Λ^0 Polarization in 800-GeV/c $pp \rightarrow p_f(\Lambda^0 K^+)$

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We report results from a study of Λ^0 polarization in the exclusive reaction $pp \rightarrow p_f(\Lambda^0 K^+)$ at 800-GeV/c. We observe a dependence of the polarization on the $\Lambda^0 K^+$ invariant mass with large (+71%) positive polarization at small mass (1.63-GeV/c^2) and large (−43%) negative polarization at large mass (2.75-GeV/c^2). This observation confirms the result of the CERN ISR R608 experiment and extends the range over which the effect is observed. The strong dependence of the polarization on the $\Lambda^0 K^+$ invariant mass suggests that the origin of the polarization is closely related to the production dynamics of the diffractively produced $\Lambda^0 K^+$ system.

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The polarization of Λ^0 hyperons produced in high energy interactions is well established experimentally [1]. Most of these observations have been of *inclusive* Λ^0 production. However, an understanding of the source of the polarization remains elusive. Many theoretical ideas have been proposed to explain the source of the polarization in the context of the Lund model, parton recombination, multiple scattering of the strange quark, gluon fusion, Regge theory, coherent scattering, low and high order QCD calculations, valence quark effects, and quark condensates [2]. However, there is, to date, no compelling explanation. Several experiments have measured Λ^0 polarization in *exclusive* events [3–7] motivated by the hope that important clues might be uncovered regarding the origin of the polarization by studies of specific final states.

We report here the results of a study of Λ^0 polarization in the diffractive reaction,

$$pp \rightarrow p_f(\Lambda^0 K^+). \quad (1)$$

These data are a part of the data set collected by Fermilab E690 during the 1991 fixed target run described elsewhere in detail [5]. A beam of 800-GeV/c protons interacted in a 14.3-cm-long liquid hydrogen target. Charged particles produced in the pp reaction and those charged particles resulting from the decays of short-lived particles were detected and measured in a multi-mini-drift chamber magnetic spectrometer. The momentum of the beam particle was measured in a separate spectrometer [8]. The event sample was reconstructed using a special computational system [9].

This analysis of E690 data was performed after the track and vertex reconstruction stage of the data analysis. The data sample used in this analysis consists of 4.7×10^9 events. Candidates for reaction (1) were selected by requiring events in which both the incoming beam proton and the outgoing "fast" proton (p_f) are reconstructed in the beam spectrometer system. In addition, the event is required to have two positively charged and one negatively charged tracks in the minidrift chamber magnetic spectrometer with two reconstructed vertices, an interaction vertex, and an unambiguous $\Lambda^0 \rightarrow p\pi^-$ decay vertex. The interaction

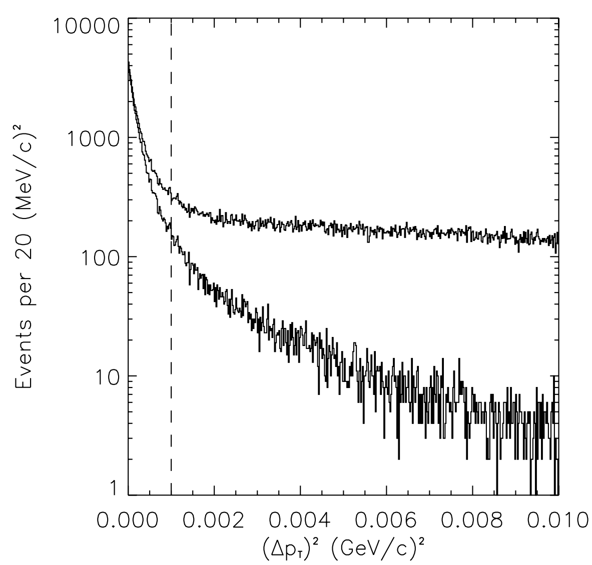

FIG. 1. Sum of p_T^2. The upper histogram is the $(\Delta p_T)^2$ distribution for all events. The lower histogram is the event distribution after the $\Delta(E - p_L)$ cut is made on the data. Events with $(\Delta p_T)^2$ less than the value indicated by the dashed line are used in this analysis.

