Azimuthal Asymmetries of Particles Emitted in Relativistic Heavy-Ion Collisions

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Experimental particle yield ratios from 14.6A-GeV/c ^{28}Si interactions with nuclei at intermediate impact parameters are correlated with the orientation of the transverse momentum of projectile fragments. The $\pi^{\pm}/p$ ratio increases and the $(d+t)/p$ ratio decreases when fragments are deflected toward the observing spectrometer. Asymmetries are confined to the target rapidity region. Assuming a spectator participant model, these results suggest the presence of significant rescattering of particles with dependences on the collision geometry.

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The importance of geometry in determining the outcome of a nucleus-nucleus collision at high energies is evidenced by the use of the terms *central* and *peripheral* in discussing such reactions. A zero-degree downstream calorimeter (ZCAL) is included as one component of experiment 802 [1] at the Brookhaven Alternating Gradient Synchrotron (AGS) to provide impact parameter selection on the basis of the energy remaining in projectile fragments. ZCAL is a conventional Fe-scintillator calorimeter which has good resolution, 3.6% for 13.6-GeV kinetic energy per nucleon ^{28}Si ions, and a linear response to the number of incident projectile nucleons [2]. The 60×60 cm^2 front face of ZCAL is located 11.7 m downstream from the target position. Correlations between transverse energy [3] or between particle yields [4] and the calorimeter energy $E_{\rm ZCAL}$ have been reported. This Letter explores the use of the position information [5] which is available from ZCAL to study a correlation not previously examined at this energy, namely, that between particle yields and the angular orientation of the transverse momentum of projectile fragments. The idea underlying this work can be understood in terms of a simple geometrical picture, the spectator-participant model, in which three regions are identified: a region of projectile-spectator nucleons, one of target spectators, and a participant zone encompassing the primary projectile-nucleon target-nucleon collisions. Projectile-spectator nucleons may reach ZCAL in the form of one or more projectile fragments whose deflections or "bounce-off" might tag the side of the target on which a noncentral interaction had occurred. In such interactions, the distribution of matter in both participant and spectator regions will be azimuthally asymmetric. Rescattering [6] of nucleons and produced particles from the primary collisions as they move out and sample these asymmetries might lead to an observable asymmetry in particle yields. Calculations [7, 8] suggest that rescattering changes particle yields from those characteristic of primary nucleon-nucleon collisions.

The present analysis emphasizes 14.6A-GeV/c ^{28}Si + Au interactions at E-802 spectrometer settings from 14° to 44°. Looking along the beam, the coordinate system is defined to have $+z$ directed forward, $+x$ to the left, and $+y$ upward. The spectrometer is on the $+x$ side of the beam, centered on the x-z plane. Its aperture extends $\sim 15°$ backward from a nominal setting. Data were acquired with an on-line trigger which required the presence of at least one particle at the front and rear of the spectrometer. Off-line analysis identified $\pi^{\pm}$, $K^{\pm}$, p, d, and t over a wide range of momenta in the spectrometer.

The normalized differences of ZCAL energy signals, (left−right)/total and (up−down)/total, are observed to be approximately proportional to fragment deflections, and a procedure for obtaining impact coordinates, (x, y), of a fragment from these signals has been described [5, 9]. Fragment transverse momentum components, $P_x^{\text{frag}} = 0.0125(x - x_0)A^{\text{frag}}$ and $P_y^{\text{frag}} = 0.0125(y - y_0)A^{\text{frag}}$, are used to define a reaction plane rather than the spatial deflections. Fragments are assumed to have the same longitudinal momentum per nucleon as the beam. The constant in the above equations is then equal to that value divided by the target to ZCAL distance (14.6/1170) and A^{frag} is approximated as the calorimeter energy divided by the beam kinetic energy per nucleon ($E_{\text{ZCAL}}/13.6$). Units for kinetic energy, momentum, and deflection are GeV, GeV/c, and cm. To avoid bias, the apparent coordinate origin (x_0, y_0) is determined from events without the requirement that there be a track in the spectrometer. Some properties of P_x^{frag} distributions are shown in Fig. 1. The distribution for a given mass is approximately Gaussian with the indicated mean and standard deviation. That values of $\langle P_x^{\text{frag}} \rangle$ scatter about zero serves to validate the determination of the coordinate origin. The analysis of events yielding tracks in the spectrometer included only those with $3 \leq A^{\text{frag}} \leq 25$. The lower cutoff excludes events where there are large uncertainties in position determination due to noise on the ZCAL signals. These central events are also associated with fragments having relatively low transverse momenta. The upper cutoff removes peripheral interactions where beam divergence and target-out corrections become important. Left-right asymmetries reported below were insensitive to these cuts: Comparable values were observed for each half of this analysis range.

