Michigan State University

National Superconducting Cyclotron Laboratory

FRAGMENT MULTIPLICITY DEPENDENT CHARGE DISTRIBUTIONS IN HEAVY ION COLLISIONS

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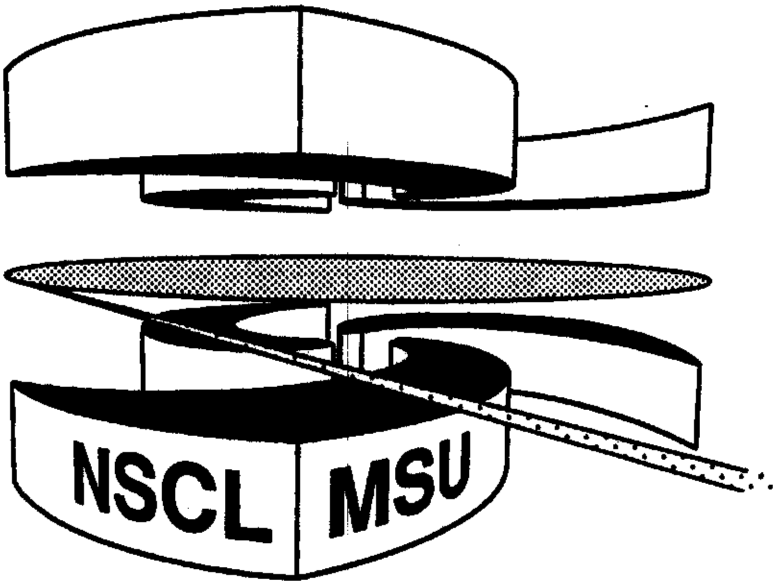

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Fragment multiplicity dependent charge distributions in heavy ion collisions

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Abstract

The multiplicity dependence of fragment charge distributions has been examined for **Kr+Au** collisions for incident energies ranging from 35 to 400 **AMeV.** Constraints unposed by charge conservation can be **parameterized,** as a function of transverse energy E_t and as a function of incident energy for central collisions, in terms of a single charge conservation parameter. At large impact parameter characterized by small E_t, it appears especially difficult to extract this charge conservation parameter. However, at small impact parameter, the procedure appears to provide a significant test of statistical multifragment models.

Fragment size distributions provide some of the more significant information about fragmentation processes[1]. Such information has provided important tests of both dynamical [2] and statistical models [3]. In the limit of infinite equilibrated systems, it plays a central role in the determination of critical exponents [4]. Recently, nuclear multi-fragmentation processes have been measured [5-8] and information about fragmentation time scales [9] and finite size effects [10] have been obtained for a variety of nuclear systems. For the nuclear systems that are produced and studied in the laboratory, the behavior of fragment size distributions may be significantly altered by breakup geometry[10], finite size effects [10] and Coulomb interaction[8]. Such alterations arise from constraints imposed by conservation laws as well as from the time dependence imposed by the expansion and disintegration of the system into the surrounding vacuum.

To examine the charge conservation effect, the intermediate mass fragment (IMF) dependent charge distributions studied in refs. [11,12] were found especially to follow a simple exponential relationship

$$P_{N_{IMF}}(Z) \propto \exp[-(\alpha_o + c\,N_{IMF})Z] \qquad (1)$$

where N_{IMF} is the multiplicity and Z is the charge of the intermediate mass fragment (IMF) with $3 \le Z \le 20$. α_o and c are taken to be excitation energy dependent constants. Percolation model studies [12] suggest that c should be inversely proportional to the charge of the prefragment ($c \propto \frac{1}{Z_0}$).

The dependence of c upon the total transverse energy of the system E_t has been investigated [11.12]. ($E_t = \sum E_i \sin^2 \theta_i$ where the summation runs over the detected particles in an event). These investigations suggest that c vanishes at small E_t and increases with E_t until reaching a saturation value. The c =0 (liquid-gas) region was interpreted [12] as due to the presence of a large residue with a mixed phase in the final state which weakens the charge conservation constraint upon the fragment distributions. Similarly, the larger values of *c* at larger E_t were interpreted [12] as reflecting the constraints imposed by charge conservation for a final state consisting of a gas of nucleons and fragments with such a residue.

