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Large-x_F Spin Asymmetry in π^0 Production by 200-GeV Polarized Protons*

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Abstract

The spin asymmetry A_N for inclusive π^0 production by 200-GeV transversely-polarized protons on a liquid hydrogen target has been measured at Fermilab over a wide range of x_F, with $0.5 < p_t < 2$ GeV/c. At $x_F > 0.3$, the asymmetry rises with increasing x_F and reaches a value of $A_N = 0.15 \pm 0.03$ in the region $0.6 < x_F < 0.8$. This result provides new input regarding the question of the internal spin structure of transversely-polarized protons.

Several experiments[1-7] have studied the transverse-spin asymmetry A_N in inclusive pion, kaon, and proton production using either polarized proton targets or polarized proton beams at energies ranging from 6 to 40 GeV. The results have shown small asymmetries in the beam fragmentation region when the beam was unpolarized and the target polarized. Large asymmetries, $A_N = 0.3$ or higher, have been observed[5,6] in the same kinematical region when the beam was polarized and the target unpolarized. At higher energies, a previous measurement[8] of A_N in inclusive π^0 production by 185-GeV polarized protons has shown an average value of $A_N = 0.10 \pm 0.03$, integrated over a broad kinematical region.

We present here the results of a new measurement to study the x_F dependence of A_N at low p_t with transversely-polarized protons for the inclusive reaction,

$$P + P \Rightarrow \pi^0 + X, \qquad (1)$$

performed at the Fermilab polarized-beam facility. The parameter A_N is defined as the left-right asymmetry of the production cross section by vertically-polarized incident particles. Positive values of A_N correspond to a larger cross section for production to the left when the beam particle spin is pointed vertically upward. This experiment covers the region of x_F from 0 to 0.8 with transverse momenta p_t from 0.5 to 2 GeV/c.

The design and performance of the beam of polarized protons arising from the decay of lambda hyperons is described in Ref. 9. The polarization of the protons is determined by tagging the beam particle trajectories. The tagged beam polarization values, which range from P_B = 0.65 to -0.65, are divided into three parts with average polarizations, P_B = 0.45, -0.45, and 0. These values were confirmed by two independent measurements[10,11] using reactions of known analyzing power. A set of spin-rotating magnets changes the direction of the beam polarization from the transverse-horizontal to the vertical direction at the experimental target and reverses the sign 4 or 5 times per hour. The same beam line has been used for similar measurements[12] with incident antiprotons.

Two independent photon detectors (D1 and D2) of different design and at different distances from the target have been used. Both detectors, shown in Fig.1, provide position and energy information from showers due to photons from π^0s produced by interactions of polarized beam protons with protons in a 100-cm liquid hydrogen target. The detector D2, located 50 m from the target and behind a sweeping magnet, is the one that had been used in the previous measurement[8] at 185 GeV. The layout, trigger conditions, and method of analysis are the same as described in Refs. 8 and 9. The detector D1, located 10 m from the target, is comprised of 504 lead-glass counters[13] in an array of 21 columns by 24 rows, offset to the left side of the beam with the first column centered on the beam axis. The size of each lead-glass block is 3.81 cm x 3.81 cm x 18 radiation lengths. The data acquisition and method of analysis are briefly outlined below.

The π^0 trigger for D1 consists of a "good" beam particle, interacting in the hydrogen target, that produces an energy deposition above a given threshold in the lead-glass calorimeter. A "good" beam particle is a proton that has both a tagged polarization value between P_B = 0.65 and -0.65 and a tagged momentum between 182 and 218 GeV/c. Data were taken at four different energy thresholds of the calorimeter, corresponding approximately to x_F values of 0.2, 0.4, 0.5, and 0.6. The data for each threshold setting were analyzed separately; the asymmetries, determined independently in overlapping kinematical regions, agree within the statistical errors. The trigger rate was typically 1500 to 2000 events per 20-sec beam spill with an average polarized beam intensity of 10^7 protons per spill.

All combinations of photon pairs satisfying the following conditions were selected as π^0 candidates:

(1) The energy asymmetry $|E_1 - E_2| / (E_1 + E_2)$ between the two shower was less than 0.8;

(2) Both photons were contained within a distance of more than one counter width from the edge of the calorimeter;

(3) The two-photon invariant mass was between 80 and 200 MeV/c^2;

(4) The transverse momentum of the π^0 was between 0.5 and 2 GeV/c;

(5) The x_F value was between 0 and 0.8.

