Spin Transfer in Inclusive Λ^0 Production by Transversely Polarized Protons at 200 GeV/c

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Surprisingly large polarizations in hyperon production by unpolarized protons have been known for a long time. The spin dynamics of the production process can be further investigated with polarized beams. Recently, a negative asymmetry A_N was found in inclusive Λ^0 production with a 200 GeV/c transversely polarized proton beam. The depolarization D_{NN} in $p\uparrow + p \rightarrow \Lambda^0 + X$ has been measured with the same beam over a wide x_F range and at moderate p_T. D_{NN} reaches positive values of about 30% at high x_F and $p_T \sim 1.0$ GeV/c. This result shows a sizable spin transfer from the incident polarized proton to the outgoing Λ^0. [S0031-9007(97)03247-X]

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The observation 20 years ago of a large negative polarization in inclusive Λ^0 production by an unpolarized proton beam at 300 GeV/c [1] renewed interest in spin as an important factor in high-energy hadron interactions. Afterwards several experiments measured large polarizations for various hyperons over a wide kinematical range [2]. Previous expectations, based on Regge theory and quantum chromodynamics (QCD) predictions, were that spin effects would vanish at high energies, since the smallness of spin-flip amplitudes and the contribution of several production channels to an inclusive process with large multiplicity of final states make it unlikely to have the coherent interference between spin nonflip and spin flip amplitudes that leads to sizable polarization effects. Recently, a significant negative analyzing power A_N has been found at 200 GeV/c in inclusive Λ^0 production by a transversely polarized proton beam at high x_F and moderate p_T ($p_T \sim 1$ GeV/c) [3]. Large A_N values have also been found in inclusive pion production with the same proton and antiproton polarized beam [4,5].

Different quark-parton models using static SU(6) wave functions were proposed to interpret these polarization effects by introducing a spin dependence into the partonic fragmentation and recombination processes [6–8]. The Λ^0 polarization is attributed to some mechanism, based on semiclassical arguments [6,7] or inspired by QCD [8], by which *strange* quarks produced in the fragmentation process acquire a large negative polarization. The features of the pion A_N data [4,5] are compatible with these models, provided that this effect occurs also for *up* and *down* quarks. The spin dynamics of these processes can be further investigated using polarized proton beams. In the previous models no correlation with the incident proton polarization is expected in inclusive Λ^0 production, since the Λ^0 spin is carried entirely by its constituent *strange* quark, and the ud di-quark (which is in a spin and isospin singlet state) propagates unperturbed as a spectator in the interaction. Therefore spin asymmetries related to the beam polarization are expected to vanish. The negative asymmetry A_N observed in Λ^0 production [3] is difficult to integrate in this picture unless the spectator ud di-quarks play a more significant role in the recombination process than generally expected [9]. Studies of other spin asymmetries in high-energy hyperon production add further input into understanding these phenomena.

In this Letter we report on the measurement of the depolarization parameter D_{NN} in inclusive Λ^0 production with the 200 GeV/c Fermilab polarized proton beam [10] and a 1.0 m long liquid hydrogen target in the kinematical range $0.2 \le x_F \le 1.0$ and $0.1 \le p_T \le 1.5$ GeV/c. The double-spin parameter,

$$D_{NN} = \frac{E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} - E\frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}{E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow} + E\frac{d^3\sigma}{dp^3}^{\uparrow\downarrow}}, \quad (1)$$

measures the fraction of the incident proton polarization transferred to the inclusively produced Λ^0. $E\frac{d^3\sigma}{dp^3}^{\uparrow\uparrow(\uparrow\downarrow)}$ is the spin-dependent differential cross section for the process $p\uparrow + p \to \Lambda^0 \uparrow + X$ with parallel (antiparallel) spin configurations for the incident proton and the outgoing Λ^0, both polarizations being orthogonal to the production plane.

The transversely polarized proton beam contained simultaneously protons of opposite *tagged* polarizations. This considerably suppressed the systematic effects. The magnitude of the average beam polarization was 0.46 ± 0.03 [10] for both signs. Typical beam intensities at the experimental target were of the order of 2×10^7 polarized protons per 20 sec spill.

