Two-Particle Quantum-Number Correlations in 400-GeV/c Proton-Nucleus Collisions

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We have measured two-particle quantum-number correlations in 400-GeV/c proton-nucleus collisions. A double-arm spectrometer was used to detect two charged particles produced near rapidity $y_{\text{c.m.}} = -0.4$ in the proton-nucleon center-of-mass system. In proton-beryllium collisions we observe positive $p\bar{p}$ and K^+K^- correlations which are independent of the transverse momenta of the particles over the range $1 \leqslant p_\perp \leqslant 1.8$ GeV/c. These correlations are weaker in proton-lead interactions.

The nature of hadronic particle production at high energies has been studied extensively through measurements of inclusive single-particle yields and multiparticle correlation strengths. Measurements at large transverse momenta ($p_\perp \gg 300$ MeV/c) have been of particular interest in regard to testing ideas of constituent scattering.[1] The measurements reported here focus on an area which has not been explored previously in great detail, namely the dependence of two-particle correlations on the quantum numbers of the detected particles. The particles were detected with moderately high transverse momenta, $1.0 \leqslant p_\perp \leqslant 1.8$ GeV/c, a range for which the notion of hadron constituents might already be applicable.

The experiment was performed at the Fermi National Accelerator Laboratory and used a double-arm spectrometer to detect and identify two charged particles produced in 400-GeV/c proton-nucleus collisions. Components of the apparatus and other results have been described elsewhere.[2] Briefly, the spectrometer was triggered by a coincidence of two charged particles which were produced near rapidity -0.4 in the proton-nucleon center-of-mass system, with transverse momenta $p_\perp \geqslant 1$ GeV/c, and with azimuthal separation near 180°. The target used for the data reported in this Letter consisted of thin, spatially separated segments of beryllium and lead.

Each arm of the spectrometer was equipped with three threshold, gas-filled Cherenkov counters (C_1, C_2, and C_3) which provided charged-hadron (p, $\bar{p}$, $K^\pm$, and $\pi^\pm$) identification. The radiating media in the counters were nitrogen at 1 atm for C_1, propane at 2.16 atm for C_2, and carbon dioxide at 1.57 atm for C_3. Pion threshold momenta in the counters were determined from reconstructed particle momentum spectra to be 5.88, 2.01, and 3.68 GeV/c for C_1, C_2, and C_3, respectively. The measured efficiencies of the counters were typically greater than 99%. Complete separation of p, K, and π was possible over a transverse-momentum range $1 \leqslant p_\perp \leqslant 1.8$ GeV/c.

The data were corrected for meson decay and misidentification of particle type due to Cherenkov inefficiencies and spurious signals. The kaon-decay correction varied from 12 to 25% depending on momentum, whereas the pion-decay correction was only 0.9 to 2.8%. The correction for counter inefficiencies was small: In the worst case, less than 2.5% of pions were misidentified as kaons in the raw data. Spurious Cherenkov signals from the traversal of the counters by other particles (including electromagnetic shower fragments) presented a more serious identification problem.[3] About 30% of kaons and protons gave logically invalid Cherenkov responses because of such additional particles. Events with invalid responses were rejected and their loss was properly taken into account in the calculation of correlation strengths. We stress that particles which gave valid responses were identified correctly with a high degree of confidence. Our systematic error in the correlation strengths was estimated from a separate set of data in which events from a pure beryllium target were observed with a rearranged experimental apparatus.[4] A comparison of the correlation strengths observed in Be from the two sets of data indicates that systematic errors were equal to or smaller than the statistical errors.

