dependent estimate of the density of the emitting source, we have examined the Coulomb parameters obtained in a moving source analysis[6] of the spectra. Comparison of these parameters as a function of Z_{obs} implies a value of $\rho/\rho_o \approx 1/3$, based solely on the experimental data. Thus, the fragment spectra provide a strong argument for thermal expansion of nuclear matter at high temperatures – or some alternative mechanism that involves significant perturbation of the nuclear Coulomb field at freezeout.

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ASSESSING THE EVOLUTIONARY NATURE OF MULTIFRAGMENT DECAY

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Large, highly excited nuclear systems are observed to undergo the process of multifragmentation, i.e., they decay into a relatively large number of intermediate mass nuclear fragments (IMFs :$3 \leq Z \leq 20$).[1–7] Current evidence suggests that these fragments are produced from the decay of systems at low density.[5,6] Recent experimental results have been interpreted in terms of diametrically opposed scenarios regarding the importance of time in the fragmentation process.[8–10] Thus, a crucial open question regarding this process is whether IMFs are produced at a single time, from a well defined (freeze-out) condition, or whether they are produced over a period of time, as the system evolves and changes.[11–13]

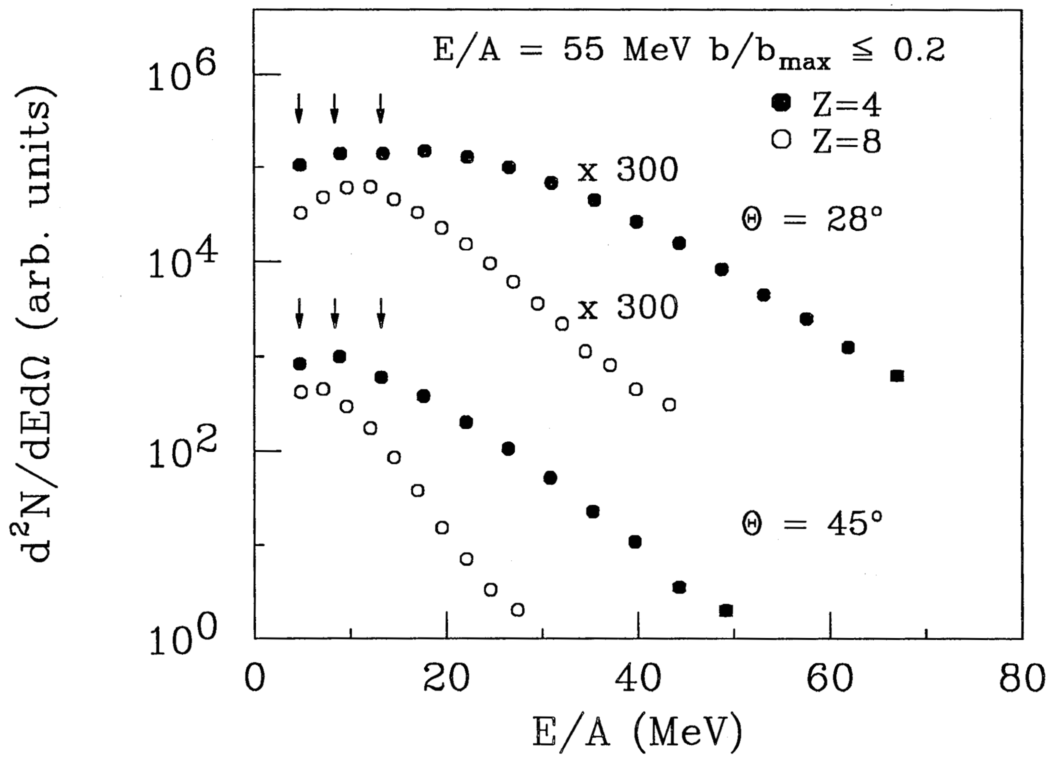

Figure 1. Inclusive kinetic energy spectra for Be and O fragments (closed and open symbols) emitted in central collisions. The arrows indicate velocity cuts of v_{min} = 3, 4, and 5 cm/ns.

The inclusive kinetic energy spectra of fragments originating from central collisions provides no answer to this question. At a given angle these spectra are smooth, relatively featureless distributions that can be described by simple Boltzmann-like functions involving a single temperature, Coulomb barrier, and source velocity, and in some cases collective expansion energy. Typical spectra are shown in Fig. 1.

