Fragment emission from expanding hot nuclear systems

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ABSTRACT. Nuclear collisions at intermediate energies lead to highly excited systems which may expand under the influence of thermal pressure and decay into multi-fragment exit channels. Experimental results addressing impact parameter selection, fragment multiplicity, fluctuations, emission time scales, and expansion dynamics will be reviewed.

RESUMEN. Las colisiones nucleares a energías intermedias llevan a sistemas altamente excitados, que pueden expandirse bajo la influencia de presión térmica y decaer a través de canales de salida de varios fragmentos. Se revisan los resultados experimentales dirigidos a la selección de parámetros de impacto, multiplicidad de fragmentos, fluctuaciones, escalas de tiempo de emisión y dinámica de expansión.

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1. INTRODUCTION

Two phase transitions are predicted to exist for bulk nuclear matter: at moderate temperatures and low densities, \( T \approx 10 \text{ MeV} \) and \( \rho < \rho_0 \), a liquid-gas phase transition is expected to occur; at high temperatures and high densities, \( T \approx 200 \text{ MeV} \) and \( \rho > \rho_0 \), a deconfinement transition to a quark-gluon plasma is predicted to take place. Nuclear collision experiments are the only accessible tool which could yield experimental information about these phase transitions. At present, no unambiguous signatures for the occurrence of either of these phase transitions are known, and it is not yet known whether nucleus-nucleus collision experiments can, indeed, provide information pertinent to the phase transitions of infinite nuclear matter.

Temperatures and densities pertinent to the deconfinement transition can be achieved in nucleus-nucleus collisions at energies of several tens or hundreds of GeV per nucleon. This research will be performed at the relativistic heavy ion collider (RHIC). Temperatures and densities pertinent to the liquid-gas phase transition can be achieved in intermediate energy collisions (\( E/A \approx 20-200 \text{ MeV} \)). In a possible reaction scenario, a hot system, formed during the initial stages of the reaction, may expand under the action of thermal pressure, possibly aided by a decompression cycle following an initial compression. If the reaction trajectory enters regions of sufficiently low density, instabilities with respect to density fluctuations can cause prompt multifragment emission. Multifragment disintegrations may, therefore, signal a liquid-gas phase transition.

Unfortunately, the interpretation of multifragment decays in terms of a spinodal decomposition is not unique. Dynamically induced density fluctuations (not directly linked with
phase instabilities) could also lead to multifragment final states [1,2]. The system could also evolve dynamically into strongly prolate, oblate or even toroidal [3] shapes for which Rayleigh instabilities could lead to multifragment disintegrations. Moreover, statistical models of compound nucleus decay also predict multiple fragment emission [4-7] that may be strongly enhanced under extreme conditions of temperature and density due to a decrease of the decay barriers. Which of these scenarios are applicable must be answered by careful experimental and theoretical investigations.

In this paper, I will sketch some of the experiments which we have recently conducted at MSU [8-15] with the goal of obtaining a better understanding of the physics underlying intermediate energy nucleus-nucleus collisions and of exploring whether conditions necessary for a liquid-gas transition in hot nuclear systems can be achieved. For this purpose, we have studied multifragment exit channels for $^{36}\text{Ar}+^{197}\text{Au}$ collisions [9-14,16] at $E/A = 35, 50, 80,$ and $110$ MeV and for $^{129}\text{Xe}+^{197}\text{Au}$ collisions at $E/A = 50$ MeV [8,15] using the MSU Miniball [17], a granular $4\pi$ detection array with low detection threshold and broad-range particle identification capability. In the following, I will review issues with regard to impact parameter selection [14], relative abundance of intermediate mass fragments ($Z_{\text{IMF}} \approx 3-20$) and light particles ($Z \approx 1, 2$) among the emitted particles [8,10,18], charged particle multiplicity fluctuations [13], emission temperatures [16], and emission time scales [9].

