Large p_T from the Fragmentation of 1.2-GeV/Nucleon ^{139}La Nuclei

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(Received 16 November 1987)

The first measurements of the transverse momenta (p_T) of heavy projectile fragments produced by fragmentation of 1.2-GeV/nucleon La are presented. The momentum distributions of the fragments ($Z \cong 26$–56) are Gaussians and broader than predicted by models based on internal momenta of the projectile nucleons. The larger p_T observed do not appear to be due solely to Coulomb effects, but are consistent with a simple model whereby nucleons from the (hot) overlap region recoil collectively into the (colder) projectile fragments. Thus p_T and the fragment mass may provide a good indication of the vector impact parameter **b**.

PACS numbers: 25.70.Np

There is considerable interest in the hydrodynamic behavior of nuclear matter in violent collisions of relativistic nuclei (RNC). At these energies the colliding nuclei interpenetrate with a velocity larger than the sound-propagation velocity in the nuclear medium. The result is shock compression and heating in the overlap region of the colliding nuclei.[1-8]

In the language of the abrasion-ablation model[9] the overlap region of the abrasion stage is called the participant region, while the remainder of the projectile and target are called spectators. It is believed that the latter receive relatively little momentum in the collision, and that fragment momentum distributions are due largely to internal nucleon momenta.[10] This appeared to be the case in the fragmentation of ^{12}C and ^{16}O at similar energies.[11] In the experiment reported here we find larger transverse momenta of the fragments than is expected on the basis of internal momenta.

Signatures of high compression and collective stopping in RNC are very important. In this regard the transfer of energy from longitudinal to transverse motion and the subsequent (sideways) emission of nuclear matter following compression was one of the first predictions of hydrodynamic calculations.[1-7] Early emulsion data[8] and later scintillator array data[12] showed sideways emission of light particles, which was interpreted as evidence for outflow.

More complete evidence for shock effects and apparent matter flow in RNC has come from recent global event analyses of light particles emitted into the nearly 4π Plastic Ball/Wall[13] and streamer chamber[14] detectors at the LBL Bevalac. It is found[13] that the mean flow angle increases with event multiplicity and that light particles of near beam rapidity have p_x' (p_T projected into the reaction plane) per nucleon in the range 0–200 MeV/c. The latter is taken as an indication of projectile fragment "bounceoff." Recent emulsion experiments[15] also detected collective flow. Calculations based on a nuclear-fluid (hydrodynamical) model predict the flow-angle data quite well.[16] Microscopic calculations[17] also produce net side splash, and a more recent calculation[18] gives a good fit to flow-angle data.[13]

We present here the first measurements of transverse momenta of heavy fragments in RNC. These were produced by the fragmentation of 1.2-GeV/nucleon ^{139}La nuclei from the Bevalac incident on carbon target nuclei. The measurements were made at the HISS (Heavy-Ion Superconducting Spectrometer) facility[19] with MUSIC, a multiple-sampling ionization chamber.[20] The experimental arrangement is described in Ref. 20. Very briefly, a collimating veto, a beam monitor, and the target were placed near the center of the HISS dipole (whose field was turned off). After passing through these the beam and fragments traveled 6.6 m and passed through MUSIC.

MUSIC has an active volume 2 m wide × 1 m × 1.5 m deep and uses time-projection-chamber principles and electronics. Ionization tracks are drifted (down) to the anode plane which, for these first tests, were divided into left and right halves and segmented along the ion tracks into sixty 2- and four 6-cm-thick anode cells. Thus 64 spatial samples of ionization are each time sampled every 100 ns to obtain 64 vertical profiles of the chamber charge distribution. The 64 samples provide a track energy-loss distribution whose average measures the mean energy deposited (which depends on the fragment velocity and on the charge as Z_F^2).

