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Large Analyzing Power in Inclusive $\pi^{\pm}$ Production at High x_F With a 22-GeV/c Polarized Proton Beam

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Abstract

The analyzing power, A_N, in inclusive charged-pion production has been measured using a $\sim$ 22-GeV/c transversely-polarized proton beam on a carbon target. A large analyzing power was found for $x_F > 0.5$ and the p_T range covered, with A_N for π^+ and π^- of similar magnitudes and opposite sign. This mirror behavior and the magnitudes are similar to $\pi^\pm$ production from 200-GeV/c polarized protons on a hydrogen target. The analyzing power for inclusive proton production has also been measured and is consistent with zero.

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At high energy, single transverse spin asymmetries have been expected to be small. However, large effects were observed both for the asymmetry A_N of inclusive production of pions from 200-GeV/c polarized protons on a hydrogen target (Fermilab E704) [1], and also for the transverse polarization P_N of many species of hyperons from unpolarized beams and targets [2]. In hyperon production, the magnitude of the polarization seems to be insensitive to energy over fixed target energies from 12 GeV to 2000 GeV, and it is only slightly smaller for nuclear targets compared to hydrogen, which is explainable as a rescattering effect [2]. There is some reason to believe that the asymmetries in meson and the polarization in hyperon production are related [3,4]. Besides being unexpectedly large with magnitudes of A_N and P_N from 0.1 to 0.4, these results show an intriguing sign behavior. The π^+ and π^- asymmetries are equal in magnitude, grow with x_F, and have opposite signs. Mirrored sign behavior is also seen for hyperon polarization.

Recent deep inelastic scattering experiments indicated that only about a third of the spin of the proton comes from the spin of the quarks [5]. The other two thirds must arise from the spin of gluons and orbital motion of quarks and gluons. One way to study the contribution of orbital angular momentum of quarks to the proton spin may be via inclusive hadron production in polarized-proton interactions [6,7]. Such reactions have also been suggested for high energy polarimeters, such as for RHIC.

In this paper, new results for $p^\uparrow + C \to \pi^\pm + X$ and $p^\uparrow + C \to p + X$ at 22 GeV are presented. The data were obtained at the Brookhaven National Laboratory AGS for $0.55 < x_F < 0.75$ and $0.6 < p_T < 1.2$ GeV/c. The results indicate very similar behavior to the 200-GeV data, with mirror π^+ and π^- asymmetries. A number of models have been advanced, referring to the orbital angular momentum of quarks, or connecting the pion asymmetries and hyperon polarization dynamics, or generating the pion asymmetry from twist-3 parton correlation functions; these will be discussed. In this letter, only a basic description and part of the data will be presented. Additional details of the apparatus and further results will be given in a future comprehensive article.

The polarization of the beam, obtained from the asymmetry of pp elastic scattering, and the asymmetry of an inclusive process were measured simultaneously. Two sets of counters, electronics, and data acquisition systems were used. These side-by-side experiments were triggered separately and the data were accumulated separately. The experimental layout is sketched in Fig. 1.

The target for the elastic experiment was CH_2 and had a dimension along the beam line of 15 mm, a width of 5 mm and height of 30 mm. The beam counter, BC, was used during setup of the experiment. The beam was transversely polarized in the vertical direction, perpendicular to the horizontal scattering plane.

The two recoil arms were identical and consisted of four recoil counters BL1, BL2, BL3, and BL4 on the left (BR1, BR2, BR3, and BR4 on the right). The recoil counters covered scattering angles from 76° to 80°. The scintillators B3 (BL3, BR3) were thick enough to absorb the recoil proton. Since energy is a function of angle for the recoil proton, an aluminum wedge was placed in front of B3 to compensate for that difference, so that the pulse height in B3 would be approximately the same for all elastically-scattered protons. A particle that reached B4 was probably a pion and was therefore vetoed.

The trajectory of the forward elastically-scattered proton was altered by passage through the analysis magnet. This particle was detected in either the scintillator FLA or FRA (FLB or FRB) when the analysis magnet was set to bend positively charged particles to the left (right). The left and right counters each covered angles from 0.80° to 1.12°, and were positioned taking into account the bending of the protons in the magnet. The elastic trigger consisted of a coincidence between BL1, BL2, and BL3, vetoed by BL4 or similarly for the right arm. Cuts were applied to the ADC and TDC values for each counter. Data from carbon and empty target runs were used to estimate and subtract backgrounds.

