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Fragment mass dependence of p_T at GeV per nucleon energies

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Measurements of the transverse momenta (p_T) of medium and heavy mass projectile fragments for a range of projectile nuclei (^{40}Ar, ^{93}Nb, ^{139}La, ^{197}Au) have been carried out. It is found that the width of the transverse momentum distributions increases more rapidly with projectile and fragment mass than predicted by models based on nucleon momenta in the projectile nuclei. The distributions can be fit by including an additional transverse momentum, p_B (for Bounce). The extracted values of p_B/A_F increase with decreasing A_F, and extrapolations to small A_F appear to be consistent with the mean values of reaction-plane-projected p_T per nucleon for light particle (e.g., nucleon) "bounce-off."

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Studies of the compressibility of nuclear matter, or more generally its equation of state (EOS), continue to be of great interest [1]. Ideally, one would like to study large systems of nucleons (such as neutron stars) where finite-size effects could be neglected. Failing that, relativistic collisions of heavy nuclei offer many possibilities. However, such studies are hardly straightforward since one cannot observe directly the time evolution of a collision, but only some properties of the collision products. One must rely heavily on theoretical simulations of the collisions to interpret the experimental data in terms of the properties of nuclear matter.

Early calculations [2,3] predicted collective (shock) compression and effects which have been termed "collective flow" and "bounce-off." Emulsion event data [4] also stimulated interest. However, it was not until the global analyses of events into nearly 4π-plastic ball/wall [5] and streamer chamber [6] detectors at the Bevalac became available that the matter flow could be clearly identified and quantified. The analyses revealed a reaction-plane flow or "side-splash" as well as an out-of-plane flow or "squeeze-out" perpendicular to the reaction plane [7]. The flow is most striking in heavier systems [8]. The data [5] also provided evidence for "bounce-off": For all but very peripheral collisions (as signaled by small, participant-nucleon multiplicities) the light particles (mainly hydrogen and helium isotopes) near beam rapidity were found to have relatively large transverse momenta ($\langle p_x \rangle \simeq 50$ MeV/c per nucleon) in the reaction plane. Light fragments exhibit a similar behavior [9]. About the

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same time we observed [10,11] that the widths of the (projected) transverse momentum distributions of heavy projectile fragments from 1.2*A* GeV ^{139}La fragmentation were larger than expected. This indicates likely bounce-off effects for heavy fragments, and the possibility of using the $\mathbf{p}_T$ of the latter as a more accurate reaction plane indicator than flow analysis, which has large uncertainties in more peripheral collisions.

Here we report momentum analyses of (the heavier) projectile fragments ($A_F \gtrsim A_P/2$) for a range of projectile (A_P) masses (Ar→Au) at Bevalac energies to compare to the La data (and its further analysis) and to earlier C and O fragmentation data [12]. We find that the (projected) transverse momentum (p_y, say) widths tend to increase with fragment mass much faster than what is predicted by models based on the internal nucleon (e.g., Fermi) momenta in the projectile.

Extracting compressibility and EOS information from experimental data is not easy. For example, using the suppression of (nucleus-nucleus) pion (and kaon) production as a measure of nuclear compressibility turns out to be unreliable in the sense that the momentum dependence of the interactions can mimic the effects of a stiffer (in compressibility) EOS. However, Maruhn and Stöcker [13] find that pion yields do rule out some equations of state, and so narrow considerably the admissible range. Recently, Jänicke and Aichelin [14] have discussed the problem of using Boltzmann-Uehling-Uhlenbeck (BUU) calculations to determine compressional energy from the particle flow. In their improved quantum molecular dynamics (QMD) model they expect energy to be conserved to better than 1%; and they find only about 15 MeV per nucleon of compressional energy for the participant nucleons. This corresponds to a momentum near 170 MeV/*c* per nucleon.

The transverse momentum data reported here are derived from several experiments carried out in the heavy ion superconducting spectrometer (HISS) experimental area at the Bevalac. The 1.65*A* GeV ^{40}Ar and ^{93}Nb data are part of experiment E772H. For ^{40}Ar the multiplicity-one projectile fragments of $8 \leqslant A_F \leqslant 40$ had their charge, mass number, and momentum determined [15]. For ^{93}Nb, charge and momentum were determined; however, problems with the velocity data have so far precluded mass determination.

The fragmentation of ^{197}Au on light targets was studied using the HISS magnet and MUSIC II for momentum analysis and charge measurement [16]. Here we focus on the multiplicity-one, medium and heavy fragment events where charge and the out-of-bending-plane deflection, y, were determined. In the ^{139}La+C experiment [11,17] MUSIC I was used to give projectile fragment charge [$\sigma(Z) \simeq 0.11$ charge units] and vertical position [$\sigma(y) \simeq 150\ \mu$].