Light charged particles and IMFs produced in collisions of ^{84}Kr + ^{197}Au were detected in the angular range $5.4° \leq \theta_{lab} \leq 160°$ by the MSU Miniball/Washington University Miniwall 4π detector array. The energy resolution for this experiment was 15%. Experimental details have been previously described.[14,15]

In this analysis, our attention is specifically directed at the question posed above, i.e., whether the fragments arise from a single condition, or during the evolution of the system. In order to select events preferentially from a single equilibrated source, we select on central collisions. We have related the charged-particle multiplicity to an impact-parameter scale following a geometrical prescription[16] and selected events which correspond to $b/b_{max} \leq 0.2$. In our definition, b_{max} refers to the maximum interaction radius for which two charged particles are emitted. These central collisions have charged particle multiplicities corresponding to $N_C \geq 24$, 33, and 38 at E/A = 35, 55, and 70 MeV, respectively. For these central collisions the average multiplicity of IMFs is $\langle N_{IMF} \rangle \approx 4$, 5, 6 at E/A = 35, 55, and 70 MeV, respectively.[14]

To address our central question, we have examined the fragment-fragment velocity correlations for different portions of the one-body velocity distribution. If the multifragmentation process were to involve a sharp freeze-out, then one would expect little dependence of these fragment correlations on different portions of the energy spectrum. On the other hand, if the yield were to arise during the evolution of the system, then different components of the spectra might arise from different conditions which could, in turn, provide different fragment-fragment correlation signals.

Fragment-fragment velocity correlations are a powerful tool for extracting information about the spatial-temporal dimensions of the emitting source.[17–24] This technique utilizes the mutual Coulomb repulsion of the fragments as a probe of the emitting system. The Coulomb repulsion results in a reduction of the probability for observing fragments at low relative velocity. Velocity correlation functions, $R(v_{red})$, were constructed, using procedures previously employed,[19] by relating the coincidence yield Y_{12} to the product of the single particle yields Y_1 and Y_2:

$$\sum Y_{12}(v_1, v_2) = C[1 + R(v_{red})] \sum Y_1(v_1)Y_2(v_2),$$

where v_1 and v_2 are the laboratory velocities of the fragments, the reduced velocity, $v_{red} = (v_1 - v_2)/(Z_1 + Z_2)^{1/2}$, and C is a normalization constant determined by the requirement that $R(v_{red}) \rightarrow 0$ at large relative velocities where the Coulomb repulsion is small.

As Figs. 2a-c indicate, the fragment-fragment correlation functions depend strongly on the kinetic energy of the fragment pairs. For each of the correlation functions shown, the fragments were selected on the basis of v_{min}, the minimum velocity of the less energetic fragment of each pair. All the correlation functions were summed over all pairs $4 \leq Z_1, Z_2 \leq 9$ emitted in the angular range $25° \leq \theta_{lab} \leq 50°$. The normalization constant for each correlation function was determined in the range $0.05\ c \leq v_{red} \leq 0.08\ c$. For orientation, the kinetic energies which correspond to these minimum velocities are depicted as the arrows on the energy spectra in Fig. 1.

All of the correlation functions exhibit a "Coulomb hole" i.e. a strong suppression of pairs of low relative velocity. As the minimum velocity of the pair is increased, a significant increase in the width of the Coulomb hole is observed at all three incident energies. To quantify this effect sufficiently to pursue qualitative observations, we have extracted the width of the Coulomb hole in the correlation function at half its asymptotic value (HWHM) for each cut of fragment energy. In Fig. 3a, the values of the widths of the Coulomb holes are plotted against the velocity cut-off (minimum velocity) used to construct the correlation function. An increase in the HWHM with increasing v_{min} is evident. For the v_{min} cuts shown, the correlation functions are affected by negligible dynamical effects. The representative error bars take into account the energy resolution. Selection of the same center-of-mass angle for each of the v_{min} cuts results in essentially the same trend observed in Fig. 3a.

The shape of the correlation function is associated with the space-time structure of the fragment emission process. In general, the wider the Coulomb hole, the smaller the separation in space-time between the emission of contributing fragments pairs. Thus, the dependence of the strength of the Coulomb interaction suggests that different space-time situations are associated with the emission related to different parts of the spectra.