To explore these issues, ^{84}Kr+^{197}Au reactions were investigated at E/A=35, 55, 70, 100, 200 and 400 MeV. Collisions at the three lower energies were measured at the National Superconducting Cyclotron Laboratory at Michigan State University while measurements at the higher three energies were performed at the Laboratoire National SATURNE at Saclay. Charged particles and IMF's were detected with the combined MSU Miniball/Washington University Miniwall 4π phoswich detector array[13]. This detector system consisted of 276 low-threshold plastic-scintillator-CsI(Tl) phoswich detectors, covering polar angles of θ_{lab} = 5.4° - 160°, corresponding to a total geometric efficiency of approximately 90% of 4π. The energy thresholds in the wall detectors located at θ_{lab} = 5.4°-25° were set to about 7 MeV (7.5 MeV) for Z=3 (10) particles. The corresponding thresholds of the Ball detectors at larger angles, θ_{lab}=25°-160°, were $E_{th}/A \sim 2$ MeV (4 MeV) for Z=3 (Z=10) particles, respectively. To avoid contamination from low energy electrons, hardware discriminator thresholds of 5 MeV were imposed on the Z=1 particles for the Miniball and 20 MeV for the Miniwall. Unit charge resolution up to $Z \approx 10$ was routinely achieved for particles that traversed the fast plastic scintillator. More details about the experiment can be found in Ref. [6].

The interplay between excitation energy deposition and charge conservation constraints can be explored alternatively by varying the impact parameter at fixed bombarding energy or by varying the bombarding energy at fixed impact parameter. Both techniques have disadvantages: collision geometries and source sizes vary significantly with impact parameter [14], while flow and reaction time scales vary significantly with incident energy[9]. Figure 1 shows the extracted values of *c* as a function of the transverse energy for the six incident energies. Except at the highest energy, *c* increases rapidly with E_t from the negative values observed in peripheral collisions at smallest E_t, passing through zero and then increases more slowly attaining a maximum values of about 0.02 to 0.03.

The observation of $c<0$ indicates that the fragment distributions become flatter with increasing fragment multiplicity, a trend that cannot be explained by charge conservation. Small E_t corresponds to peripheral collisions where charged particles are less important than neutrons in removing excitation energy. Thus the constraint of small E_t may be rather ineffective at constraining the excitation energy deposition at large impact parameter. Shifts in the mean impact parameter occur at fixed E_t when gates are placed on the IMF multiplicity because at large impact parameters, IMF multiplicity is strongly impact parameter dependent.

To explore the magnitude of these cross gating effects, α-α azimuthal correlations were analyzed as functions of N_{IMF}. Such correlations, containing information about the angular momentum and directed transverse flow, have been shown by previous analyses to be more anisotropic at larger impact parameters [15]. Fig. 2 shows α-α correlations for Kr+Au reaction at E/A=35 MeV for different values of the IMF multiplicity and events with E_t < 100 MeV where the value of the extracted *c* parameter passes through zero. All α-α correlations exhibit V shapes with enhanced emission at $\Delta\phi = 0°$ and 180°, reflecting a preference of the emission of both α particles in the reaction plane. These anisotropies decrease with N_{IMF}, consistent with smaller average impact parameter and larger average excitation energy deposition for the events with large IMF multiplicity. Thus the negative values of *c* can be attributed to this impact parameter bias and to the observed trend of flatter charge distributions for more central collisions[16]. The vanishing values for *c* in Fig. 1 and Ref. [11,12] simply reflect a mixture between collisions with poorly defined impact parameter with negative c and more central collisions with positive c. Thus $c=0$ does not provide a signature for the co-existence region [12].

Figure 1 suggests that c seems to be most accurately assessed at central collisions where impact parameter fluctuations are less important. To explore further the effects of charge conservation[11, 12], we examine the c values using a reduced impact parameter $(\hat{b}=b/b_{max})$ constructed from the charge particle multiplicity following Ref. [6] The central collision gate used in the present work is defined to be $\hat{b}<0.25$. c values obtained by fitting the multiplicity dependent charge distributions for fragments with $Z\geq3$, shown as solid points in the left panel of Fig. 3, increase gradually with incident energy. This trend is consistent with the simultaneous requirements of charge conservation accompanied by a general increase of the charge particle multiplicity with incident energy, reflecting a monotonic increase in excitation energy deposition with incident energy.

