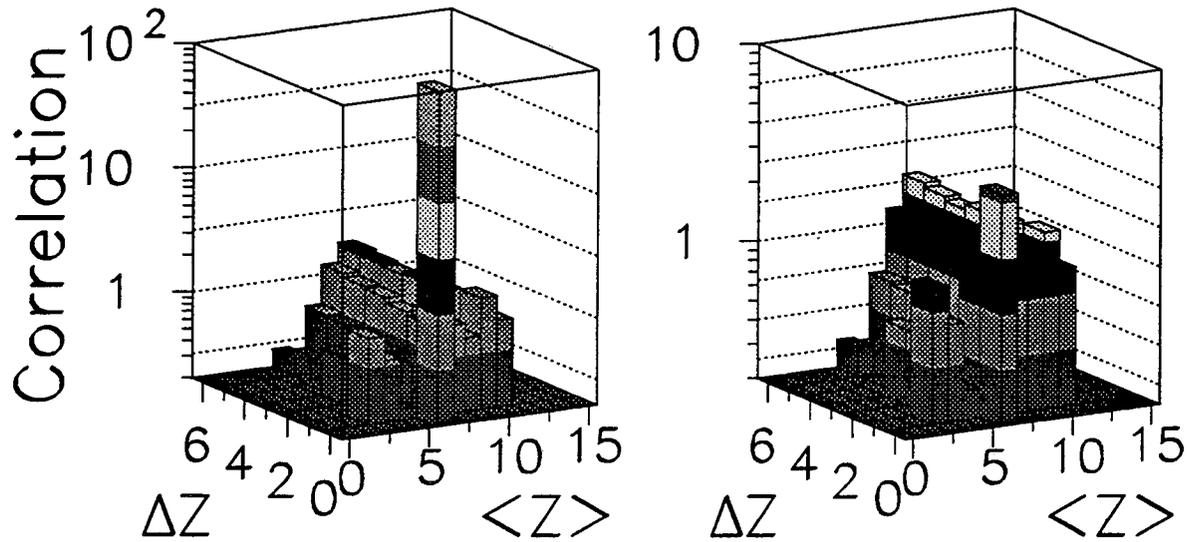


FIG. 4. Higher order charge correlations from the simulations for  $N_{IMF} = 6$ . Randomly, 0.1% of the events were chosen to have equal-sized fragments; A width of  $\omega = 0$  has been chosen (left panel). On the right panel, the results for a width  $\omega = 2$  are presented. Note the logarithmic scale of the correlation axis.

width of  $\omega = 0$  and  $\omega = 2$ , respectively. The comparison between the two particle and the higher order charge correlation functions for the same simulations using  $\omega = 0$  shows an enhancement of  $\sim 20\%$  for the first case (right panel of Fig. 1) while the signal in the second case exceeds the “background” by roughly a factor of 100 (left panel of Fig. 4). Since the yield in the  $\Delta Z = 0$  bin increases dramatically with *any* enhancement of events with equal-sized fragments, it should be sufficient to examine this bin only; the correlations at higher values of  $\Delta Z$  represent the “background”.

We have analysed our experimental data and determined the higher order charge correlation functions. The results are shown in Fig. 5 for the reaction Xe+Cu at 50 MeV/nucleon. For comparison, we also show the results of the simulation already shown in the right panel of Fig. 4 for  $N_{IMF} = 6$ ,  $P = 0.1\%$ , and  $\omega = 2$ . As discussed above, we compare the correlation values for  $\Delta Z = 0$  (solid symbols) with the data obtained for  $\Delta Z > 0$  (open symbols). No signals are observed that can be attributed to an enhanced production of nearly equal-

