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MULTIFRAGMENTATION AND FLOW IN CENTRAL COLLISIONS OF HEAVY SYSTEMS*

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MULTIFRAGMENTATION AND FLOW IN CENTRAL COLLISIONS OF HEAVY SYSTEMS

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Experimental results are presented on the production of light particles \((A < 5)\) and intermediate mass fragments \((6 < A < 18)\) over a large solid angle. The reactions \(200\text{ MeV}/n \text{Au} + \text{Au}\) and \(\text{Au} + \text{Fe}\) were studied to provide information on multifragmentation processes and collective flow.

1. INTRODUCTION

Fragment production in nucleus-nucleus collisions at intermediate energies has become extremely interesting in recent years. A variety of models has been proposed predicting widely differing mechanisms for fragment formation with very little experimental data to distinguish between them. The models range from fragment emission from a gas of nucleons and fragments in thermal and chemical equilibrium\(^{1,2,3}\) to fragment formation in a nuclear liquid-vapor phase transition\(^{4,5}\) shattering of target and projectile due to dynamical instabilities\(^6\), partial- or non-equilibrium processes\(^{7,8}\) and statistical models\(^{9,10,11}\). Furthermore, the flow of light particles in such collisions\(^{12,13}\) has recently been interpreted as evidence for the presence of collective phenomenon in the form of decompression. Predictions have been made that an even stronger collective effect should be observed in the flow of nuclear fragments\(^3,14\). Most experiments until present have studied single fragment inclusive distributions yielding little information on multifragmentation. Only recently have coincidence experiments been performed to gain

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additional information on the fragment correlations and the multifragmentation process. In this paper we present first results on the production of light particles (A < 5) and intermediate mass fragments (6 < A < 18) over a large solid angle and attempt to provide information on multifragmentation processes and the collective flow of fragments.

2. EXPERIMENT

The LBL/GSI Plastic Ball/Wall detector system\textsuperscript{15} was used to study light and intermediate mass fragments over a large solid angle in 200 MeV/n Au + Au and Au + Fe reactions at the Bevalac. The Plastic Ball consists of 815 CaF\textsubscript{2}(AE)-Plastic Scintillator(E) telescope modules covering the angular region from 10 to 160 degrees with hydrogen and helium isotope identification. The Plastic Wall covers all angles smaller than 10 degrees with 60 pairs of scintillator counters, with particle identification for 1 ≤ Z ≤ 6 via time-of-flight and energy loss. Computer-controlled high voltage modules were implemented on the 160 Ball modules which lie forward of 30 degrees in the lab, to enable online gain-matching. With a reduction in gain for these forward Ball modules, their energy loss spectra were extended, thus enabling the simultaneous measurement of all produced nuclei from hydrogen to neon. This can be seen in Fig. 1 where the particle identification spectrum is displayed using the ΔE-E energy loss signals. Unit separation of nuclear charges for 1 ≤ Z < 10 is observed; Z = 1 isotope separation is shown in the insert. A calibration for the fragment charge identification was made by detecting low energy neon beams and neon fragmentation products at the Bevalac using time-of-flight techniques. In order to be identified, fragments must traverse the 4 mm thick CaF\textsubscript{2}. This yields a low energy cut-off of approximately 35-40 MeV/n, which is acceptable in the forward laboratory direction due to the kinematic boost of the projectile.

Another addition to the present experimental setup was a gas proportional chamber\textsuperscript{16} covering 0 ± 2 degrees in the lab. The zero degree detector with its five wire planes enabled extremely high position resolution for projectile remnants. The measurements of intermediate mass fragments forward of 30 degrees in the lab, corresponding for 200 MeV/n Au + Au to the forward hemisphere in the center of mass, in addition to the 4π acceptance for light charged particles allows a multifragmentation study with events characterized by charged particle multiplicity.