Such considerations are generally embodied in statistical multifragmentation models [3, 19,20]. To illustrate how measurements of multiplicity dependent fragment charge distributions may provide meaningful constraints on statistical models, we have calculated c using the statistical multifragmentation (SMM) model of refs. [17,18] which assumes the bulk fragmentation of a thermalized prefragment. The SMM model assumes that only a fraction of the system is thermalized, that this thermalized prefragment expands collectively, and that the remainder of the system is emitted via a pre-equilibrium initial stage. Very successful reproductions of experimental data [19,20] for central collisions have been obtained within the SMM model. Source sizes, excitation energies, and collective expansion velocities, for the exact same system in the present study were adjusted in ref. [19] to reproduce the central impact parameter gated fragment multiplicities, charge distributions and mean transverse energies. The predicted c values are plotted as open points in the left panel of Fig. 3. (All theoretical calculations have been filtered through the experimental detection arrays.) The solid lines are drawn to guide the eye. In general, the predicted *c* is much higher than the experimental values indicating a stronger charge and energy conservation constraint within these calculations than is experimentally observed.

The corresponding source sizes used in ref. [19], (A_o =183, 183, 169, 155, and 118 for incident energies of 35, 55, 70, 100, and 200 AMeV) are much smaller than the total system, ^{84}Kr+^{197}Au, which has A_o=281. To illustrate how much larger the calculated system would need to be in order to reproduce *c*, A_o was increased in the calculations while keeping the excitation energies (8.5 MeV per nucleon) and therefore charge distributions and expansion energy (11 MeV per nucleon) and therefore mean transverse energies fixed for the ^{84}Kr+^{197}Au system at 200 AMeV incident energy[19]. The right panel of Fig. 3 shows the resulting calculated dependence of *c* upon A_o. In order for the calculated *c* values to agree with experimental measurement (bound by the two dashed lines), the calculated source size must be increased from 118 to 240. Unfortunately, such drastic increase in source size would result in a gross overprediction the mean number of IMF observed by a factor of 2. The inconsistency could be due to dynamical suppression of fragment production from collective expansion [7] that would favor smaller excitation energies or due to a multi-step thermal cooling during the expansion. In any case, tests of the charge conservation constraints contained in the multiplicity dependent fragment charge distributions provide unique and useful information about the size of the thermalized prefragment.

In summary, the multiplicity dependent fragment charge distributions have been studied for the Kr+Au reactions from 35 to 400 AMeV. The extraction of the charge conservation parameter is found to be problematic for peripheral collisions with low E_t where impact parameters are poorly defined. For central collisions, the charge conservation parameter is stable and can provide useful guidance for theoretical models.