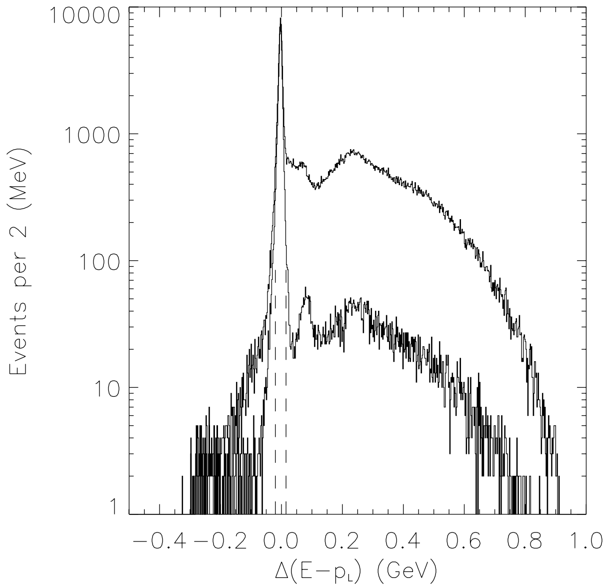

FIG. 2. Difference of final and initial $E - p_L$. The upper histogram is the $\Delta(E - p_L)$ for all events; the lower histogram is the distribution after the $(\Delta p_T)^2$ cut is made on the data. Events with $\Delta(E - p_L)$ between the values indicated by the dashed lines are used in this analysis.

vertex is required to be located within the target fiducial volume. The third track and the reconstructed Λ^0 are required to point back to the primary vertex. The selection requirements are satisfied by 198 257 events.

Conservation of energy and momentum was used to ensure that candidates for reaction (1) were correctly identified. To implement the conservation laws two event variables are used: (i) $(\Delta p_T)^2$, the square of the difference of the initial beam $\mathbf{p_T}$ and the sum of the final state particle $\mathbf{p_T}$, and (ii) $\Delta(E - p_L)$, the difference of the initial $E - p_L$ and the sum of the final state particle

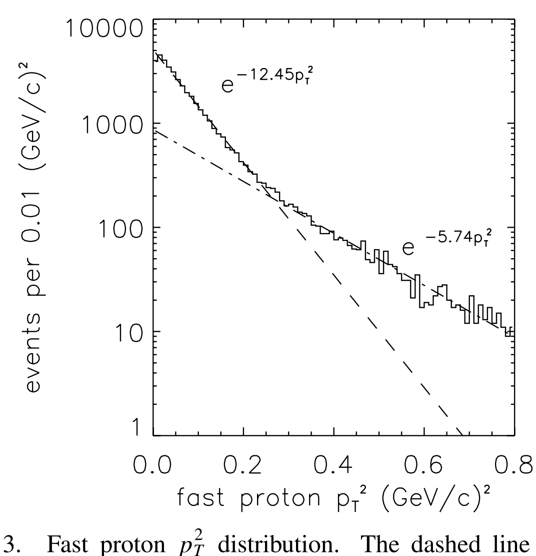

FIG. 3. Fast proton p_T^2 distribution. The dashed line is the result of fitting the distribution for $p_T^2 < 0.25$ (GeV/c)^2; the dot-dashed line is for $p_T^2 > 0.25$ (GeV/c)^2.

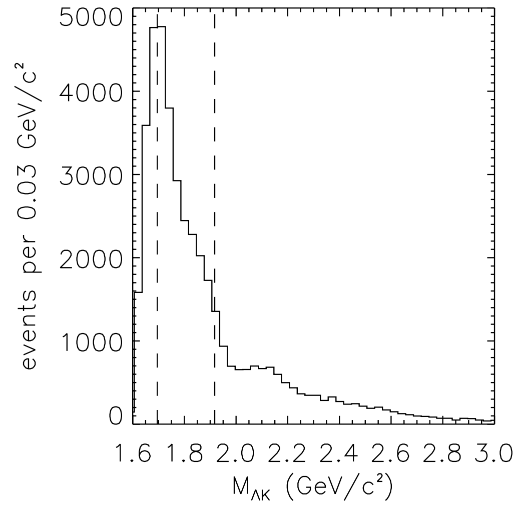

FIG. 4. $M_{\Lambda K}$ invariant mass distribution. The dashed lines indicate $M_{\Lambda K} = 1.70$- and 1.92-GeV/c^2, as in Fig. 6.

