Analyzing Power Measurement in Inclusive Λ^0 Production with a 200 GeV/c Polarized Proton Beam

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The considerable polarization of hyperons produced at high x_F has been known for a long time and has been interpreted with various theoretical models in terms of the constituents' spin. Recently, the analyzing power in inclusive Λ^0 hyperon production has also been measured using the 200 GeV/c Fermilab polarized proton beam. The covered kinematic range is $0.2 \leq x_F \leq 1.0$ and $0.1 \leq p_T \leq 1.5$ GeV/c. The data indicate a negative asymmetry at large x_F and moderate p_T. These results can further test the current ideas on the underlying mechanisms for hyperon polarization.

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It is well known that hyperons produced at high x_F show a large polarization P_0 independent of $\sqrt{s}$ [1]. More recently, significant values of the analyzing power A_N [2] have been found at large x_F in inclusive pion production by polarized proton beams at medium and high energies. The features of the pion data are compatible with current models of the hyperon polarization [3,4], based on the idea that quarks are produced in fragmentation processes with transverse polarization and leading valence quarks remember their polarization in the parent proton. Other models [5], more closely related to QCD, tend to underestimate the hyperon polarization. These effects appear already at relatively low values of transverse momentum ($p_T \sim 1.0$ GeV/c), where perturbative QCD is not expected to be directly applicable. The hyperon polarization, however, remains remarkably constant up to the highest measured p_T's ($\sim$3.5 GeV/c for Λ^0), and might represent a serious challenge to the QCD prediction of vanishing single-spin effects.

New studies of single-spin asymmetries in high energy hyperon production may further help in clarifying these phenomena. In this Letter we report on the measurement of the analyzing power A_N in inclusive Λ^0 production at 200 GeV/c using the Fermilab polarized proton beam incident on a 1.0 m long liquid hydrogen target (LHT). The kinematic range of the measurement ($0.2 \leq x_F \leq$

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1.0, $0.1 \le p_T \le 1.5$ GeV/c) covers the region of the onset of the hyperon polarization P_0, and our data agree with previously published results of this parameter.

The polarized proton beam [6] was obtained by selecting protons from the weak decay of Λ^0 particles produced in a primary beryllium target by the Fermilab Tevatron 800 GeV/c extracted proton beam. Decay protons emitted near ±90° in the Λ° rest frame are transversely polarized with respect to their direction in the laboratory frame. The average value of their polarization was determined by tagging their trajectories in the horizontal plane at an intermediate focus. The tagged beam polarization ranged from -0.65 to $+0.65$; the simultaneous use of both signs of polarization allowed suppression of systematic biases. A set of dipole magnets (spin rotator) changed the transverse beam polarization direction from horizontal to vertical at LHT without affecting the beam direction. In order to further suppress systematic errors, the polarity of the spin rotator magnets was reversed every 15 Tevatron spills. Typical beam intensities at LHT were $(1.0-2.0) \times 10^7$ polarized protons per 20 sec Tevatron spill. Events with beam polarization values from 0.35 to 0.65 and -0.65 to -0.35 were used in the analysis. The absolute value of the average beam polarization P_B for these events was 0.46 for both signs (positive if oriented upwards).

The polarized proton beam interacting with LHT produced Λ^0 hyperons in the inclusive process $p\uparrow + p \to \Lambda^0 + X$. The analyzing power A_N for this process was determined by measuring the yields of Λ^0's in a well-defined azimuthal angular interval, using vertically polarized protons of both polarization signs

$$A_N = \frac{1}{P_B\langle\cos\phi\rangle}\,\epsilon_N = \frac{1}{P_B\langle\cos\phi\rangle}\,\frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}\,.$$

ϕ is the azimuthal angle between the beam polarization axis, directed vertically upward, and the normal to the Λ^0 production plane ($\vec{p}_{\text{beam}} \times \vec{p}_\Lambda$). The selected azimuthal angular interval for the asymmetry calculations was ±60° from the horizontal plane to beam-right, giving $\langle\cos\phi\rangle \approx -0.85$. ϵ_N is the asymmetry in the number of Λ^0's produced for positive ($N\uparrow$) and negative ($N\downarrow$) spin orientation of the beam protons at LHT, normalized to the corresponding beam flux. $N\uparrow$ is obtained by combining events having positive tagged polarization and spin rotator states with events having negative tagged polarization and spin rotator states. $N\downarrow$ is obtained from events with opposite tagged polarization and spin rotator states. This asymmetry, to a good accuracy, is independent of detector efficiency and acceptance as well as event reconstruction efficiency, since particle yields were measured with the same apparatus and both polarizations simultaneously.