Figure 1 shows data obtained for the fragmentation of 1.2-GeV/nucleon ^{139}La on nuclei in a 2.68-g/cm^2 $^{\mathrm{nat}}$C target. The scatter plot (top) shows the track average drift time versus energy loss (upper scale) and charge (lower scale) for 54 2-cm cells. The projected raw data

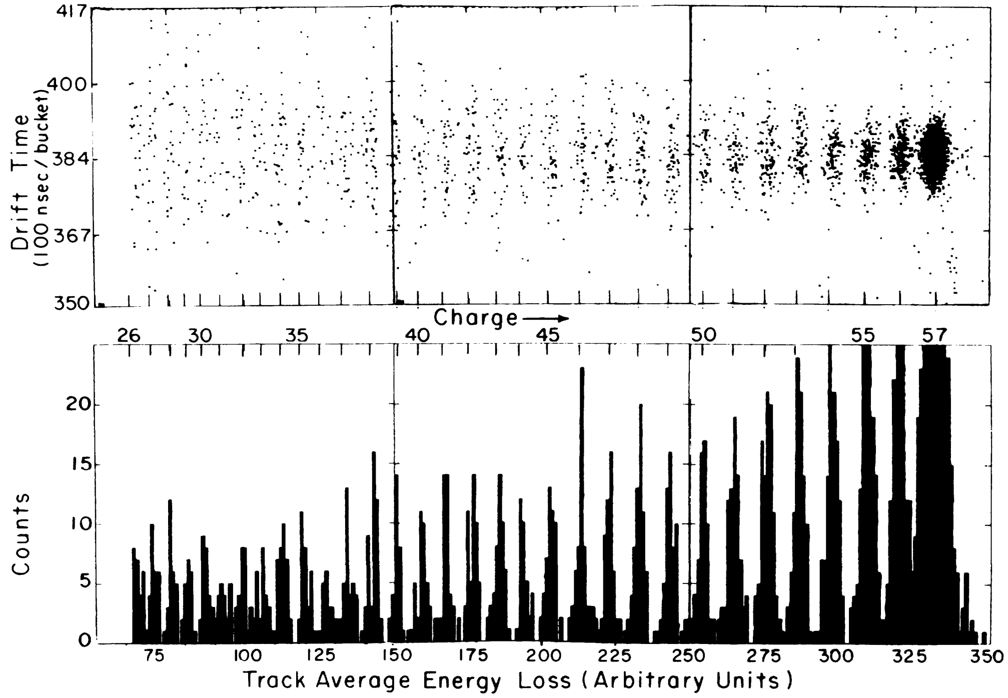

FIG. 1. Top: Drift time vs track average energy loss and charge of fragments from ^{139}La (1.2 GeV/nucleon)+C. Bottom: Projected spectrum.

(Fig. 1, bottom) indicate a charge resolution (FWHM) of $\cong 0.3e$ (charge units). (No correction for velocity variation has been made.) The raw parameters we measured in this experiment were thus the fragment charge and the track vertical angle θ_x as it traversed the MUSIC detector (Fig. 2).

In converting the data $\sigma(p_x)$, we assume that the longitudinal component of momentum has a narrow distribution centered near the beam value per nucleon as has been shown earlier.[11,21] Thus, these p_x and p_T projected onto the detector and not onto the reaction plane as is often used in analyses (e.g., Ref. 13), following the proposal of Danielewicz and Odyniec.[22] We could not determine the reaction plane except in the sense, as we suggest later, that the heavy-projectile-fragment p_T may do so. In the spirit of the abrasion-ablation model, the charge-to-mass ratios of the fragments are taken to be that of the beam. The uncertainties assigned to the

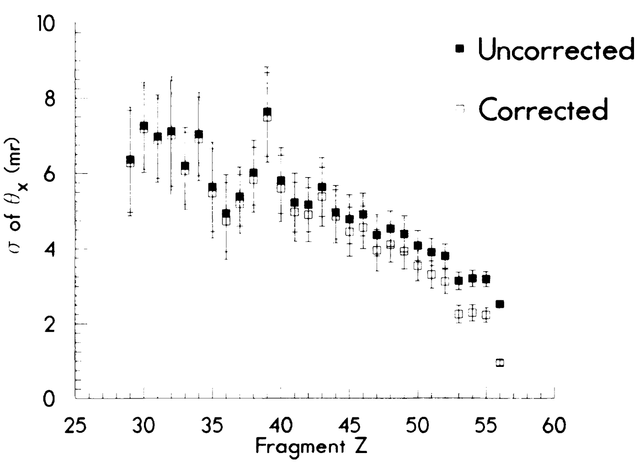

FIG. 2. The fragment angular distribution widths, $\sigma(\theta_x)[\equiv\theta_x(\text{rms})]$, vs fragment charge before and after corrections for multiple Coulomb scattering and beam angular dispersion.