The asymmetry of this process was used to estimate the polarization of the beam using the analyzing power $A_N(pp) = 0.040 \pm 0.004$ at t = -0.15 (GeV/c)^2. This value was determined from a phenomenological analysis of existing $A_N(pp)$ data at different beam momenta [8–10]. This error gives a lower limit to the uncertainty in the beam polarization. The polarization was obtained from the equation:

$$P = (\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}})/[A_N(pp) \cdot (\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_L^{\downarrow} \cdot N_R^{\uparrow}})], \quad (1)$$

where $N_L^{\uparrow}$ ($N_L^{\downarrow}$) is the number of elastic scatters with beam polarization up (down) and the forward proton goes left normalized to the incident intensity. Similarly, N_R is the normalized number of elastic scatters when the forward proton goes right normalized to the incident intensity. The beam polarization was estimated to be 0.271 ± 0.059 (stat.) ± 0.028 (syst.). These uncertainties dominate the systematic error for the inclusive results.

An entirely separate set of counters, H1-4, S1-3, and a threshold Cerenkov counter, were used to measure the asymmetry of inclusive pion production (see Fig. 1). The transversely-polarized proton beam impinged upon a 4.0-cm thick carbon target. The x-positions (the horizontal coordinate) of charged particles emerging from the target were measured before and after the analyzing magnet in the hodoscopes H1 and H2 (16 counters each), H3 (24 counters) and H4 (28 counters). These last two hodoscopes also measured the vertical position of the particle tracks. Each of these hodoscopes consisted of 6-mm wide scintillators with 1/3 overlap. The magnetic field provided a p_t−kick of around 1 GeV/c and could be reversed to select the charge of the inclusive particles. The x-positions from these four hodoscopes provided for measurement of the production and bend angles, and hence also, momentum, x_F, and p_T. The Cerenkov counter filled with CO_2 at a pressure of ~ 2 atmospheres allowed the differentiation between pions and protons. The trigger consisted of a coincidence among scintillators S1, S2, and S3, and hits in 3 out of 4 hodoscope x-planes in H1-4. The halo veto scintillator HV was used to define the beam better and caused an electronic veto of events. For π^+ the Cerenkov counter was required in the trigger to eliminate the large flux of protons, except for some special runs.

Data were collected at 21.70 and 22.75 GeV/c, written to disk, and analyzed off-line. The number of events recorded for the analysis magnet set for negatives in the spectrometer was approximately 2,600,000 for inclusive π^-, with $\sim 20\%$ of these reconstructed events. When the analysis magnet was set for positives, approximately 1,100,000 inclusive protons and 3,500,000 inclusive π^+ triggers were recorded, with $\sim 67\%$ and $\sim 51\%$ respectively being reconstructed events. In addition, cuts on the reconstructed events [11,12] were applied to: a) a quantity similar to χ^2 for a track fitted to the hodoscope hits, b) the x position of the track projected to the target, and c) the Cerenkov counter ADC and TDC values.

The beam intensity of 3 x 10^7 per 1.5-sec spill was monitored with two luminosity telescopes consisting of three scintillators each placed at $\pm 16°$ in the vertical plane defined by the beam-momentum and -polarization vectors. This angle with respect to the beam momentum placed these telescopes at $\sim 90°$ in the center of mass (c.m.) frame. These two facts combined to minimize any possible polarization effects in the beam normalization. An ionization chamber was also used to monitor beam intensity. The polarization was reversed every other spill, which greatly limits the systematic errors.

The analyzing power as a function of x_F was calculated by the formula:

$$A_N = (N^{\downarrow} - N^{\uparrow})/[P(N^{\uparrow} + N^{\downarrow})], \quad (2)$$

where $N^{\uparrow}(N^{\downarrow})$ is the normalized number of inclusive particles produced going to the right when the polarization of the beam is up (down) for the appropriate value of $x_F = 2p_L/\sqrt{s}$ (p_L is the pion longitudinal momentum in the pp c.m. system and $\sqrt{s}$ is the total c.m. energy.) The results of this experiment are plotted in Fig. 2a, and compared to the E704 data in Fig. 2b. It should be noted that the acceptance of this experiment (E925) is significantly narrower, both in x_F and p_T, than that in E704. The p_T regions $0.7 < p_T < 2.0$ GeV/c in E704 and $0.6 < p_T < 1.2$ GeV/c in E925 have been used for the data shown.

The signs of the inclusive pion-production asymmetries are found to be the same at 22 GeV/c as at 200 GeV/c. Data at lower momenta [13,14] are consistent in sign and show a similar rise with x_F for π^+, but are smaller in magnitude for π^-. The value of A_N at 22 GeV/c has the same order of magnitude as at 200 GeV/c. In these two sets of data, there is a difference in both the target (carbon versus hydrogen) and momentum (22 versus 200 GeV/c). It is planned to do similar measurements at 22 GeV/c in a future run with a hydrogen target. Inclusive proton production exhibits no measurable asymmetry. Some lower-energy proton data show a small, but significant, asymmetry (up to 5%) for targets of hydrogen and deuterium [13,15]. There are no predictions for inclusive proton production as far as we know.