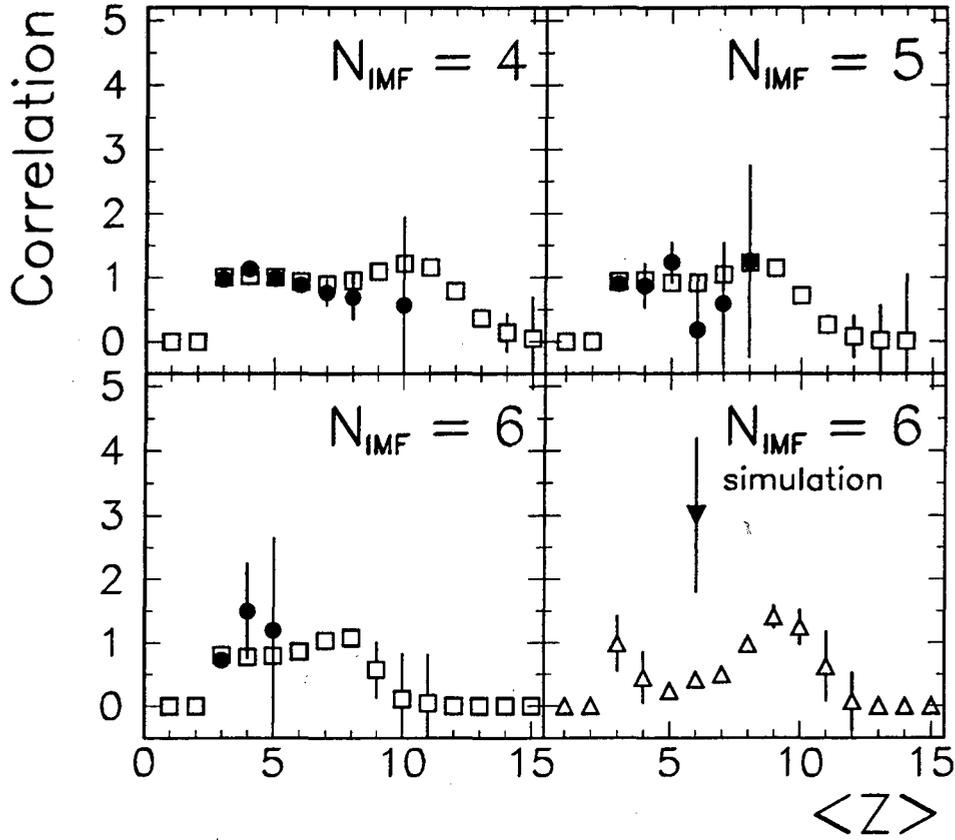


FIG. 5. Higher order charge correlations for the reaction Xe+Cu at 50 MeV/nucleon for  $4 \leq N_{IMF} \leq 6$ . For comparison, we show the results of the simulation for  $N_{IMF} = 6$  and  $\omega = 2$  (lower right panel). The full symbols indicate the events where  $\Delta Z = 0$ , the open symbols show the “background” defined by  $\Delta Z > 0$ . For further details, see text.

sized fragments. This results in an upper limit of breakup events with nearly equal-sized fragments of less than 0.05% if we assume a width  $\omega < 3$ . Furthermore, we have experimentally studied the reactions Ar+Au at 50 and 110 MeV and Xe+Au at 50 MeV/nucleon [16,18]: Similar results have been obtained for these systems albeit with significantly poorer statistics. Thus, the Xe+Cu system has been used to establish an upper limit and to explore the utility of this novel technique.

In conclusion, we have investigated two particle and higher order charge correlation functions of multifragment decays to search for the enhanced production of nearly equal-sized fragments predicted in several theoretical works. Two particle charge correlation functions

are sensitive even to those enhancements from events where a number of equal-sized fragments might be accompanied by heavy partners, as could be expected from the breakup of a necklike structure. While the higher order charge correlations are not sensitive to necklike emission, they do provide an even more sensitive tool for identifying enhancements associated with the emission of all nearly equal-sized fragments. The analysis of experimental data for the reactions Xe+Cu and Xe+Au at 50 MeV/nucleon and Ar+Au at 50 and 110 MeV/nucleon, however, shows no evidence for a preferred breakup into nearly equal-sized fragments. Recently, two groups have reported experimental signatures of possible formations of non-compact geometries in the reactions  $^{86}\text{Kr}$  on  $^{93}\text{Nb}$  at  $E/A=65$  MeV and Pb+Au at  $E/A=29$  MeV, respectively [22,23]. It would be very interesting to analyze these data using the new method presented in this letter.

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- \* Present address: INFN-Sez. di Bari, 70126 Bari, Italy.
- † Present address: Chalk River Laboratories, Chalk River, Ontario K0J 1J0, Canada.
- ‡ Present address: Physics Department, Hope College, Holland, MI 49423.
- § Present address: Instituto de Fisica, Universidade de Sao Paulo, C.P. 66318, CEP 04389-970, Sao Paulo, Brazil.
- || Present address: Department of Chemistry, Indiana University, Bloomington, IN 47405.
- ¶ Present address: Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany.
- \*\* Present address: Physics Department, Seoul National University, Seoul, 151-742, Korea.
- †† Present address: Lawrence Berkeley National Laboratory, Berkeley, CA 94720.
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LAWRENCE BERKELEY LABORATORY  
UNIVERSITY OF CALIFORNIA  
TECHNICAL AND ELECTRONIC  
INFORMATION DEPARTMENT  
BERKELEY, CALIFORNIA 94720