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Abstract: An analysis of charged particle distributions is performed to search for large fluctuations and signals of **intermittency** in ^{36}**Ar+**^{197}**Au** reactions at **E/A=35-110 MeV.** When the effects of impact-parameter averaging are reduced by appropriate cuts on the total transverse energy, charged particle multiplicity distributions narrower than Poisson distributions are observed. Standard bond-breaking percolation calculations predict overly large fluctuations, while microcanonical and evaporation calculations predict fluctuations smaller than those observed, suggesting that conservation laws prevent **intermittency** signals of non-trivial origin.

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Weakly excited nuclei decay primarily by fission and light particle evaporation. For excitation energies much higher than the binding energy, explosive disintegration into light particles ($Z \leq 2$) takes place. Between these two extremes, there is a regime for which copious production of intermediate mass fragments (IMF: $3 \leq Z \leq 20$) is observed [1-8]. The mechanism causing such multifragment decays is not yet understood and a subject of current debate.

A recent analysis [9] of fragment size distributions observed in reactions induced by gold on emulsion at E/A=1 GeV [8] saw evidence for intermittency, which might indicate that fragmentation processes are scale invariant. In this work, we take up the problem of intermittency by analyzing the factorial moments of charge distributions observed in $^{36}Ar+^{197}Au$ reactions at beam energies between 35 and 110 MeV per nucleon [6].

The occurrence of intermittency is deduced from the factorial moments [10]

$$F_k(\Delta) = \sum_{i=1}^{Z_0/\Delta} \langle N_i(N_i-1)\ldots(N_i-k+1)\rangle \Big/ \sum_{i=1}^{Z_0/\Delta} \langle N_i\rangle^k , \qquad (1)$$

where Z_0 is the total charge of the disintegrating nuclear system, Δ is a binning parameter, and N_i is the number of fragments with charges in the interval $(i-1)\Delta < Z \leq i\Delta$ where $i=1,\ldots,Z_0/\Delta$. The ensemble average $\langle\ \rangle$ is performed over all fragmentation events considered. Intermittency is defined by a relation [10]

$$F_k(\Delta') = F_k(a\Delta) = a^{-f(k)} F_k(\Delta) , \qquad (2)$$

between factorial moments $F_k(\Delta')$ and $F_k(\Delta)$ obtained for two different binning parameters Δ and $\Delta'=a\Delta$. Here, the intermittency exponent $f(k)$ is related to the fractal dimension d_k by $f(k)=d_k(k-1)>0$. Generally, evidence for intermittency has been obtained by examining the double logarithmic plot of $\ln F_k$ *vs.* $-\ln\Delta$. Plots which show lines of positive slope are consistent with nonzero fractal dimension and considered to display intermittency. By construction, the factorial moments $F(\Delta)$ are unity for Poisson distributions. Hence, Poisson distributions do not exhibit intermittency. The expression for the second factorial moment can be written as

$$F_2(\Delta=Z_\circ) = \frac{\Sigma_i \langle N_i(N_i-1)\rangle}{\Sigma_i \langle N_i\rangle^2} = 1 + \frac{\Sigma_i(\sigma_i^2 - \langle N_C\rangle)}{\Sigma_i \langle N_i\rangle^2}, \qquad (3)$$

where $\langle N_i\rangle$ and σ_i denote the mean value and the variance of the multiplicity distribution in the i-th bin. Thus, distributions which are narrower (broader) than Poisson distributions possess moments which are less (greater) than unity. For the special case of $\Delta=Z_\circ$, Eq. 3 reduces to the simple form

$$F_2(\Delta=Z_\circ) = 1 + \frac{\sigma_C^2 - \langle N_C\rangle}{\langle N_C\rangle^2}, \qquad (4)$$

where $\langle N_C\rangle$ and σ_C^2 are the mean value and the variance of the charged particle multiplicity distribution.

