Fragment distributions for highly charged systems


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Charge and transverse energy distributions for intermediate mass fragments have been extracted for central

\(^{84}\text{Kr}^{+}\) \(^{197}\text{Au}\) collisions at \(E/A = 35–400\) MeV. The slopes of the measured fragment charge distributions
decrease monotonically with incident energy, consistent with the expectations for highly charged systems, but
not with recent critical exponent analyses. Statistical model calculations, which reproduce the experimental
trends, suggest that post-breakup fragment secondary decays alter significantly the observed charge distribu-
tions. Radial expansion velocities extracted from these calculations follow the systematics of \(\text{Au}+\text{Au}\) colli-
sions.

For infinite systems near a critical point, relationships be-
tween thermodynamic parameters are largely governed by a
set of critical exponents \([1,2]\). Theoretical \([3]\) and experi-
mental prescriptions \([4]\) for extracting critical exponents for
the nuclear liquid-gas phase transition from nuclear colli-
sions assume that the observed fragment mass distributions
differ little from those for infinite nuclear matter near critical
density, and therefore decrease most gradually with mass for
reaction trajectories that pass through the critical point. The
presence of long range Coulomb interactions, however, com-
plicates the extrapolation of increasingly heavy laboratory
systems towards the thermodynamic limit characteristic of
critical phenomena \([1,2]\). Furthermore, post-breakup second-
ary decays \([5]\) alter the observed fragment charge distribu-
tions. Both have been assumed to be negligible in previous
analyses \([4,6,7]\).

Assumptions underlying present critical exponent analy-
ases of highly charged systems have been undermined by re-
cent calculations \([8,9]\). Classical molecular dynamics calcula-
tions of highly charged systems predict a monotonic
evolution of the fragment charge distributions characterized...
by $Y(A) \propto A^{-\tau}$, from flat distributions with $\tau=1$ at low-excitation energies to steeply falling charge distributions at high-excitation energies [8]. In contrast to corresponding calculations for neutral systems [9,10] and the assumptions of critical exponent analyses, a minimum in the value of $\tau$, that could indicate critical phenomena, is not predicted for highly charged systems at moderate temperature [8]. Fragment yields may also be enhanced by a Coulomb driven evolution towards a bubblelike breakup geometry [11,12]. Consistent with these expectations, extremely flat charge distributions have been observed in central Au+Au collisions at $E/A=35$ MeV [13], but predictions [8] for highly charged systems of a monotonic decrease of the slopes of the fragment charge distributions with incident energy have not been tested until now. Detailed comparisons of statistical model calculations are also provided in this paper which reveal the charge distributions after secondary decay to be significantly steeper than those before secondary decay, rendering questionable present techniques [3,4,6,7] for critical exponent extraction. Comparisons of these calculations to transverse energy distributions suggest that the extracted radial expansion velocities are similar to those observed for symmetric systems.

The experimental data were measured using two different accelerators. Measurements at $E/A=35$, 55, and 70 MeV were performed at the National Superconducting Cyclotron Laboratory of Michigan State University by bombarding gold targets of 1.3 mg/cm$^2$ by $^{84}$Kr beams of 35 MeV and gold targets of 4 mg/cm$^2$ by $^{84}$Kr beams of 70 MeV. Measurements at 100A, 200A, and 400A MeV were performed at the Laboratoire National SATURNE at Saclay by bombarding $^{84}$Kr beams on gold targets of 5 mg/cm$^2$ areal density. Charged particles were detected with the Miniball/Miniball 4$\pi$ array [14] consisting of 268 phoswich detectors covering 5.4°$\leq \theta_{lab} \leq 160°$ with a geometric efficiency of approximately 90% of 4$\pi$.

Detectors with particle identification thresholds of $E_{th}(A=4$ MeV) for $Z=3(10)$ particles were constructed from 80 $\mu$m thick plastic scintillator foils and 3 cm thick CsI(Tl) crystals and used at forward angles, $5.4° \leq \theta_{lab} \leq 25°$. Detectors with particle identification (PID) thresholds of $E_{th}(A=2$ MeV) for $Z=3(10)$ particles were constructed from 40 $\mu$m thick plastic scintillator foils and 2 cm thick CsI(Tl) crystals and used at backward angles, $25° \leq \theta_{lab} \leq 160°$. Unit charge resolution up to $Z=12$ was achieved for particles that traversed the fast plastic scintillator. Lithium ions that punched through the CsI(Tl) crystals were not counted as IMF’s because they were not distinguished from light particles. To ensure accurate energy determination, low-energy thresholds of $E/A=5$ MeV were imposed in software on fragments of $Z=3-8$, respectively, for the determination of mean transverse energy values. For consistency with Ref. [15], charge distributions and fragment multiplicities were obtained using the software thresholds of Ref. [15]. This information was used to project all the theoretical calculations, described herein, upon the experimental acceptance. A “reduced” impact parameter scale $\bar{b}=b/b_{max}$ was constructed from the charged particle multiplicity following Refs. [15,16]; the constraint $\bar{b}=0.25$ was applied to select central collisions. A value of $b_{max}=10$ fm, determined by direct beam counting at $E/A=200$ MeV, provides an approximate impact parameter calibration.

