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[5]Because of the steep falloff of the photon spectra with increasing $p_\perp$, we find that our neglect of the photon pairs with lower $p_\perp$ causes an error of less than 2% in the measured invariant cross sections.

[6]The contamination in the p and π^+ samples from misidentified particles is $\lesssim 0.5\%$. In the π^- sample the contamination is $\lesssim 0.1\%$.

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Λ^0 Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium

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Λ^0 polarization has been observed in $p + \mathrm{Be} \to \Lambda^0 + \text{anything}$ at 300 GeV. A total of 1.2×10^6 Λ^0 decays were recorded at fixed lab angles between 0 and 9.5 mrad, covering a range of kinematic variables $0.3 \leq x \leq 0.7$ and $0 \leq p_\perp \leq 1.5$ GeV/c. The observed polarization was consistent with parity conservation and increased monotonically with increasing $p_\perp$, independently of x, reaching $P_\Lambda = 0.28 \pm 0.08$ at 1.5 GeV/c.

Multiparticle-final-state reactions form the major part of the total cross section at high energies. The general case is difficult to treat both experimentally and theoretically because of the high multiplicity. Inclusive channels of the form $a + b \to c + X$, however, may be described in a fairly simple way because of the sum over the unobserved states X. There has been considerable experimental and theoretical activity in the study of kinematic distributions of inclusive channels for various choices of particles a, b, and c.[1] If any of these three particles has spin, then polarization effects are possible which furnish information sensitive to interference between various amplitudes contributing to the reaction. It is known that as the energy increases polarization effects in elastic scattering become very small.[2] Few measurements of high-energy inclusive polarization effects have been made.[3] This Letter reports the first observation of substantial polarization effects in inclusive production at 300 GeV. The polarization was observed in the channel $p + \mathrm{Be} \to \Lambda^0 + X$. A reaction of this type, where particle c is a Λ^0 hyperon, is particularly well suited to polarization measurements because the Λ^0 serves as its own spin analyzer through the decay $\Lambda^0 \to p + \pi^-$.[4]

Figure 1 shows the apparatus. The 300-GeV protons were deflected vertically (positive angles upwards) with a magnet 150 m upstream of the Λ^0 production target, and then restored to the target with magnets 5 m upstream, to obtain production angles between 0 and 9.5 mrad in a vertical plane. The neutral beam was defined by a fixed collimator with its axis in the horizontal plane. The collimator was 5.3 m long, compared to the decay length for 150-GeV/c Λ^0's of 10.4 m. A vertical magnetic field (the sweeping magnet) of 21 kG was applied to the collimator. A circular tungsten aperture 4 mm in diameter at 3.2 m defined

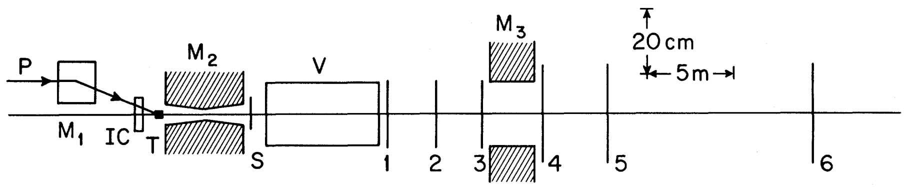

FIG. 1. Elevation view of the Fermilab neutral hyperon beam. 300-GeV protons were incident from the left. M_1 is the restoring magnet for production-angle variation. IC and T are ion chamber and Be target. M_2 is the collimator and sweeper. S is a veto counter; V is the decay vacuum; and 1–6 are multiwire proportional chambers. M_3 is the analyzing magnet.

a solid angle of 1.2 μsr. The production target was a beryllium cylinder 6 mm in diameter and 15 cm long.