2. IMPACT PARAMETER SELECTION

Information about the impact parameter is extracted from quantities which relate to the collision geometry via simple intuitive pictures. Most impact parameter filters represent some measure of the "violence" of the reaction which, in turn, is assumed to be related to the collision geometry. Common impact parameter filters are based upon the measured multiplicity of charged particles $N_C$ [18-21], the transverse energy $E_t$ [22], or the summed charge of particles emitted at intermediate rapidity $Z_v$ [23]. For collisions with incident energies of a few hundred MeV per nucleon, the summed charge, $Z_{\text{bound}}$, of particles with atomic number $Z \geq 2$ [24] has also been used. (This quantity is the complement of $N_1$, the combined p, d, and t multiplicity.)

If one assumes a monotonic relationship between impact parameter $b$ and an observable $X$, one can define a reduced impact parameter scale via the geometrical relation

$$\hat{b}(X) = \frac{b(X)}{b_{\text{max}}} = \sqrt{\frac{1}{\sigma_R} \int_X^{\infty} \frac{d\sigma(\xi)}{d\xi} d\xi},$$

where $\sigma_R$ is the reaction cross section. The reduced impact parameter scale ranges from $\hat{b} = 1$ for glancing collisions to $\hat{b} = 0$ for head-on collisions.

A priori, it is unclear to what extent different observables $X$ select similar or equivalent impact parameters, and whether one technique provides superior resolution as compared to another. For $^{36}\text{Ar}+^{197}\text{Au}$ collisions of $E/A = 35-110$ MeV, this question was investigated in Ref. [14] for impact parameter filters based upon $X = N_C, E_t, Z_v,$ or $N_1$. 
The overall similarity of various impact parameter filters was established and quantitative questions concerning the resolution of individual methods were addressed. For the selection of central collisions, filters based upon $E_t$ had slightly better resolution than filters based upon $Z_y$, $N_C$, and $Z_{bound}$.

For central collisions, the particle emission pattern must be axially symmetric. For non-central collisions, on the other hand, the emission pattern is generally not axially symmetric. Non-isotropic azimuthal distributions are readily detected by measuring azimuthal correlation functions,

$$1 + R(\Delta \phi) = \frac{\sigma_2(\phi_1 - \phi_2)}{\sigma_1(\phi_1)\sigma_1(\phi_2)},$$

where $\phi_i$ denotes the azimuthal angle of particle $i$, $\Delta \phi = \phi_1 - \phi_2$, and $\sigma_1$ and $\sigma_2$ are the single and two-particle cross sections for a given class of events. Figure 1 illustrates that central collisions can, indeed be selected, by appropriate cuts on the reduced impact parameter [25]: the azimuthal correlation functions become isotropic for impact parameter filters corresponding to $\delta \rightarrow 0$.

3. FRAGMENT ADMIXTURES

The solid points in Fig. 2 show the average number of detected intermediate mass fragments, $\langle N_{IMF} \rangle$, as a function of the raw charged particle multiplicity, $N_C$, for the Xe +
Au reaction [8] at $E/A = 50$ MeV. Calculations with the microscopic QMD and QPD transport models of Refs. [1,2] predict average fragment multiplicities much smaller than observed experimentally [8]. Both numerical simulations underestimate the growth of density fluctuations leading to fragment emission.

Open circles and crosses in Fig. 2 show multiplicities predicted by the statistical compound nuclear decay code GEMINI [4], and the dashed curves depict predictions of the statistical compound nuclear model of Ref. [5]. None of these calculations for the decay of excited nuclei of normal nuclear density can reproduce the high IMF multiplicities measured for $N_C > 20$. When hot nuclei are allowed to expand [6], however, significantly larger IMF multiplicities are predicted and reasonable agreement with the data is obtained (solid curves, star- and diamond-shaped points).

A number of theoretical investigations of phase transitions in finite nuclear systems have been based on percolation models [26–30]. Percolation models are attractive, since they exhibit a well-defined phase transition for infinite systems and since they allow straightforward generalizations to finite systems. They have been rather successful [26] in describing the observed [31] power-law behavior of measured fragment mass distributions and in developing techniques to extract critical exponents.