Secondary charged particles produced at LHT or coming from decays downstream were measured with a forward spectrometer (Fig. 1) stretching 50 m from LHT to the farthest downstream detector. Particle trajectories were recorded with 42 multiwire proportional planes grouped in 12 chambers with 1 mm (PC1, PC2) or 2 mm wire spacing and two (PC4′, PC7, PC7′) or four plane views. A dipole magnet (BM109) with a 1.4 T vertical field directed upward ($\int B\,dl \sim 3$ T m) was used for momentum analysis of charged particles. A threshold Cherenkov counter (C1) downstream of the magnet, filled with He gas at 0.280 g/cm^2, detected charged pions above 40 GeV/c, but not protons up to 200 GeV/c. Its acceptance covered protons from Λ^0 decays deflected to beam-right by the magnet, but not beam protons and negative particles (including π^-'s from Λ^0 decays.).

The trigger required a *good beam* signal (i.e., beam particles with successfully tagged momentum and polarization, identified as protons by the beam line Cherenkov counters) and selected events of the expected Λ^0 decay topology by using hodoscopes H3–H5 downstream of the magnet. [The acceptable configurations of hodoscope hit patterns were obtained from Monte Carlo studies and were implemented in the trigger by means of memory look-up units. Beam particles noninteracting in the LHT or background due to showers arising from secondary interactions in the spectrometer were suppressed by using a beam veto H6 at the downstream end.]

The identification of Λ^0's produced at LHT was accomplished by reconstructing their decay into p and π^-. On the basis of chamber information, charged tracks were reconstructed upstream and downstream of the magnet. The partial track segments were linked using the vertical projection (nonbending plane) across the entire spectrometer, thus allowing momentum

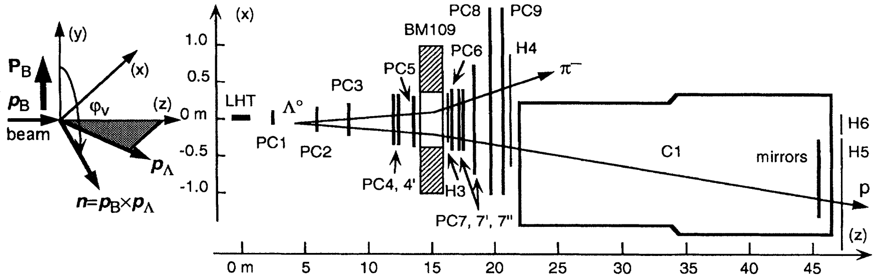

FIG. 1. Top view of the E704 forward spectrometer layout showing all essential elements and the reference system.

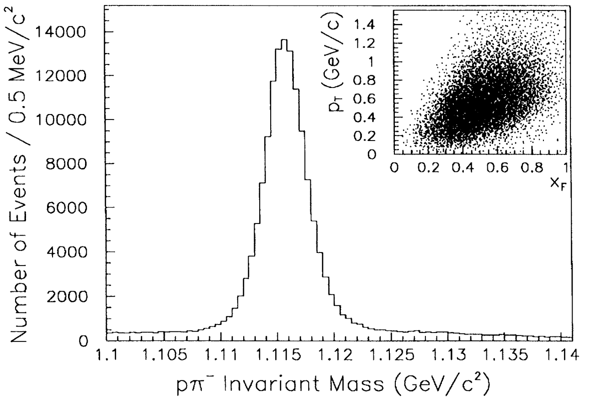

FIG. 2. Reconstructed Λ^0 invariant mass. The inset shows the x_F vs p_T scatter plot for selected Λ^0.