Thus, for all the projectiles heavier than ^{40}Ar we use only the fragment charge Z_F and the vertical deflection y (or equivalently the θ_y value) to determine p_y of the fragment. We assume that the fragments have (essentially) beam projectile velocity, i.e., projectile momentum per nucleon ($=p_0$) (as has been observed [12,15]). Then $\theta_y = p_y/p_z = p_y/p_0 A_P$ (P=projectile), so $p_y = \theta_y p_0 A_P$ is determined from θ_y.

The measured θ_y have to be corrected for multiple Coulomb scattering (MCS) and for the angular dispersion of the beam. θ_y (MCS) was typically 1 mrad and θ_y (beam) was 1–2 mrad. We use the measured beam divergence (y deflection distribution) and calculated MCS to correct for these effects as is done in Ref. [17], wherein Fig. 4 shows $\sigma(\theta_y)$ corrected and uncorrected. The corrections are appreciable for $Z_F(A_F)$ near $Z_P(A_P)$.

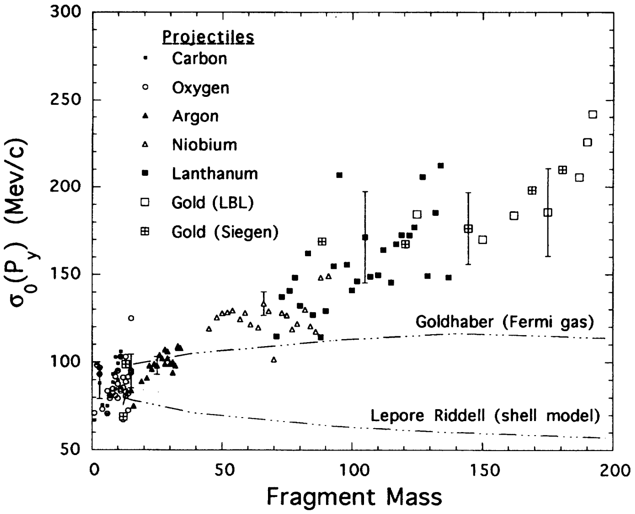

FIG. 1. σ_0(expt) plotted vs A_F (see text) for various projectiles (as keyed) at Bevalac energies. Typical uncertainties are shown. In the figures, "Fragment Mass" refers to the abrasion fragment mass, which is not measured, but is an average value inferred from $A_F = A_P Z_F / Z_P$.

As noted above, for ^{93}Nb, ^{139}La, and ^{197}Au, only fragment charge Z_F (and not mass) was determined. However, the models involve the mass of the fragment and in particular the mass of the "abrasion fragment." In the abrasion-ablation (AA) model [18] which can be used for noncentral and peripheral collisions (the case here), the abrasion fragment consists of the spectator nucleons. In the ablation stage we assume that the abrasion or prefragment deexcites largely by particle emission. Data [16,19] show that neutron emission dominates for medium and heavy fragments (due to the Coulomb barrier). Assuming mainly neutron emission, it follows that in these cases the charge of the detected fragment is a good estimate of that of the abrasion fragment. In this spirit we assume that the average mass of the abrasion fragment is given by $A_F/Z_F = A_P/Z_P$.

The uncertainty $\sigma(A_F)$ in A_F produces an increase in $\sigma(p_y)$ which is appreciable only for A_F values near A_P where $\sigma(p_y)$ is changing fairly rapidly with A_F. We estimate $\sigma(A_F)$ using the method introduced by Morrissey *et al.* [20], which is based on the zero point vibration of the giant dipole resonance (GDR) of the projectile nucleus. The $\sigma(p_y)$ values are corrected for this effect (assuming it adds in quadrature) before σ_0(expt) values are extracted. For example, the correction reduces $\sigma(p_y)$ by $\simeq 3\%$ for $A_P - A_F = 4$ which, for ^{197}Au, ^{139}La, and ^{93}Nb beams, corresponds to the largest A_F in Figs. 1 and 2. The correction becomes smaller as $A_P - A_F$ increases. We allow 100% uncertainty in this correction as is reflected in the error bars.

