Formation of Hot Nuclei with GeV p and π^- Beams

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4π studies of multiple charged-particle emission in GeV π^-- and proton-induced reactions on a Au target have been performed with the ISiS detector array. Multiplicity, charge, and angular distributions yield nearly identical results for both p and π^- beams, suggesting an independence of hadron type in initiating the fast cascade and subsequent energy deposition in the struck nucleus. The excitation functions show little sensitivity to beam momentum, consistent with a saturation in deposition energy and the concept of limiting fragmentation. However, the intermediate mass fragment multiplicities and fragment charge distributions depend strongly on collision violence. [S0031-9007(97)03752-6]

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In order to prepare hot nuclear matter at temperatures up to and beyond the vaporization regime, two dynamical pathways are usually followed. One involves GeV light-ion beams incident on heavy target nuclei, which produces highly excited, low-density residues on a very fast time scale [1,2]. Such studies emphasize the influence of thermal effects on the disassembly process. The alternative approach utilizes heavy-ion beams of a few hundred MeV/nucleon and introduces important collective variables such as density compression, radial flow, and shape distortions [3]. Understanding the evolution of temperature, density, angular momentum, etc., for hot nuclear systems formed via both approaches is essential to determining the properties of the nuclear equation of state for finite nuclei.

In this Letter we address the former, or thermal, aspect of this problem, presenting the first exclusive results for GeV proton- and π^--induced multifragmentation reactions for which Z-identified fragments are measured with good granularity and large solid-angle and energy acceptance. The qualitative results of these measurements are emphasized, in particular, the dependence of reaction observables on hadron type, projectile momentum, and collision violence. The results are also related to earlier studies [4] that served to stimulate much of the interest in multifragmentation phenomena, as well as to recent exclusive studies with ^{3}He [2,5], antiproton [6], and peripheral Au + Au reactions [7].

The experiment was performed with the Indiana Silicon Sphere (ISiS) 4π detector array [8] at the Brookhaven Alternating Gradient Synchrotron (AGS) accelerator (E900). Secondary positive beams of momentum 6.0, 10.0, 12.8, and 14.6 GeV/c and negative beams at 5.0, 8.2, and 9.2 GeV/c were incident on a 1.8 mg/cm^2 ^{197}Au target. Here we associate the positive beam with protons (although a significant π^+ component is present at low beam momentum) and negative beam with π^- ($\gtrsim$95%). Average beam intensities were approximately 4×10^6 particles/spill and blank runs were taken periodically to ensure that the effects of the beam halo did not affect the data. The reaction focus was defined by either a 1×1 cm^2 or 2×2 cm^2 ^{197}Au foil suspended on two 50 μm tungsten wires attached to a 5×5 cm^2 aluminum frame. Identified light charged particles (LCP: $^{1-3}$H and ^{3,4}He) and intermediate-mass fragments (IMF: $3 \leq Z \lesssim 16$) were detected with the ISiS array,

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which contains 162 gas-ionization chamber/silicon/CsI detector telescopes, each having an energy acceptance for Z identification of $0.7 \leq E/A \leq 95$ MeV per fragment nucleon. Angular coverage was 14°–86.5° and 93.5°–166°.

The hardware multiplicity trigger required valid fast signals in three or more silicon detectors in the array. In addition, all ejectiles with energies $E \geq 16$ MeV in the CsI detector (but ΔE fast signal too low to trigger the corresponding silicon discriminator) were recorded for each accepted event, along with the silicon linear signal. These signals provided information on the multiplicity of fast cascade ejectiles (primarily charged hadrons) with energies $\sim 100-400$ MeV. This definition closely follows that of "gray particles" used in emulsion studies ($\sim 50-400$ MeV). The ISiS array was complemented by a $15 \text{ cm} \times 15$ cm upstream total beam (TB) counter, an annular ring veto (RV) scintillator, a 28 mm beam definition counter (BC), and a segmented inner/outer scintillator array (UV) upstream from the target for halo veto and beam alignment. The acceptance trigger logic was thus TB $\cdot$ $\overline{\text{RV}}$ $\cdot$ BC $\cdot$ $\overline{\text{UV}}$ $\cdot$ ISiS.