It is convenient to study the quantum-number correlations independently of the kinematic correlations by confining the investigation of the quantum-number correlations to the two-particle inclusive measurements.[5] For these purposes we designate one of the arms of the apparatus as the trigger side and the other arm as the opposite side. Both the trigger-side and opposite-side particles are constrained to have $1 \leq p_\perp \leq 1.8$ GeV/c. The hadrons in the opposite arm are separated by electric charge and denoted by h^+ and h^-. We then calculate p, K^+, and π^+ fractions opposite a particular hadron t in the trigger arm, and denote these fractions by $(p/h^+)_t$, $(K^+/h^+)_t$, and $(\pi^+/h^+)_t$. Similarly, the negative-particle fractions are denoted by $(\bar{p}/h^-)_t$, $(K^-/h^-)_t$, and $(\pi^-/h^-)_t$. The strength of the quantum-number correlation between an opposite-side particle and each trigger-side particle is defined as the ratio of the fraction opposite a particular trigger hadron t to the fraction averaged over all trigger hadrons h. For example, the $p\bar{p}$ correlation is given as $(p/h^+)_{\bar{p}}/(p/h^+)_h$.

The dependence of the opposite-side particle fractions on the identity of the trigger particle is shown in Fig. 1 for p-Be and p-Pb collisions. For p-Be collisions the values of the opposite-side particle fractions show a strong dependence on the identity of the trigger-side particle. The proton fraction opposite $\bar{p}$ is enhanced by a factor of 1.92 ± 0.09 compared to the proton fraction opposite all trigger hadrons. A similar enhancement by a factor of 1.41 ± 0.07 is observed for K^+ opposite K^-, compared to K^+ opposite all trigger hadrons. The π^+ fractions exhibit depletions opposite $\bar{p}$ and K^- which are a reflection of the strong $p\bar{p}$ and K^+K^- correlations, since the three fractions $(p/h^+)_t$, $(K^+/h^+)_t$, and $(\pi^+/h^+)_t$ must add up to unity for each trigger hadron t.

The $p\bar{p}$ and K^+K^- correlations observed in the Be data are significantly smaller in the Pb data as demonstrated in Table I. In the Pb data, the $p\bar{p}$ enhancement is only 1.26 ± 0.09, and the K^+K^- enhancement is only 1.10 ± 0.07.

We have also investigated the $p_\perp$ dependence of the quantum-number correlations observed in the Be data. We divide the data sample into several

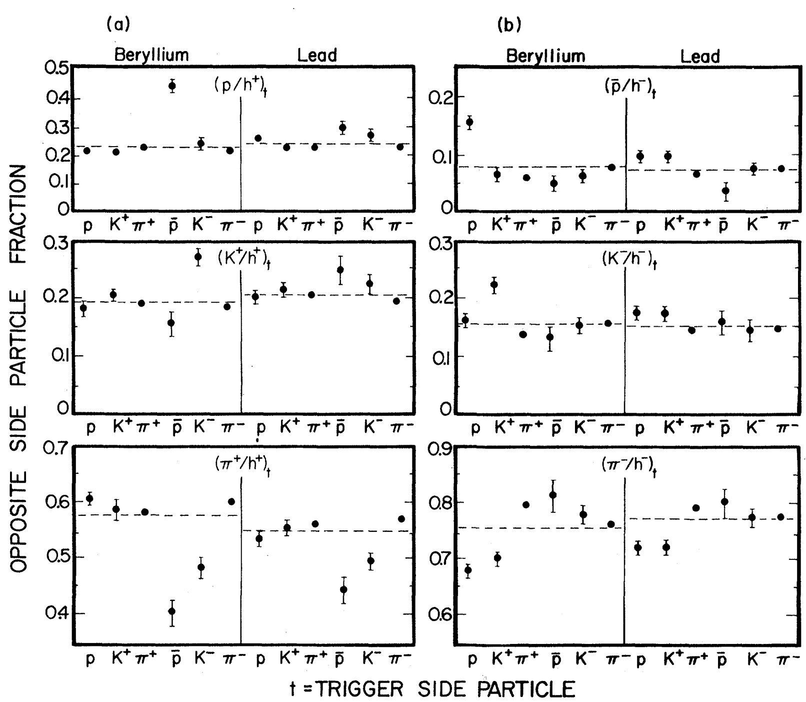

FIG. 1. Dependence of the opposite-side particle fractions on the trigger particle species for p-Be and p-Pb interactions: (a) Positive-particle fractions, (b) negative-particle fractions. All particles are restricted to the range $1 \leq p_\perp \leq 1.8$ GeV/c. The dashed line indicates the opposite-side fraction for each case averaged overall trigger hadrons. The error bars are shown only when they are larger than the points, and are statistical only.