Signals of intermittency have been interpreted as indicative of some underlying physics, such as a phase transition, a cascading process [10], or some as-yet-unidentified source of self-similarity in the break-up process. However, for narrow charged particle multiplicity distributions, $\sigma_C^2 < \langle N_C\rangle$, a rise in the factorial moments as a function of decreasing bin size may be of trivial origin. For example, if Poisson distributions are constrained by a fixed sum of bin occupations, the fluctuations are reduced because statistical independence of individual bin occupations is lost, and $F_2(\Delta=Z_\circ)<1$. As the number of bins becomes larger, independence between bin occupations is approached, and the moments may increase. Intermittency as an indicator of nontrivial physics seems to be on firmer ground when $F_k>1$. This condition could be met in near-critical systems exhibiting larger than Poisson fluctuations. Evidence for such large fluctuations must be sought in events representing similar initial conditions, i.e. narrow ranges of excitation energy and impact parameter.

In order to explore whether there is a basis for non-trivial intermittent behavior in a reaction in which multifragment emission has been observed, we analyzed the first and second moments of the charged particle multiplicity distributions measured [6], with a low-threshold 4π-detector array [11], for $^{36}Ar+^{197}Au$ collisions over a broad range of energies, 35 MeV $\leq$ E/A $\leq$ 110 MeV. Event selection was performed by cuts on the total transverse energy, $E_t=E\bullet\sin^2\theta$, of the emitted charged particles. For orientation, we also provide an empirical impact parameter scale by using the geometrical prescription [12,13],

$$\hat{b}(E_t) = (1/\sqrt{\sigma_R}) \left\{ \int_{E_t}^{\infty} \frac{d\sigma(\varepsilon)}{d\varepsilon} d\varepsilon \right\}^{1/2}, \qquad (5)$$

where $d\sigma(E_t)/dE_t$ is the cross section for events for which the transverse energy of all detected charged particles falls into the interval $E_t \pm \frac{1}{2}dE_t$ and σ_R is the reaction cross section for events satisfying the trigger condition $N_C \geq 2$ [6]. The "reduced" impact parameter $\hat{b}$ assumes values of $\hat{b}\approx1$ for peripheral collisions and $\hat{b}\approx0$ for the most violent collisions characterized by large values of E_t. This impact parameter scale is very similar [13] to alternative scales derived from the total charged particle multiplicity or the intermediate rapidity charge.

The top panel in Fig. 1 shows the measured two-dimensional correlation between transverse energy E_t and charged particle multiplicity N_C for $^{36}Ar+^{197}Au$ collisions at E/A=110 MeV. The observed correlation indicates that collisions with decreasing impact parameters lead to increasing average values of both observables, E_t and N_C. The dashed and dot-dashed curves in the bottom panel of Fig.1 depict charged particle distributions selected by narrow cuts on E_t, corresponding to reduced impact parameters $\hat{b}(E_t)\approx 0.1$ and 0.6. The dotted curves illustrate the effects of increasing the widths, ΔE_t, of the cuts as indicated by dotted horizontal lines in the top panel. For central collisions, the N_C-distribution is rather insensitive to ΔE_t, but for more peripheral collisions it suffers considerable broadening as ΔE_t is increased.

The broadening due to impact parameter averaging is illustrated more quantitatively in Fig. 2. The top, center and bottom panels of the figure depict the quantities $\sigma_C^2/\langle N_C\rangle$, σ_C^2, and $\langle N_C\rangle$, respectively, as a function of transverse energy. For orientation, reduced impact parameters extracted via Eq. 5 are given by the upper scale. Solid circular, open square-shaped and star-shaped points show values obtained for cuts of widths ΔE_t=20, 180 and 340 MeV, respectively, centered at the given values E_t. For narrow cuts on E_t, the charged particle multiplicity distributions are inconsistent with $F_2(\Delta=Z_0) > 1$, since $\sigma_C^2/\langle N_C\rangle < 1$. For near-central collisions, $\hat{b}(E_t)\lesssim 0.3$, the extracted values of $\sigma_C^2/\langle N_C\rangle$ exhibit little dependence on the widths of the applied cuts. However, for larger impact parameters, $\hat{b}>0.4$, wide cuts on E_t cause an artificial broadening of the multiplicity distributions resulting from the superposition of distributions with displaced centers. Poorly defined ensembles of events may therefore exhibit larger than Poisson variances, $\sigma_C^2/\langle N_C\rangle > 1$. However, these large variances are an artifact from impact parameter averaging and they do not represent intrinsic fluctuations of the decaying system.