A model by Meng and Liang [6] explains the asymmetry in meson production as due to a correlation between the spin of the proton and the orbital motion of the valence quarks. The u-valence quarks are more likely to be polarized in the same direction as the proton spin, whereas the d-valence quark is more likely to be polarized in the opposite direction to the proton spin. When the surfaces of a polarized beam proton and an unpolarized target proton come into contact, a π^+ will form from a valence u quark and a sea $\overline{d}$ quark and go left (with higher probability) when the polarization is up. A π^- will form from a valence d quark and a sea $\overline{u}$ quark and go right (with higher probability) when the polarization is up. Their model matches the data at least qualitatively and may provide an interesting way to picture the physics causing the asymmetry.

In a model by Troshin and Tyurin [7] the main role in the generation of the asymmetries in inclusive π production belongs to the orbital angular momentum of the quark-antiquark cloud in the internal structure of constituent quarks. The x_F dependence of asymmetries in $\pi^\pm$ production at large x_F reflects the corresponding dependence of constituent quark polarization in the polarized proton. The model has described well the large x_F asymmetries at 200 GeV.

The relativistic formulation of the quark recombination model for polarizations of hyperons and mesons [4] has also successfully reproduced both the E704 inclusive pion data and numerous hyperon P_N results.

Another model by Anselmino et al. [16] explains the pion asymmetry using perturbative QCD. They consider the role of the parton intrinsic $k_\perp$ in the initial polarized proton. They conclude that although leading twist effects vanish in single spin asymmetries, higher twist effects may be important. They are able to reproduce the main features of the 200-GeV/c pion data with their model. Other work also supports the idea that twist-3 contributions can lead to non-zero asymmetries [17].

A recent paper by Qiu and Sterman [18] predicts an A_N dependence at large x_F, based on a "valence quark-soft gluon" approximation. The twist-3 parton correlation functions that couple quark and gluon fields become important in the large x_F region; lower order twist-2 effects do not contribute to A_N. One of their curves is shown in Fig. 2b compared to the 200-GeV/c data. Their theory seems to predict only a slow change with energy for a given p_T, and explains the gross features of both the 22- and 200-GeV/c data.

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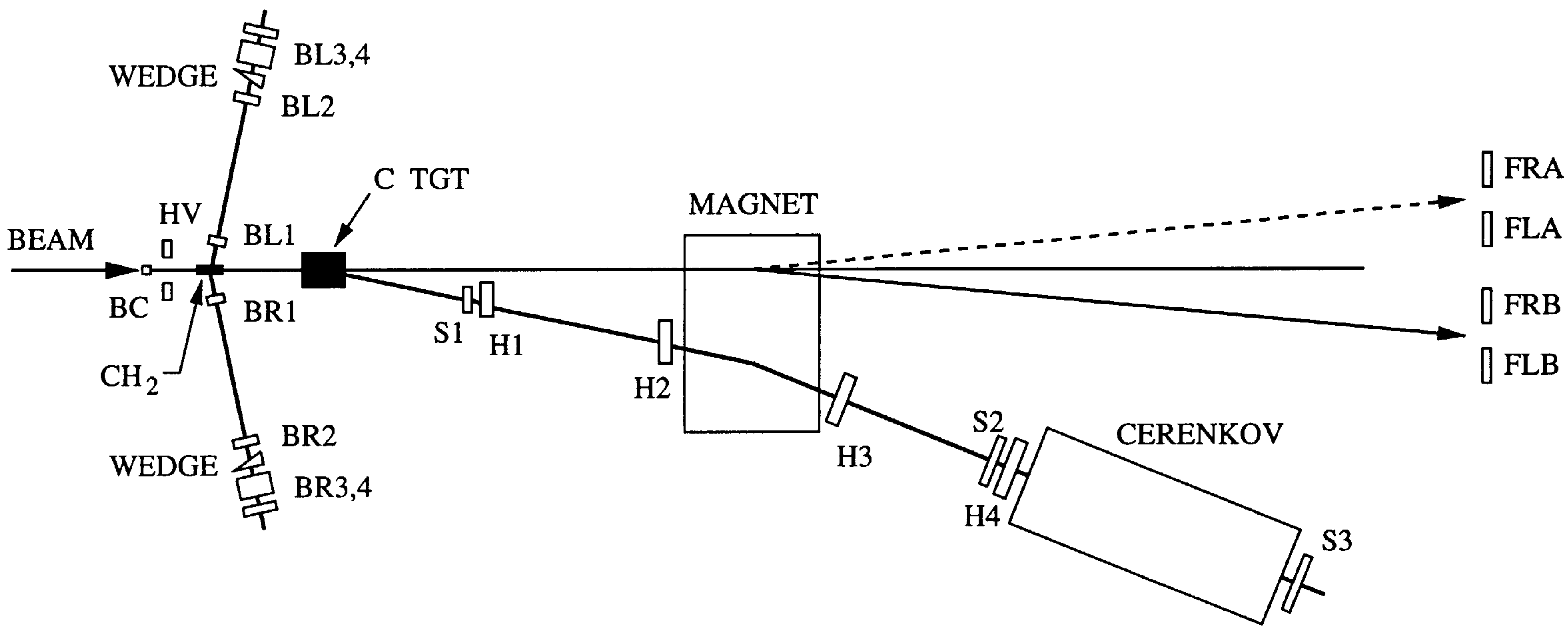
FIGURES

