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E. Renshaw Foxford, V.E. Viola, R. Legrain, E.C. Pollacco,
C. Volant, R.G. Korteling, W.A. Friedman

DAPNIA

Département d'Astrophysique, de Physique des Particules, de Physique Nucléaire et de l'Instrumentation Associée
CEA/Saclay F-91191 Gif-sur-Yvette Cédex

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TIME DEPENDENCE OF MULTIFRAGMENTATION IN
LIGHT-ION-INDUCED REACTIONS

G. Wang^a, K. Kwiatkowski^a, K. B. Morley^{a*}, D. S. Bracken^a,
E. Renshaw Foxford^{a*}, W. A. Friedman^b, R. G. Korteling^c, R. Legrain^d,
E. C. Pollacco^d, V. E. Viola^a and C. Volant^d

ABSTRACT

The evolution of multifragmentation reactions has been investigated via large-angle correlations of IMFs emitted in the 4.8 GeV ^3He bombardment of ^{197}Au nuclei. Relative IMF-IMF velocity data agree well with fission kinetic energy systematics for IMFs with $Z \geq 8$, but increasingly deviate above the fission prediction as the IMF charge decreases. This result depends only weakly on IMF multiplicity. The results suggest that IMF emission occurs from an evolving system in which lighter fragments are emitted preferentially from a hotter, more dense source prior to breakup of a dilute residue that also produces heavier fragments. The data are compared with both time-dependent (EES) and simultaneous (SMM) multifragmentation models.

^aDepartments of Chemistry and Physics and IUCF, Indiana University, Bloomington, IN 47405

^bDepartment of Physics, University of Wisconsin, Madison, WI 53706

^cDepartment of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada

^dCEA DAPNIA/SPhN, C.E. Saclay, F-91191 Gif-sur-Yvette, Cedex, France

*Present address: Los Alamos National Laboratory, Los Alamos, NM

*Present address: Microsoft Corporation, Seattle, WA

Understanding the breakup dynamics of highly excited nuclei is central to determining the thermodynamic properties of finite nuclear matter under extreme conditions of temperature and density [1]. Because of the strong influence of the Coulomb interaction on nuclei undergoing multifragment disintegration, relative velocities (v_{rel}) of fragment pairs emitted at large angles with respect to one another provide a useful probe of the time evolution of the hot system and the source dimensions at freezeout [2,3]. By selecting pairs of fragments emitted in opposite directions, sensitivity to the source-fragment interaction is emphasized, rather than that of the fragment-fragment pair. In this letter, we report v_{rel} distributions for pairs of intermediate-mass fragments (IMF: $3 \leq Z \leq 15$) emitted in the 4.8 GeV $^3\text{He} + ^{197}\text{Au}$ reaction. The experimental results are first examined relative to the baseline Coulomb predictions of fission kinetic energy systematics and then compared with two differing models, the time-dependent expanding emitting source model [4] and the simultaneous statistical multifragmentation model of Ref. 5, similar in general approach to Refs. 6- 8. Related experimental results for the $^3\text{He} + ^{197}\text{Au}$ system are contained in Refs. 9 and 10.

For the purposes of large-angle correlation studies, light-ion projectiles afford the opportunity to sample a large range of emission angles, since only the target-like source contributes to the multifragmentation yield. In addition, intranuclear cascade (INC) and Boltzmann-Uehling-Uhlenbeck (BUU) simulations indicate that energy deposition is rapid ($\tau \leq 30$ fm/c), there is little compression, and the excited residual nucleus exists in a state of depleted density following the initial stages of the collision [11]. Hence, the breakup is expected to be primarily the result of thermal and Coulomb effects, with little influence from decompression-driven radial expansion or angular momentum, as in heavy-ion reactions.

The data were obtained at the Laboratoire National Saturne, using the ISiS detector array which contains 162 triple detector telescopes covering 74% of 4π [12]. The high multiplicity events in these reactions have been shown to exhibit a nearly isotropic IMF rapidity pattern and are dominated by low-energy ejectiles ($E/A \leq 4$ MeV) [9,10]. In the present analysis, IMF pairs were sampled for polar angles greater than 30° and separation angles in the interval $\psi_{\text{rel}}(1,2) = 180^\circ \pm 40^\circ$, where $\psi_{\text{rel}}(1,2) = \arccos [\vec{v}_1 \cdot \vec{v}_2 / |\vec{v}_1||\vec{v}_2|]$. The IMF energy acceptance was $0.7 \leq E/A < 10$ MeV/nucleon, corresponding to velocities in the range $2.3 \leq v_{\text{rel}} < 8.8$ cm/ns. The angular acceptance and upper energy limit were chosen to minimize the nonequilibrium IMF component in this analysis [9]. Relative velocities, v_{rel} , for the Z-identified fragments were calculated from the measured kinetic energies using average fragment masses based on two sets of experimental data for similar systems [13,14], rather than the frequently-used but incorrect assumption $A = 2Z$. Data points represent the average and error bars indicate the upper and lower extremes of these two mass assumptions.