As a preliminary comment, the experimental observables in the present study, both inclusive and multiplicity gated, strongly resemble those measured for the 4.8 GeV ^{3}He + ^{197}Au reaction, described in detail in Refs. [2] and [5]. The high multiplicity/deposition-energy events in the ^{3}He studies have been shown to be consistent with isotropic emission from a hot, expanding source moving with average velocity $v/c \sim 0.01$. Deposition energies up to 1.5 GeV per event are deduced from the spectra of thermal-like fragments. Based upon the correspondence with the ^{3}He data set, we interpret the physics of the present hadron-induced reactions similarly.

We first examine the probability distributions, $N_c/\sum_i N_c(i)$, as a function of observed total charged-particle multiplicity, $N_c = N(\text{LCP}) + N(\text{IMF})$, for events in which at least one IMF is detected. These are shown in Fig. 1 for the seven systems studied in this work. Corrections for geometric acceptance ($\sim 70\%$) and energy thresholds ($E/A < 0.7$ MeV) are not included in the values of N(LCP) and N(IMF), nor are unidentified fast-cascade hadrons. The left-hand frame compares the probability distributions obtained with proton beams, and the right-hand frame provides the same information for π^- beams. The center frame compares the results for p and π^- projectiles at the same total kinetic energy of 9.1 GeV (9.2 GeV/c π^- and 10.0 GeV/c p). Charged-particle multiplicities up to $N_c \sim 30$ are measured in each case, with a most probable value of $N_c \sim 10$. These values are larger than those previously reported by Warwick *et al.* [9]; however, detector thresholds were much higher and the coverage limited to the forward hemisphere in that work, making direct comparisons difficult.

In Fig. 2, the measured IMF probability distributions are shown; proton results are on top, π^- results on the bottom, and the π^-/p comparison at the same total energy in the center. The IMF multiplicity distributions extend up to $N_{\text{IMF}} = 10$ and strongly resemble the results for the 4.8 GeV ^{3}He + ^{197}Au reaction [2,5]. In addition, there is qualitative agreement with data from peripheral ^{197}Au + ^{197}Au reactions [7]. While the thermal-like observables in the present study show little sensitivity to beam momentum, analysis of the probability distributions that include fast-cascade hadrons shows a systematic

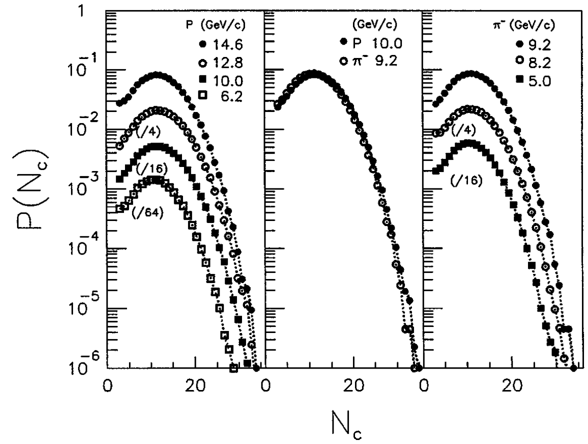

FIG. 1. Probability distributions for measured charged-particle multiplicities from ^{197}Au for events with at least one IMF as a function of beam momentum. Left: proton beams; right: π^- beams; and center: p and π^- beams at 9.1 GeV total energy. Distributions are scaled according to legend in figure.