TABLE I. Comparison of ratios of particle fractions for particle-antiparticle pairs in p-Be and p-Pb interactions. These ratios would be unity if there were no quantum-number correlation in the production of particle-antiparticle pairs. The error bars are statistical only.

Ratio	Be	Pb
$(p/h^+)_{\bar{p}}/(p/h^+)_h$	1.92 ± 0.09	1.26 ± 0.09
$(K^+/h^+)_{K^-}/(K^+/h^+)_h$	1.41 ± 0.07	1.10 ± 0.07
$(\pi^+/h^+)_{\pi^-}/(\pi^+/h^+)_h$	1.04 ± 0.01	1.03 ± 0.01

ranges according to the sum $p_s = |p_{\perp 1}| + |p_{\perp 2}|$, and difference $p_d = \| p_{\perp 1}| - |p_{\perp 2}\|$, of the magnitudes of the transverse momenta of each particle. (For the geometry of our apparatus, p_s is approximately equal to the effective mass of the pair, and p_d is approximately equal to the total $p_\perp$ of the pair.) For particle a ($=p$, K^+, π^+) we calculate the ratio of the particle fractions $(a/h^+)_{\bar{a}}/(a/h^+)_h$ at each bin. We observe no statistically significant dependence of the ratio with p_d, and hence we integrate over p_d and show the ratio as a function of p_s in Fig. 2. We find no evidence for a $p_\perp$ dependence of the correlations as we vary the $p_\perp$ of each particle over the range $1 \leq p_\perp \leq 1.8$ GeV/c.

Results on quantum-number correlations in kinematic regions different from the one covered in our experiment have been reported elsewhere. The results of Albrow *et al.*[6] at $\sqrt{s} = 53$ GeV, $\Delta\varphi = 90°$, $\Delta y > 1.4$, and $p_\perp \leq 1$ GeV/c are in qualitative agreement with our data in that significant positive-correlation effects are observed only with K^+K^- and $\bar{p}p$ pairs. The data of Fisk *et al.*[7] at 400 GeV/c and $2 < p_\perp < 6$ GeV/c led those authors to conclude that correlations at large $p_\perp$ were only weakly dependent on quantum numbers. We consider the behavior of quantum-number correlations with $p_\perp$ an interesting and not completely answered question.

In summary, we observe proton-antiproton and K^+K^- correlations for hadron pairs produced in 400-GeV/c p-Be collisions near $y_{\text{c.m.}} = -0.4$ with $\Delta\varphi \simeq 180°$ and $1 \leq p_\perp \leq 1.8$ GeV/c. In this kinematic region, these correlations are significantly smaller for production in large nuclei such as lead.[8] We also observe that these correlations have no strong dependence on the transverse momenta of the particles. These data should provide a fairly strict test of models which address particle production in the moderately high-$p_\perp$ range covered by this experiment.

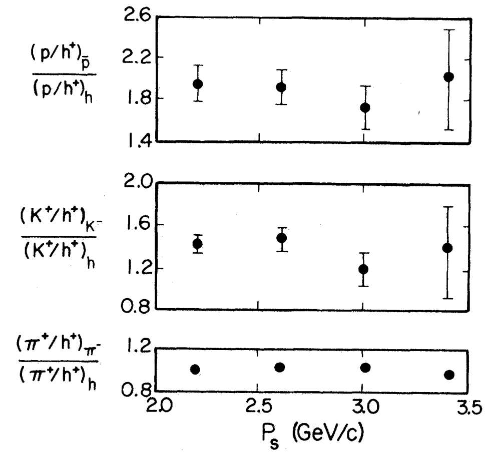

FIG. 2. p_s dependence of particle-antiparticle quantum-number correlations in p-Be collisions. p_s is the sum of the magnitudes of the transverse momenta of the two particles; the data have been integrated over $p_d = \| p_{\perp 1}| - |p_{\perp 2}\|$. The error bars are shown only when they are larger than the points, and are statistical only.