Λ^0 hyperons produced at the experimental target were identified by reconstructing their decay $\Lambda^0 \to p\pi^-$. Charged particles were measured in a forward spectrometer, described in Refs. [3,4], equipped with 42 multiwire proportional planes and a 3 T m $\int Bdl$ dipole analyzing magnet. A threshold Cherenkov counter, C1, downstream of the magnet, was used for proton identification.

Secondary Λ^0 decay vertices (V^0's) were searched by combining proton tracks identified by C1 with negatively charged tracks, assuming that they were π^-'s [3]. It was required that (1) the closest distance in space of the two tracks was <2 mm and that the V^0 decay vertex was located between 20 and 540 cm downstream of the target end; (2) the V^0 came from the target and matched there the beam impact point within 2 mm in the transverse plane; (3) the V^0's populated the decay phase space region corresponding to Λ^0 decays, bounded by $0.45 < (p_L^+ - p_L^-)/(p_L^+ + p_L^-) < 0.95$ and $q_T = q_T^+ = q_T^- < 0.12$ GeV/c, where p_L^+ (p_L^-) is the longitudinal component of the positive (negative) track momentum and q_T is the transverse component of these momenta with respect to the V^0 line of flight.

These selection cuts led to a clean Λ^0 peak in the $p\pi^-$ invariant mass spectrum, centered at 1.116 GeV/c^2 with a width $\sigma = 1.7$ MeV/c^2 and an estimated 2% uniform background below the Λ^0 peak, as most sources of background were suppressed by the vertex fiducial volume cut, the selection of the Λ^0 decay phase space region, and $K_S^0 \to \pi^+\pi^-$ decays were rejected by C1. We selected Λ^0's in a mass window of ± 5.1 MeV/c^2 about the peak. For the D_{NN} analysis we required additionally that the Λ^0's were produced to the beam right in the azimuthal angular interval of $\pm 60°$ from the horizontal plane around the beam axis. A sample of about 40 000 Λ^0's was thus selected.

For each x_F and/or p_T bin, the double-spin parameter D_{NN} was extracted from the Λ^0 decay proton angular distribution in the Λ^0 rest frame by defining four sets of events, integrating separately the decay proton angular distribution above and below the Λ^0 production plane for the two opposite beam polarizations. D_{NN} is then obtained from the asymmetry,

$$D_{NN} = \frac{1}{P_B\langle\cos\phi_V\rangle}\frac{2}{\alpha_\Lambda} \times \frac{(N_{\rm up}^+ + N_{\rm down}^-) - (N_{\rm up}^- + N_{\rm down}^+)}{(N_{\rm up}^+ + N_{\rm down}^-) + (N_{\rm up}^- + N_{\rm down}^+)}, \quad (2)$$

where, for instance, $N_{\rm up}^+$ is the number of Λ^0's produced by beam protons polarized upward and emitting decay protons in the positive hemisphere with respect to the normal to the production plane. P_B is the proton beam polarization, ϕ_V is the angle between the beam polarization axis directed upward and the normal to the production plane ($\langle\cos\phi_V\rangle \approx -0.85$ in the selected azimuthal range), and $\alpha_\Lambda = 0.642$ is the $\Lambda^0 \to p\pi^-$ decay asymmetry.

The depolarization D_{NN} is given in Table I and shown in Fig. 1 as a function of p_T averaged over the x_F interval of 0.2–1.0. D_{NN} increases with p_T to significantly large positive values with an indication of flattening in p_T above 1.0 GeV/c, while at low p_T values it is compatible with zero. Figure 2 and Table II show the double-spin parameter D_{NN} as a function of x_F averaged over the p_T interval of 0.1–1.5 GeV/c. At large x_F values D_{NN} reaches positive values as large as 0.30 at $p_T \sim 1$ GeV/c (see also Table I, row 6–11, where the p_T dependence is shown for two separate x_F intervals), while almost no dependence in x_F is observed for $x_F < 0.6$, where D_{NN} is compatible with zero or slightly positive. In Figure 3 the D_{NN} data are split into two p_T intervals and plotted as a function of x_F. At low p_T they appear to be essentially zero, while in the high p_T bin they show large positive values.