In Fig. 3, the results of bond percolation calculations [12] for the decay of spherical nuclear systems are compared to fragment admixtures measured [8,10] for $Xe + Au$ and $Ar + Au$ collisions at the indicated energies. Thick and thin curves represent results of filtered and unfiltered bond-percolation calculations [26], respectively, using the critical bond-breaking parameter, $p = 0.7$. For the bond-percolation model [26], these calculations give upper bounds for the admixture of IMFs among the emitted charged particles. Solid
and dashed curves show percolation calculations for composite systems formed in Xe + Au and Ar + Au collisions; dot-dashed curves show calculations for the simultaneous multifragment decays of Xe projectile and Au target nuclei. The percolation calculations are consistent with the IMF admixtures observed for the Ar + Au system, but they fail to reproduce the large values measured for the Xe + Au system. It is intriguing that bond percolation calculations for less compact geometries such as toroidal systems (predicted to exist by BUU transport models [32]) are able to produce sufficiently high IMF admixtures to be compatible with the Xe + Au data, and it would be very exciting if the formation of such exotic nuclear systems could be confirmed by independent and more direct experimental methods.

4. CHARGED PARTICLE FLUCTUATIONS

The question has been raised [13] whether multifragmenting systems might exhibit large scale fluctuations or evidence for intermittency, which could indicate that fragmentation processes are scale invariant. Intermittency as an indicator of nontrivial physics is generally sought for systems exhibiting larger than Poisson fluctuations. Evidence for such large fluctuations must be sought in events representing similar initial conditions. However, constraints from conservation laws may lead to reduced fluctuations because statistical independence of individual bin occupations is lost.
Figure 4. Relation between $\sigma_C^2/\langle N_C \rangle$ and $\langle N_C \rangle$. Solid points show experimental values extracted from near-central $^{36}$Ar + $^{197}$Au reactions at $E/A = 35, 50, 80$ and $110$ MeV. Open points depict results of calculations. Open circles: standard bond-percolation model [26] using $p = 0.6$ and $0.7$ (the open triangle illustrates the magnitude of instrumental distortions); open diamonds: percolation model with fixed number of broken bonds; open squares: predictions by GEMINI [4]; star shaped points: predictions by Copenhagen fragmentation model [7]. From Ref. [13].

Figure 4 depicts the relation between $\langle N_C \rangle$ and $\sigma_C^2/\langle N_C \rangle$ extracted [13] for central ($b < 0.3$) Ar + Au collisions at $E/A = 35, 50, 80$, and $110$ MeV. Here, $\langle N_C \rangle$ and $\sigma_C$ denote the mean value and the variance of the measured charged particle multiplicities. At all energies, the fluctuations of the charged particle multiplicity are considerably smaller than expected for Poisson distributions (for which $\sigma_C^2/\langle N_C \rangle = 1$).

These surprisingly narrow charged particle multiplicity distributions may result from phase space constraints imposed by energy conservation [13]. In Fig. 4, the effect is illustrated by bond percolation calculations in which the number of broken bonds corresponds to excitation energy. In standard percolation calculations, shown by open circular points, the number of broken bonds is allowed to fluctuate from event to event, and the predicted fluctuations in $N_C$ are much larger than observed experimentally. If, on the other hand, one requires a fixed number of broken bonds (i.e. a fixed excitation energy), the widths of the charged particle distributions are strongly reduced (see open diamonds). More realistic statistical model calculations [4,7] which incorporate energy conservation on an event-by-event basis predict even smaller fluctuations. Examples of such calculations are shown by the open square- and star-shaped points which depict predictions of the sequential decay model GEMINI [4] and of the Copenhagen fragmentation model [7], respectively. The experimental $N_C$-distributions are somewhat broader than predicted by these latter two models, possibly due to imperfect impact parameter selection [13]. Broadening due
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![Diagram showing emission temperatures](image)

**Figure 5.** Emission temperatures extracted from the relative populations of widely separated states in $^4$He and $^5$Li. Data from Refs. [33–35].