A multiwire proportional chamber system and spectrometer magnet of conventional design were used to reconstruct the decays $\Lambda^0 \to p + \pi^-$. The spectrometer system could record 220 events per 1-sec beam spill. The trigger required a coincidence between signals from each of the first five proportional chambers. At 0.5 mrad 40% of the triggers reconstructed as Λ^0, with mass resolution (full width at half-maximum) of 6 MeV/c^2. At 9.5 mrad 10% of the triggers reconstructed as Λ^0. The other triggers were $K_s^0 \to \pi^+ + \pi^-$ along the vacuum decay length, and conversions $\gamma \to e^+ + e^-$ and neutron stars in the thin windows and other material in the neutral-beam path. A typical 80 000-trigger magnetic tape required about 1 h. Data were taken at eight production angles: -2.5, -1.5, $+0.5$, $+1.5$, $+3.5$, $+5.5$, $+7.5$, and $+9.5$ mrad. At each angle data were taken for both polarities of the sweeping magnetic field. The analyzing magnet was periodically reversed. Beryllium target and "no target" data were interleaved. The Λ^0 (target out)/(target in) yield was 2%.

In the rest frame of the Λ^0 the proton distribution is $dN/d\Omega = (1+\alpha P\cos\theta)/4\pi$, where θ is the angle between the proton momentum and the Λ^0 spin, P is the magnitude of the polarization, and $\alpha = 0.647 \pm 0.013$.[5] In this frame let $\hat{z}$ be parallel to the Λ^0 momentum, $\hat{x}$ be horizontal, and $\hat{y}$ be in a vertical plane, positive upwards. Each component of the proton asymmetry was measured separately using the maximum-likelihood method. For the z component the likelihood term for the ith event was $L_i = (1+\alpha P_z \cos\psi_i)/[\int d\cos\psi\,(1+\alpha P_z \times \cos\psi)]$, where ψ_i is the polar angle between the Λ^0 momentum vector and the proton momentum vector in the Λ^0 rest frame. The denominator was evaluated over the acceptance of the spectrometer for each event separately. The unknown parameter (αP_z) was then obtained by maximizing $L = \prod_i L_i$.

The three components of asymmetry were measured in the hyperon rest frame downstream of the sweeping magnet channel, after the Λ^0's had passed through a vertical magnetic field with $\int B\,dl = 117 \pm 3$ kg m. Λ^0's polarized in the horizontal plane should precess through an angle greater than 90° between the beryllium target and the decay region. The advantage of this precession was that the z component of the asymmetry would change sign as the sweeper polarity was reversed, giving a useful handle on the presence of polarized Λ^0's. This is shown schematically in Fig. 2(a). The polarity of the sweeper did not affect the detection efficiency of the apparatus in any way. Experimental evidence for a sweeper-dependent asymmetry is presented in Fig. 2(b), where αP_z versus production angle θ_Λ is plotted for the 150-GeV/c Λ^0 momentum bin. The separation between sweeper + and sweeper − is attributed to a reversal of αP_z. Neighboring momentum bins showed the same trend. Plots similar to Fig. 2(b) were made for all three components of the asymmetry in momentum bins 20 GeV/c wide between 70 and 210 GeV/c. The data were consistent with the initial spin along $\hat{x} = (\vec{p}_\Lambda \times \vec{p}_p)/|\vec{p}_\Lambda \times \vec{p}_p|$. Thus the z component reversed as the sweeper polarity was reversed, while the x and y components remained unchanged. One half the difference between results for sweeper + and sweeper − was taken as αP_z, while results for the two polarities were averaged to obtain αP_x and αP_y. No statistically significant asymmetry was observed at any momentum in any of the three components for angles less than 3.5 mrad. In particular 157 000 events at ± 0.5 mrad showed no effect in any component of the asymmetry, serving to check for parity-nonconserving polarization in production, Λ^0 polarization due to a polarization of the incident diffractively scattered proton beam, and geometrical biases in the appa-