Even narrow cuts on E_t may not eliminate all broadening from impact parameter averaging, since the intrinsic resolution of the applied impact parameter filter is finite (and unknown). Hence, we can only establish upper limits for the intrinsic widths of the charged particle multiplicity distributions. Our measurements can therefore only discriminate against models predicting too broad distributions, but not against models predicting distributions narrower than observed.

Figure 3 depicts the relation between $\langle N_C\rangle$ and $\sigma_C^2/\langle N_C\rangle$ extracted for central ($\hat{b}(E_t)\lesssim 0.3$) $^{36}Ar+^{197}Au$ collisions at the incident energies of E/A=35, 50, 80, and 110 MeV. Although the mean charged particle multiplicity increases as a function of beam energy, the observed ratio $\sigma_C^2/\langle N_C\rangle \approx 0.3$ is nearly independent of beam energy. At all energies, the fluctuations of the charged particle multiplicity are considerably smaller than expected for Poisson distributions.

In order to explore effects resulting from phase space constraints such as energy conservation, we performed calculations with the bond-percolation model of refs. [14,15]. For simplicity, we assumed the decay of the composite system (A=233, Z=97). Calculations with bond-breaking parameters close to the critical value of p=0.7 have already been shown [16] to reproduce the element distributions measured for the present reaction. Standard percolation calculations (in which the number of broken bonds is allowed to fluctuate from event to event) predict fluctuations in N_C which are much larger than observed experimentally. Open circular points in Fig. 3 show representative results for p=0.6 and 0.7. The open triangular point illustrates the magnitude of instrumental distortions [16] for the case p=0.7. These distortions are too small to affect our conclusions. If one introduces a constraint analogous to energy conservation by requiring the total numbers of broken bonds to remain constant, much narrower charged particle distributions are produced (see open circular points). These illustrative calculations suggest that the widths of impact parameter selected charged particle multiplicity distributions are strongly affected by phase space constraints due to energy conservation.

This conclusion is corroborated by more realistic statistical model calculations which incorporate energy conservation. The open square- and star-shaped points show predictions of the sequential decay model GEMINI [17] and of the Copenhagen fragmentation model [18], respectively. (The individual points represent results obtained for the decay of heavy compound nuclei at various representative excitation energies.) Although GEMINI has been shown to predict insufficient numbers of fragments [6,7], it can still provide a benchmark for the assessment of phase space constraints due to energy conservation. The Copenhagen fragmentation model can produce sufficient numbers of fragments. This model incorporates energy and momentum conservation for the different partitions and as well as the correct quantum statistics for fragments with the same neutron and proton numbers; it is similar in spirit to the models of refs. [19-22]. Both microcanonical and sequential decay models predict ratios $\sigma_C^2/\langle N_C\rangle$ somewhat smaller than observed experimentally, and they do not show intermittency [23,24].

Second factorial moments as a function of binning resolution are presented in Fig. 4. The solid points represent experimental data selected by a narrow cut on central collisions at E/A=110 MeV. A slightly positive slope is observed, but the moments are smaller than unity. As argued above, this positive slope may be of trivial origin. In order to corroborate this point, we include the results of percolation calculations performed for p=0.7. The open squares depict predictions of standard calculations for which the total number broken bonds is allowed to fluctuate for different partitions. These calculations predict large factorial moments which decrease for increased binning resolution, i.e. the distribution does not exhibit intermittency. The open diamonds show results of calculations for which the number of broken bonds was constrained to be constant. As expected from our qualitative arguments, the factorial moments are strongly reduced in magnitude, and they exhibit a small increase as a function of binning resolution, similar to that observed experimentally. This increase appears to be of little significance.

In summary, we argue that an intermittent signal is meaningful only when it is observed in data selected by a narrow cut in impact parameter, and only when the magnitude of the moments is greater than unity. These two conditions are never simultaneously met in our data. A suprisingly small value of about $\sigma_C^2/\langle N_C\rangle \sim 0.3$, much smaller than that of a Poisson distribution, was measured in central collisions, independent of beam energy. The reduction of the widths of the charged particle distributions below those expected for Poisson distributions are comparable to the reductions caused by the constraints imposed by energy conservation. Any fluctuation analysis, such as a search for intermittency, must consider the reductions of fluctuations for finite systems which stem from phase space constraints due to conservation laws and take them into account.