The early momentum measurements of Greiner *et al.* [12] for light projectile ^{16}O at 2.1 GeV and ^{12}C at 1.05 and 2.1

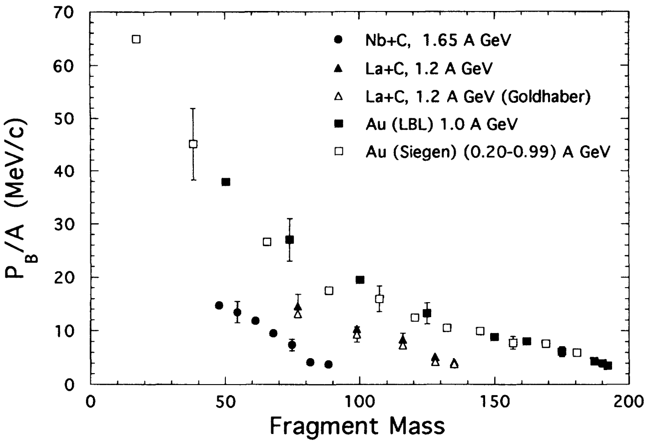

FIG. 2. The transverse momentum parameter per nucleon p_B/A_F plotted vs A_F (as defined in Fig. 1). For La+C, values of p_B/A_F using both LR and Goldhaber models are shown. Typical uncertainties shown are ±15%. Au (LBL) is for Mg and Au (Siegen) for a plastic (CR39) target.

GeV per nucleon showed similar x, y, and z momentum distributions in the projectile frame (allowing for a small z direction downshift). These distributions are well described by Gaussians whose variances are given approximately (Fig. 1) by the model of Goldhaber [21] in which the only correlation among nucleons is given by momentum conservation. In the projectile frame this model predicts $\sigma^2(p_x) = \sigma^2(p_y) = \sigma^2(p_z) = \sigma_0^2 A_F(A_P - A_F)/(A_P - 1)$. For the Fermi gas model of the nucleus, $\sigma_0^2 = p_f^2/5$, where p_f is the Fermi momentum in the projectile nucleus. The model of Lepore and Riddell [22] (LR) uses shell model wave functions with harmonic oscillator Gaussian factors and predicts a smaller σ_0 (Fig. 1).

In our earlier analysis [11] of the surprisingly large $\sigma(p_y)$ values for the ^{139}La+C data, the best fit to the data yielded $\sigma_0(\text{expt}) \simeq 169$ MeV/c and there was a trend (Fig. 1) for the extracted σ_0 values to increase with A_F, and to lie above the Goldhaber model value of $\sigma_0(G) \simeq 112$ MeV/c, based on Fermi momentum values [23], and above the Lepore and Riddell value of $\sigma_0(LR) \simeq 61$ MeV/c.

Bertsch [24] has shown how momentum anticorrelations suppress fragment momentum fluctuations and, in the case of ^{40}Ar fragmentation [25], will reduce the p_z width, as described by $\sigma(p_z)$, by $\simeq 15\%$ below the Fermi gas model value, resulting in better agreement with the data. Other modifications to the model have been considered. The end result seems to be that when nuclear effects, such as momentum anticorrelation [24], smaller peripheral nucleon momenta [26], or Pauli blocking [27] are included, they all seem to reduce the $\sigma(p_i)$ to values below the Goldhaber and in some cases [15] even below the LR predictions.

Figure 1 shows experimental values of σ_0 as determined from our measurements of transverse momentum distributions for ^{40}Ar, ^{93}Nb, and ^{139}La (all incident on C nuclei). The ^{139}La values have been published in Ref. [17]. Also shown are the σ_0 values extracted from the data for ^{12}C and ^{16}O [12], and those for 1.1A GeV ^{197}Au+Mg as measured by Müller *et al.* [16]. The Siegen group [28], for (200–986)A MeV ^{197}Au incident on plastic track and Ag targets, derive $\sigma(p_y)$ values from their transverse momentum determinations and fit these with the Goldhaber A_F dependence. Their fit value of σ_0 for multiplicity-one, heavy fragments of $75 \lesssim A_F \lesssim 175$ is $\bar{\sigma}_0$ (plastic) $= 176 \pm 3$ MeV/c. For Ag targets they obtain $\bar{\sigma}_0(\text{Ag}) = 205 \pm 5$. Their σ_0 values for plastic are shown in Fig. 1.

The dot-dashed lines in Fig. 1 trace the predicted σ_0 values from Goldhaber [21] and from Lepore and Riddell [22]. For $\sigma_0^2(G) = p_f^2/5$ we use the p_f values of Moniz *et al.* [23]. The experimental values, $\sigma_0(\text{expt})$, derived from ^{12}C and ^{16}O fragmentation [12] tend to lie between the predictions of Lepore and Riddell (shell model) [22] and Goldhaber (Fermi gas) [21]. The $\sigma_0(\text{expt})$ values derived from our 1.65A GeV ^{40}Ar+C fragmentation p_y measurements are, on average, larger than those from ^{12}C and ^{16}O and tend to cluster around and below $\sigma_0(G)$ and have a tendency to increase with A_F.

