Multifragmentation: thermal vs. dynamic effects


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Reactions of 1.8 - 4.8 GeV $^3$He, 5.0 - 9.2 GeV/c $\pi^-$ and 6.0 - 14.6 GeV/c protons with $^{nat}$Ag and $^{197}$Au targets have been studied with the ISIS 4$\pi$ detector array. From reconstructed events, excitation-energy distributions have been determined and combined with a $^2$H/$^3$He isotope-ratio thermometer to study the heating curve for the thermal-like component of these reactions. Dynamic effects also manifest themselves in the data, as evidenced by deposition-energy saturation above $\sim$5 GeV, IMF emission during expansion, and sideways peaking of the IMF angular distributions for beam energies $E_b \geq 10$ GeV.

1. INTRODUCTION

Complex nuclei can be rapidly heated in the vicinity of the spinodal region in GeV hadron/light-ion-induced reactions via hard N-N scatterings and multiple excitations of baryonic resonances[1]. Preparation of hot nuclei via this path emphasizes the thermal aspects of the disassembly process and at the same time makes contributions due to the collision dynamics more transparent. Here we examine the temporal and thermal evolution of highly excited residues formed in bombardments of $^{nat}$Ag and $^{197}$Au targets with GeV light ions. Exclusive studies of light-charged particles and intermediate-mass fragments were performed with the Indiana Silicon Sphere (ISIS) detector array[2], using beams of 1.8 - 4.8 GeV $^3$He at the Saclay Saturne II accelerator (E228), and 6.0 - 14.6 GeV/c protons and 5.0 - 9.2 GeV/c $\pi^-$ at the Brookhaven AGS (E900).

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In prior publications, we have examined the properties of the fragmenting source as a function of collision violence\[3\]-[7]. These studies have shown that the most violent events originate from a rather slowly moving source (v/c ≈ 0.01) that produces a nearly isotropic emission pattern for IMFs. This behavior indicates that multifragmentation processes in these reactions occur from systems that are at least in “kinetic” equilibrium. The most striking feature of the spectra associated with these high multiplicity events is the large yield of sub-Coulomb IMF’s (E_{IMF}/A ≤ 2.5 MeV)—which gives direct evidence for thermal expansion to a breakup density of ρ/ρ_0 < 1/3.

The breakup time scale for the sub-Coulomb events has been examined via small-angle IMF-IMF correlation functions\[8\]. When compared with the N-body Coulomb-trajectory simulation of Glasmacher[9], this analysis yields very short breakup times for heavy IMFs, τ < 20 - 50 fm/c. This breakup time is of the same order as the characteristic time, τ ≈ h/T, or ~ 40 fm/c, for thermal fluctuations of an equilibrated source with T = 5 MeV. In order to reproduce the experimental correlations, spectra and multiplicities, the simulation requires a breakup density of ρ/ρ_0 ∼ 0.25 and the heaviest residue in the N-body ensemble must have a charge Z < 20 and be randomly placed in the breakup volume.

2. THE HEATING CURVE

The short time scales for disassembly and large multiplicity of observed IMFs suggest the possible existence of a nuclear liquid-gas phase transition. This is a subject of great current interest in multifragmentation studies\[10\]. In order to investigate the heating curve for these hot systems produced with simple beams, we have reconstructed the total excitation energy per event from the experimental spectra\[11\]. The total excitation energy E* in an event is defined by the sum:

\[ E^* = \sum_i K_i + M_n(K_n) + Q \]  \hspace{1cm} (1)

where K_i is the kinetic energy for each charged ejectile detected in an event of multiplicity, M_c, M_n is the neutron multiplicity, taken from experimental data \[12\]; (K_n), is the average neutron kinetic energy, and Q is the reaction Q-value. Corrections for ISiS geometry are included. This procedure also yields the mass and charge of the fragmenting residue.

Based on the character of the spectra—which show classical thermal-like and nonequilibrium components—two assumptions have been made in computing E*/A of the residue. The first includes only thermal-like ejectiles\[4\], defined as:

\[ K_i \leq (9.0 \cdot Z_i + 40) MeV \] \hspace{1cm} for 197Au, and
\[ K_i \leq (5.8 \cdot Z_i + 46) MeV \] \hspace{1cm} for natAg.