Data for Au at the 44° spectrometer setting were examined in the most detail. The 24×10^3 events accepted yielded 25×10^3 fully verified tracks: 14×10^3 p, 3.8×10^3 π^+, 4×10^3 π^-, 2×10^3 d, 240 t, 260 K^+, and 35 K^-. Initial emphasis was placed on protons, which originate, at these angles, largely from the target nucleus, and on the produced pions. To improve statistics, π^+ and π^- were combined: Their sum is denoted $\pi^{\pm}$. Mean momenta and rapidities of the pions and of the protons are uncorrelated with either P_x^{frag} or P_y^{frag}. There is, however, a significant correlation between the $\pi^{\pm}/p$ number ratio and P_x^{frag}. As illustrated in Fig. 2(a) this ratio increases linearly with P_x^{frag}. It is convenient to quantify the asymmetry of a given particle ratio as the relative change of that ratio over the P_x^{frag} range conveniently accessible experimentally, −1 to +1 GeV/c. The linear least-squares fit shown in Fig. 2(a) indicates a change of $(+34 \pm 8)\%$ in the $\pi^{\pm}/p$ ratio over this range. From a simple geometrical picture of projectile-fragment bounce-off, it is plausible that deflections of projectile fragments

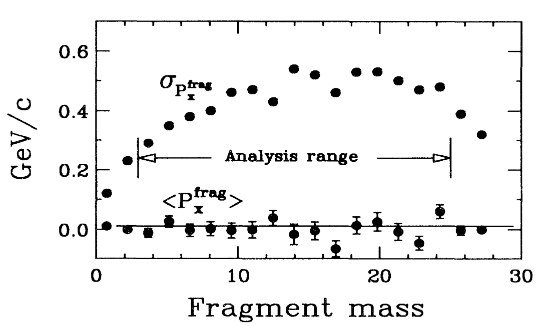

FIG. 1. Properties of transverse momentum spectra of projectile fragments as a function of total fragment mass ($A^{\text{frag}} = E_{\text{ZCAL}}/13.6$). The mean x component $\langle P_x^{\text{frag}} \rangle$ and standard deviation $\sigma_{P_x^{\text{frag}}}$ are shown for minimum-bias events from interactions of 14.6A-GeV/c ^{28}Si with Au. Arrows indicate the range of intermediate impact events included in this study of particle-fragment correlations.

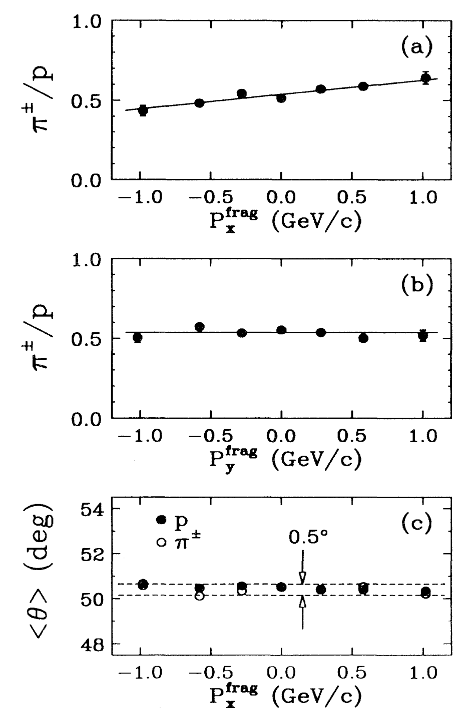

FIG. 2. (a) Correlation between the $\pi^{\pm}/p$ ratio and the x component of projectile-fragment momenta P_x^{frag}. (b) The same ratio as a function of P_y^{frag}. (c) Mean polar angle of pions and protons as a function of P_x^{frag}. All data are for interactions of 14.6A-GeV/c ^{28}Si ions with Au observed at the 44° spectrometer setting.

