Single-Spin Asymmetry in Inclusive Reactions $p_\uparrow + p \rightarrow \pi^+ + X$, $\pi^- + X$, and $p + X$ at 13.3 and 18.5 GeV/c

S. Saroff,[a] B. R. Baller,[b] G. C. Blazey,[c] H. Courant, K. J. Heller, M. L. Marshak, and M. A. Shupe[d]
University of Minnesota, Minneapolis, Minnesota 55455

D. S. Barton, G. Bunce, A. S. Carroll, S. Gushue, Y. I. Makdisi, and L. Remsberg
Brookhaven National Laboratory, Upton, New York 11973

S. Heppelmann
Pennsylvania State University, University Park, Pennsylvania 16802

J. J. Russell
Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 8 September 1989)

Data are presented for the left-right asymmetry in inclusive production of π^+, π^-, and p with proton beams (polarized normal to the scattering plane) of 13.3 and 18.5 GeV/c incident on a liquid-H_2 target. At both energies the asymmetry in π^+ production grows steadily to about 25% near the kinematic limit, whereas the π^- and p asymmetries are consistent with zero over the measured range of p_t, 1.1–2.2 GeV/c.

PACS numbers: 13.85.Ni, 13.88.+e

Large spin effects increasing with transverse momenta (p_t) are common, albeit unexpected and unexplained, phenomena. A large asymmetry was observed for inclusive π^0 production at CERN (Ref. 1) and Serpukov[2] using an unpolarized beam on a polarized proton target for p_t up to 3.0 GeV/c. Large hyperon polarization at high energy[3] is the basis of new precise measurements of hyperon and magnetic moments. The availability of the Brookhaven Alternating Gradient Synchrotron (AGS) polarized proton beam made possible a search for other inclusive spin effects without the requirement of a large polarized-target correction to the data. Inclusive studies are particularly interesting as they relate to the parton model, where high-p_t pion production in proton-proton interactions may come about through collisions of hard valence partons.[4] The asymmetry of inclusives may reflect the spin dependence of the parton subprocesses as well as the spin content of the protons.

The measurement of the left-right asymmetry in inclusively produced hadrons has been carried out since the first appearance of transversed polarized proton beams at the Argonne 12 GeV Zero Gradient Synchrotron (ZGS) in 1975, and more recently with polarized beams at the AGS and Fermilab. Most of the measurements to date have been done at transverse momenta below 1.0 GeV/c.[5–7] The exceptions have been the two π^0 asymmetry experiments[1,2] and an AGS experiment which probed asymmetries for K_S^0,[8] Λ^0,[8] and Σ^0 (Ref. 9) production for $p_t < 1.6$ GeV/c.

The experiment which is presented here extends the charged-pion and proton data to higher p_t with sufficient statistics to map the behavior of the asymmetry over a large range of p_t and x_f at two energies.

The data were taken during a run of the polarized proton beam at the Brookhaven AGS, using an apparatus located in the $C1$ beam line. The beam intensity and polarization were stable at both energies, yielding approximately 10^7 protons per pulse on target and polarization in the range $P_B = 0.45$–0.60. Beam polarization monitoring involved a combination of devices. A "fish-line" polarimeter[10] internal to the synchrotron periodically measured the polarization of the beam prior to extraction. Our experiment included a pair of two-arm nonmagnetic polarimeters measuring the analyzing power A_n in pp elastic scattering near $t = -0.3$ (GeV/c)^2, where it is locally maximum. It accumulated events giving $\Delta P_B = \pm 0.15$ each hour. The experiment running concurrently in the D line,[10] operated a two-arm magnetic polarimeter which accumulated statistics more rapidly. After a 5% correction for differences in depolarizing effects in the $C1$ and D beamlines,[11] these polarimeters give consistent measurements of polarization. We have chosen to use the higher-statistics D-line measurements to determine analyzing power throughout this analysis.

The experimental apparatus differed little from that used in other unpolarized two-body exclusive scattering experiments near 90° c.m. done by our group.[12] A vertical bend magnetic spectrometer measured the product particle of the inclusive reaction in the horizontal plane. The spectrometer consisted of a 48D48 magnet preceded and followed by proportional and drift chambers for tracking and scintillation hodoscopes for triggering. Two Cherenkov counters following the magnet were both set for pion identification ($\gamma_{\text{threshold}} = 21.0$). The trigger included logic matrices on scintillator and drift-chamber

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elements in the bend direction to select particles above a minimum momentum. The acceptance in azimuth (vertical) was $\pm 3.5°$, the horizontal $\pm 2.5°$, and the target was a meter of liquid hydrogen.