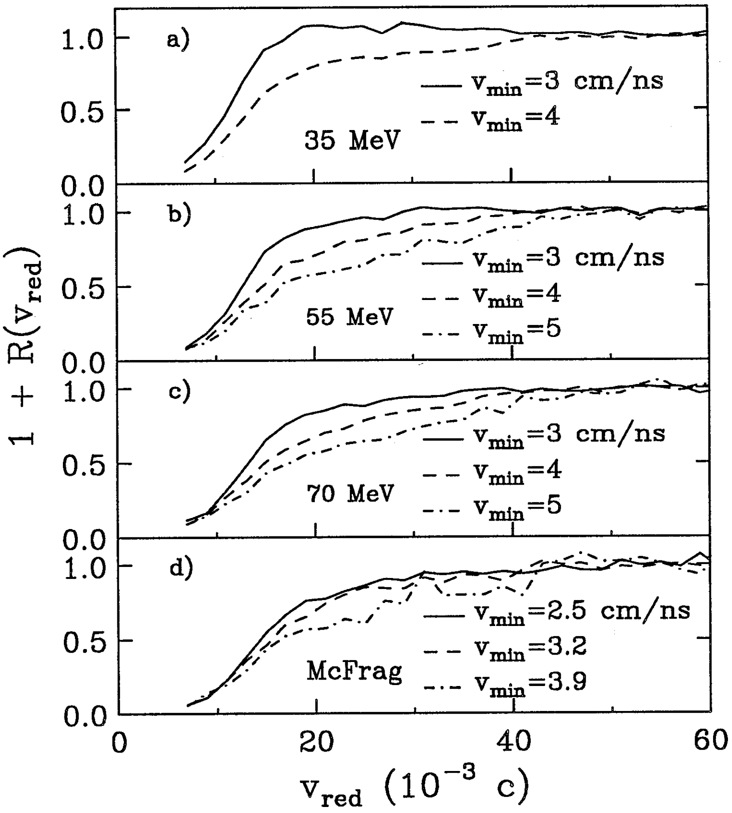

Figure 2. a-c) Experimental correlation functions at E/A = 35, 55, 70 MeV with different restrictions on v_{min}. d) Correlation functions constructed from the predictions of a microcanonical ensemble model for different restrictions on v_{min}.

Specifically, the higher energy fragments are emitted with smaller space-time separation between fragments. This result is a clear indication of an evolutionary process.

To examine the general trends observed in the correlation functions further, we have performed 3-body Coulomb trajectory calculations in which we assume fragment emission from the surface of a source of fixed initial size. The source was assumed to be a nucleus with $Z = 40, A = 92$ and a radius of 7 fm.[25] The distribution function for the time between emissions was assumed to have the form $\exp(-t/\tau)$, which is characterized by a single time constant, τ. Correlations functions, characterized by v_{min}, were constructed from the 3-body Coulomb trajectory calculations. The observed inclusive correlation function, at 55 MeV/A, is well described by the decay of a R = 7 fm source with a characteristic emission time of τ = 100 fm/c. Within the context of our 3-body model, the dependence of the width of the Coulomb hole on the minimum velocity for different values of τ is shown as solid lines in Fig. 3a.

The trend manifested by the 3-body calculations is opposite the trend observed in the data; namely, one finds a decrease in width with increasing minimum velocity. This decrease may simply be associated with an increase in the initial spatial separation of the members of the pair due to the increasing velocity of the first emitted fragment. If one were to assume that variation in time separation is more significant than the variation in spatial separation, and if one makes some reasonable assumption of source size, then each observed hole width can be associated with a given emission time constant through comparison with the 3-body calculations. This procedure has been used to obtain the points displayed in Fig. 3b, which relate mean emission times to the minimum velocity