away from the spectrometer, $P_x^{\rm frag} < 0$, will be associated, on the average, with interactions which take place on the far side of the target nucleus. The observed asymmetry suggests a depletion of pions relative to protons as the products of the primary nucleon-nucleon collisions propagate through the target nucleus on their way to the spectrometer. Consistent with such a picture, no up-down asymmetry is seen in Fig. 2(b). The dependence of the $\pi^\pm/p$ ratio on azimuthal angle ϕ is consistent with an $a + b\cos\phi$ variation.

Both beam divergence and beam motion can be ruled out as significant contributors to the observed asymmetry. A measured fragment angular deflection might be a trivial consequence of an interaction of a beam particle moving at that angle. Changes in the $\pi^\pm/p$ ratio would then be ascribed to a rotation of the coordinate system about the y axis combined with differing angular distributions for the pions and protons. The observed result would require a rotation of $\sim 10°$ since there is a $(30\pm3)\%$ increase in the $\pi^\pm/p$ ratio between 44° and 34°. No experimental evidence for a such a rotation correlated with $P_x^{\rm frag}$ is seen in Fig. 2(c). The beam position moves by $\sim$ 0.5 cm in the x direction at ZCAL as the AGS momentum changes during extraction; however, the experimental $\pi^\pm/p$ ratio was observed to be independent of this motion.

The correlation between the $\pi^\pm/p$ ratio and $P_x^{\rm frag}$ might only be a consequence of transverse motion of the source of the particles. Spectrometer detection efficiency is a complicated function of particle type, momentum, and angle [10] which suppresses the detection of low momentum particles. Doppler shifts would be larger for the more slowly moving protons and the spectrometer cutoff would tend to increase the $\pi^\pm/p$ ratio for sources moving away from the spectrometer and vice versa. The momentum distribution of a projectile fragment is thought to arise from a random selection of participant nucleons from the Fermi momentum sphere of the projectile [11]. Conservation dictates that some system, assumed to be the emitting source, will have a transverse momentum equal and opposite to that observed for the projectile remnant. Since the mean mass of fragments included in the present analysis is ~ 10, a plausible lower estimate for the mass of the momentum conserving system would be the eighteen projectile participants plus an equal number of target participants. The range $|P_x^{\rm frag}| \leq 1$ GeV/c then sets an upper limit of $|\beta_x^{\rm source}| \leq 0.028$ for such a mass 36 system. From a comparison of the Doppler shifted and unshifted spectra, we estimate that the number of pions detected would decrease by 4.9% and that of protons by 6.4% as $\beta_x^{\rm source}$ varied from $+0.028$ to -0.028. The 1.5% net change in the $\pi^\pm/p$ ratio indicates that the influence of source motion in this simple picture is small. Most of the observed asymmetry then reflects rescattering or some more complicated dynamical effect.

Left-right asymmetries of several other particle production ratios are examined in Fig. 3. The absence of a correlation between the π^+/π^- ratio and $P_x^{\rm frag}$, Fig. 3(a), justifies our combining π^+ and π^- yields. The negative asymmetry parameter, $(-46\pm10)\%$, of the $(d+t)/p$ correlation, Fig. 3(b), may be contrasted with the positive asymmetry of $\pi^\pm/p$. Surprisingly, nucleon aggregates typified by $d+t$ appear to be enhanced relative to protons when the spectrometer views the side of the target nucleus away from the participant region, possible evidence that fast nucleons find partners on their passage through spectator matter. Poor statistics preclude any strong conclusions about the $K^+/\pi^\pm$ correlation, Fig. 3(c). However, the negative asymmetry, $(-48\pm35)\%$, is in the direction of some enhancement of K^+ when the participant zone is viewed through the target nucleus, possible evidence for an influence of rescattering on particles produced in the primary nucleon-nucleon interactions. The dependence of the left-right asymmetries of the $\pi^\pm/p$ and $(d+t)/p$ ratios on pseudorapidity η is shown in Fig. 4. Large asymmetries, either positive or negative, are characteristic of the target rapidity region. They disappear as the spectrometer moves toward the rapidity of the nucleon-nucleon center of mass, 1.72 at this beam energy.