3. MULTIFRAGMENTATION

Multiplicity distributions of fragments with 3 ≤ Z < 10, observed in the
forward hemisphere in the center of mass frame, are displayed in Fig. 2 for the Au + Au system. Events are divided into five total charged particle multiplicity M bins,\(^\text{17}\) corresponding to \(0 < M \leq 23\), \(23 < M \leq 46\), \(46 < M \leq 69\), \(69 < M \leq 92\) and \(M > 92\) for Au + Au and \(0 < M \leq 12\), \(12 < M \leq 25\), \(25 < M \leq 37\), \(37 < M \leq 50\) and \(M > 50\) for Au + Fe. These charged particle multiplicity bins are labeled MUL1, MUL2, MUL3, MUL4, and MUL5, respectively, and range from few observed charges (peripheral collisions) to very high multiplicities in the most central collisions. As seen in Fig. 2 most peripheral collisions (MUL1) result in a low fragment multiplicity. These fragments have energies close to that of the projectile. A large projectile remnant is usually observed in the zero degree detector in peripheral collisions. The remnant becomes smaller as the charge multiplicity increases, corresponding to decreasing impact parameter. In more central collisions (MUL4 and MUL5) practically all of the projectile charge is observed in the form of light and intermediate mass fragments, with no large projectile remnant remaining. As seen in Fig. 2 there are on the average 3-4 energetic fragments in the forward hemisphere per event for central collisions. Extrapolation of this measurement to 4\(\pi\) leads
Fig. 2 Fragment multiplicity distributions for five total charge multiplicity bins increasing from MUL1 to MUL5.

Many fragments produced in central collisions are emitted at larger angles and with rapidities intermediate between those of the projectile and target. A near isotropic emission pattern in the center of mass is observed for near-central collisions (MUL4) with a smooth transition to isotropy in the most central ones (MUL5). This is expected for fragmentation from the participant region of projectile-target overlap. If this system were equilibrated, the particle and fragment energy spectra in the perpendicular direction would be a measure of the temperature.

Displayed in Fig. 3 are the mean perpendicular momenta per nucleon $P_{⊥}$ of emitted hydrogen, helium, lithium and carbon nuclei plotted as a function of rapidity $y$. Results for three multiplicity bins are shown. The perpendicular
momenta of both light and intermediate mass fragments are larger in central collisions, where the entire system breaks up, than in gentler peripheral collisions. A distinct difference in $P_\perp$ between the intermediate mass fragments and $Z = 1, 2$ is observed and will be discussed later.

Fast forward-going fragments, observed at near-projectile rapidity, have lower perpendicular momenta than those at midrapidity. This further suggests that breakup of the projectile rather than emission from the participant region, even in high multiplicity events, is mainly responsible for producing these fragments. Helium appears to be an exception, with no present explanation. It is important to note that in all cases the mean $P_\perp$
changes smoothly with rapidity. This emphasizes the difficulty in unambiguously identifying any potentially equilibrated midrapidity subsystem from the overall distribution.

4. COLLECTIVE FLOW OF FRAGMENTS

In order to study the flow of the fragments, the transverse momentum analysis technique was used to determine the reaction plane of each event. The vector difference of the transverse momentum components of particles going forward and those going backwards is used together with the beam axis to define the reaction plane.

Fig. 4 presents directivity plots showing the azimuthal correlation of

![Diagram](image-url)
emitted fragments with the reaction plane. The angle plotted is the azimuthal emission angle of each fragment with respect to the reaction plane defined by the \( Z = 1,2 \) light particles. The left-hand column contains relatively peripheral collisions, and the right relatively central ones. Collisions at extremely large or small impact parameters result in poorly defined reaction planes and are not shown here. The three curves in each box correspond to the rapidities of the emitted fragments: \( 0.32 < y < 0.42 \) (circles), \( 0.42 < y < 0.52 \) (squares), and \( 0.52 < y < 0.62 \) (crosses), where the projectile rapidity is 0.64. Although the rapidity dependence of the correlation is more pronounced for central collisions, midrapidity fragments are always less correlated with the reaction plane than projectile-like fragments. In the limit of complete thermalization, azimuthally symmetric emission of midrapidity particles is expected. The presence of the correlation between fragments and the reaction plane suggests this picture to be too simple.

The observed correlations may be explained in terms of collective flow, which should be more important for central collisions than peripheral ones. This is observed by the stronger correlation on the right side of Fig. 4. If the correlation is a result of collective motion, the random thermal motion generated in such energetic collisions will reduce the effect. For a system at a fixed temperature, heavier fragments will have lower thermal velocities than lighter ones. Thus the resultant velocity vector, which is a sum of the thermal and flow velocity vectors, will be influenced more by the latter. The correlations in Fig. 4 are stronger for the heavier fragments, perhaps reflecting the increasing influence of the flow component as the fragment mass increases.