Data for positive and negative particles were collected separately by reversing the polarity of the analyzing magnet. The asymmetry parameter measured in this experiment is defined as follows:

$$A_n = (1/P_B)(N_u - N_d)/(N_u + N_d)\,,$$

where N_u and N_d are the normalized number of particles that scatter to the left looking downstream, with the beam polarized up and down, respectively, and P_B represents the average beam polarization. Acceptance and beam-flux factors cancel in the ratio if the beam polarization remains stable. The AGS polarization was reversed from up to down alternately on successive spills, so that "left" and "right" data are acquired in the same apparatus, which is stationary to one side of the beam. Since there are intensity variations, the beam monitors summed the relative up and down fluxes on a spill-by-spill basis and were used to normalize the up and down counts.

Our primary beam-flux monitors included (1) a gas ionization chamber upstream of the target and (2) the rate of primary event triggers, a fourfold coincidence of the spectrometer hodoscope planes with no trigger matrix (momentum) requirement. The latter was experiment-dead-time gated, and was not prone to saturate. It operated on the assumption that the bulk of event triggers are low-p_t inclusive at low x_f of various particle types, and have no net asymmetry. This assumption, and the consistency of the monitors, was checked by comparing (1) and (2), which showed agreement in the up-to-down ratio of 0.3%. An absolute calibration of the monitors and acceptance, necessary to obtain cross sections, was uncertain to a factor of 2.

The data for all reactions and both energies are displayed in Fig. 1 as a function of p_t. Errors shown are statistical, including the small errors from the measurement of beam polarization. Absolute errors on the polarimeter calibration, not shown in the figure, are ± 0.056 at 13.3 GeV/c and ± 0.077 at 18.5 GeV/c.[10] The π^+ asymmetry at 13.3 GeV/c is sizable, with a linear growth from zero near p_t of 1.0 to approximately 25% at the highest transverse momentum. The behavior at 18.5 GeV/c is similar. The π^- and p inclusives show little or no asymmetry at similar kinematic settings. It should be noted that since no Cherenkov identification of kaons was performed, the p inclusive data are likely to contain a 3% to 8% kaon contamination. The removal of this contamination would probably not change the conclusion that the asymmetry is zero.

The dependence of the π^+ asymmetry on x_f, the longitudinal momentum fraction, and on $x_t = p_t/(s/4)^{1/2}$ are explored in Fig. 2. In Fig. 2(a) the data were divided

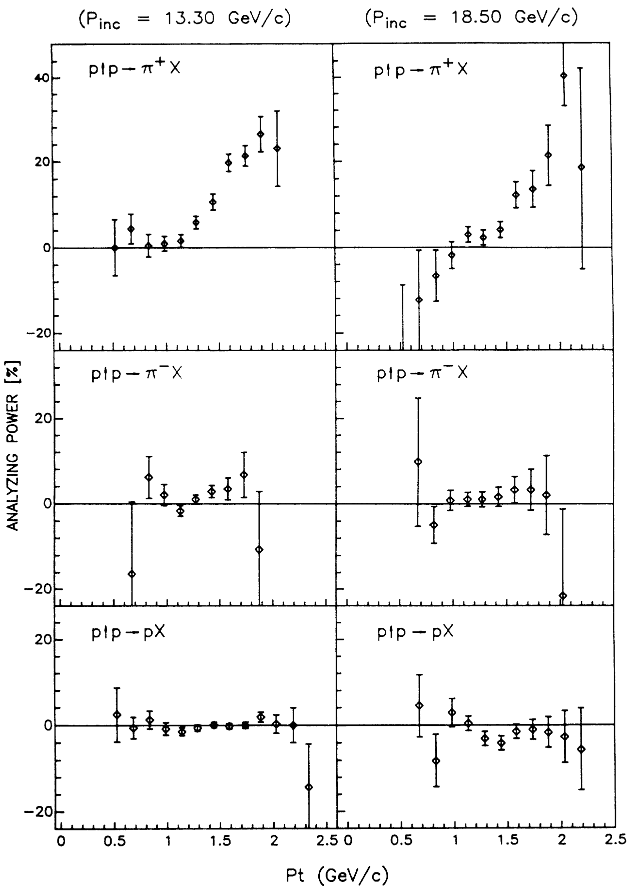

FIG. 1. The asymmetry, or analyzing power, $A_n = (1/P_B) \times (N_u - N_d)/(N_u + N_d)$, for three inclusive reactions (π^+, π^-,p), at two incident momenta ($p_{\rm inc} = 13.3$ and 18.5 GeV/c) as a function of transverse momentum (p_t). N_u (N_d) are the number of π^+, π^-, or p scattering to the left looking downstream, with the incident proton polarized up (down).

into narrow strips in x_f and plotted in overlay as a function of p_t. The asymmetry appears to be independent of x_f in this kinematic region. Figure 2(b) shows that the asymmetry is primarily a function of x_t for the combined 13.3- and 18.5-GeV/c data.