$E - p_L$. These two variables should be zero if energy and momentum are conserved in the event, which is the case if all of the particles in the event have been observed. The exclusive isolation cuts used in this analysis are $(\Delta p_T)^2 < 0.001$ (GeV/c)^2 and -0.020-GeV $< \Delta(E - p_L) < 0.015$-GeV. The event distributions in $(\Delta p_T)^2$ and $\Delta(E - p_L)$ are shown in Figs. 1 and 2, respectively. The cut limits are chosen to maximize the number of events in the data sample while reducing the number of background events. When these cuts are applied, the sample contains 42 717 events. The additional

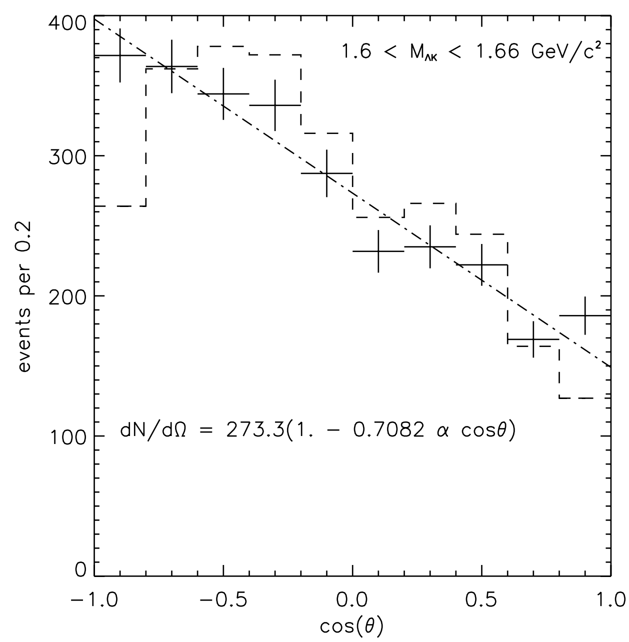

FIG. 5. The proton cosθ distribution in the Λ rest frame with respect to the vector normal to the Λ production plane, $\hat{n}$. The dashed histogram is the uncorrected data, the points with error bars are the corrected data, and the dot-dashed line is the result of a fit to Eq. (4).

TABLE I. Λ^0 polarization for bins of M_X.

M_X (GeV/c^2):	1.630	1.675	1.715	1.745	1.775	1.810	1.850	1.895	1.940	2.000	2.090	2.195	2.325	2.500	2.750
$\mathcal{P}$ (%):	71 ± 5	60 ± 4	34 ± 4	26 ± 5	28 ± 5	21 ± 5	17 ± 5	14 ± 5	40 ± 7	37 ± 6	20 ± 6	3 ± 6	−11 ± 7	−14 ± 7	−43 ± 8

constraint of longitudinal momentum conservation is satisfied (within the 200-MeV/c resolution) by the previously described cuts. Additional cuts on direct particle identification available from the time-of-flight system and the highly segmented Cerenkov system greatly reduce the number of events in the sample.

The number of background events is estimated to be ≈200 from Fig. 2. The major background is from the reaction $pp \to p\Sigma^0 K^+$, where $\Sigma^0 \to \Lambda^0\gamma$, where the undetected γ has $E - p_L \approx 0$. The cuts above would require the γ to have $p_T < 30$-MeV/c. This background is estimated by the Monte Carlo method to be less than 5%.

Two variables can be used to describe the dynamics of reaction (1) completely if we reinterpret the reaction as

$$pp \to p_f X\,, \tag{2}$$

with the X system subsequently "decaying" to $\Lambda^0 K^+$. Figures 3 and 4 show the distribution of the two variables: fast proton transverse momentum squared (p_T^2) and the $\Lambda^0 K^+$ invariant mass ($M_{\Lambda K}$), respectively. Figure 3 is indicative of diffractive proton scattering, i.e., forward peaking of the scattered proton.

The polarization of the Λ^0 is observed with respect to the vector normal to the Λ^0 production plane defined as

$$\hat{n} \equiv \frac{\vec{P}_{\rm beam} \times \vec{P}_\Lambda}{|\vec{P}_{\rm beam} \times \vec{P}_\Lambda|}\,, \tag{3}$$

where $\vec{P}_{\rm beam}$ and $\vec{P}_\Lambda$ are the momentum vectors of the incident beam proton and of the Λ^0, respectively.

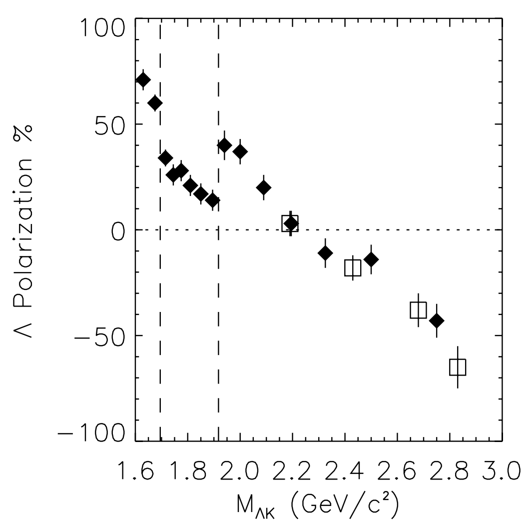

FIG. 6. Λ^0 polarization as a function of $M_{\Lambda K}$. The dashed lines indicate rapid changes in the polarization. Our data are shown as filled diamonds. The data of Ref. [3] are shown as the open squares.