The minimum distance between the two photons from π^0s produced in the target was 48 mm at x_F = 0.3 and decreased to 21 mm at x_F = 0.7. Over this x_F region, the π^0 reconstruction efficiency decreased from >95 % to 30 %, due to partial overlapping of the two showers. The mass resolution varied from ±9 MeV/c^2 at x_F = 0.1 to ±30 MeV/c^2 at x_F = 0.7. The photon-pair background under the π^0 mass peak, due to uncorrelated pairs and π^0s produced outside the target volume, varied from 15 % to 25 %. The asymmetry in the invariant-mass region from 250 to 450 MeV/c^2 was found to be consistent with zero, within statistical errors of less than 3 % over the entire range of x_F.

More than 25 % of the 7 x 10^6 events recorded with D1 reconstruct a π^0. About 38 % of the reconstructed π^0s have transverse momenta greater than 0.5 GeV/c, and these 656,000 events were used for further analysis. The data from D2 presented here correspond to a total of 24,300 π^0 events.

The values of A_N measured with D1 are given in Table I as a function of x_F averaged over the corresponding p_t-regions. For the intervals of x_F where D1 and D2 cover the same region of p_t, the values measured with the two detectors, given in Table II, agree within the statistical errors. The combined results are also given in Table II and are shown in Fig.2(a). The asymmetry parameter A_N is small and consistent with zero for x_F < 0.3. At larger x_F, the asymmetry rises with increasing x_F and reaches A_N = 0.15 ± 0.03 in the interval from x_F = 0.6 to 0.8.

The errors given in the tables and figures are only statistical. For both detectors, the systematic errors due to possible geometrical bias and time-dependent drifts in the apparatus are minimized by the periodic spin-reversal of the beam particles. An upper limit on the remaining false asymmetry is obtained by: (a) calculating the "beam-spin-reversal asymmetry" for π^0s produced by beam particles with average tagged polarization of zero, (b) calculating the asymmetries separately for the two parts of the data with opposite-sign beam polarizations, and (c) comparing the results from the three separate measurements (one at 185 GeV and two at 200 GeV) with two different detectors. The estimated upper limit for possible false asymmetries is $\Delta A_N = 0.01$ at $x_F < 0.5$ and $\Delta A_N = 0.03$ at the largest values of x_F. The relative systematic errors proportional to A_N are estimated to be 10 % and are due principally to the uncertainty in the beam polarization, with a small contribution from the uncertainty in background subtraction under the π^0-mass peak. The "beam-spin-reversal asymmetry" with unpolarized beam is consistent with zero for both detectors and is given for D1 in Table I and Fig.2(b). The present data are in good agreement with the average asymmetry measured in the previous experiment[8] at 185 GeV/c.

The dependence of the asymmetry on both p_t and x_F, measured with D1, is shown in Table III and Fig.3. At $x_F > 0.5$, the asymmetry as a function of p_t rises rapidly from zero at $p_t = 0$ to $A_N \approx 0.14$ at $p_t = 0.8$ GeV/c, whereas A_N remains consistent with zero up to $p_t = 1.4$ GeV/c at low x_F. It is interesting to note that the dependence on x_F and p_t shown in Table II and Fig.3 bears a yet unexplained resemblance to the polarization of lambda hyperons produced from an unpolarized initial state[14].

Our results can be summarized by the observation that the asymmetry in π^0 production is largest when the pion longitudinal momentum is close to the beam momentum.

It is instructive to examine the corresponding data for charged pion production. Among the different measurements of A_N in inclusive production reactions at lower energies, two polarized beam experiments[5,6], at 6 and 11.8 GeV/c, had studied the process,

$$P + P \Rightarrow \pi^+ + X, \qquad (2)$$

over a wide region of x_F. The asymmetries were also found to increase when the pion longitudinal momentum approached the beam momentum. The similarity between π^+ and π^0 production processes may be expected, since both involve u-quark scattering.

A recent theoretical discussion of transverse single-spin asymmetries is given in Ref. 15. We describe here three approaches which have been proposed to explain the nonzero single-spin asymmetry A_N in pion production with polarized beams or targets. Each uses a different picture for the proton internal spin structure: transverse quark spin, transverse and orbital angular momentum of the constituents, or rotating color charges.