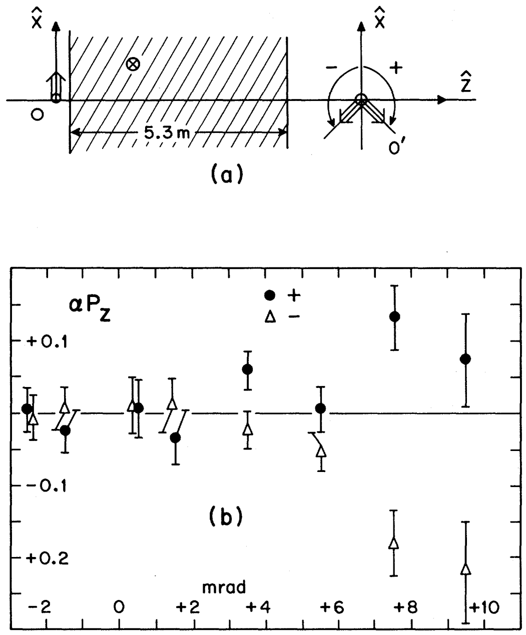

FIG. 2. (a) Horizontal-plane view of the motion of Λ^0 spin in the magnetic field of the collimator. Hyperons were produced at O. Double arrows represent the spin directions. Positive polarity precesses a negative moment clockwise. The polarization components were measured at O'. (b) αP_z as a function of θ_Λ for 140 GeV/$c \leq p_\Lambda \leq 160$ GeV/c. A sweeper-dependent asymmetry appears for $\theta_\Lambda \geq 3$ mrad.

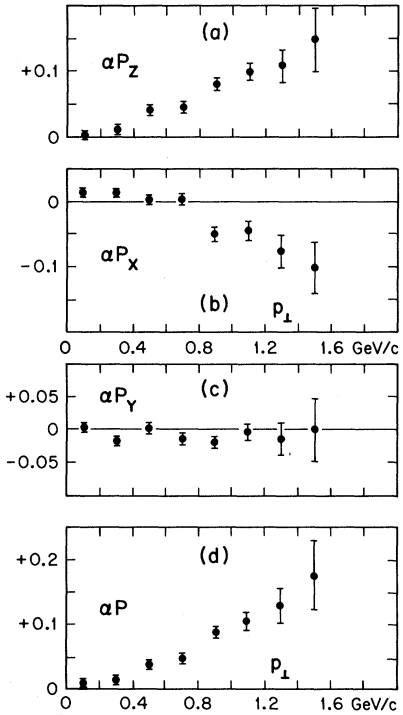

FIG. 3. Three components and magnitude of the $\Lambda^0 \to p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.

ratus. As a further check on geometrical biases, the data sample for the decay $K_s^0 \to \pi^+ + \pi^-$ (156 000 events) was analyzed for a "polarization" in the same way as $\Lambda^0 \to p + \pi^-$, and showed no statistically significant effect.

To convert the observed asymmetry components from the variables $\alpha P_z(\theta_\Lambda, p_\Lambda)$ as shown in Fig. 2(b) into scaling variables $\alpha P_z(p_\perp, x)$ the substitutions $p_\perp = p_\Lambda \theta_\Lambda$ and $x \sim p_\Lambda/(300$ GeV/$c)$ were made. Within the statistical accuracy of the data, $\alpha \times P_z(p_\perp, x)$ obtained in this way was found to be independent of x in the range $0.3 \leq x \leq 0.7$, so that the data for all x bins were combined to obtain asymmetries as a function only of $p_\perp$. The plots for $\alpha P_z(p_\perp)$, $\alpha P_x(p_\perp)$, and $\alpha P_y(p_\perp)$ measured at the point O' in Fig. 2(a) are shown in Figs. 3(a), 3(b), and 3(c). The ratio $\alpha P_x/\alpha P_z$ is a measure of the magnetic moment of the Λ^0, and should be independent of $p_\perp$. A comparison of Figs. 3(a) and 3(b) shows that this is indeed the case for $p_\perp \geq 0.8$ GeV/c, where the magnitude of the observed polarization is statistically different from zero. If the sign of the magnetic moment is assumed negative, and the magnitude is assumed less than $1.2\mu_p$ (μ_p = proton magneton), then the average precession angle Ω is $\pi/2 + \tan^{-1}(\alpha P_x/\alpha P_z)$. The experimental value of $\Omega = 122° \pm 10°$ combined with the field integral quoted above gives $\mu_\Lambda = (-0.57 \pm 0.05)\mu_p$.[6] From Fig. 3(c) the average value of the parity-nonconserving component αP_y is -0.009 ± 0.003. The other parity-nonconserving component at the point O in Fig. 2(a), the z component, can be obtained by comparing sweeper + and sweeper − data, with the result that if ω is the angle between $\vec{P}$ and $\hat{x}$ at production, $P\sin\omega = 0.005 \pm 0.003$. Figure 3(d) shows the $p_\perp$ dependence of $|\alpha P| = [(\alpha\vec{P}\cdot\hat{x})^2 + (\alpha\vec{P}\cdot\hat{z})^2]^{1/2}$. The polarization increases monotonically with increasing $p_\perp$ over the range of $p_\perp$ observed. At $p_\perp = 1.5$ GeV/c the observed value is $\alpha P = 0.18 \pm 0.05$, corresponding to $P = 0.28 \pm 0.08$. For $p_\perp \geq 0.8$ GeV/c, $\langle \alpha P \rangle = 0.100 \pm 0.007$.

