FORMATION OF HOT NUCLEAR MATTER WITH LIGHT-ION PROJECTILES

K.B. Morley, K. Kwiatkowski, D.S. Bracken, E. Renshaw Foxford, V.E. Viola, and N.R. Yoder
Indiana University, Bloomington, Indiana 47408

R. Legrain, E.C. Pollacco, and C. Volant
CEA Saclay, Saclay, France

R.G. Korteling
Simon Fraser University, Burnaby, BC, Canada

J. Brzychczyk
Jagellonian University, Krakow, Poland

W.A. Friedman
University of Wisconsin, Madison, Wisconsin

H. Breuer
University of Maryland, College Park, Maryland 20742

In order to probe the behavior of nuclear matter under extreme conditions of temperature and density, target-projectile interactions that dissipate several hundred MeV on a very fast time scale ($\lesssim$30 fm/c) are required. For light-ion-induced reactions on complex nuclei, this situation can be achieved via hard N-N scattering and the excitation of Δ and higher resonances, followed by rescattering and/or reabsorbtion of the decay pions. Systems excited in this way provide a unique perspective relevant to studies of the nuclear equation of state in that they are expected to be destabilized primarily by thermal forces – in contrast to heavy-ion-induced reactions, where compressional and rotational forces can strongly influence the breakup dynamics.

The distribution of deposition energy and multifragmentation of highly excited nuclei have been studied with the Indiana Silicon Sphere 4π detector array (ISiS) at the Laboratoire National Saturne in Saclay, France. Beams of 1.8, 3.6 and 4.8 GeV ^{3}He ions were used to bombard 1.0-mg/cm^2 ^{nat}Ag and 1.5-mg/cm^2 ^{197}Au targets. The ISiS array[1] consists of 162 triple-element detector telescopes and covers polar angles from 14° to 86.5° in both forward and backward hemispheres. Each telescope contains a gas-ionization counter operated at ~17 Torr of C_3F_8; a 500 μm passivated silicon detector, followed by a 28 mm CsI(Tℓ) crystal with photodiode readout. Discrete charge identification is achieved for Z=1−16 ejectiles over a dynamic range from $E/A \approx 0.8$ MeV (including target, window and gas thickness) up to $E/A = 96$ MeV (range is narrower for H isotopes).