The fragmentation-recombination model[16] applied to pion production by polarized protons[17] at large x_F and relatively small p_t assumes the transfer of a leading beam valence quark from the proton to the pion and the transmission of the beam-polarization information via the transverse spin of the quarks. In the description of transverse quark spin given in Ref. 18, the quark polarization is not necessarily small, in spite of neglecting the quark masses. It is known from the parton distribution functions for the proton, that u-quarks are predominant at large x_{Bj}. The Yale-SLAC experiment[19] had shown that in longitudinally-polarized protons, quarks with large x_{Bj} (i.e., u-quarks) carry a substantial fraction of the parent-proton spin. The fragmentation model assumes that the same holds for the leading u-quarks in transversely-polarized protons. The model, which is energy-independent, predicts the correct signs and a ratio $A_N(\pi^+)/A_N(\pi^0) \approx 2$, in agreement with the ratio between the data presented here and the results in Refs. 5 and 6. The alternate model described in Ref. 20 also assumes transverse polarization of the quarks in transversely polarized protons. In these models, the increase of A_N at large x_F is attributed to a specific mechanism which dominates pion production when $x_F \Rightarrow 1$ and which has a characteristic spin dependence.

A second phenomenological approach is proposed in Ref. 21, where the beam particle polarization is not transmitted via the spin of its constituents, but by the correlation of their longitudinal and transverse momentum. As a consequence, the constituents of vertically-polarized protons can have left-right asymmetric transverse momentum distributions, leading to different cross sections at equal hadron production angles for the left and right. The finite transverse dimension of the proton, together with transverse and orbital angular momentum of the constituents, can introduce the necessary spin-dependent phase into the production amplitudes. Here, the x_F dependence of A_N is attributed the x_F dependence of the transverse-momentum asymmetry, not to a particular process specific to the production of pions with longitudinal momentum close to the beam momentum.

A third way to transmit the beam-polarization information is implicitly suggested in Ref. 22. The authors invoke transverse forces generated by the interaction of rotating color charges in the spinning proton with the gluon field of the target.

In summary, the x_F-dependence of A_N at $p_t < 2$ GeV/c measured in the present experiment shows that the asymmetry increases from zero to relatively large values when the π^0 longitudinal momentum approaches the beam momentum. At the highest x_F values attained, the cross sections for π^0 production from opposite beam-spin states differ by a factor of 1.3 to 1.4. The sign and the magnitude of the asymmetry, the high energy at which it is observed, and its characteristic x_F dependence provide new input regarding the internal spin structure of transversely-polarized protons.

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FIGURE CAPTIONS

Fig.1 The schematic layout of the apparatus.

Fig.2(a) The asymmetry parameter A_N in the reaction $P + P \Rightarrow \pi^0 + X$ at 200 GeV as a function of x_F, averaged over p_t. $\sigma\uparrow/\sigma\downarrow$ is the ratio of the π^0 production cross sections for opposite beam spins.

Fig.2(b) The "false asymmetry" calculated for events with average beam polarization of zero, as a function of x_F.

Fig.3 The asymmetry A_N in the reaction $P + P \Rightarrow \pi^0 + X$ at 200 GeV, measured with detector D1, as a function of p_t for $0<x_F<0.3$ (closed circles) and for $0.5<x_F<0.8$ (open squares).

TABLE I. The asymmetry parameter A_N for inclusive π^0 production by 200-GeV polarized protons measured in detector D1 for different regions of x_F, averaged over the p_T regions given in column 2. The "false asymmetry" (false A_N) is calculated using the unpolarized portion of the beam.