The relative velocity distributions are plotted in Fig. 1 for IMF pairs with identical charges ($Z_1 = Z_2$); neighboring charges ($Z_1 = Z_2 \pm 1$) are included for heavier fragments to improve statistics. The uppermost curve accounts for event pairs for all possible charge combinations. The centroid of the total distribution in this work is significantly higher than that reported in Ref. 15 for similar GeV ^4He -induced reactions on ^{197}Au , which has been interpreted in terms of a breakup density of $\rho/\rho_0 \sim 1/7$ [16].

In Fig. 2, the centroids of the relative velocity distributions for pairs of similar IMFs ($Z_1 = Z_2$, or for heavier fragments $Z_2 = Z_1 \pm 1$) are plotted as a function of IMF charge for three different observed multiplicity (N_{IMF}) conditions, as indicated in the inset. For light IMFs, there

is a slight decrease in v_{rel} with increasing N_{IMF} ; for the heaviest IMFs, the centroids for all three multiplicity bins appear to converge. The widths of the light IMF distributions also appear to increase significantly for higher N_{IMF} values, whereas they are nearly the same for $Z \geq 8$ fragments. This result suggests that a broader distribution of source conditions may be responsible for lighter IMFs.

In order to provide a baseline for comparing the sensitivity of the v_{rel} data to the Coulomb field of the emitting source, the centroids in Fig. 2 are compared with values based on fission kinetic-energy-release (TKE) systematics [17]. The “fission-like” estimates assume two successive fission steps from the post-cascade heavy residue. The Z and A of the fissioning source are estimated from well-tested INC calculations [18], which are in agreement with source reconstruction calculations based on the experimental data [19]. These predict a range of residue nuclides between $Z = 72$, $A = 179$ and $Z = 65$, $A = 165$ for deposition of excitation energies between 5 to 10 MeV per residue nucleon, respectively. This range is accounted for by the shaded region in Fig. 2. For nuclei in this mass range, fission TKE systematics yield a radius parameter $r_0 = 1.8$ fm for the effective charge-separation distance at scission, $d = r_0 (A_1^{1/3} + A_2^{1/3})$. Compared to a value of $r_0 = 1.2 - 1.4$ fm for nuclei at normal density, this would correspond to a density of $\rho/\rho_0 \approx 1/3 - 1/2$ if the separation were radial instead of axial. No enhancement of v_{rel} due to the temperature of the source is included in these calculations; such a correction would require a larger value of r_0 to reproduce the heavier IMF data.

The most prominent feature of Fig. 2 is that even for the most violent events ($N_{IMF} \geq 6$), the experimental centroids for the lighter IMFs lie well above the predictions of the simple Coulomb-repulsion predictions of fission systematics. This picture does not change appreciably

if additional centrality cuts are imposed on the data, or if the calculated v_{rel} values are supplemented by a thermal source with $T = 5$ MeV. This suggests that on average, light IMFs have their origin in more dense and/or hotter sources of higher charge than their heavier partners, perhaps reflecting coalescence processes associated with secondary scatterings during the latter stages of the cascade.

In contrast, for the heaviest IMFs ($Z \geq 8$), there is good overall agreement with the fission systematics. The corresponding radius parameter is consistent with emission from an expanded/dilute source with $\rho < \rho_0/2$. Thus, these results imply a time-dependent picture of multifragmentation in which light IMFs are emitted from a hot, expanding source, followed by breakup of a dilute residue in which all IMF charges are emitted.

In Fig. 3(a), the average relative velocity centroids for all N_{IMF} bins in Fig. 2 are compared with predictions of two hybrid models. For both model calculations, identical INC calculations [18] provided the distribution of residue mass, charge and excitation energy produced in the fast cascade phase of the reaction. This distribution then served as input for the time-dependent expanding evaporating source (EES) [4] and simultaneous (SMM) multifragmentation [5] models. The default conditions of both models, which have been successful in fitting heavy-ion multifragmentation data [1], have been employed. For comparison with the data, energy thresholds were imposed on both calculations to conform to the ISiS detector acceptance and software cuts ($2.3 \leq v_{rel} \leq 8.8$ cm/ns).