The solid points in Fig. 1 show the fragment charge distributions for the six incident energies. These distributions decrease monotonically with fragment charge and can be approximately described by a power law of the form $Y(Z)=C\cdot Z^{-\tau}$. Using this functional form, fits for $3\leq Z\leq 12$, shown by the solid lines, follow the experimental yields in the figure closely. The extracted values for $\tau$ are shown as the solid circles in the lower panel of Fig. 2. Consistent with the classical molecular dynamics calculations for highly charged systems [8] and contrary to the assumptions of critical exponent analyses [3,4,6,7], $\tau$ increases monotonically with incident energy and does not have a minimum at intermediate energies. The lowest value for $\tau$ ($\tau=1.4$), attained at $E/A=35$ MeV, is somewhat more than half of the value $\tau=2.3$ that is expected to characterize the mass distribution of a system at the critical point in the liquid-gas phase diagram [1,2].

Previous attempts to use quantum molecular dynamics model [17] failed to reproduce the average IMF multiplicities in multifragmentation processes [15,18]. The QMD model also fails to describe the impact parameter dependence of IMF fragments produced [18]. Thus it is interesting to investigate whether a satisfactory agreement might be obtained with statistical models and what values of the parameters of such calculations are thereby required. To explore this issue, the statistical multifragmentation model (SMM) calculations were performed [19], varying the excitation energy, density, and collective flow of the fragmenting system to fit the data. Since two-fragment correlations provide evidence that the limit of a single freeze-out time is not attained...
Experimental values for kinetic energy and scattering angle of the reaction 55/197 collisions as functions of the incident energy per nucleon. See text for details. (Theoretical uncertainties in 55/197 are typically ±0.2.)

Collective motion influences the energy spectra and consequently the detection efficiency for fragments in the experimental array, but is not a priori predicted by the SMM model. Previous investigations indicate that the attractive nuclear mean field can support a form of “rotational” flow at low-incident energies [21]. At higher-incident energies this rotational flow decreases and flow is primarily in an outward or “radial” direction [22,23] due to pressure from nucleon-nucleon collisions and from the high-density nuclear equation of state in the central overlap region. To bracket these two limits, the influence of collective flow was estimated in the limits of purely collective rotational flow and purely collective radial expansion assuming a breakup density of ρ/ρc = 1/6 [19,24].

Collective flow was explored by computing the mean transverse energy 〈Ei〉 = ΣiEi sin2θi, where Ei and θi are the kinetic energy and scattering angle of the ith fragment. Experimental values for 〈Ei〉, shown as the solid points in Fig. 3, generally increase with incident energy and, except for the two highest energies, with the fragment mass. At 55/197, however, a clear decrease of 〈Ei〉 with fragment mass is observed supporting the observations of Refs. [22,23] that heavier fragments do not participate fully in the transverse expansion, due to a suppression of fragment formation in rapidly expanding nuclear systems [25].

SMM model calculations were performed with excitation energies per nucleon, equilibrium source sizes, and collective flow velocities that optimize the agreement with the fragment charge distributions, total fragment multiplicities, and transverse energies, respectively. Calculations with two sets of optimized parameters, listed in Table I, reproduce the experimental multiplicities (top panel of Fig. 2), the slopes of the charge distributions (bottom panel of Fig. 2) and the transverse energies (Fig. 3) reasonably well. All calculations have been filtered through the spatial and energy limitations of the detector arrays. Virtually identical agreements with the data are obtained via calculations with parameter set 1 (dashed lines) which assumes a purely collective rotational flow and parameter set 2 (solid lines) which assumes purely radial flow, provided the mean rotational flow energy per nucleon 〈Erot/A〉 in set 1 and the mean radial flow energy per nucleon 〈Er/A〉 in set 2 make equal contributions to the transverse energy; i.e., 〈Erot/A〉 + 〈Er/A〉 = 〈Etrans/A〉.