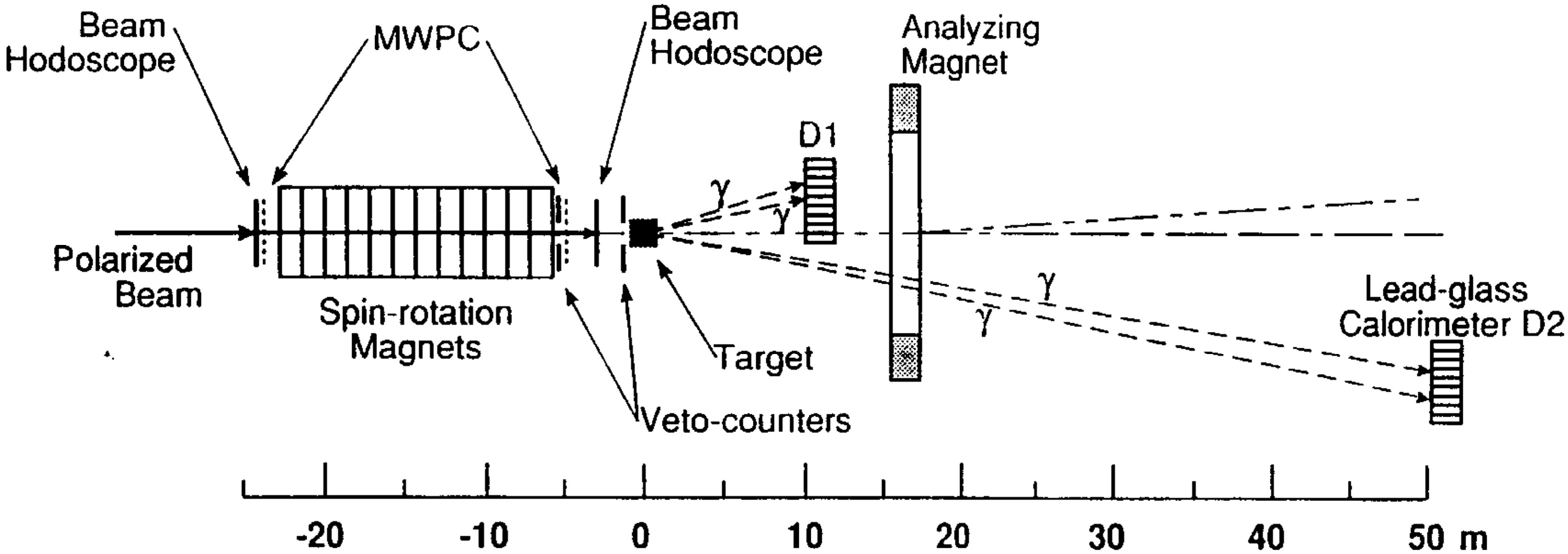
x_F	p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	No. π^0 Events	A_N (%)	False A_N (%)
0.0 – 0.1	0.5 – 2.0	0.7	76 000	−0.1 ± 1.2	0.6 ± 1.2
0.1 – 0.2	0.5 – 2.0	0.7	219 000	0.8 ± 0.8	0.5 ± 0.8
0.2 – 0.3	0.5 – 2.0	0.8	146 000	0.7 ± 1.0	0.6 ± 1.0
0.3 – 0.4	0.6 – 2.0	0.8	100 000	4.1 ± 1.1	−0.5 ± 1.1
0.4 – 0.5	0.7 – 2.0	0.9	69 000	6.1 ± 1.2	−0.3 ± 1.2
0.5 – 0.6	0.8 – 2.0	1.0	32 000	12.1 ± 1.7	0.0 ± 1.7
0.6 – 0.8	0.8 – 2.0	1.1	14 000	15.0 ± 2.7	1.8 ± 2.6

TABLE II. The asymmetry parameter A_N measured in each of the detectors, D1 and D2, and also the combined value, given as a function of x_F.

$\langle x_F \rangle$	A_N (%)		
	D1	D2	D1 + D2
0.03	-0.1 ± 1.2	...	-0.1 ± 1.2
0.13	0.8 ± 0.8	...	0.8 ± 0.8
0.23	0.7 ± 1.0	...	0.7 ± 1.0
0.33	4.1 ± 1.1	4.2 ± 1.9	4.1 ± 1.0
0.43	6.1 ± 1.2	6.8 ± 2.4	6.2 ± 1.1
0.53	12.1 ± 1.7	8.1 ± 4.1	11.5 ± 1.6
0.67	15.0 ± 2.7	...	15.0 ± 2.7

TABLE III. The asymmetry parameter A_N given as a function of both p_T and x_F.

x_F	p_T (GeV/c)	$\langle p_T \rangle$ (GeV/c)	A_N (%)
0.0 – 0.3	0.2 – 0.4	0.25	0.0 ± 0.7
	0.4 – 0.6	0.45	0.0 ± 0.7
	0.6 – 0.8	0.65	0.1 ± 0.9
	0.8 – 1.0	0.85	−1.4 ± 1.4
	1.0 – 1.4	1.10	1.1 ± 1.8
	1.4 – 2.0	1.55	14.3 ± 3.9
0.3 – 0.5	0.4 – 0.6	0.45	1.2 ± 1.2
	0.6 – 0.8	0.65	6.2 ± 1.2
	0.8 – 1.0	0.85	4.6 ± 1.6
	1.0 – 1.4	1.10	2.3 ± 1.7
	1.4 – 2.0	1.55	4.7 ± 3.0
0.5 – 0.8	0.6 – 0.8	0.65	4.5 ± 2.3
	0.8 – 1.0	0.85	14.8 ± 2.1
	1.0 – 1.4	1.10	10.1 ± 4.4
	1.4 – 2.0	1.55	14.1 ± 4.2