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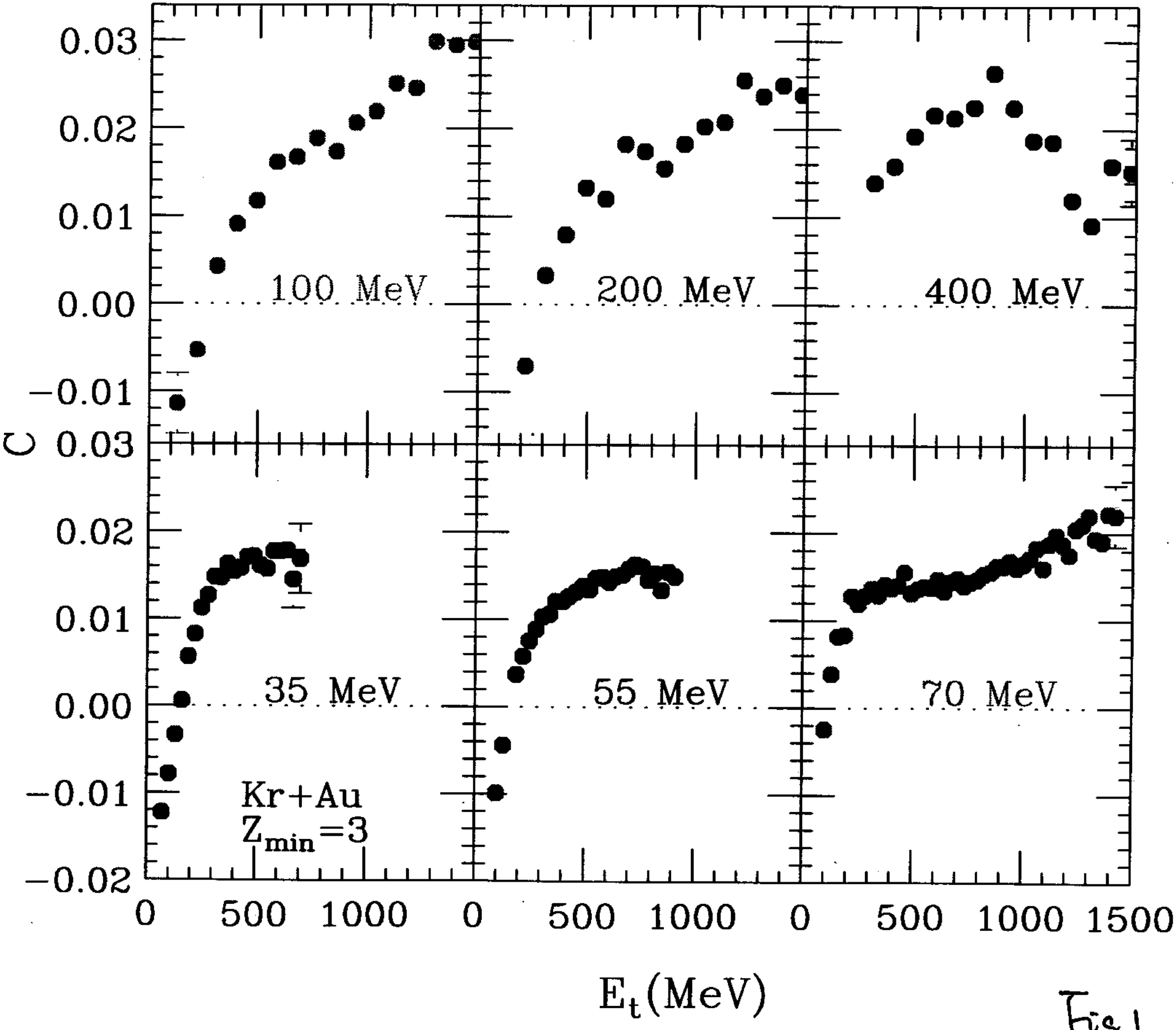
Figure Captions:

Figure 1. Charge conservation parameter *c* as a function of transverse energy E_t for the Kr+Au systems at incident energies from 35-400 AMeV.

Fig. 2. IMF multiplicity gated α-α correlation functions for the Kr+Au system at 35 AMeV with E_t<100 MeV.

Fig. 3. Right hand panel: *c* plotted as a function of incident energy for data (solid points) and SMM predictions (open points). Left hand panel: *c* plotted as a function of source sizes used in the SMM calculations for 200 MeV. The double dashed lines enclosed the experimental value.



C
0.03
0.02
0.01
0.00
−0.01
0.03
0.02
0.01
0.00
−0.01
−0.02
100 MeV
200 MeV
400 MeV
35 MeV
55 MeV
70 MeV
Kr+Au
Z$_{min}$=3
0
500
1000
0
500
1000
0
500
1000
1500
E$_t$(MeV)