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References:

1. Y.D. Kim, et al., Phys. Rev. Lett. **63** (1989) 494.
2. E. Piasecki et al., Phys. Rev. Lett. **66** (1991) 1291.
3. Y. Blumenfeld et al., Phys. Rev. Lett. **66** (1991) 576.
4. S.J. Yennello et al., Phys. Rev. Lett. **67** (1991) 671.
5. C.A. Ogilvie et al., Phys. Rev. Lett. **67** (1991) 1214.
6. R.T. de Souza et al., Phys. Lett. **B268** (1991) 6.
7. D.R. Bowman et al., Phys. Rev. Lett. **67** (1991) 1527.
8. C.J. Waddington and P.S. Freier, Phys. Rev. **C31** (1985) 888.
9. M. Ploszajczak and A. Tucholski, Phys. Rev. Lett. **65** (1990) 1539.
10. A. Bialas and R. Peschanski, Nucl. Phys. **B273** (1986) 703; ibid. **B308** (1988) 857.
11. R.T. de Souza et al., Nucl. Instr. and Meth. **A295** (1990) 109.
12. C. Cavata et al., Phys. Rev. **C42** (1990) 1760.
13. L. Phair et al., Michigan State University preprint MSUCL 831 (1992).
14. W. Bauer et al., Phys. Lett. **150B** (1985) 53; Nucl. Phys. **A452** (1986) 699.
15. W. Bauer, Phys. Rev. **C38** (1988) 1927.
16. L. Phair et al., Michigan State University preprint MSUCL 819 (1992).
17. R.J. Charity et al., Nucl. Phys. **A483** (1988) 371.
18. J.P. Bondorf et al., Nucl. Phys. **A443** (1985) 321; Nucl. Phys. **A444** (1986) 460; H.W. Barz, et al., Nucl. Phys. **A448** (1986) 753.
19. S. Koonin and J. Randrup, Nucl.Phys. **A474** (1987) 173.
20. B.H. Sa and D.H.E. Gross, Nucl. Phys. **A437** (1985) 643.
21. D.H.E. Gross, et al., Phys. Rev. Lett. **56** (1986) 1544.
22. Zhang Xiao-Ze, et al., Nucl.Phys. **A461** (1987) 641, ibid. 668.
23. H.W. Barz et al., Phys. Rev. **C** (1992), and Nucl. Phys. **A** (1992) in press.
24. B. Ellatari et al., preprint Strasbourg PHTH 19-91 (1991).