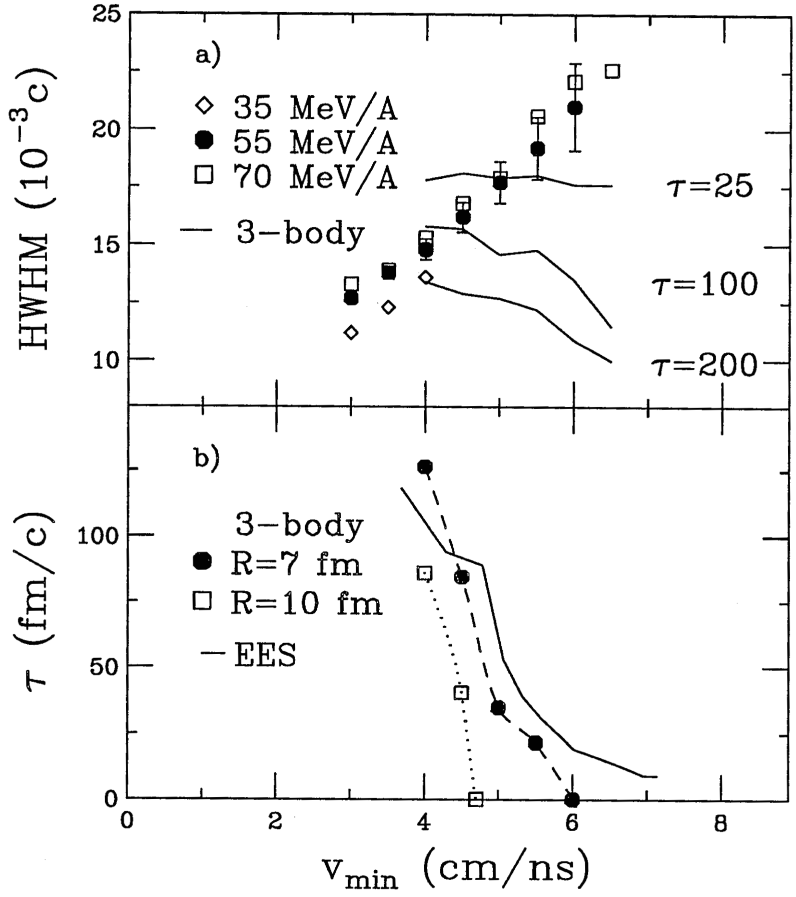

Figure 3. a) Dependence of the Coulomb interaction (HWHM) between fragments on the minimum fragment velocity. Diamonds, circles and squares represent the experimental data at E/A = 35, 55, and 70 MeV, respectively. Solid lines indicate the results of 3-body Coulomb trajectory calculations for τ = 25, 100, and 200 fm/c. b) Dependence of the extracted emission time on the minimum velocity of the fragment pair. The solid circles and open squares correspond to the experimental data at E/A = 55 MeV.

cut-offs in the spectra. The two different sets of points arise from the use of two different values for the source radius in the reference trajectory calculations.

We have examined the predictions of two multifragmentation models the first, representative of the *freeze-out* scenario (where all fragments are formed at a single time), and the second, based on an *evolutionary* scenario (where the system changes as the fragments are emitted).

The freeze-out model we have examined is the Berlin microcanonical statistical model (McFrag).[26,27] The source was assumed to have $Z = 79, A = 197$ with an excitation energy of 2400 MeV and a freeze-out radius of ≈13 fm to reproduce roughly the experimentally measured IMF and charged particle multiplicities at E/A = 55 MeV.[22] The dependence of the correlation function on the fragment velocity predicted by the McFrag model is shown in Fig. 2d. Since all the fragments are emitted simultaneously, the only dependence of the correlation function on final spectral velocity comes from the sampling of different initial spatial configurations of the final decay fragments. This feature appears to provide the correlation functions only a weak dependence on the fragment kinetic energy.

For the second model we examined the predictions of the EES model[13] which explicitly incorporates emission during the evolution of the system. In this model, the source temperature changes with time due to adiabatic changes in density and particle emission. The portion of the energy spectrum associated with each instant in time is provided by instantaneous properties. A schematic calculation was done for an initial source of A=197 and Z=79, with an initial temperature of 12 MeV. Due to the changing conditions, the mean separation times vary with the velocity of the fragments. The calculation shows a decreasing mean emission (separation) time with increasing fragment energy. This result can be understood as follows: The most energetic part of the spectra is populated for the highest temperatures and Coulomb energies. These conditions exist only early in the evolution of the system. At later times, fragments with high kinetic energies are rarely emitted. This confined "window" of opportunity for high energy fragments affects the mean separation time associated with their emission. The model suggests that the mean separation time increases with decreasing fragment energy until the vicinity of the yield peak where it levels off. For the very lowest velocity fragments the separation times grows sharply. These fragments are predominately emitted under conditions of low temperature and low source charge, where the predicted emission process is slowest. An attempt has been made to compare the qualitative predictions of the EES model with the trends shown in Fig. 3b. The model prediction for pairs of ^{9}Be fragments (transformed to the laboratory) are compared with the experimental data in Fig. 3b. Differences between the schematic model calculations and the data indicate that the precise relationship between changes in the source properties and fragment emission dynamics is not yet fully understood. However, prediction of the same trend observed experimentally suggests that changes in the source characteristics and fragment formation occur on commensurate time scales.

In summary, we have examined the relationship between the fragment-fragment velocity correlation functions, and the velocity of the fragments from which they are constructed, for central collisions in the reaction ^{84}Kr+^{197}Au at E/A=35, 55, and 70 MeV. In each of these cases there is an increase in the width of the Coulomb hole of the correlation function with increasing fragment velocity. This trend is opposite the trend obtained with trajectory calculations that assume a single decay constant and source size. A statistical model that assumes fragment emission from an evolving system qualitatively predicts the general trend of the observed data. The strong relationship between the fragment velocities and the mean emission times suggests that there are changes in the character of the source on a time scale concurrent with the fragment emission, and thus that the mechanism of multifragmentation is evolutionary.

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