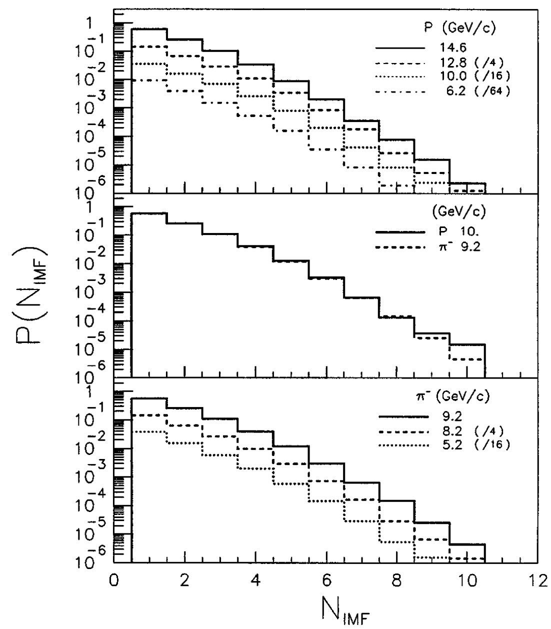

FIG. 2. Probability distributions for measured IMF multiplicities from ^{197}Au for events with at least one IMF as a function of beam momentum. Top: proton beams; bottom: π^- beams; and center: p and π^- beams at 9.1 GeV total energy. Distributions are scaled according to legend in figure.

increase in the number of high multiplicity events with increasing beam momentum.

Two features stand out in Figs. 1 and 2. First, there is little sensitivity to beam momentum for either hadron type. This result most likely reflects a saturation in deposition energy for incident beam energies above 5 GeV and can be understood as a consequence of the increased projectile energy being compensated by increased transparency of the heavy nucleus to fast-cascade hadrons [1]. Similar observations have been reported for the lighter ^{3}He + ^{nat}Ag system above 3.6 GeV [5]. This apparent saturation in deposition energy accounts for the observation of limiting fragmentation [10] and energy-independent cross sections for IMF formation [11] in hadron-induced reactions above about 5 GeV [4].

The second observation is that both projectile types produce nearly identical total-charged-particle and IMF multiplicity distributions, as emphasized by the comparison of p and π^- data at 9.1 GeV total beam energy in the center panel of Figs. 1 and 2. Emulsion and radiochemical studies [12] have suggested a similar conclusion. This insensitivity indicates that the initial collision step is independent of hadron type and that, on average, the subsequent hard scatterings and resonance excitations during the fast cascade evolve similarly as far as deposition energy in the heavy residue is concerned. Both the bombarding-energy and hadron-type independence are in qualitative agreement with intranuclear cascade code calculations of Toneev [13].

In order to illustrate the dependence of the observed IMF multiplicity on collision violence, in Fig. 3 we have plotted the average number of IMFs $\langle N_{\rm IMF} \rangle$ as a function of the parameter $Z_{\rm obs}$, which is the sum of the charges of all ejectiles detected in a given event. As a gauge of collision violence, $Z_{\rm obs}$ scales directly with IMF multiplicity and transverse energy [5] and can be related to the total deposited excitation energy in an event [14]. The systematic increase in $\langle N_{\rm IMF} \rangle$ with collision violence ($Z_{\rm obs}$) for all systems in Fig. 3 parallels the observed behavior in the 4.8 GeV ^{3}He + ^{197}Au reaction [5], as well as the 6 GeV ^{86}Kr + ^{197}Au reaction in the region of $Z_{\rm obs}$ overlap [15].

Much of the recent interest in multifragmentation and its relation to the nuclear equation of state was stimulated by inclusive measurements of GeV-proton-induced reactions on complex nuclei [15]. These studies used a power law, $\sigma(Z) \propto Z^{-\tau}$, to characterize the charge distributions of IMFs emitted in these reactions. In Fig. 4, we show representative charge distributions (normalized to Li fragments) for several systems as a function of collision violence ($Z_{\rm obs}$). Despite the existence of autocorrelation effects, these data demonstrate that, as with the multiplicity distributions, the total charge distributions are nearly identical for all seven systems. There is, however, a strong dependence of the charge distribution on $Z_{\rm obs}$. One also observes a systematic increase in the relative $Z = 5, 6$ yields with increasing $Z_{\rm obs}$, which is a common signature of equilibrated IMF emission at lower energies [16]. However, this could also be due to sequential decay, perhaps associated with the observed deficit of $Z = 8$ and 9 fragments yields. This deposition-energy dependence is also nearly identical for all systems and for both forward and backward hemispheres.