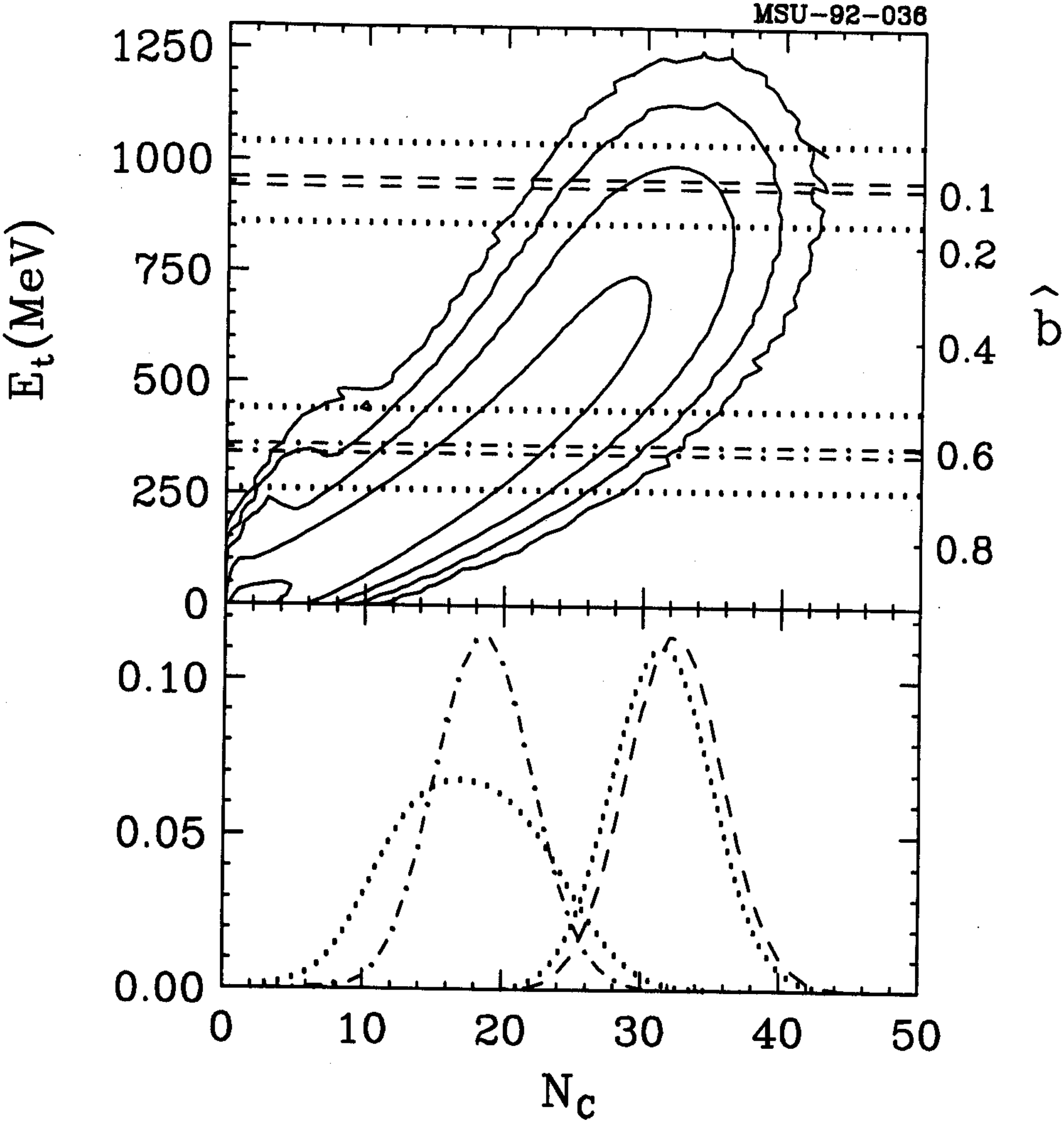
Figure Captions:

Fig. 1: Upper part: Measured relation between transverse energy E_t and total charged particle multiplicity for $^{36}Ar+^{197}Au$ reactions at E/A=110 MeV. Lower part: Charged particle multiplicity distributions for the cuts on E_t, indicated in the top panel.

Fig. 2: Bottom, center and top panels show the mean values $<N_C>$, variances σ_C^2, and ratios $\sigma_C^2/<N_C>$ of the charged particle multiplicity distributions for $^{36}Ar+^{197}Au$ reactions at E/A=110 MeV. These quantities were selected by various cuts on the transverse energy; the mean values of these cuts are given by the abscissa and the widths are given in the figure. The upper scale gives the reduced impact parameter $\hat{b}$ related to E_t via Eq. 5.