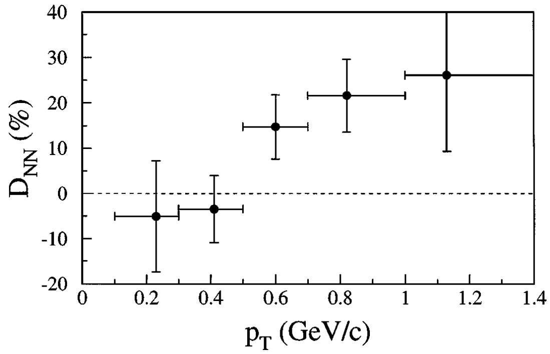

FIG. 1. Depolarization D_{NN} data as a function of p_T in $p\uparrow + p \to \Lambda^0 + X$ at 200 GeV/c. The errors shown are statistical only.

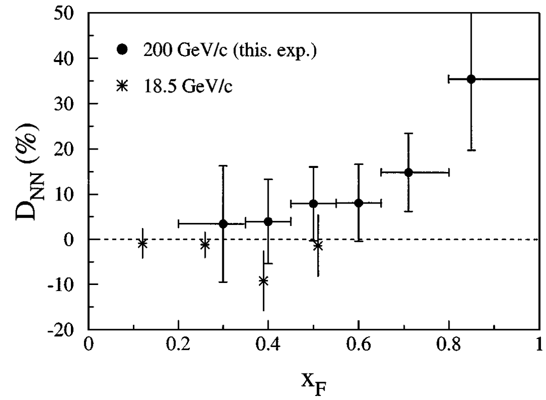

FIG. 2. Depolarization D_{NN} data as a function of x_F. The errors shown are statistical only. Also shown are D_{NN} measurements at 18.5 GeV/c from Ref. [12] ($\langle p_T \rangle \sim 1.0$ GeV/c for the plotted points).

The D_{NN} results thus obtained are independent to a good accuracy of apparatus and reconstruction biases, since Λ^0's were measured with the same apparatus and opposite beam polarizations simultaneously. Systematic errors from sources such as the uncertainty on the beam polarization and the background below the Λ^0 peak were estimated to be negligible compared to statistical ones. For a further check of systematic biases we evaluated D_{NN} for non-Λ^0 events ($p\pi^-$ combinations outside the Λ^0 mass window and K_S^0). This *background* D_{NN} is essentially independent of p_T and x_F, and, for instance, it is -0.025 ± 0.062 for $x_F < 0.5$ ($+0.028 \pm 0.050$ for $x_F > 0.5$) and 0.010 ± 0.044 for $p_T < 0.6$ GeV/c (-0.009 ± 0.082 for $p_T > 0.6$ GeV/c). We also evaluated the Λ^0 polarization P_0 by averaging over opposite beam polarizations and found a good agreement with existing polarization results obtained with unpolarized protons [2]. For example, we obtained $P_0 = -0.052 \pm 0.030$ for $\langle p_T \rangle \sim 0.5$ GeV/c, $\langle x_F \rangle \sim 0.4$, and $P_0 = -0.281 \pm 0.034$ for $\langle p_T \rangle \sim 0.9$ GeV/c, $\langle x_F \rangle \sim 0.7$.

A few D_{NN} measurements in inclusive Λ^0 production were previously performed with polarized proton beams at much lower energies of 6 GeV/c [11], 13.3 GeV/c, and 18.5 GeV/c [12]. Figure 2 also shows data obtained at 18.5 GeV/c for a bin about $\langle p_T \rangle \sim 1.0$ GeV/c [12]. The present data appear to be compatible with the data of [12] over their overlapping kinematical region, which, however, doesn't extend above $x_F \sim 0.5$, and where both are close to zero. The range of overlap doesn't extend to large x_F, where the present data show significantly large effects, and therefore no statement about the energy dependence of D_{NN} can be made in this case. More recently, a sizable spin transfer has been inferred in Ω^- production by high-energy neutral beams containing transversely polarized Λ^0's and Ξ^0's [13]. These data, at

TABLE I. Depolarization D_{NN} data for $p\uparrow + p \to \Lambda^0 + X$ at 200 GeV/c as a function of p_T. The errors are statistical only; systematic errors were estimated to be negligible compared to the statistical ones (see text).