Further data which also support the above interpretation, are displayed in Fig. 5. Plotted is the mean of the transverse momentum projected onto the reaction plane normalized by the transverse momentum vector modulus, \( \langle p_x/|p_T| \rangle \), as a function of the rapidity of the particle for \( Z = 1,2,3 \) and 6. Positive and negative values of \( \langle p_x/|p_T| \rangle \) correspond to emission projected into the reaction plane, but on opposite sides. Fig. 5 clearly shows that a larger part of the fragment's perpendicular momentum lies in the reaction plane as the fragment mass increases. The \( Z = 3,6 \) fragments are more aligned in the plane than the \( Z = 1,2 \) particles which have been interpreted to flow collectively.\(^{12,13,18}\) Furthermore, the absolute value of the transverse momentum per nucleon projected into the reaction plane (not shown) also increases with fragment mass. The observations in Figs. 4 and 5 strongly suggest that the fragments exhibit stronger flow effects than lighter particles.
In addition to the Au + Au reaction, the Au + Fe reaction at 200 MeV/n was chosen for study, because the entire central rapidity region of this reaction lies between 10 and 30 degrees where $1 \leq Z < 10$ charge identification was possible. Displayed in Fig. 6 is a plot of the mean transverse momentum per nucleon for $Z = 2$ particles projected onto the plane as a function of the particle's rapidity. In contrast to Fig. 5 the reaction plane is defined, in this case, by a heavy projectile residue detected in the zero degree counter and the beam. Plotted are four multiplicity bins MUL1 to MUL4, which correspond to progressively decreasing impact parameter. Positive values of the ordinate correspond to the particle appearing on the same side of the beam as the heavy residue. For peripheral collisions (MUL1) the $Z = 2$ particles lie on the opposite side of the beam as the heavy residue. As the collision becomes more central, and the effects of collective flow more important, the particle is more likely to be found on the same side of the beam as the heavy projectile residue. Particles emitted closer to target rapidity are always emitted on the opposite side of the beam from the projectile residue.
Fig. 6. Mean transverse momentum per nucleon projected onto the reaction plane (defined by a detected projectile residue) for $Z = 2$ nuclei as a function of lab rapidity. Plotted are curves for total charge multiplicity bins (MUL1, 2, 3, 4) corresponding to decreasing impact parameter in the direction of the arrow.

5. SUMMARY DISCUSSION

In peripheral collisions fragments are observed mainly as a single evaporation product from a large projectile or target remnant. Rapidity plots show a fragment distribution about the projectile rapidity with a hole corresponding to the Coulomb energy between the fragment and a heavy projectile remnant, boosted to the projectile reference frame.

Multifragmentation occurs for more central collisions where complete disintegration of the interacting nuclei takes place with no remaining spectator fragments. In the forward c.m. hemisphere of central Au + Au collisions there are in the mean three to four energetic fragments ($3 \leq Z \leq 6$) and as many as twelve observed. These large numbers of fragments must generally be considered in deducing the entropy of the system. Furthermore, the fragments observed in the most central collisions are isotropic in the c.m. frame. This suggests possible equilibration for near-zero impact parameter collisions. These observations in the angular and
multiplicity distributions as a function of centrality must be quantitatively compared to theoretical results in order to determine the models appropriate for describing the fragment production.

A large amount of nonisotropic fragment flow is observed in the reaction plane determined by the light particles. This flow becomes more pronounced the heavier the observed fragment and as the collisions become more central, except for the most central collisions where the distributions become isotropic. The fragment flow is much more pronounced than that of the light \((Z = 1,2)\) particles. Theoretical predictions exist\(^3,14\) which point to enhanced flow in the fragments.

In correlations between \(Z = 2\) particles and a projectile residue for peripheral \(\text{Au} + \text{Fe}\) collisions, the light particles near projectile rapidity are observed to appear more often on the opposite side of the reaction plane from the incident beam, i.e. at "negative scattering angles." As the impact parameter decreases for progressively more central collisions, the light particles near projectile rapidity shift to "positive scattering angles." Those near the Fe target rapidity always appear on the opposite side of the reaction plane from the incident projectile. Recent theoretical work\(^7,20\) has attributed these effects to the presence of the attractive nuclear mean field.

Finally, fragment emission from a thermalized fireball would be isotropic and have no correlation with the reaction plane. The strong alignment in the reaction plane and the increased flow of the fragments compared to the light particles suggests collective effects. In this case the velocity of a particle or fragment will consist of thermal and collective velocity components. If all particles and fragments are emitted from a single source at a fixed temperature, then the thermal component is smaller for heavier masses and the collective component more prominent. A reduction in the thermal velocity component is observed in the mean transverse momentum for \(Z = 1,2,3\) but not for heavier masses. However, if freezeout times vary as a function of the fragment mass and the temperature decreases with time, as in isentropic expansion, this scenario would be considerably more complicated. In the end dynamical effects must be considered in theoretical approaches.

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