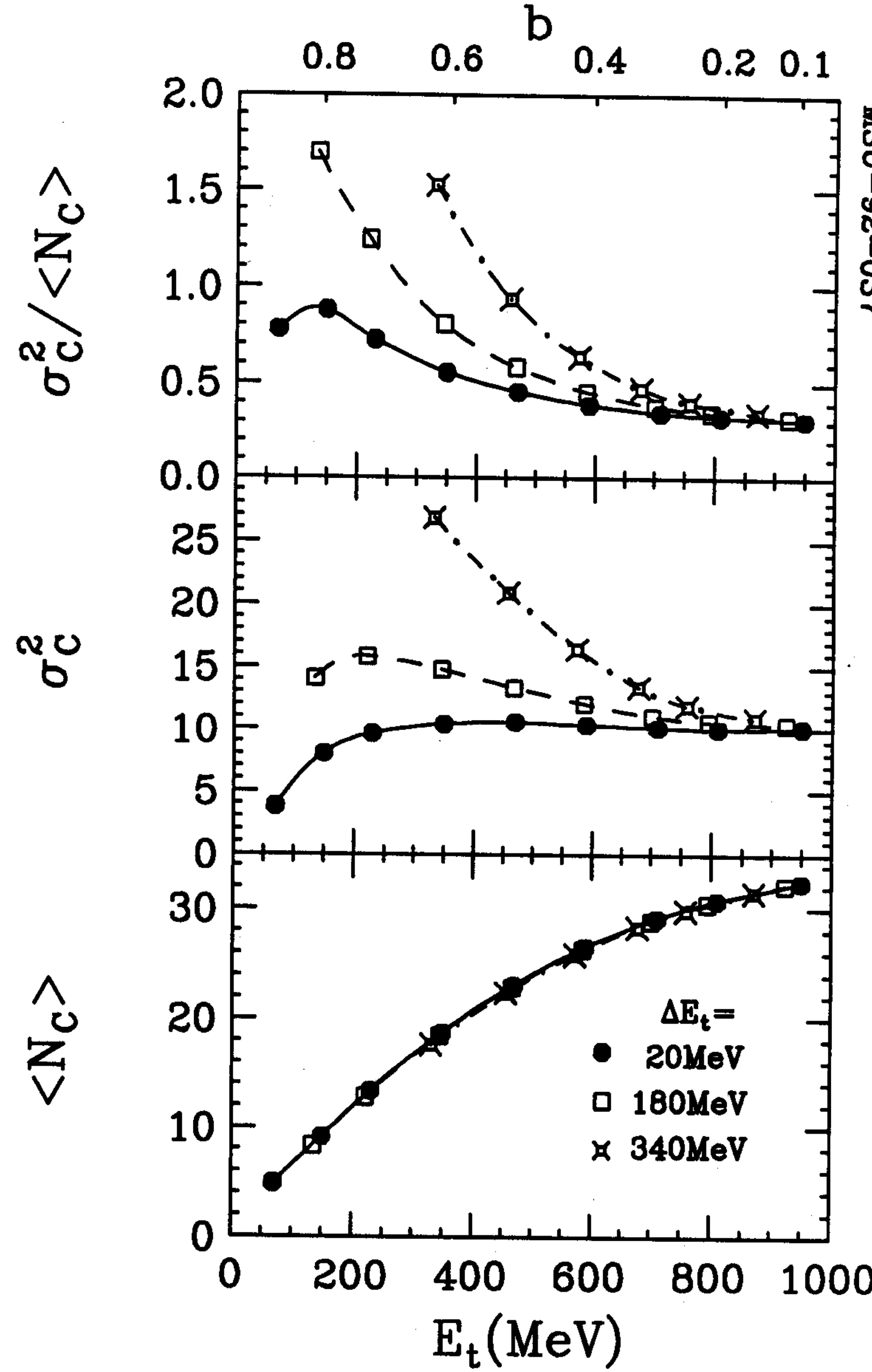
Fig. 3: Relation between mean charged particle multiplicity $<N_C>$ and the ratios $\sigma_C^2/<N_C>$. Solid circular points: experimental values extracted from near-central $^{36}Ar+^{197}Au$ reactions at E/A=35, 50, 80 and 110 MeV. Open circles: predictions by standard bond-percolation model using p=0.6 and 0.7 [14-15]; (the open triangle illustrates the magnitude of instrumental distortions [16]); open diamonds: percolation model prediction with fixed number of broken bonds; open squares: predictions by evaporation model [17]; star-shaped points: predictions by Copenhagen fragmentation model [18].

Fig. 4: Scaled factorial moments as a function of binning resolution. Solid points show experimental results for central $^{36}Ar+^{197}Au$ collisions at E/A=110 MeV. Open points show results from percolation calculations using p=0.7. Open squares depict calculations in which the total number of broken bonds is allowed to fluctuate; open diamonds represent calculations in which the total number of bonds is kept fixed.