Figure 3 displays our π^+ asymmetry data at 13.3 GeV/c in the context of previous measurements. Included are results from an earlier ZGS experiment,[5] and an AGS experiment which ran concurrently with ours.[13] This diplot in x_f and x_t suggests differences in the theoretical explanations for low- and high-p_t behavior. For example, Dragoset *et al.*[5] explain the data in the region below $p_t = 1.0$ ($x_t = 0.3$) in terms of u channel baryon exchange, which can account for the change of sign about $x_t = 0.2$. Above $x_t = 0.3$, the data have a tendency to reach a maximum value at high x_f or high x_t, in the vicinity of the elastic limit. The kinematic boundary, $x_r = (x_t^2 + x_f^2)^{1/2} = 1$, is indicated in the figure. The data suggest that the relevant kinematic variable for large-angle inclusive asymmetry (empirically, for

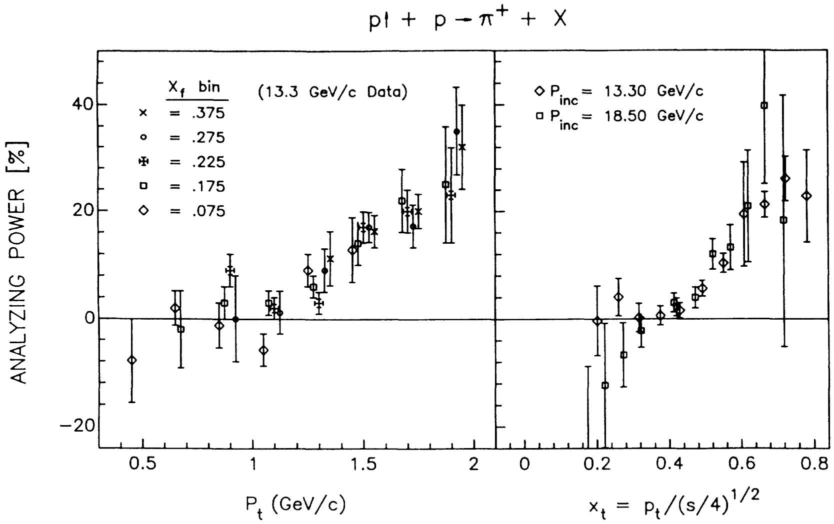

FIG. 2. The asymmetry A_n, as defined in Fig. 1, for the inclusive production of π^+. The left-hand plot divides the 13.3-GeV/c data into regions of x_f to illustrate that in this data set A_n is independent of x_f. The right-hand plot shows that, for the two incident momenta measured, x_t acts as a scaling variable for A_n.

$x_t > 0.3$) may be x_r, although more data would be needed to establish this dependence.

Large-x_f hyperon data for p_t in the range 1-2 GeV/c have been interpreted in the context of a parton fragmentation and recombination model.[14] Within this model asymmetry for meson production derives from the recombination of a polarized valence quark from the polarized proton with a polarized sea antiquark.[8] The antiquark polarization is presumed to result from the same mechanism that polarizes hyperons in production. This parton recombination model predicts analyzing power (A_n), polarization, and spin transfer for many processes, based on two parameters which represent spin-orbit couplings for slow sea partons and fast valence partons. Values for these parameters are obtained from data. They lead to a prediction of $A_n(\pi^+)=0.38$ and $A_n(\pi^-)=-0.13$ at large x_f.[7] It is assumed in the model that the spin of the proton is carried by the valence quarks according to the proton SU(6) wave function. The model has been generally successful.