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[3]The relative frequency of spurious Cherenkov sig-

nals was estimated from single-particle inclusive data in which one arm was used as the trigger, and the other (untriggered) arm recorded the relative frequency of Cherenkov signals.

[4]The original configuration of the apparatus is described by Bintinger *et al.* (Ref. 2), and the rearranged configuration (for which one of the Cherenkov counters was relocated behind the magnet) is described in Ditzler *et al.* (Ref. 2).

[5]Our kinematic correlation results are reported in D. A. Finley *et al.*, Phys. Rev. Lett. 42, 1031 (1979) (this issue).

[6]M. G. Albrow *et al.*, Phys. Lett. 65B, 295 (1976).

[7]R. J. Fisk *et al.*, Phys. Rev. Lett. 40, 984 (1978).

[8]The observation that heavier nuclei reduce quantum-number correlations as well as kinematic correlations (see Finley *et al.*, Ref. 2) is consistent with an inelastic multiple-scattering process.

Nucleon-Number Dependence of Inclusive Dihadron Production in Proton-Nucleus Collisions at 400 GeV/*c*

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We have measured the nucleon-number (A) dependence of hadron-pair production in 400-GeV/c proton-nucleus collisions, using Pb and Be targets. Charged-hadron pairs were observed near rapidity $y_{\rm c.m.} = -0.4$ with $\Delta\varphi \cong 180°$. The A-dependence exponent rises from 1.1 to 1.2 in the range $2.0 \leq |p_{\perp 1}| + |p_{\perp 2}| \leq 4.5$ GeV/c. The dihadron $p_\perp$ correlation function is significantly smaller for Pb than for Be.

Several unexpected results have recently raised interest in hadron production on heavy nuclei. The multiplicity of hadron-nucleus collisions grows with nuclear size much less rapidly than a simple cascade model would predict.[1] On the other hand, the inclusive production of high-$p_\perp$ particles rises as A^α with α significantly greater than 1.[2-4] Theoretical models which attempt to describe this behavior include multiple scattering, nucleon clusters, and decay of high-mass states.[5] We report here the results of an experiment on the A dependence of dihadron production.[6] Only charged particles were detected, and for the purposes of this paper no distinction is made between π, K, and p. The quantum-number correlations observed in lead and beryllium have been reported separately.[7]

This experiment was performed at the Fermi National Accelerator Laboratory in a 400-GeV/c proton beam, with a typical intensity of 4×10^7 sec^{-1}. Other results and a detailed description of the apparatus have been published previously.[8] The apparatus consisted of two identical magnetic spectrometers placed at 100 mrad on opposite sides of the beam. In the proton-nucleon center-of-mass system, each spectrometer was centered at $\theta = 110°$ and subtended about $\pm 10°$ in polar angle, and $\pm 17°$ in azimuth. The trigger required each hadron to have $p_\perp \geq 1$ GeV/c.

Measurements of the A dependence were made with a target of nine 1.3-mm lead segments followed by three 6.1-mm beryllium segments, all 3.8 mm wide. Data were taken on both nuclei simultaneously with targets of equal width in order to eliminate uncertainties arising from beam normalization or changes in experimental conditions. The good spatial resolution of the spectrometer drift chambers allowed unambiguous identification of the target element, as shown in Fig. 1. The acceptance of the spectrometer was uniform over the length of the target. The data were corrected for beam attenuation in the tar-