p_T interval (GeV/c)	D_{NN}	$\langle x_F \rangle$	$\langle p_T$(GeV/c)$\rangle$
	$0.2 \le x_F \le 1.0$		
0.1–0.3	-0.5 ± 0.12	0.42	0.23
0.3–0.5	-0.035 ± 0.074	0.49	0.41
0.5–0.7	0.147 ± 0.071	0.56	0.60
0.7–1.0	0.216 ± 0.081	0.61	0.82
1.0–1.5	0.26 ± 0.17	0.66	1.13
	$0.2 \le x_F \le 0.5$		
0.1–0.4	-0.03 ± 0.10	0.38	0.29
0.4–0.6	0.14 ± 0.11	0.40	0.49
0.6–1.0	0.20 ± 0.13	0.42	0.74
	$0.5 \le x_F \le 1.0$		
0.5–0.7	0.09 ± 0.09	0.65	0.60
0.7–1.0	0.24 ± 0.09	0.67	0.82
1.0–1.5	0.31 ± 0.18	0.69	1.14

TABLE II. Depolarization D_{NN} data for $p\uparrow + p \to \Lambda^0 + X$ as a function of x_F (the errors are statistical only).

x_F interval	D_{NN}	$\langle x_F \rangle$	$\langle p_T$(GeV/c)$\rangle$
	$0.1 \le p_T \le 1.5$ GeV/c		
0.20–0.35	0.03 ± 0.13	0.30	0.41
0.35–0.45	0.039 ± 0.093	0.40	0.49
0.45–0.55	0.079 ± 0.082	0.50	0.57
0.55–0.65	0.081 ± 0.086	0.71	0.71
0.80–1.0	0.35 ± 0.16	0.85	0.79
	$0.1 \le p_T \le 0.6$ GeV/c		
0.2–0.4	-0.05 ± 0.11	0.33	0.37
0.4–0.6	0.01 ± 0.08	0.49	0.42
0.6–0.8	-0.02 ± 0.11	0.68	0.47
	$0.6 \le p_T \le 1.5$ GeV/c		
0.3–0.5	0.17 ± 0.12	0.43	0.77
0.5–0.7	0.19 ± 0.09	0.60	0.81
0.7–1.0	0.37 ± 0.11	0.79	0.84

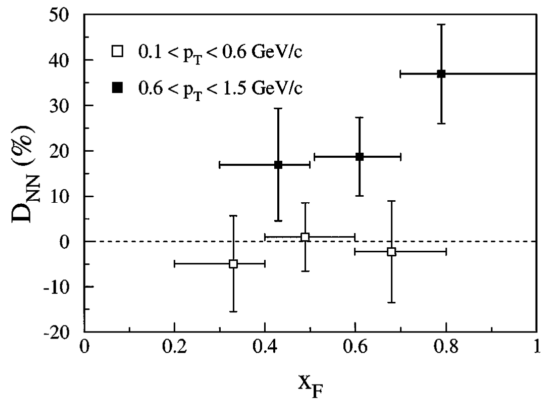

FIG. 3. Depolarization D_{NN} data as a function of x_F divided into two p_T intervals of $0.1 \leq p_T \leq 0.6$ GeV/c (open squares) and $0.6 \leq p_T \leq 1.5$ GeV/c (full squares). The errors shown are statistical only.

even higher energies than the present ones, suggest also that the spin dependence of hyperon production on the beam polarization might be of a general nature, although possibly associated with different mechanisms.

The kinematical dependence of present D_{NN} results shows, in magnitude, a behavior similar to the hyperon polarization in unpolarized proton collisions [2]. The observed D_{NN} results, as in the case of the A_N data in inclusive Λ^0 production [3], cannot, however, be directly obtained from a mechanism such as proposed to explain the Λ^0 polarization [6–8], where a highly polarized *strange* quark produced in the fragmentation process recombines with an unpolarized ud spectator di-quark from the incident proton independently of its polarization. Our results indicate a substantial spin transfer as large as 30% at high x_F ($x_F > 0.6$) and $p_T \sim 1$ GeV/c from the incident polarized proton to the inclusively produced Λ^0.

More recent models based on nonperturbative approaches and peripheral mechanisms with an underlying quasibinary subprocess, such as a π exchange mechanism [14] or resonance-decay interference between real and virtual channels [15], were proposed to explain the Λ^0 polarization. These models might also accommodate a more substantial spin dependence in the Λ^0 production process, such as the one shown by the present data. A model, based on the idea of rotating constituents in polarized protons [16], is fairly successful in accounting for the observed A_N behavior in pion production. This model also appears to reproduce qualitatively the Λ^0 analyzing power and the D_{NN} data presented in this Letter.

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