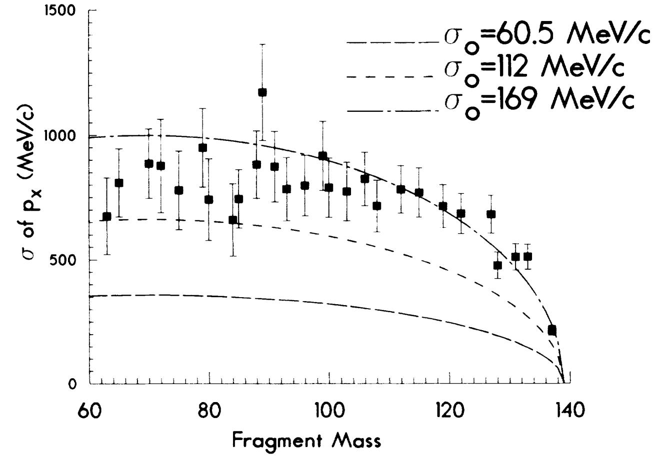

FIG. 3. The $\sigma(p_x)$ values derived from the data of Fig. 2 plotted against fragment mass (see text). The dash-dotted curve is the best fit with the Goldhaber form. Also shown are the predictions of Goldhaber ($\sigma_0 = 112$ MeV/c) and that based on the model of Lepore and Riddell ($\sigma_0 = 60.5$ MeV/c).

points in Fig. 3 contain contributions due to the assignment of the fragment mass (2.5%–7.0%), electron drift velocity in MUSIC (4%), longitudinal velocity (0.8%), and statistics (6%–16%). These $\sigma(p_x)$ values are $\simeq 15\%$ smaller than those reported earlier.[23]

Comparisons with predictions based on the models of Goldhaber[10] (G) and Lepore and Riddell[24] (LR) are also shown in Fig. 3. The former is based on an independent-particle (Fermi gas) model in which the only correlation among the nucleons in the projectile and in the fragment nucleus of A and F nucleons, respectively, is that given by conservation of momentum. The latter model uses independent-particle shell-model wave functions whose main features are harmonic-oscillator Gaussian factors. The behavior of a real nucleus is expected to lie between these two predictions. The Goldhaber prediction is that

$$\sigma(p_x) = \sigma(p_y) = \sigma(p_z)[F(A-F)/(A-1)]^{1/2}.$$

In this model, dependence on the Fermi momentum is via $\sigma_0^2 = p_f^2/5$. Here the p_f of La is taken to be 250 MeV/c.[25] The LR $\sigma(p_j)$ values for La are 0.54 times those of Goldhaber. For both models the predicted $\sigma(p_x)$ (Fig. 3) are smaller than those obtained from the measurements.

Bertsch[26] argues that momentum anticorrelations of the nuclear shell model should suppress momentum fluctuations, as shown by the LR calculations.[24] In fact, the fragmentation of ^{12}C (^{16}O) at 1.05 and 2.1 (2.1) GeV/nucleon (Ref. 11) and of Ar at 213 MeV/nucleon (Ref. 20) yielded values of $\sigma(p_z)$ 15%–20% lower than the Goldhaber values.

A fit to the data (dash-dotted line in Fig. 3) with the Goldhaber form yields a mean $\bar{\sigma}_0 = 169 \pm 12$ MeV/c, as compared to $\sigma_0(\mathrm{G}) = 112$ and $\sigma_0(\mathrm{LR}) = 60.5$ MeV/c. The fit is systematically below the data at large F and above it at medium F, thus indicating a fragment mass dependence for σ_0. A thicker (5.56 g/cm^2) C target gave $\bar{\sigma}_0 = 175 \pm 13$ MeV/c, which indicates that the effect of multiple nuclear interactions is small.

The earlier data on ^{12}C and ^{16}O indicated[11] that $\sigma(p_x) = \sigma(p_z)$ with, as noted above, $\sigma_0 \simeq 15\%$–20% less than the Goldhaber value. The larger σ_0 extracted here from our p_x measurements suggests that for heavy projectiles there is some additional physics that needs to be taken into account. We have fitted the p_x distributions by assuming a transverse momentum (bounce) $\equiv p_T(B)$ and convoluting this with a Gaussian distribution of Goldhaber type. The fits are reasonable (χ^2/degree of freedom $=0.8$–1.3) and the extracted $p_T(B)$ average $\simeq 900$ MeV/c over the range $F = 70$ to 100. $p_T(B)$ decreases to 700 MeV/c at $F = 127$. $p_T(\mathrm{Coul})$ can be estimated from relativistic electrodynamics.[27] A simple two-stage calculation based on the abrasion-ablation model yields $p_T(\mathrm{Coul}) \simeq 350$ MeV/c for $F = 90$.