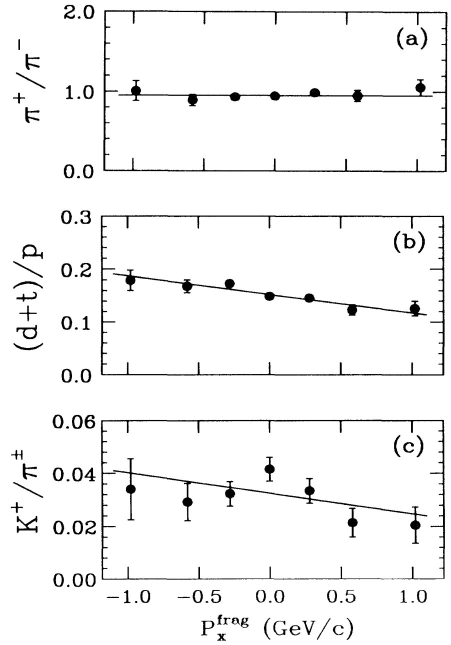

FIG. 3. Correlations between particle ratios, as indicated, and $P_x^{\rm frag}$ for the reactions of 14.6A-GeV/c ^{28}Si with Au observed at the 44° spectrometer setting. Solid lines are linear least-squares fits.

Some data were also examined for ^{28}Si interactions with Cu and Al at the 44° spectrometer setting. Left-right asymmetries of the $\pi^\pm/p$ ratio for Cu, $(32\pm5)\%$, and for Al, $(30\pm5)\%$, are comparable to the $(34\pm8)\%$ for Au. There is some evidence for a target dependence of the $(d+t)/p$ ratio: Observed asymmetries are

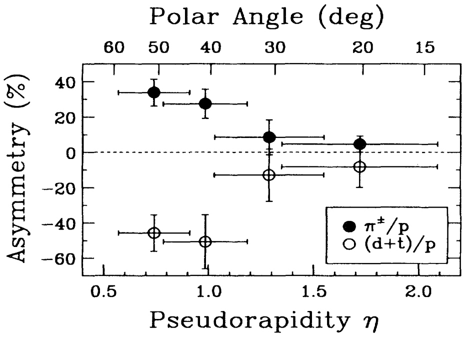

FIG. 4. Dependence of the left-right asymmetries of the $\pi^{\pm}/p$ and $(d+t)/p$ ratios on pseudorapidity for interactions of 14.6A-GeV/c ^{28}Si ions with Au at intermediate impact parameters. Horizontal error bars show the range of η included at each spectrometer setting.

$(-46\pm10)\%$, $(-37\pm11)\%$, and $(-14\pm14)\%$ for Au, Cu, and Al, respectively.

In summary, correlations between particle production ratios and transverse momenta of projectile fragments are observed for intermediate impact parameter collisions. The azimuthal asymmetries are confined to the target rapidity region. There is a significant depletion of pions and an enhancement of nucleon aggregates relative to protons for interactions which can be interpreted as occurring on the side of the target nucleus away from the observer. The data also hint that K^+ mesons are favored relative to pions under the same conditions. These results appear to provide experimental evidence that rescattering can modify the distribution of products of the primary nucleon-nucleon collisions. Quantitative calculations which trace the full development of nucleus-nucleus collisions have tended to focus on central events [7, 8, 12]. The asymmetries observed in the present work offer the possibility of an additional test of these theoretical models at intermediate impact parameters.

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