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AUTHOR(S) B.V. Jacak, H.C. Britt, A.I. Gavron, J. Wilhelmy,
Los Alamos National Laboratory

K.G.R. Doss, G. Claesson, H.-A. Gustafsson, J.W. Harris,
A.M. Poskanzer, H.-G. Ritter, L. Teitelbaum, M. Tincknell,
S. Weiss, H. Wieman, LBL, Berkeley, CA

K.-H. Kampert, B. Kolb, H.R. Schmidt, Gesellschaft fur
Schwerionenforschung, West Germany

R. Ferguson, ORNL, Oak Ridge, TN

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

MULTIFRAGMENTATION IN INTERMEDIATE ENERGY HEAVY ION COLLISIONS

B. V. Jacak,^{*} H. C. Britt,^{*} G. Claesson,^{**} K. G. R. Doss,^{**} R. Ferguson,^{**}
A. I. Gavron,^{*} H.-A. Gustafsson,^{**} H. Gutbrod,[‡] J. W. Harris,^{**}
K.-H. Kampert,[‡] B. Kolb,[‡] A. M. Poskanzer,^{**} H.-G. Ritter,^{**} H. R. Schmidt,[‡]
L. Teitelbaum,^{**} M. Tincknell,^{**} S. Weiss,^{**} H. Wieman,^{**} J. Wilhelmy^{*}

^{*}Los Alamos National Laboratory,
Physics Division
Los Alamos, NM 87544

^{**}Lawrence Berkeley Laboratory,
1 Cyclotron Road
Berkeley, CA 94720

[‡]Gesellschaft für Schwerionenforschung,
Postach 11 05 41
D-6100 Darmstadt 11, West Germany

^{**}Oak Ridge National Laboratory
P. O. Box X, Bldg. 6003
Oak Ridge, TN 37831

There has been considerable recent interest in the production of intermediate mass fragments ($A > 4$) in intermediate and high energy nucleus-nucleus collisions. The mechanism for production of these fragments is not well understood and has been described by models employing a variety of assumptions. Some examples are: disassembly of a system in thermal equilibrium into nucleons and nuclear fragments,^{1,2} liquid-vapor phase transitions in nuclear matter,³ final state coalescence of nucleons⁴ and dynamical correlations between nucleons at breakup^{5,6}.

Previous studies of fragment production, with one exception,⁷ have been single particle inclusive measurements: the observed fragment mass (or charge) distributions can be described by all of the models above. To gain insight into the fragment production mechanism, we used

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the GSI/LBL Plastic Ball/Wall detector system⁸⁾ to get full azimuthal coverage for intermediate mass fragments ($Z < 10$) in the forward hemisphere in the center of mass system while measuring all the light particles in each event.

The complete measurement of light particles (p, d, t, ^3He , ^4He) allows us to determine the charge multiplicity of participant baryons, which increases as the impact parameter between the projectile and target nuclei gets smaller. In addition, the complete measurement of light particles allows us to perform global analyses of the events and look for collective effects in fragment emission by comparing to flow effects seen in the light particles. Lastly, the large acceptance for intermediate mass fragments in the Plastic Ball allows us to measure their multiplicities event-by-event. This experiment should help to differentiate the various models by allowing a better characterization of the system breaking up, as well as yielding information on the impact parameter of the collision. We measured fragmentation for 200 MeV/nucleon Au + Au and Au + Fe, using the inverse kinematics in the latter case to focus fragments from the large reaction partner into our detectors. Presented here are first results from the experiment. These will not yet allow us to determine the exact fragmentation mechanism, but will provide many constraints on the results of the various models.

The observed participant charge multiplicity distribution for Au + Au is shown in figure 1. We have used this quantity to sort the events into groups according to impact parameter, as indicated by the lines in the figure. The events with the fewest observed charges (labeled "mul1") correspond to the most peripheral collisions, while the events with the highest charge multiplicities ("mul5") arise from central collisions. The drop in the number of events with very low

Au + Au (multiplicity trigger)

Fig. 1. Participant charge multiplicity distribution for Au + Au.

multiplicities is a result of the trigger used in the experiment, which was designed to discriminate against the most peripheral collisions.

Figure 2 shows a density plot of the invariant cross section for lithium fragments from Au + Au, as a function of the rapidity and the perpendicular momentum per nucleon. The five parts of the figure correspond to the five cuts on the participant charge multiplicity indicated in figure 1. No corrections for the angular and energy cutoffs in the detector have been applied to the data. Thus two distinct sections are visible in each plot, corresponding to the two subsections of the detector system which were sensitive to intermediate mass fragments.

Fig. 2. Multiplicity selected rapidity plots for lithium fragments for Au + Au.

It is evident from the figure that peripheral collisions give rise to fragments with rapidities very close to the beam rapidity, consistent with expectations for fragmentation of a slightly excited projectile. In the "mull" plot we see a hole in the yield at exactly the beam rapidity, corresponding to coulomb repulsion between the emitted lithium fragment and a heavy remnant of the Au projectile. In events where a projectile remnant is observed, the azimuthal angles of the remnant and fragments are correlated, supporting the picture of fragments evaporated from a large projectile residue.