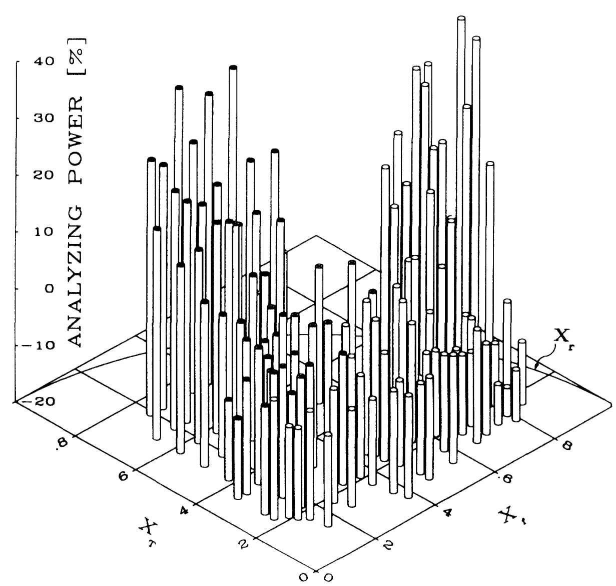

FIG. 3. A_n, as defined in Fig. 1, is shown as a function of x_t and x_f, along with data from previous measurements. The curve $x_r = 1$ is indicated. Columns with solid tops are the current data set, × tops are from Ref. 13, and blank tops are from Ref. 5. Statistical errors in all data sets are similar, and no error brackets have been indicated. (Figure 2 displays these errors for the current experiment.) This plot shows that the behavior of A_n is quite regular, and approaches the largest values as x_r approaches the elastic limit, excluding $x_t < 0.3$.

The apparent x_r dependence of the π^+ data, the large effect for π^0 at small x_f, and the small π^- result lead us to speculate whether the parton recombination model might be generalized. If the pion is produced from the hadronization of a single leading quark scattered from the beam proton, then large x_r corresponds to a quark with a large fraction of the beam momentum or the large-x part of the proton structure function. The difference, then, between π^+ and π^- asymmetries may derive from a difference in the spin information carried by the u and d quarks in the polarized proton. Deep-inelastic scattering experiments show that the longitudinal component of proton spins is, at large x, carried predominantly by the u quark.[15] Sum rules link this large-x longitudinal spin dependence to large transverse u quark asymmetry at large x.[16]

To produce an asymmetry in production, the reaction dynamics must be sensitive to the spin direction of the valence quark in the produced meson. In the parton recombination model the mechanism for this is related to the observed large hyperon polarization in inclusive production.[3] Here, we rely on semiclassical models of inclusive hyperon polarization.[14,17,18] Both the Lund flux-tube model[17] and the Thomas precession model[14] produce polarized Λ^0 hyperons through the acceleration of s quarks from the sea. With either model, $\bar{u}$ or $\bar{d}$ quarks accelerated from the sea would also be polarized, in the same direction as s quarks. This direction is $-\hat{\mathbf{y}}$, where $\hat{\mathbf{y}} = \hat{\mathbf{b}} \times \hat{\mathbf{\Lambda}}$ ($\hat{\mathbf{b}}$ denotes the direction of the beam). To produce a π^+ meson, then, the valence u quark from the polarized proton combines with a $\bar{d}$ quark from the sea. The $\bar{d}$ spin must be opposite to the u-quark spin to produce the π^+, resulting in a positive π^+ asymmetry for a negative $\bar{d}$ polarization.

It may be possible, then, to relate three phenomena: the inclusive left-right asymmetry of hadrons produced by polarized protons, deep-inelastic scattering from polarized protons at high x, and inclusive hyperon polarization. Clearly, more data to establish x_r scaling are required, as well as asymmetry measurements for other mesons. Observed π^0 asymmetry is large and the same sign as the π^+ result.[19] Although $K^{\pm}$ asymmetries have only been measured at low p_t,[5] K_S^0 asymmetry is negative as expected by the model.[8] Our inclusive proton asymmetry was small, as were measurements at lower p_t at Fermilab.[6] Λ^0 asymmetry (A_n) is small as expected, and the model was extended by allowing a spin-flip term to fit Σ^0 data.[9]

Our results may be summarized as follows. The π^- and p asymmetries are small or zero. The π^+ asymmetry is large. Its energy dependence scales with x_t and grows from zero at low x_t to about 25%–30% as x_t approaches 1. The asymmetries in this kinematic region show no x_f dependence, and, in light of inclusive data from various experiments, we suggest that the relevant kinematic variable may be x_r and that the asymmetry grows with x_r. We believe that the regularities of these data, and those from other spin experiments, suggest that simple descriptions involving valence-quark scattering and recombination processes may be successful, and could lead eventually to an improved understanding of the large spin effects observed in hard scattering. In particular, the difference between π^+ and π^- asymmetries may derive from a difference in the spin information carried by the u and d quarks in the proton at large x.

This research was supported by the U.S. Department of Energy and the National Science Foundation.