Fig 1

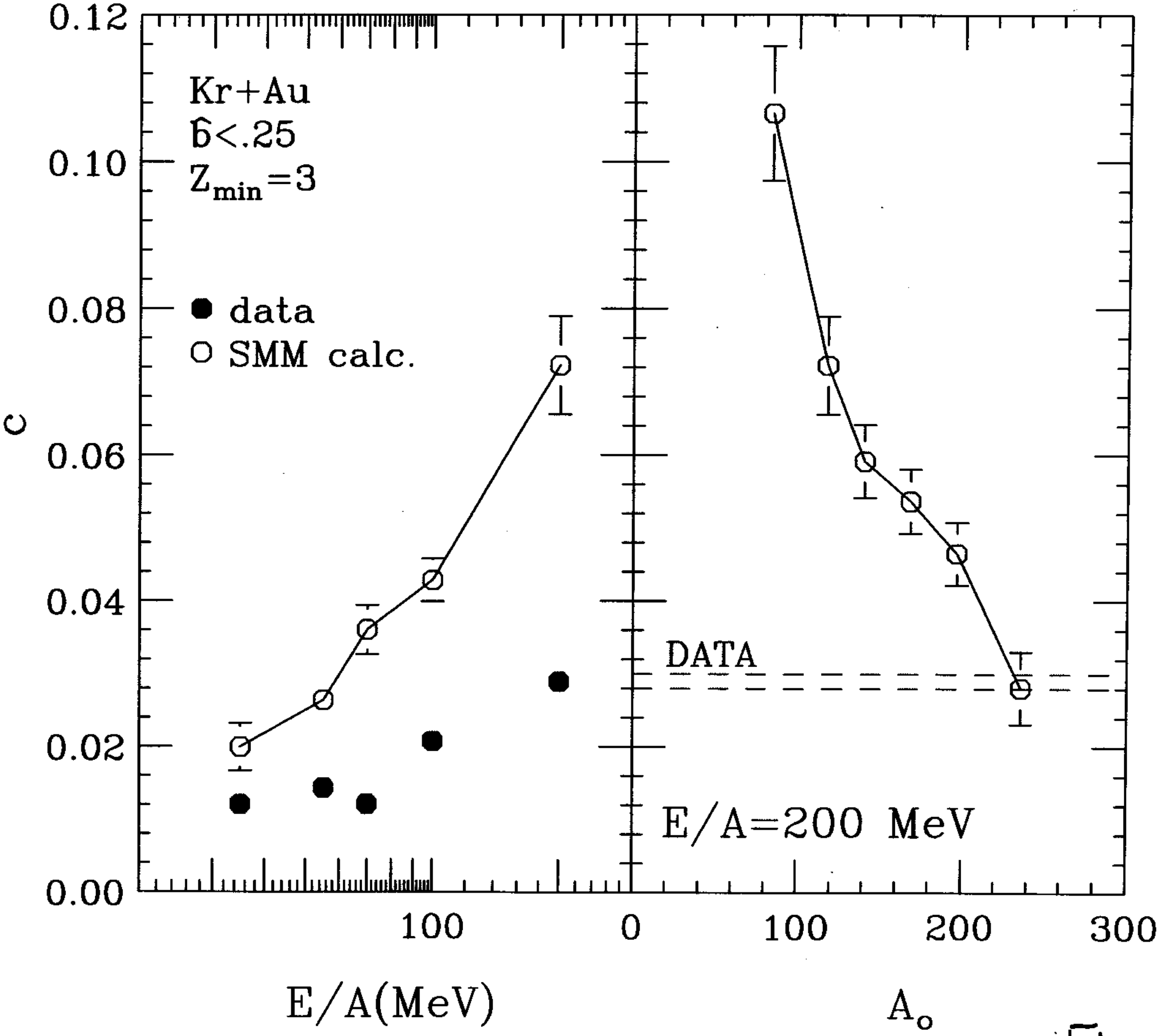

0.12
0.10
0.08
0.06
0.04
0.02
0.00
c
Kr+Au
b̂<.25
Z_{min}=3
● data
○ SMM calc.
100
E/A(MeV)
0
100
200
300
A_o
DATA
E/A=200 MeV