The second sum includes pre-equilibrium ejectiles, defined as all particles with K_i/A ≤ 30 MeV \[13\]. Because of the experimental trigger and geometrical inefficiencies, the reconstruction procedure is uncertain below E* ≤ 200 MeV. The excitation-energy probability
distributions for the 4.8 GeV $^3$He + $^{197}$Au system are shown in fig 1, along with predictions of the ISABEL intranuclear cascade code [14]. Since the INC code predicts the total energy dissipated in the residue prior to equipartition, in principle it should account for both thermal-like and pre-equilibrium ejectiles. This is consistent with the experimental observations.

![Figure 1](image_url)

**Figure 1.** Total excitation energy distribution for 4.8 GeV $^3$He + Au reaction. Dot-dashed line includes only thermal-like ejectiles, dashed line includes particles with $E/A \leq 30$ MeV, and the solid line is INC prediction.

Using the thermal-like excitation energies and residue masses from the reconstructed data, we have constructed the heating curve for the 4.8 GeV $^3$He + $^{\text{naf}}$Ag, $^{197}$Au systems in fig. 2. Here the temperatures $T$ are determined via a $(^2\text{H}/^3\text{H})/(^3\text{He}/^4\text{He})$ double-isotope ratio thermometer [15]. Nearly identical behavior is observed for both targets. The heating curve shows an initial rapid increase in $T$ with increasing $E^*/A$, a distinct slope change near 2–3 MeV, and a gradual increase—but no plateau—thereafter. These data are compared with a simple Fermi gas prediction (using $a = A/11$ MeV$^{-1}$) and two model calculations: the expanding emitting source (EES) model of Friedman [16] and the statistical multifragmentation (SMM) model of Botvina [17]. The intrinsic SMM thermodynamical temperature is greater than the predicted $T_{\text{app}}$ for $E^*/A \leq 7$ MeV. In both models, the initial excitation-energy distribution and the corresponding mass and charge of the residue were taken from INC calculations [14]. In each case, the dashed line gives the full model prediction and the solid line is the model with the ISIS detector $\sim 30$ MeV He isotope-identification thresholds imposed. Overall, the agreement is fairly good, with the data falling slightly above the models. The difference between the two cases
indicates that the apparent isotope-ratio temperature grows with increasing He spectral energy.

Figure 2. Heating curves for 4.8GeV $^3$He + Au, Ag reactions. Temperatures were determined from $^2$H/$^3$He double isotope ratios. Left panel compares with EES model; right panel with SMM model with detector energy cuts imposed on theory (solid lines). Both calculations are shown only for Au target. Right panel also shows SMM thermodynamic temperature (dot-dashed curve).

The reason for this increase appears to be the strong dependence of the $^3$He/$^4$He ratio on He kinetic energy [18]. This creates a significant isotope-ratio temperature sensitivity to ejectile energy. This is shown in fig. 3, where the top frame shows temperature dependence on He energy for three cuts in $E^*/A$. The most highly excited residues give the highest temperatures and these decrease systematically with He energy. Also shown are the corresponding EES predictions for several $E^*/A$ values. This behavior can be thought of as due to a “cooling” effect [19]. However, as shown in the bottom frame of fig. 3, the model $^3$He/$^4$He ratios only agree with the with the experimental values for relatively low He energies. The large deviation at kinetic energies above $K_f \gtrsim 50$ MeV suggests that nonequilibrium/coalescence processes may also play an important role in the observed ratios. The SMM model calculations show even weaker dependence of $T_{app}$ on $E_{He}$.

3. DYNAMIC EFFECTS

The question of nonequilibrium fragment emission accentuates the necessity to understand the full dynamical evolution of the reaction process prior to breakup. As discussed in the previous section (fig. 1), the distribution of excitation energy in the hot, thermal-like residues extends over a very broad range, reaching values up to $\sim 1.5$ GeV for the $^{197}$Au target.
Figure 3. Upper frame: Temperature dependence on He ejectile kinetic energy at $\theta_{LAB} = 137^\circ$ (solid lines and symbols). Dot-dashed lines show EES predictions for selected values of $E^*/A$. Lower frame: $^3\text{He}/^4\text{He}$ ratios as a function of He kinetic energy for Ag (left-) and Au target (right-panel) at laboratory angles 43$^\circ$ and 137$^\circ$. The solid lines in right panel compare EES calculations for two extreme values of excitation energy.
It is also of interest to examine the dependence of energy deposition on beam momentum and projectile type. In fig. 4 (left frame) we show the average number of IMFs per event as a function of beam momentum for \( \pi^- \) and proton projectiles incident on \(^{197}\)Au [7]. These are shown as a function of collision violence, as gauged by the total observed charge in an event, \( Z_{\text{obs}} \). While there is a strong increase in average IMF multiplicity with increasing collision violence, the results are essentially independent of beam momentum and hadron type.