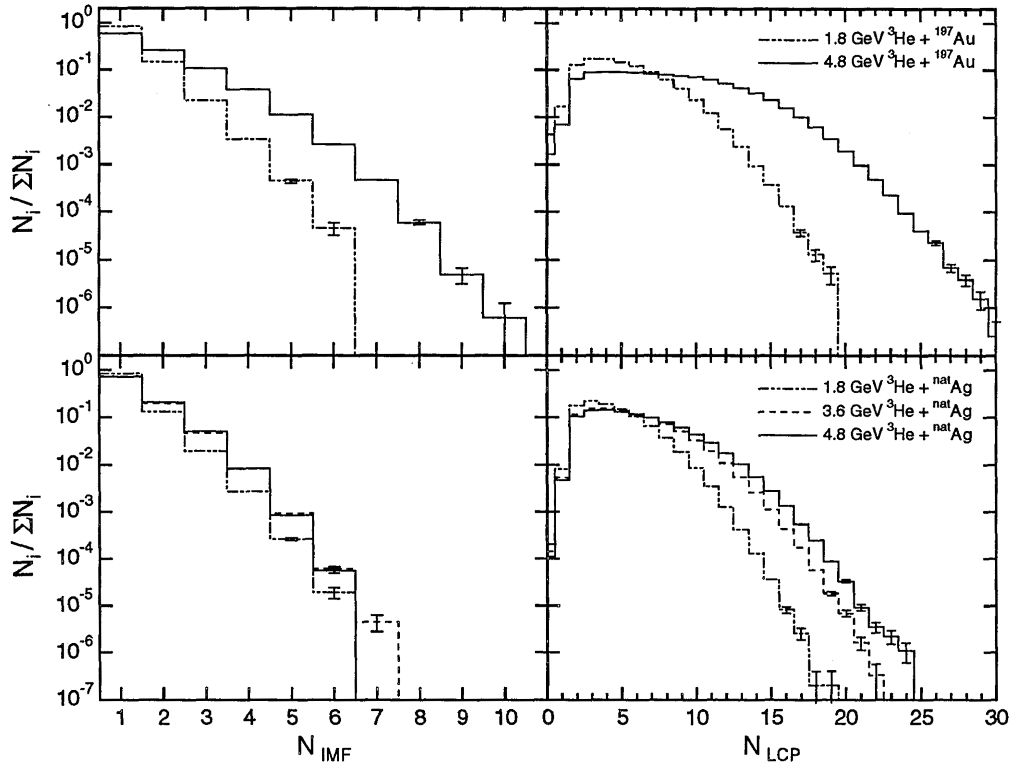

Figure 1. Observed IMF multiplicity distributions (left column) for ^{3}He + ^{nat}Ag (bottom) and ^{197}Au (top) reactions at energies indicated on figure. The right column gives LCP multiplicity distributions for these same systems.

Two prominent results from these studies are: (1) observation of a saturation in deposition energy for the ^{3}He + ^{nat}Ag system near 4 GeV bombarding energy, indicating the upper projectile energy for nuclear stopping has been reached,[2] and (2) evidence for multifragmentation from an extended emitting source with density $\rho/\rho_o \approx 1/3$, suggesting significant nuclear expansion prior to breakup.[3]

One important gauge of deposition energy in the collision is given by the multiplicity distribution of intermediate-mass fragments ($3 \leq$ IMF $\lesssim 20$). In Fig. 1 the observed IMF multiplicity distributions are shown for each of the systems studied here. As a general trend, the results scale with projectile energy and target mass. The exception is the 3.6 and 4.8 GeV ^{3}He + ^{nat}Ag measurements, where nearly identical distributions are observed, suggesting similar deposition energy characteristics.

Also shown in Fig. 1 are the multiplicities of light-charged particles (LCP = H and He). For the LCP distributions it is observed that the 4.8 GeV ^{3}He energy leads to a higher multliplicity than at 3.6 GeV. In order to investigate the possible influence of the reaction dynamics on this result, all ejectile spectra have been separated into thermal and fast components, based on the character of the fragment energy spectra. When this separation is performed, the thermal components of the 3.6 and 4.8 GeV multiplicity distributions are found to be identical; i.e. the LCP difference in Fig. 1 for these two energies is due to an increase in the fast component at the higher energy.

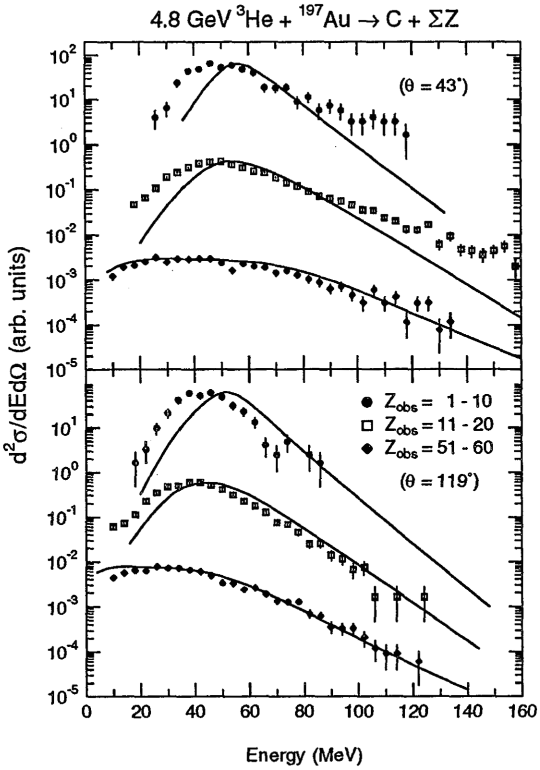

Figure 2. Laboratory energy spectra of carbon fragments from the 4.8 GeV ^{3}He + ^{197}Au reaction, gated on total observed charge. Points are for Z_{obs} = 1–10 (top); Z_{obs} = 11–20 (middle) and Z_{obs} = 41–50 (bottom). Lines are predictions of the INC/EES model, normalized so that the maximum probabilities are equal.