One needs a mechanism for producing additional transverse momentum. For nucleon-nucleon scattering at these energies the cross section $d\sigma/dt$ is forward peaked towards small four-momentum transfer t.[28] Thus one struck nucleon recoils at angles near 90° while the other is little changed in direction or energy. In collisions along the participant-spectator interface, nearly 50% of the recoil nucleons are directed towards the "spectator" projectile fragment, and so can transfer energy and momentum to this projectile fragment (or prefragment) which deexcites to become the detected projectile fragment (PF).

From the data on $d\sigma/dt$ (Ref. 28) one can calculate the average $\langle (t) \rangle \simeq 400$ MeV/$c = \mathbf{q}$ (three-momentum) for elastic scattering. The $\mathbf{q}(\theta)$ distribution in the projectile frame (PF) peaks near $\theta = 75°$. ($\theta = 0°$ is along the target direction in the projectile frame.) Thus, stopping the recoil nucleation in the PF transfers an average of $\simeq 400$ MeV/c in the transverse and $\simeq 100$ MeV/c in the longitudinal direction.

A complete calculation of the momentum transferred to the PF when the C (target) nucleus passes through the La nucleus is beyond the scope of this paper. However, an estimate can be made with the energy-transfer model of Hufner, Schäfer, and Schurmann[29] and Oliveira, Donangelo, and Rasmussen.[30] In the latter it is assumed that as the recoiling nucleon advances through the PF it loses energy by further N-N collisions. The deposited energy is assumed to be $dE = -\alpha E\, dx/\lambda$, where $\alpha = 0.25$ is the fraction of energy lost per collision, and $\lambda(\mathrm{mfp}) = (\rho\sigma_{NN})^{-1}$. $\rho = 0.16$ fm^{-3} and $\sigma_{NN} \simeq [(550\ \mathrm{MeV})/E]$ fm^2 is a good approximation for $50 \lesssim E \lesssim 150$ MeV. With the above model the average energy deposited per nucleon in a PF of $A = 64$ is $\simeq 40$ MeV. The corresponding average momentum deposited is $\simeq 300$ MeV/c (at a mean angle of $\bar{\theta} \cong 75°$). The azimuth ϕ of $\mathbf{q}$ varies from near zero to near π so the average $\langle q_x \rangle_\phi$ is $2q/\pi$ or $\simeq 200$ MeV/c. Thus, in a single event one needs only three or four nucleons from the participant region to recoil and stop in the PF to produce (collectively) the additional p_x required to explain the measured values (Fig. 3). These nucleons will also each contribute $\simeq 50$ MeV/c towards the slowing down of the PF in the lab frame. The effects of the nucleons emitted in the ablation stage have been neglected.

If, as we believe, the extra $p_T(B)$ reflects collision dynamics, then it may be possible to use measurements of the PF to determine the azimuth of the reaction plane. In fact, calculations[31] of nuclear collisions indicate that measurements of heavy PF determine the azimuth rather well. This has been seen very recently in light-PF p_T.[32] Of course, the effects of the internal momenta of the nucleons in the projectile nuclei introduce some uncertainties in the use of $p_T(B)$ to determine the azimuth. According to the abrasion-ablation model, the PF mass provides a measure of the impact parameter, b. Thus, measurements of heavy PF may be one of the easiest and best ways of determining the vector, **b**. Such determinations are important for the study of nuclear flow, etc., and the extraction of nuclear equation-of-state information.

We are grateful to F. Bieser, I. Flores, and J. Porter at Lawrence Berkeley Laboratory and to E. Barasch, C. Castaneda, and J. Drummond at the University of California, Davis, for willing and essential assistance. We acknowledge the support of the National Science Foundation, the Department of Energy, and NASA. Four of us (C.E.T., B.C.M., M.L.W., and J.C.Y.) acknowledge support through Associated Western Universities.

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