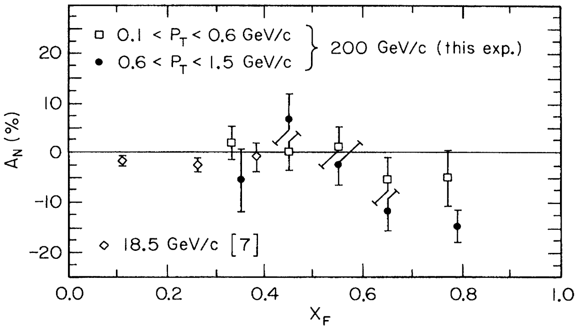

FIG. 3. A_N data for $p\uparrow + p \rightarrow \Lambda^0 + X$ as a function of x_F. Data at 18.5 GeV/c [7] (◇) are also shown.

reconstruction for the individual trajectories. The single track reconstruction efficiency was about 85%. For the identification of events containing a neutral secondary vertex (V^0 candidate), corresponding to a potential Λ^0 decay, pairs of oppositely charged tracks were selected such that (i) the closest approach of the two tracks in space was <2 mm. The fiducial volume for the V^0 vertex was chosen from 20 to 540 cm downstream the end of the target. (ii) The vector sum of the momenta of the two particles ($\vec{p}^{\,+} + \vec{p}^{\,-}$) defining the V^0 line of flight, pointed to the production vertex in the target and matched the beam impact point there (within 2 mm in the transverse plane). (iii) These momenta were distributed such that $0.45 < \alpha < 0.95$ and $q_T = q_T^+ = q_T^- < 0.12$ GeV/c, where $\alpha = (p_L^+ - p_L^-)/(p_L^+ + p_L^-)$ is the asymmetry of the longitudinal components of the positive and negative track momenta and q_T is the transverse component of these momenta with respect to the Λ^0 line of flight. This criterion corresponds to selecting the region populated by Λ^0's in the V^0 decay phase space.

The selected events led to a very clean Λ^0 peak in the $p\pi^-$ invariant mass distribution (Fig. 2) with a rather small background, as most K_S^0 decays were rejected by C1. The reconstructed invariant Λ^0 mass was 1.116 GeV/c^2, with a width $\sigma = 1.7$ MeV/c^2. About 40 000 Λ^0 were selected for the asymmetry calculations in a mass interval of ± 5.1 MeV/c^2 centered at 1.116 GeV/c^2. The uniform background was estimated to be about 2% below the selected Λ^0 peak.

Table I contains the analyzing power A_N results as a function of x_F, averaged over the range $0.1 < p_T < 1.5$ GeV/c (Fig. 3) and divided into the two separate intervals $0.1 < p_T < 0.6$ and $p_T > 0.6$ GeV/c. The quoted errors are statistical only. The A_N results as a function of p_T are listed in Table II for three cases: averaged over the

TABLE I. A_N results as a function of x_F averaged over the p_T range of 0.1–1.5 GeV/c (rows 1 to 5) and divided into two p_T intervals of 0.1–0.6 GeV/c (rows 6 to 10) and 0.6–1.5 GeV/c (rows 11 to 15).

p_T interval (GeV/c)	x_F interval	A_N (%)	$\langle x_F \rangle$	$\langle p_T \rangle$ (GeV/c)	No. events
0.1–1.5	0.2–0.4	0.7 ± 3.0	0.33	0.44	7447
	0.4–0.5	2.7 ± 2.9	0.45	0.54	8135
	0.5–0.6	−0.3 ± 2.8	0.55	0.61	8322
	0.6–0.7	−8.8 ± 3.1	0.65	0.68	6807
	0.7–1.0	−11.8 ± 3.1	0.79	0.77	6570
0.1–0.6	0.2–0.4	2.2 ± 3.4	0.33	0.36	5936
	0.4–0.5	0.4 ± 3.6	0.45	0.40	5204
	0.5–0.6	1.3 ± 3.8	0.55	0.43	4465
	0.6–0.7	−5.2 ± 4.7	0.65	0.46	2834
	0.7–1.0	−4.8 ± 5.7	0.77	0.49	1762
0.6–1.5	0.2–0.4	−5.3 ± 6.5	0.35	0.73	1511
	0.4–0.5	7.0 ± 4.7	0.45	0.79	2931
	0.5–0.6	−2.3 ± 4.0	0.55	0.81	3857
	0.6–0.7	−11.5 ± 3.9	0.65	0.84	3973
	0.7–1.0	−14.5 ± 3.4	0.79	0.87	4808