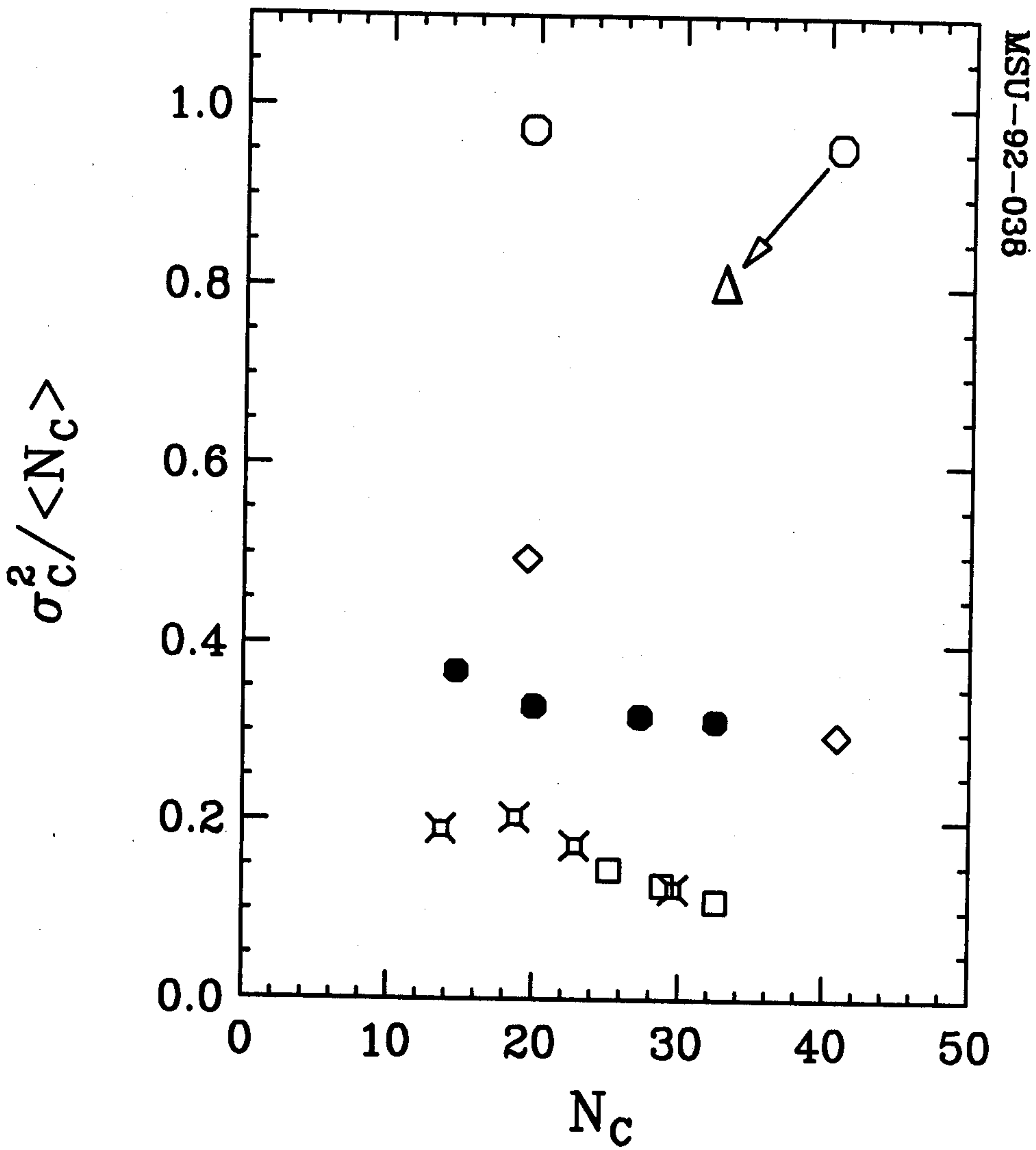
MSU-92-036
1250
1000
750
500
250
0
E_t(MeV)
0.1
0.2
0.4
0.6
0.8
$\hat{b}$
0.10
0.05
0.00
0
10
20
30
40
50
N_c