The orientation of the spin vector $\vec{P}_\Lambda$ normal to the production plane and the functional dependence $P_\Lambda(p_\perp)$ are both consistent with the hypothesis that the polarization arises in the inclusive channel through strong interaction. Any model of this high-energy inclusive reaction should accommodate a monotonic rise of P_Λ with increasing $p_\perp$, and a weak dependence of P_Λ on the scaling variable x. The observed x range corresponds to a missing mass M of the recoil system X of 13 GeV $\leq M \leq 20$ GeV. If the polarization is produced by the interference of two amplitudes f_1 and f_2, $P_\Lambda = 2\,\mathrm{Im} f_1 f_2^*/(|f_1|^2+|f_2|^2)$, then it will have a weak x dependence provided that f_1 and f_2 depend on x in the same way, which cancels in the ratio.

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Spin from Isospin in a Gauge Theory*

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We show that in an SU(2) quantum gauge field theory, with isospin symmetry broken spontaneously by a triplet of scalar mesons, isospinor degrees of freedom are converted into spin degrees of freedom in the field of a magnetic monopole.

Classical solutions to gauge theories[1] mix spatial and internal symmetry indices; for example an isotriplet vector field $A_a^{\,i}(\vec{r})$ is proportional to $\epsilon_{aij}\hat{r}^j$. We now know that such solutions play a role in the corresponding quantum theory; in a weak-coupling limit they approximate matrix elements of the quantum field between soliton-monopole states.[2] It is natural to ask the following: Does the conjunction of spin and internal symmetry persist in the quantum theory; and, when internal symmetry is spontaneously broken, do internal degrees of freedom reappear as spin degrees of freedom?

An affirmative answer to this question is indicated by our investigation[3] of the interaction of an isospinor, spin-$\frac{1}{2}$ fermion with a monopole, arising in an SU(2) Yang-Mills-Higgs model with spontaneously broken isospin symmetry.[4] We found in the quantum theory a tower of spinless states, describing dyons with magnetic charge $Q_m = \pm 1/e$ and electric charge $Q_e = \pm (N/2)e$ (e is the gauge coupling constant and N is an integer or zero). Moreover, the quantum Fermi field Ψ effects a transition between them, $\langle Q_m, Q_e - e/2| \times \Psi | Q_m, Q_e\rangle \neq 0$. This matrix element is related to the static, zero-energy solution of a c-number Dirac equation in the monopole field. The solution $\psi_{\nu n}$ (ν refers to Dirac indices; n to isospin indices) has vanishing lower components ($\nu = 3, 4$), while the upper components have the form

$$\psi_{\nu n} = f(r)(1/\sqrt{2})(s_\nu^{\,+} s_n^{\,-} - s_\nu^{\,-} s_n^{\,+}), \qquad \nu, n = 1, 2, \tag{1}$$

where s^+ (s^-) is a Pauli up (down) bispinor, and f is a normalized wave function.

In the transition form factor (1), spin and isospin form an antisymmetric singlet. This explains mathematically the curious circumstance that a spinor field should possess nonvanishing matrix elements between spinless states. Evidently degrees of freedom of the spontaneously broken isospin symmetry survive as spin degrees of freedom, and couple to Dirac spin. For physical clarification, consider the nonvanishing crossed matrix element $\langle Q_m, Q_e - e/2; -Q_m, -Q_e| \times \Psi|0\rangle$, which describes the creation of two spinless dyons by a spin-$\frac{1}{2}$ field. Angular momentum is conserved, since as is well known, the total angular momentum of magnetic systems