Beam
Hodoscope
MWPC
Beam
Hodoscope
Analyzing
Magnet
D1
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Lead-glass
Calorimeter D2
Spin-rotation
Magnets
Target
Veto-counters
-20
-10
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20
30
40
50 m

Figure 1

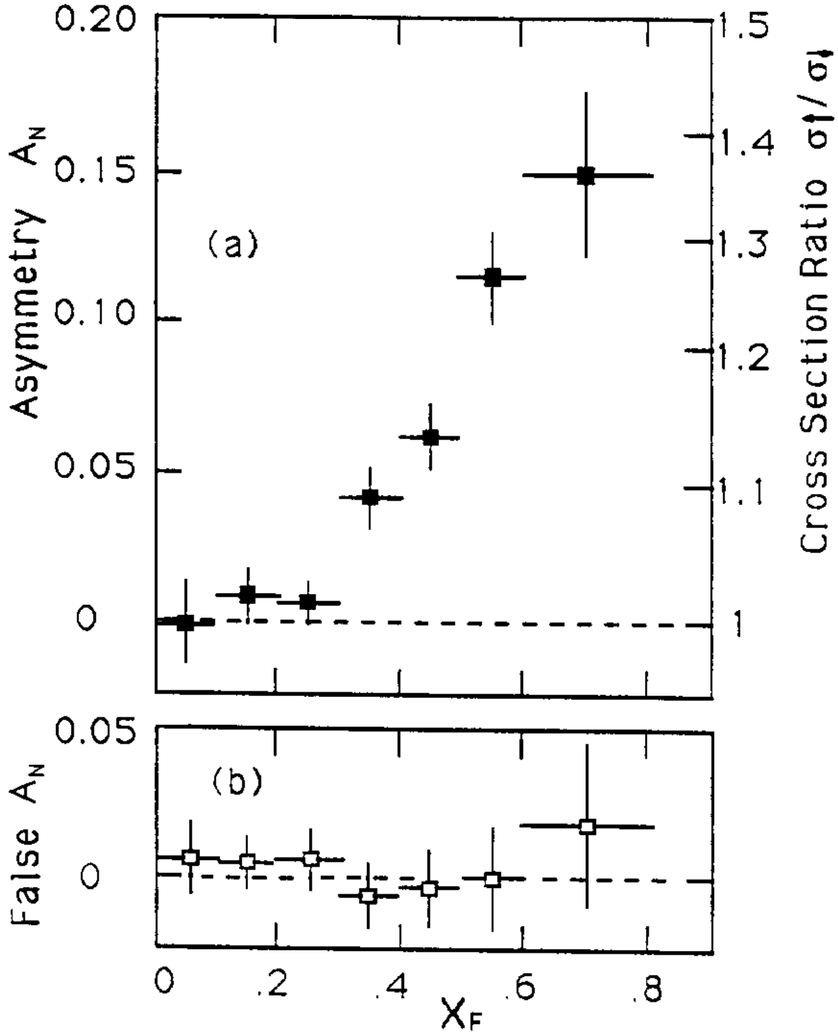

Figure 2

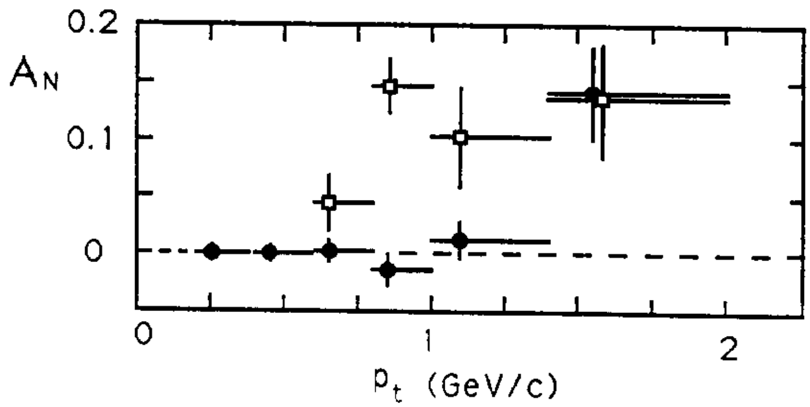

Figure 3