The small values of fE in these SMM model calculations, coupled with the large values for 〈Ei/A〉 and 〈Erot/A〉, cor-

![FIG. 2. Experimental (solid points) and theoretical (solid and dash lines) fragment multiplicities (upper panel) and power law parameters τ (Y x Z−1/2; lower panel) for central 84/Kr + 197/Au collisions as functions of the incident energy per nucleon. See text for details. (Theoretical uncertainties in τ or 〈NIMF〉 are typically ±0.2.)](Image)

![FIG. 3. Experimental (solid points) and theoretical (solid and dash lines) fragment transverse energies for central 84/Kr + 197/Au collisions as functions of the incident energy per nucleon. Uncertainties in the calculated values of 〈Ei〉, shown for parameter set 1, are essentially the same for parameter set 2.](Image)

### TABLE I. Parameters of SMM calculations chosen to optimally describe the experimental data.

<table>
<thead>
<tr>
<th>Ebeam/A (MeV)</th>
<th>Set</th>
<th>fA</th>
<th>fE</th>
<th>〈Erot/A〉 (MeV)</th>
<th>〈Ei/A〉 (MeV)</th>
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<td>35</td>
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<td>1.2</td>
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<td>0.0</td>
<td>0.9</td>
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<tr>
<td>55</td>
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<td>0.65</td>
<td>0.76</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>55</td>
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<td>0.65</td>
<td>0.71</td>
<td>0.0</td>
<td>1.9</td>
</tr>
<tr>
<td>70</td>
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<td>0.60</td>
<td>0.74</td>
<td>4.0</td>
<td>0.0</td>
</tr>
<tr>
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</tr>
<tr>
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<td>8.0</td>
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<td>0.0</td>
<td>19</td>
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FIG. 4. Systematics of the radial velocities as a function of the excitation energy of the participant source. The solid squares are data from $^{84}\text{Kr}+\text{Au}$ central collisions. The open [26] and closed [23,27] circles are experimental values extracted from the central $\text{Au}+\text{Au}$ collisions.

respond to thermal excitation energies of 5.3–11.9 MeV/nucleon and indicate that the local thermal environment at breakup is much cooler than one would expect if the incident energy were completely thermalized ($E_N = 1, \langle E_{	ext{rot}}/A\rangle = \langle E_r/\langle A\rangle\rangle = 0$). Similar to $\text{Au}+\text{Au}$ collisions [22,23], major portions of this nonthermal energy are converted to collective energy of expansion. For the $\text{Kr}+\text{Au}$ system, the solid squares in Fig. 4 show the dependence of the radial expansion velocity defined by

$$\langle \beta \rangle = 1.37 \sqrt{\frac{E_r}{A m_N c^2}},$$

where $m_N$ is the nucleon mass, as a function of the excitation energy of the participant source. Here the excitation energy of the participant source has been calculated for $b=2$ fm using the participant-spectator model assuming a straight line geometry. For comparison, the open [26] and closed [23,27] circles in Fig. 4 show the mean radial velocities extracted for central $\text{Au}+\text{Au}$ collisions. Both asymmetric and symmetric systems show similar trends. Data for even more asymmetric systems are needed, however, to really establish the dependence of collective expansion in entrance channel mass asymmetry.

The excitation energies per nucleon of the fragmenting system assumed by the SMM calculations were essentially constrained by the slope parameters $\tau$ of the fragment charge distribution. As shown in the bottom panel of Fig. 2, neither nature nor the SMM model have any difficulty producing fragmentation events characterized by a slope parameter $\tau$ much less than the minimum value $\tau = 2.3$, characteristic of a neutral liquid-gas phase admixture at the critical point. These small slope parameters become even more difficult to accommodate within critical exponent analyses such as those of Refs. [3,4,6,7] when one realizes that secondary decay makes a significant contribution to the power law parameters for the calculated charge distributions and possibly, to the measured ones as well. Considerable modifications of calculated charge distributions from secondary decay are also predicted in other approaches [28]. Present critical exponent extrapolations neglect such secondary decay corrections and therefore should be viewed as questionable.

In summary, charge distributions for intermediate mass fragments have been extracted for central $^{84}\text{Kr}+^{197}\text{Au}$ collisions at energies ranging from $E/A = 35–400$ MeV. Consistent with recent calculations for finite highly charged systems, the slopes of the fragment charge distributions decrease monotonically with incident energy and at low energies, are characterized by “power laws” with powers much less than those deduced from recent critical exponent extractions. Statistical model calculations indicate moderately low breakup excitation energies, and reveal that post-breakup fragment decays alter significantly the observed charge distributions rendering present critical exponent extraction techniques problematic. Finally, the radial expansion velocities extracted from SMM calculations for the $\text{Kr}+\text{Au}$ system follow a similar systematic trend previously observed in central $\text{Au}+\text{Au}$ collisions.

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[24] These collective velocities affect the fragment velocities, but not the multiplicities.
[28] H.F. Xi (private communication).