The σ_0 values derived from the p_y measurements for the fragments from 1.65A GeV ^{93}Nb+C collisions tend to lie near or above the $\sigma_0(G)$ prediction and those from 1.2A GeV ^{139}La+C above. The σ_0 values for ^{197}Au at 1.1A GeV [16] and fragment multiplicity=1 data at (200–986)A MeV [28] lie well above the predicted values.

Overall, one sees (Fig. 1) that in both magnitude and rate of increase with A_F the $\sigma_0(\text{expt})$ values tend to be above the model predictions for medium and heavy fragments. This is probably due in large part to the transfer of compressional energy to the spectator(s), as well as to Coulomb forces. [Earlier we argued [11] that part of the additional momentum (and excitation energy) could be due to participant nucleons rescattered and/or absorbed by the spectator matter.] Khan *et al.* [29] describe our La+C, p_y distributions using a collision description based on the optical potential between the colliding nuclei.

For data with adequate statistics we fit the momentum distributions by assuming an additional transverse p_B (for Bounce) folded with a Goldhaber or LR (Gaussian) distribution [17]. Otherwise we use $\sigma_y(\text{expt})$ and assume $\sigma_B^2 = \sigma_y^2(\text{expt}) - \sigma_y^2(\text{LR})$ and take $p_B = \sqrt{2}\sigma_B$ as the transverse bounce used for Fig. 2. For La σ_y (Goldhaber) is also used. On the basis of theoretical arguments [24,26,27] $\sigma(\text{LR})$ is judged to be more realistic. The measured momentum distributions and extracted p_B are also affected by particle (assumed to be mainly neutron) emission. We argue [17] that the fluctuation from isotropic neutron emission is of the order of $87\sqrt{n/3}$ MeV/c for p_x, etc., where n is the number of neutrons evaporated. From our Au data [16] and from those of Binns *et al.* [19], we assume n increases with ΔZ [19] to reach the values $\langle n(\text{La}) \rangle \simeq 12$ and $\langle n(\text{Au}) \rangle \simeq 16$ for $\Delta Z \geqslant 3$. This is a small correction, appreciable only for fragments with A_F near A_P, and we apply it for La and Au when calculating σ_0 values.

Stokstad [30] has reviewed fragmentation for momentum distributions from low up to GeV per nucleon energies. Morrissey [31] has commented that the large p_y, which are considerably larger than those given by the parametrization he suggests [32], are due to assuming too large a projectile fragment mass. However, Dreute *et al.* [33] have shown that this is not the case; even if one uses the most probable *detected* fragment mass as parametrized by Sümmerer *et al.* [34], large p_y values result. In addition, as we argue above, the theories apply to the abrasion rather than the detected fragment, so the former and not the latter should be used.

If we extract p_B from the transverse momentum distributions as described above, we find (Fig. 2) that the p_B/A_F values increase as one goes to smaller values of A_F and appear to extrapolate to the region of the large ("bounce-off") values ($\simeq$40–100 MeV/c per nucleon) observed for light particles [5,9] in central collisions. The latter are for symmetric (in A) systems which have larger Coulomb, etc., forces; so only qualitative comparisons can be drawn. A second caveat is that for Au fragmentation the smallest A_F data approach the region where multifragmentation dominates [35]. Figure 2 indicates (in the spirit of the AA model) that p_B/A increases with decreasing impact parameter This increase is probably produced by the release of additional compressional and Coulomb energy in the more central collisions. Calculating the Coulomb contribution to p_B is not simple. The contributions of participant protons as well as spectators have to be included. We estimate p_B(Coul) to be around 1/3 of p_B(tot).

Relating these p_B/A (and other) momentum measurements to nuclear compressibility and interaction momentum dependence, and extracting EOS information, requires detailed comparisons with model predictions. As noted earlier, great progress is being made in these difficult and sophisticated calculations. Clearly, more complete (global) measurements of each collision will be invaluable. Experiments at GSI and at LBL (by the EOS Collaboration) should provide these.

In summary, we have determined the transverse momenta of heavy projectile fragments (those with $A_F \gtrsim A_P/2$) and have extracted "bounce-off" momenta, $p_B = p_B(A_P, A_F)$ which are transverse momenta over and above those due to internal nucleon momenta in the projectile nuclei. The p_B values per nucleon, p_B/A_F, increase as A_F decreases and tend to be larger for the fragments of heavier projectiles (Fig. 2). Extrapolating these p_B/A values to small A_F values appears to put them in line with mean values of reaction-plane-projected p_T per nucleon extracted from light particle "bounce-off" measurements.

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