TABLE II. A_N results as a function of p_T averaged over the x_F range of 0.2–1.0 (rows 1 to 5) and divided into two x_F intervals of 0.2–0.5 (rows 6 to 9) and 0.5–1.0 (rows 10 to 14).

x_F interval	p_T interval (GeV/c)	A_N (%)	$\langle x_F \rangle$	$\langle p_T \rangle$ (GeV/c)	No. events
0.2–1.0	0.1–0.4	0.7 ± 2.7	0.44	0.29	8732
	0.4–0.6	−0.8 ± 2.4	0.53	0.50	11 469
	0.6–0.8	−5.4 ± 2.7	0.58	0.69	9412
	0.8–1.0	−7.8 ± 3.7	0.62	0.89	4999
	>1.0	−9.1 ± 5.1	0.67	1.16	2669
0.2–0.5	0.1–0.4	2.3 ± 3.3	0.37	0.29	6068
	0.4–0.6	0.3 ± 3.7	0.39	0.49	5072
	0.6–0.8	2.8 ± 4.9	0.41	0.69	2943
	0.8–0.7	1.7 ± 7.8	0.43	0.88	1142
0.5–1.0	0.1–0.4	−2.9 ± 4.8	0.60	0.31	2664
	0.4–0.6	−1.6 ± 3.1	0.63	0.51	6397
	0.6–0.8	−8.9 ± 3.1	0.66	0.69	6469
	0.8–1.0	−10.6 ± 4.2	0.68	0.89	3857
	>1.0	−11.5 ± 5.5	0.70	1.17	2312

x_F range of $0.2 < x_F < 1.0$ (Fig. 4) and divided into the separate intervals $0.2 < x_F < 0.5$ and $0.5 < x_F < 1.0$. A number of consistency checks have been performed to establish that the asymmetry results were free of systematic effects. We evaluated the *false* asymmetries by averaging over opposite spin rotator states [$\epsilon_S = (-0.6 \pm 0.5)\%$] or over both tagged polarization signs [$\epsilon_B = (0.3 \pm 0.5)\%$]; $P_B = 0$ at LHT for these sets of events.

The data presented indicate a substantial negative A_N at relatively large $x_F (> 0.5)$ *and* moderate $p_T (> 0.6$ GeV/c), while for $x_F < 0.5$ *or* $p_T < 0.6$ GeV/c A_N is compatible with zero. The only previous results on A_N in inclusive Λ^0 production were obtained at much lower energies [7]. Data at 18.5 GeV/c ($x_F < 0.5$), also shown in Fig. 3 (open diamonds), agree with the present data for the same x_F region, where A_N is measured to be small. The trend of the present results shows similar behavior as the existing Λ^0 polarization data [1], thus suggesting a common interpretation. However, most of the previously quoted models [3–5] explain the Λ^0 polarization by the recombination of a polarized s quark with an unpolarized (ud) spectator diquark, independent from the beam polarization. These results on A_N hence cannot be easily integrated in this framework, unless spectator diquarks play a more significant role than generally expected [8]. Recently proposed models that describe hyperon polarization by mechanisms involving either interference of direct and resonance channels [9] or dominance of peripheral π exchange [10], dominated by quasi-two-body subprocesses, might more easily accommodate the similarity of P_0 and A_N. Conversely, the onset of substantial asymmetry A_N in Λ^0 production further strengthens the case brought up by the Λ^0 polarization that single-spin effects might be appreciably larger than expected from perturbative QCD.

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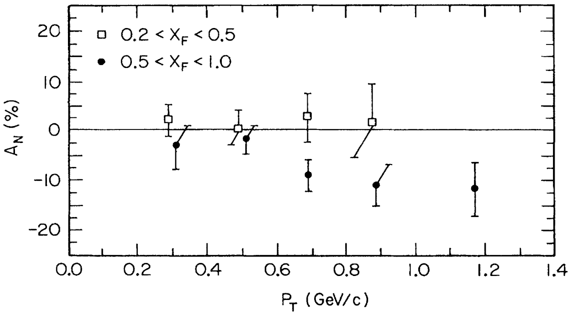

FIG. 4. A_N data for $p\uparrow + p \rightarrow \Lambda^0 + X$ as a function of p_T.

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