In the more central collisions in the highest multiplicity bins, we see many lithium fragments emitted with smaller rapidities, intermediate between those of the target and the projectile. In contrast to the forward peaked angular distributions arising from peripheral collisions, these fragments are emitted relatively isotropically in the center of mass system. Such behavior is what one might expect when the projectile nucleons impart more energy to the target and create an excited region which moves at a velocity approximately halfway between that of the projectile and the target.

The transition between the peripheral and central collisions is very smooth, with a gradual shift in the rapidities of the observed fragments away from the projectile rapidity. In order to check if both projectile-like and midrapidity fragments are formed in the same event, we chose events with multiple fragments and required that at least one fragment fall into a midrapidity window. We made a rapidity plot similar to figure 2 of the other fragments in the event, and found that the mixing occurs event-by-event; even in the central collisions where midrapidity fragments are formed, we observe some associated projectile rapidity fragments.

In order to check our detection efficiency for multiple fragments, we summed the charges observed in the forward c.m. hemisphere for the Au + Au reaction and compared this with the charge of one Au nucleus. The result is shown in figure 3, plotted as a function of the participant charge multiplicity. For peripheral collisions, we observe a large projectile remnant in many events, these correspond to the small lobe on the left (low multiplicity) side of the figure. As the charge of the projectile remnant is not well measured, it is assigned one half the charge of the projectile. It is clear that the remnant charge is underestimated for the most peripheral collisions and overestimated as the impact parameter and projectile remnant become

Fig. 3 Sum of charges observed in forward c.m. hemisphere, as a function of the participant charge multiplicity.

smaller. For central collision (large multiplicities), we observe almost all of the Au charge in the form of light and intermediate mass fragments. These results indicate that in central collisions the system breaks up into rather small pieces with no large remnant. Also, we gain confidence that we may study fragment multiplicities event by event due to the high efficiency of the detector system.

The total intermediate mass fragment multiplicity is found to increase with increasing participant baryon charge multiplicity. In peripheral collisions, the few fragments which are formed are preferentially emitted at angles less than ten degrees in the lab. More fragments are produced in central collisions, and these fragments are found at larger angles.

Figure 4 shows the multiplicity distributions for fragments observed at angles between 10 and 30 degrees in the lab. It should be noted that for the Au + Au system, 30 degrees in the lab corresponds to 90 degrees in the center of mass frame. The five curves correspond to the same five cuts on the participant charge multiplicity that were described in figure 1 and used in figure 2. In central collisions, the most probable fragment multiplicity is 3-4, with a tail out to as many as 9 fragments. For peripheral collisions the distribution peaks at zero to one fragment, with a smaller tail to high multiplicities. The multiplicities of fragments emitted to small angles are very low, regardless of impact parameter.

Fig. 4. Multiplicity distributions of intermediate mass fragment detected at 10-30 degrees in the laboratory.

Collective flow of nuclear matter upon re-expansion has been proposed as an important signature of compression effects. Two collective effects, the side-splash of the participants and the bounce-off of the spectator nucleons have been observed at the Plastic Ball^{9]}. A sensitive test for collective flow can be found in the transverse momentum analysis of Danielewicz and Odniewicz^{10]}. This method determines the reaction plane from the transverse momentum transfer between the forward and backward hemispheres in the center of mass, and then examines the mean transverse momentum per nucleon $\langle p_x/A \rangle$ in this reaction plane as a function of the center of mass rapidity. By removing auto-correlations (i.e. calculating the reaction plane for each individual particle from the transverse momentum sum of all the other particles), this method is sensitive to the real dynamic correlations.

Figure 5 shows the mean transverse momentum per nucleon projected

Fig. 5. Mean transverse momentum per nucleon in the reaction plane, as a function of c.m. rapidity for Au + Au.

into the flow plane for the Au + Au reaction. The calculation includes only $Z=1$ and $Z=2$ particles, and may be compared to analyses of earlier Plastic Ball experiments^{11]}. All observed light particles are included in the figure; those originating from the projectile or target spectators were not removed. The curve shows the s-shape typical for the collective transverse momentum transfer between the forward and backward hemispheres. Close to the target and projectile rapidities the curve bends towards the axis because of contamination from spectator matter.

We have examined the intermediate mass fragments for flow effects by looking at the azimuthal correlation between the reaction plane and the emission angle of the fragments. We find that fragments are preferentially emitted in the same direction as the flow direction, and that this correlation gets stronger for more massive fragments.

As a first step in studying the origins of multiple fragments, we construct the "effective source" of the fragments by summing the 4-momenta of the observed fragments. This source moves with a velocity similar to the beam velocity in the case of peripheral collisions, and slows down as the impact parameter decreases. We again calculated the reaction plane from the light particles, and looked at the projection of the "effective source" transverse momentum per nucleon in and out of the reaction plane. As with the fragment singles, the source azimuthal angle is correlated with the reaction plane. The transverse momentum per nucleon in the reaction plane increases for more central collisions, reaching a maximum of about 150 MeV/c. Perpendicular to the reaction plane, the source transverse momentum shows no preferred direction.

We are currently studying whether the intermediate mass fragment energy distributions and multiplicities can be reproduced with models incorporating the various assumptions mentioned earlier. These models must also reproduce the observed flow effects, thus rather stringent criteria have already been established by these experiments.

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