Other observables related to the deposition energy, such as the total observed charge and the total energy per event for themal particles, also show nearly identical distributions at 3.6 and 4.8 GeV. On this basis we conclude that maximum projectile stopping is reached near 4 GeV for the ^{3}He + ^{nat}Ag system. This result is in good agreement with energy deposition predictions of INC calculations.[4] Analysis of the total themal energy per event indicates that maximum deposition energies of ~1000 MeV are reached in ^{3}He + ^{nat}Ag collisions and ~1600 MeV for ^{3}He + ^{197}Au.

Evidence for nuclear expansion in the breakup of the hot residues formed in these reactions is provided both by the IMF multiplicity distributions and the character of the IMF kinetic energy spectra. The IMF multiplicity data in Fig. 1 have been compared with the results of a hybrid intranuclear cascade/expanding evaporating source model.[5] In this model a value of K = 144 MeV is used for the effective nuclear compressibility parameter and multifragmentation occurs near $\rho/\rho_o \approx 1/3$. In addition to providing good agreement with the IMF multiplicity distributions, the model gives a good account of the fragment energy spectra. In Fig. 2 the spectra of carbon fragments are shown, gated on total observed charge in the ISiS array, Z_{obs}. The magnitude of Z_{obs} should provide a gauge of the collision violence in our detection scheme. With increasing Z_{obs} bin, it is found that there is a systematic decrease in the Coulomb peak energy, a broadening of this peak toward lower energies and a hardening of the spectral slopes. The model calculation (lines) reproduces the qualitative features of the data well. However, without significant expansion the model fails severely in comparison with the data.

The evolution of the fragment spectra with increasing collision violence (Z_{obs}) emphasizes the strong distortion of the Coulomb field of the fragmenting source. As an independent 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.

1. K. Kwiatkowski, *et al.*, Nucl. Instrum. & Methods, A **353**, 212 (1994); also, in press.
2. K.B. Morley, *et al.*, submitted to Physics Letters.
3. K. Kwiatkowski, *et al.*, Phys. Rev. Lett., in press.
4. Y. Yariv and Z. Fraenkel, Phys. Rev. C **24**, 488 (1981).
5. W.A. Friedman, Phys. Rev. C **42**, 667 (1990); K. Kwiatkowski, W.A. Friedman *et al.*, Phys. Rev. C **49**, 1516 (1994).
6. K. Kwiatkowski, *et al.*, Phys. Lett. **171B**, 41 (1986).

ASSESSING THE EVOLUTIONARY NATURE OF MULTIFRAGMENT DECAY

E. Cornell, T.M. Hamilton, D. Fox,* Y. Lou, and R.T. de Souza
Department of Chemistry and Indiana University Cyclotron Facility, Indiana University, Bloomington, Indiana 47405

M.J. Huang, W.C. Hsi, C. Schwarz,§ C. Williams, D.R. Bowman,* J. Dinius, C.K. Gelbke, T. Glasmacher, D.O. Handzy, M.A. Lisa,‡ W.G. Lynch, G.F. Peaslee,** L. Phair,‡ and M.B. Tsang
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

G. VanBuren,† R.J. Charity, and L.G. Sobotka
Department of Chemistry, Washington University, St. Louis, Missouri 63130

W.A. Friedman
Department of Physics, University of Wisconsin, Madison, Wisconsin 53076

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]