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[a]Now at Thinking Machines Inc., 245 First Street, Cambridge, MA 02142-1214.

[b]Now at Fermilab, Batavia, IL 60510.

[c]Now at University of Rochester, Rochester, NY 14627.

[d]Now at University of Arizona, Tucson, AZ 85721.

[1]J. Antille *et al.*, Phys. Lett. **94B**, 523 (1980).

[2]V. D. Apokin *et al.*, in *Proceedings of the Seventh International Symposium on High Energy Spin Physics, Protvino, U.S.S.R., 1986* (Institute of High Energy Physics, Serpakhov, U.S.S.R., 1987), Vol. 2, p. 83.

[3]G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113 (1976); L. G. Pondrom, Phys. Rep. **122**, 57 (1985), and references therein; B. Lundberg *et al.*, Phys. Rev. D **40**, 3557 (1989).

[4]The parton model predicts a power-law dependence in p_t of the inclusive cross section. Fermilab data for π^+ production show a $p_t^{-8.2}$ dependence at fixed x_t for $p_t > 2$ GeV/c [D. Antreasyan *et al.*, Phys. Rev. D **19**, 764 (1979)]. AGS data show exponential falloff for a fit between $0 < p_t < 2.1$ GeV/c with large errors above $p_t = 1.7$ [E. W. Beier *et al.*, Phys. Rev. Lett **37**, 1114 (1976)].

[5]R. D. Klem *et al.*, Phys. Rev. Lett. **36**, 929 (1976); W. H. Dragoset *et al.*, Phys. Rev. D **18**, 3939 (1978).

[6]M. Corcoran *et al.*, Phys. Rev. D **22**, 2624 (1980); **24**, 3010(E) (1981).

[7]B. E. Bonner *et al.*, Phys. Rev. Lett. **61**, 1918 (1988).

[8]B. E. Bonner *et al.*, Phys. Rev. D **38**, 729 (1988).

[9]B. E. Bonner *et al.*, Phys. Rev. Lett. **62**, 1591 (1989).

[10]Fatah Khiari, Ph.D. thesis, University of Michigan, 1986 (unpublished); F. Z. Khiari *et al.*, Phys. Rev. D **39**, 45 (1989).

[11]G. Bunce, Brookhaven Internal Report No. BNL 29856, 1981 (unpublished).

[12]B. R. Baller *et al.*, Phys. Rev. Lett. **60**, 1118 (1988); G. C. Blazey *et al.*, Phys. Rev. Lett. **55**, 1820 (1985).

[13]R. Moss, Ph.D. thesis, Rice University, 1988 (unpublished).

[14]T. A. DeGrand and H. I. Miettinen, Phys. Rev. D **24**, 2419 (1981); T. A. DeGrand *et al.*, Phys. Rev. D **32**, 2445 (1985).

[15]E. Leader, in *Proceedings of the Second Conference on Intersections Between Particle and Nuclear Physics, Lake Louise, Canada, 1986*, edited by D. Geeseman, AIP Conference Proceedings No. 150 (American Institute of Physics, New York, 1986), pp. 257–271; G. Baum *et al.*, Phys. Rev. Lett. **51**, 1135 (1983).

[16]J. Soffer, in Proceedings of the Symposium on the Future of Polarized Physics, Fermilab, July 1988 (to be published); A. V. Efremov and O. V. Teyaev, Phys. Lett. B **200**, 363 (1988).

[17]B. Anderson *et al.*, Phys. Lett. **85B**, 417 (1979).

[18]J. Szwed, Phys. Lett. **105B**, 403 (1981).

[19]We note that two of the π^0 production experiments (Refs. 1 and 2) were carried out with a polarized target and that the Ann Arbor convention [J. Ashkin *et al.*, in *Proceedings of the Workshop on Higher Energy Polarized Proton Beams, Ann Arbor, 1977*, edited by A. D. Kirsch and A. J. Salthouse, AIP Conference Proceedings No. 42 (American Institute of Physics, New York, 1978), p. 142] is ambiguous between polarized-beam and polarized-target experiments concerning the definition of the sign for A_n. We define a positive asymmetry for pions produced in the direction $\hat{\mathbf{P}} \times \hat{\mathbf{p}}$, with $\hat{\mathbf{P}}$ the proton polarization direction and $\hat{\mathbf{p}}$ its momentum direction. We understand that the inclusive π^0 asymmetry (Refs. 1 and 2) has the same direction as our π^+ asymmetry and the Fermilab π^0 measurement (Ref. 7) [A. Vasiliev and D. Crabb (private communication)].