In the INC/EES calculation, the effective compressibility parameter is $K = 144$ MeV, for which $\rho = \rho_0/3$ at breakup [19]. This value of K is comparable to that estimated for a finite-charged nucleus relative to standard nuclear matter [20]. The model of Ref. 19 has been

previously shown to account for the IMF multiplicities and energy spectra in the 4.8 GeV $^3\text{He} + ^{197}\text{Au}, ^{\text{nat}}\text{Ag}$ reactions [10]. The default SMM calculation [5] assumes instantaneous statistical decay of the hot expanded residue into many fragments from a freezeout volume with a critical radius corresponding to $\rho = \rho_0/3$. No preequilibrium stage is included between the fast cascade and breakup steps in either of these calculations.

In comparing with the data, the most sensitive test of the models is their ability to account for the slope/curvature of the v_{rel} vs. Z dependence. The absolute magnitude of the results can be altered by adjusting the radius parameter r_0 , but this has minimal effect on the curvature. In Fig. 3(a), the INC/EES simulation is in general agreement with the v_{rel} data, both in absolute magnitude and the curvature of the Z dependence. The agreement is less satisfactory for the INC/SMM case, although for the heaviest fragments ($Z \geq 8$), an increase in the freezeout density to $\rho = \rho_0/2$ brings the simulation in line with the data, also shown in Fig. 3. However, this adjustment would not affect the slope/curvature and thus would still significantly underpredict the v_{rel} centroids for the lighter IMFs.

The larger predicted average relative velocities for the low- Z fragments for the INC/EES calculation relative to those for INC/SMM is consistent with the emission of IMFs early in the expansion phase of the highly excited residues. During this period, the source density is higher, as are both the source charge and temperature, thus producing more energetic fragments. In addition, the early (light) fragments may receive an expansion boost [4]. This pre-breakup IMF emission stage, in which ejectiles with $Z \leq 6$ are preferentially emitted, bridges the interval between the fast cascade and multifragment breakup. It is an aspect of the disassembly mechanism that is present in the EES but not in the SMM model. While a preequilibrium option

can be implemented preceding the SMM stage in the code of Ref. 5, it allows only for H and He emission and hence would affect the present results only by cooling the source and reducing the charge of the residue. This argues for the inclusion of some form of IMF precursor stage in comparing the statistical model calculations with data.

Finally, in Fig. 3(b), the model dependence on source density is examined. Here, the schematic INC/EES model is compared with the ^{197}Au data for two cases, $K = 144 \text{ MeV}$ (expansion) and $K = \infty$ (no expansion). The latter case corresponds to emission from a static source at normal nuclear matter density. The similarity in light IMF v_{rel} values for both assumed values of K reflects the similar probability for fragments to be emitted early in the de-excitation process from a higher- Z source closer to normal density. In addition, the Li fragments from the $K = 144 \text{ MeV}$ calculation may exhibit some velocity enhancement due to the expansion boost. As the fragment charge increases, the calculation clearly shows a significant increase in the relative velocity centroids from the stiffer, more compact source. This provides additional support for the existence of expansion-like effects in multifragmentation.

In summary, the experimental results suggest that for the most highly excited residues, fragmentation is a time-dependent phenomenon in which light IMFs are emitted preferentially from a hot, expanding source, followed by a near-simultaneous breakup that is primarily responsible for heavier fragments. Comparisons with hybrid model INC/EES and INC/SMM calculations provide better agreement for light IMFs with the EES approach. Both models can account for the heaviest IMFs satisfactorily. These data point to the need for inclusion of IMF formation via coalescence processes during the late stages of the cascade, prior to breakup of the dilute residue.

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Figure Captions

Fig. 1 Relative velocity distributions for IMF pairs for various IMF charges, as indicated on figure. Data are for 4.8 GeV $^3\text{He} + ^{197}\text{Au}$ reaction.

Fig. 2 Average relative velocity centroids and widths for fragment pairs with $Z_2 = Z_1$, $Z_2 = Z_1 \pm 1$ and separation angle $\psi_{\text{rel}} = 180^\circ \pm 40^\circ$, for the 4.8 GeV $^3\text{He} + ^{197}\text{Au}$ reaction, gated on IMF multiplicity. Shaded area gives expected average velocity centroids for fission TKE systematics, as described in text. Insert indicates distribution of IMF multiplicities with the gates highlighted.

Fig. 3 (a) Average relative velocity for fragment pairs for 4.8 GeV $^3\text{He} + ^{197}\text{Au}$ reaction. Predictions of the INC/EES calculation are given by solid line and INC/SMM predictions by dot-dashed lines ($\rho = \rho_0/3$) and dashed line ($\rho = \rho_0/2$).

(b) Average relative velocity for centroid fragment pairs. Comparison is with INC/EES model for two conditions: $K = 144$ MeV (solid line, corresponding to expansion) and $K = \infty$ (dashed line, corresponding to emission from a system at normal nuclear matter density).