A power-law parametrization has been performed on all the data as a function of projectile type, incident energy, and total thermalized energy. Values of the power-law parameter τ as a function of $Z_{\rm obs}$ are shown in Fig. 3. For low $Z_{\rm obs}$, values of $\tau \sim 3.5$ are found, typical of dynamically produced IMFs in preequilibrium or coalescencelike processes [16]. With increasing collision

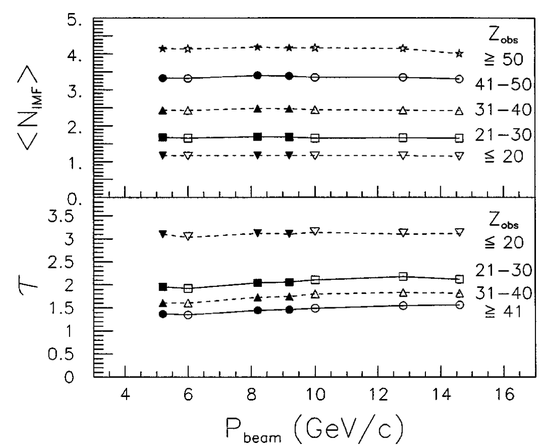

FIG. 3. Beam momentum dependence of average IMF multiplicity (top) and power-law exponent (bottom) gated on $Z_{\rm obs}$ intervals, as indicated in figure.

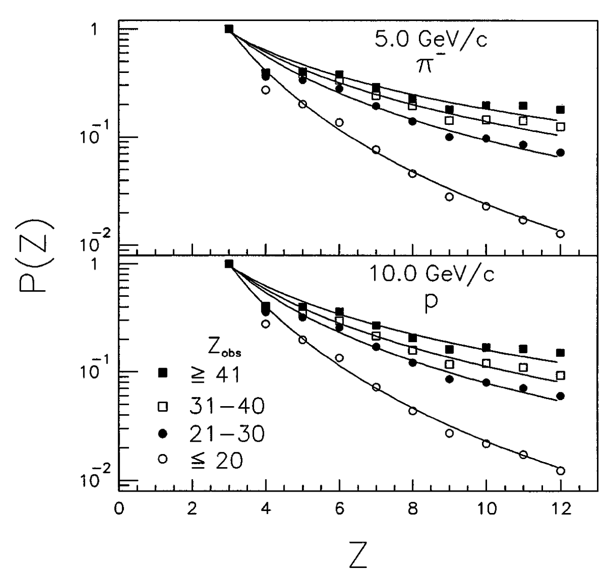

FIG. 4. Total charge distributions for 5.0 GeV/c π^- (top) and 10.0 GeV/c proton (bottom) bombardment of ^{197}Au. Results are shown as a function of $Z_{\rm obs}$.

violence, the τ parameters systematically decrease for large Z_{obs} values. This indicates that the formation of large clusters becomes increasingly more probable as the collision violence increases. Approximately the same values have also been determined for well-documented equilibrated systems formed in both light- and heavy-ion reactions [16]. With respect to the τ values at high deposition energies, large-angle correlation studies show that the dominant equilibriumlike component of the most violent events is complemented by a significant contribution from dynamically produced IMFs [17]. Since the charge distributions for dynamically produced IMFs fall off much more steeply than for equilibriumlike ejectiles, removal of this component from the power-law fits would further reduce the τ values.

In summary, we have employed a high acceptance detector array to study the disintegration of hot residues formed from bombardment of ^{197}Au nuclei with p and π^- beams between 5 and $15\ \mathrm{GeV}/c$. The observed charged-particle and IMF multiplicity distributions, as well as the total charge distributions, show little dependence on either hadron type or beam momentum in this regime. This suggests a saturation of deposition energy for hadron-induced reactions (consistent with limiting fragmentation) and a lack of sensitivity to hadron type in initiating the hadron-hadron fast cascade. The results are similar to those obtained for GeV ^{3}He and indicate the utility of hadron projectiles in forming hot nuclear matter. Measured IMF multiplicities and charge distributions depend strongly on collision violence and are qualitatively consistent with a dynamic production mechanism ($\tau \sim 3.5$) for low deposition energies and thermal-like properties for the largest ($\tau \sim 1.5$).

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