![Figure 4. Beam momentum dependence of average IMF multiplicity gated on \( Z_{\text{obs}} \) (left frame). Observed multiplicity distributions for “gray” protons, with energies \(100 < E_p \leq 450\)MeV, as a function of beam momentum (right frame).](image)

Examination of both the total charged-particle and IMF multiplicity distributions shows that they are essentially identical over this entire momentum range; this is also true for the 4.8 GeV \(^3\)He + \(^{197}\)Au system, but not at lower \(^3\)He energies. These results suggest a saturation of deposition energy for light-ion-induced reactions above \( \sim 5 \) GeV—consistent with limiting fragmentation—and a lack of sensitivity to hadron type in initiating the fast hadron-hadron cascade. INC calculations are consistent with both effects [20].

While the deposition energy in the hot residue appears to be nearly independent of beam momentum, the initial spray of fast cascade, or “gray” protons (100 MeV \( \lesssim E \lesssim 450 \) MeV) increases systematically as the beam momentum is increased. This is shown in the right-hand frame of fig. 4, where the multiplicity distributions of “gray” particles are shown for the proton-induced reactions. These energetic fast particles produced early in the cascade are responsible for carrying off a significant fraction of the available beam energy, at the cost of deposition energy in the residue.

Another manifestation of the collision dynamics is found in the IMF angular distributions, shown in fig. 5. Here the left-hand frame shows the angular dependence of the inclusive data on beam momentum for proton-induced reactions. At 6.2 GeV/c, a monotonic decrease in differential cross section with increasing angle is observed, very similar
to results for the $^3$He-induced reactions at lower energies\[4\]. However, at 10 GeV/c and above a broad shoulder develops at about 50° to the beam axis. Similar effects have been observed at 28 GeV\[21\].

As thermalization progresses, dynamic effects lead to the emission of nonequilibrium LCPs and IMFs via preequilibrium/coalescence-like processes. The right-hand frame of fig. 5 shows the angular distributions gated on collision violence ($Z_{obs}$) for the 10 GeV/c p + $^{197}$Au reaction. The peaking appears to be most pronounced for intermediate values of $Z_{obs}$. One intriguing explanation for the sideways peaking of IMFs is the possibility of a shock wave induced by the projectile momentum front. However, more mundane origins, such as emission from recoils preferentially scattered at large angles to the beam axis in mid-central collisions may also account for the peaking. The data are currently under further investigation in order to understand this effect.

Another type of dynamic effect is the emission of IMFs during early stages of expansion of a largely equilibrated system prior to breakup. Large-angle IMF-IMF relative velocity correlations have been analyzed to investigate the spatial properties of the emitting source\[6\]. For heavy fragments, the data are consistent with Coulomb emission from a source expanded to $\rho/\rho_0 \sim 0.3$. On the other hand, lighter fragments, especially Li and Be, diverge significantly above the Coulomb baseline, suggesting contributions to the yield from a hotter, more dense source early in the expansion. Comparison with the EES and SMM models are consistent with this interpretation. While both models satisfactorily describe the data for heavier IMFs, only the EES calculation – which includes fragment emission during expansion – successfully accounts for the lighter IMFs. While these pre-breakup effects are not dominant, they complicate the evaluation of the residual excitation energy, as illustrated in fig. 1, and comparisons with statistical multifragmentation models.
4. SUMMARY

Both thermal and dynamic behavior of multifragmentation reactions induced by GeV proton, $\pi^-$ and $^3$He beams has been studied with the ISIS 4$\pi$ detector array. Reconstructed excitation energy distributions and temperatures derived from the $(^{2/3}\text{H})/(^{3/4}\text{He})$ isotope ratio thermometer have been used to construct the heating curve for the 4.8 GeV $^3$He + $^{\text{nat}}$Ag, $^{197}$Au reactions. The data indicate a slope change near $E^*/A \sim 2 - 3$ MeV and a gradual monotonic increase thereafter. Relatively good agreement is found with both EES and SMM models, both of which predict a phase transition in finite nuclei. These studies demonstrate that deposition energy in the residue saturates for beam energies above 4–5 GeV and is hadron-independent. Dynamic production of IMFs is evidenced by the peaking of the angular distributions near 50°, an effect that appears to be most pronounced for mid-central collisions.

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