5. Emission Temperatures

Statistical treatments of fragment emission processes require the knowledge of the local excitation energy density (or temperature) at the time of emission. Emission temperatures have been determined from relative populations of states. Particularly suitable for such investigations are widely separated states in $^4$He and $^5$Li for which uncertainties due to feeding from higher lying states are of minor importance [33–35]. Figure 5 summarizes emission temperatures determined [33–35] for a number of reactions with incident energies ranging from $E/A = 35–200$ MeV. The extracted temperatures are of the order of 4–6 MeV, significantly smaller than “kinetic” temperature parameters which characterize the slopes of the kinetic energy spectra of emitted particles, and they exhibit a small, but significant rise with incident energy [35]. These features can be understood [36] in terms of the expanding compound nucleus model of Ref. [6]. Alternative interpretations in terms of nonequilibrium transport models exist [35] and cannot be ruled out. Note however, that these transport models predict too small fragment multiplicities.
FIGURE 6. Two-fragment correlation functions measured for the $^{36}$Ar + $^{197}$Au reaction. From Ref. [37].

6. EMISSION TIME SCALES

Information about the time scale of multifragment emission processes can be extracted from fragment-fragment correlation measurements [9]. Correlation functions measured for the $^{36}$Ar + $^{197}$Au reaction [9,37] are shown in Fig. 6. The correlation functions are shown as a function of the reduced relative velocity, $v_{\text{red}} = v_{\text{rel}} \times (Z_1 + Z_2)^{-1/2}$, and summed over fragment pairs with $4 \leq Z_{\text{MF}} \leq 9$, see Ref. [9] for technical details. The correlation functions exhibit a pronounced minimum at $v_{\text{red}} \approx 0$ which is mainly due to the repulsive Coulomb final state interaction between the two coincident fragments. The width of this minimum is sensitive to the source dimension and the time scale of emission.

The curves in Fig. 6 represent calculations with the classical version of the Koonin-Pratt formula. The derivation of this formula is based upon the assumption that the final-state interaction between the two detected fragments dominates, that final-state interactions with all remaining particles can be neglected, and that the correlation functions are determined by the two-body density of states as corrected by the interactions between the two particles. For two-fragment correlations, these assumptions are not strictly valid, and Coulomb distortions in the mean field of the residual system introduce uncertainties for the fragment emission time scales approximately 50%.

Time scales extracted from the comparison between experiment and theory are of the order of 100 fm/c or less. These time scales are commensurate with the time scales for which nonequilibrium transport phenomena may not be negligible, and they are well within the realm of current microscopic transport theories. The failure of these microscopic theories to produce sufficient numbers of fragments presents therefore a particularly challenging problem for future investigations.
7. Summary

Considerable progress has been made in studies of nucleus-nucleus collisions leading to multifragment final states:

- Empirical impact parameter filters can be constructed which allow the selection of small impact parameter collisions, and it is possible to cross-calibrate impact parameter filters based upon different observables and assess their respective resolution.

- For incident energies below $E/A \approx 100$ MeV, multifragmentation occurs primarily in central collisions. Microscopic transport theories, explicitly constructed for the treatment of multifragment disintegrations, fail to account for the large number of fragments observed experimentally. Statistical models which allow for fragment emission from a low-density phase, on the other hand, are rather successful in reproducing the observed large fragment admixtures.

- For impact parameter selected reactions, fluctuations in the charged particle multiplicity were shown to be much smaller than fluctuations of Poisson distributions, indicating that fluctuations in finite systems can exhibit considerable damping due to phase space constraints imposed by conservation laws.

- Studies of two-fragment correlation functions indicate that multifragmentation time scales are short, $t \approx 100$ fm/c, and that fragment emission already sets in during the early nonequilibrium stages of the reaction.

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References