Fig 2

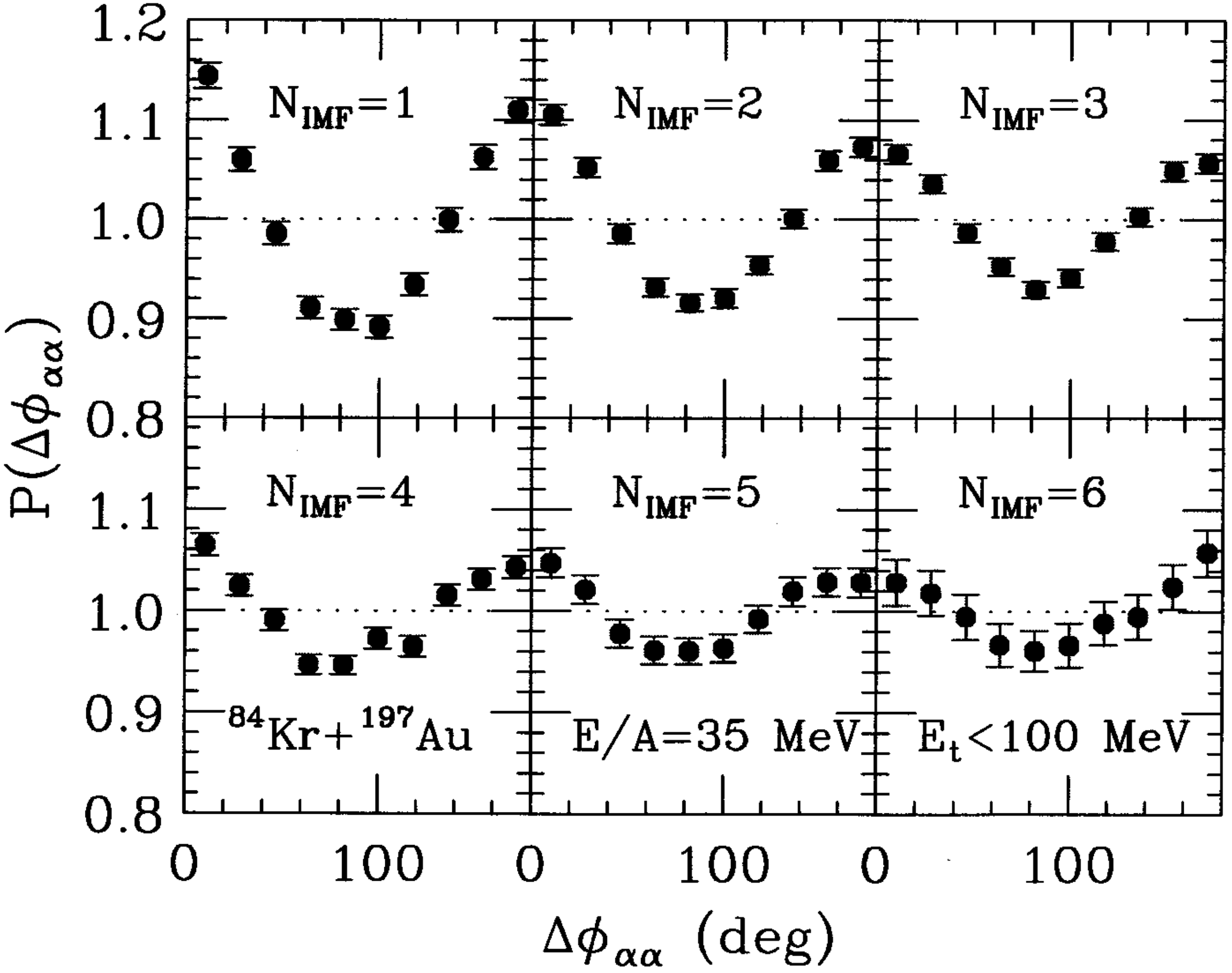

1.2
1.1
1.0
0.9
0.8
1.1
1.0
0.9
0.8
$P(\Delta\phi_{\alpha\alpha})$
$N_{IMF}=1$
$N_{IMF}=2$
$N_{IMF}=3$
$N_{IMF}=4$
$N_{IMF}=5$
$N_{IMF}=6$
$^{84}Kr+^{197}Au$
E/A=35 MeV
$E_t<100$ MeV
0
100
0
100
0
100
$\Delta\phi_{\alpha\alpha}$ (deg)

Fig 3