Fig. 1



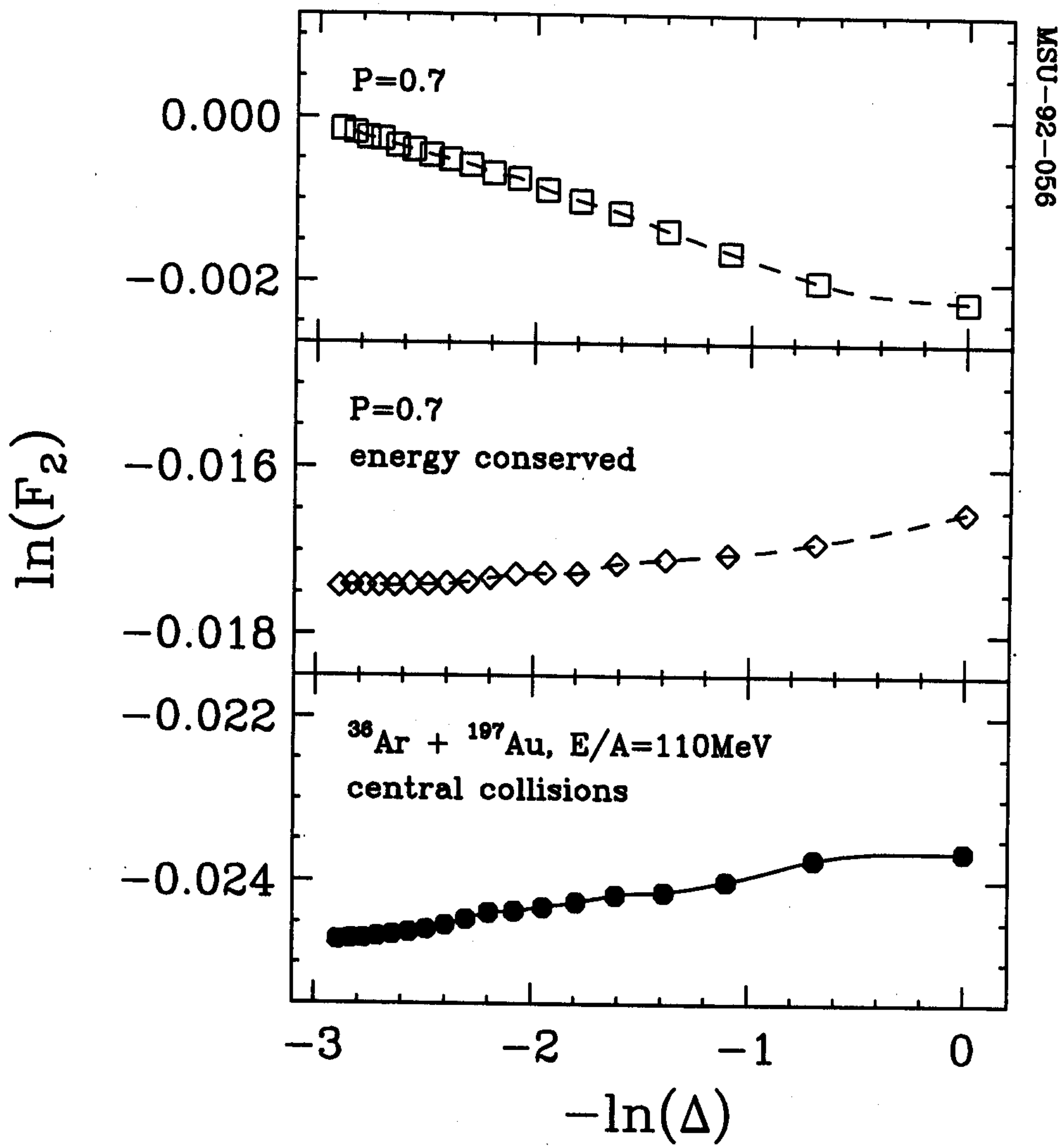
$\hat{b}$
0.8
0.6
0.4
0.2
0.1
MSU-92-037
$\sigma_c^2/\langle N_c\rangle$
2.0
1.5
1.0
0.5
0.0
σ_c^2
25
20
15
10
5
0
$\langle N_c\rangle$
30
20
10
0
$\Delta E_t=$
20MeV
160MeV
340MeV
0
200
400
600
800
1000
E_t(MeV)

Fig. 2



1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
$\sigma_c^2/\langle N_c \rangle$
N_c
MSU-92-038

Fig. 3



P=0.7
P=0.7
energy conserved
^{36}Ar + ^{197}Au, E/A=110MeV
central collisions
0.000
−0.002
−0.016
−0.018
−0.022
−0.024
ln(F$_2$)
−3
−2
−1
0
−ln(Δ)
MSU-92-056

Fig. 4