FIG. 1. Schematic (not to scale) of the experimental setup showing the C and CH_2 targets, analyzing magnet, and particle detectors, as described in the text.

FIG. 2. Inclusive asymmetries, A_N, measured as functions of x_F at a) 22 GeV/c from this experiment and b) 200 GeV/c [1]. The error bars shown at both energies are statistical only, and exclude the systematic uncertainty in the beam polarization. The curves are from Qiu and Sterman [18] for inclusive π^+ (dashed) and π^- (dot-dashed) production.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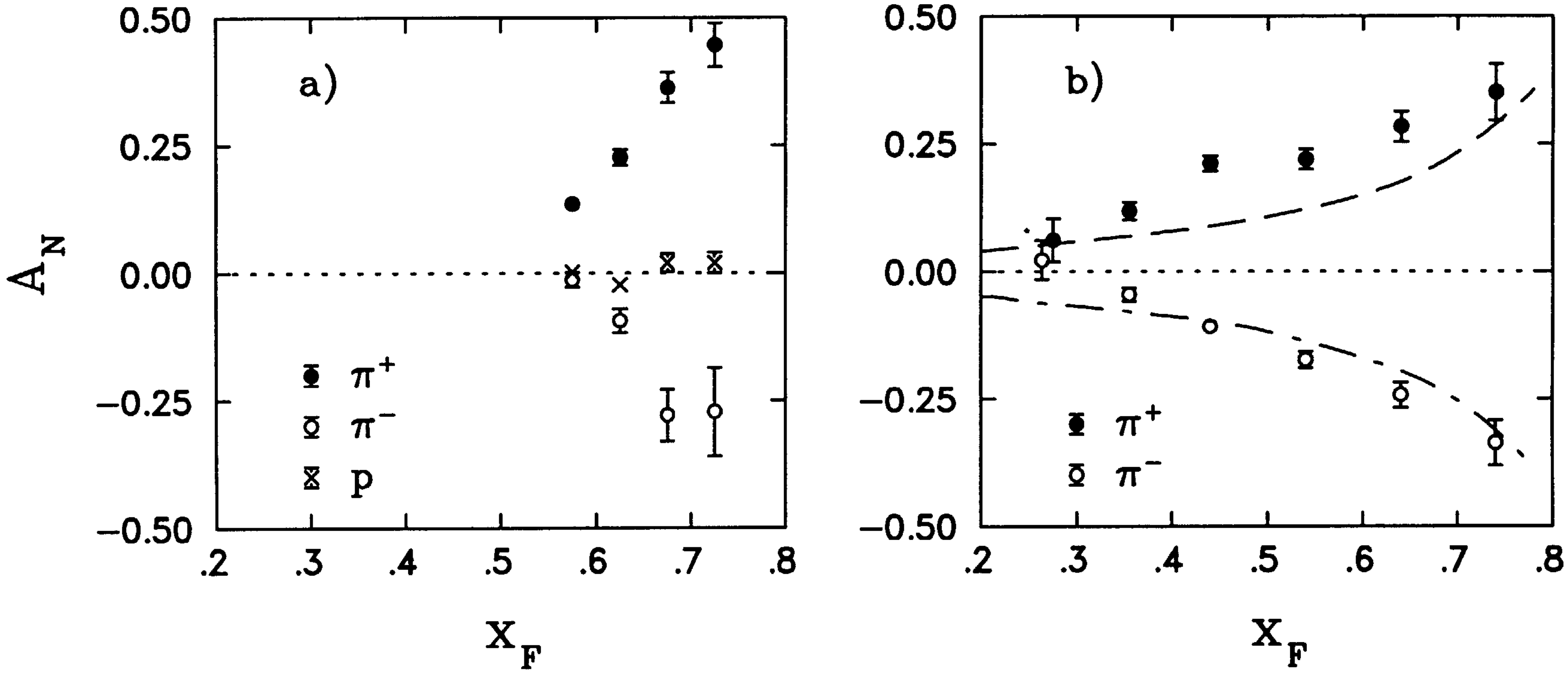

a)
b)
0.50
0.25
0.00
−0.25
−0.50
.2
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.4
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.8
A_N
X_F
π^+
π^-
p