The angular distribution of the proton in the Λ^0 rest frame has the following dependence on the Λ^0 polarization:

$$dB/d\Omega = N_0(1 - \alpha\mathcal{P}\cos\theta)\,, \tag{4}$$

where α is the Λ^0 decay asymmetry parameter (equal to 0.642 ± 0.013 [10]) and $\mathcal{P}$ is the Λ^0 polarization (note that the sign of the polarization, opposite that of conventional definitions, accounts for the fact that Λ^0 is produced in the hemisphere opposite the scattered beam proton). The polarization is determined by a linear fit of a function of the form (4) to the $\cos\theta$ distribution of the proton, for two free parameters: a normalization constant, N_0, and polarization, $\mathcal{P}$. The $\cos\theta$ distribution for 1.6-GeV/$c^2 \leq M_{\Lambda K} \leq 1.66$-GeV/$c^2$ is shown in Fig. 5.

A Monte Carlo simulation has been run to correct the small effect of the finite detector acceptance of the apparatus. For each bin of $M_{\Lambda K}$, Monte Carlo events were produced with zero polarization, and $\cos\theta$ distributions were generated as in the data analysis. The Monte Carlo histograms were normalized to an average of one per bin. The acceptance determined by the Monte Carlo in this fashion is used to correct the data distributions by dividing the corresponding data histograms by the normalized Monte Carlo histograms. The resulting fits of the $\cos\theta$ distributions before and after the corrections agree. In Fig. 5 the fit value of $\mathcal{P}$ is $+69 \pm 5\%$ and $+71 \pm 5\%$ for the acceptance uncorrected and corrected distributions, respectively. The $\chi^2/(N - \text{d.o.f.} = 18)$ for these two results are 11.4 and 1.4, respectively, for 2 degrees of freedom. Note that the polarizations agree within error bars. The acceptance correction is applied to the $\cos\theta$ distributions used in this analysis.

The data are binned in $M_{\Lambda K}$ and the polarization of the Λ^0 is determined for each bin. The results are shown in

TABLE II. Λ^0 polarization (%) for bins of x_F and p_T. The number of events in each bin is also indicated.

p_T bin (GeV/c)	x_F bin −1−−0.8	−0.8−−0.7	−0.7−−0.6	−0.6−−0.5
0.0–0.2	+27 ± 5	+24 ± 4	+9 ± 7	···
	3098	5360	1765	···
0.2–0.4	+39 ± 5	+39 ± 3	+16 ± 4	−7 ± 18
	3569	11645	5181	314
0.4–0.6	+47 ± 6	+57 ± 4	+26 ± 6	+20 ± 18
	487	4099	2481	262
0.6–0.8	···	+17 ± 9	−22 ± 9	−4 ± 21
	···	1055	959	208
0.8–1.0	···	−24 ± 13	−57 ± 13	···
	···	448	475	···
1.0–1.2	···	−38 ± 19	−42 ± 17	···
	···	203	217	···

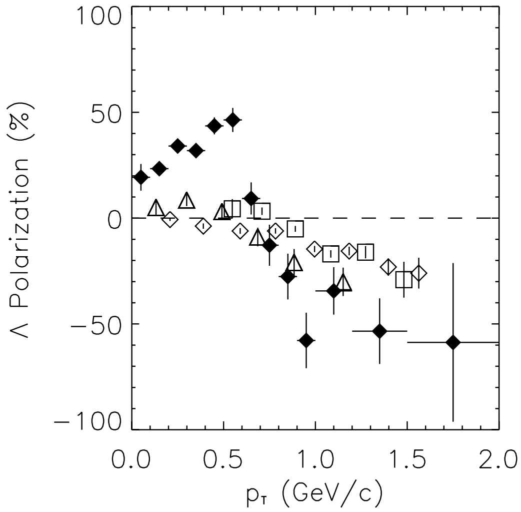

FIG. 7. Λ^0 polarization as a function of $p_{T\Lambda}$: filled diamonds are from this analysis, open triangles are from [5], open squares are from [11], and the open diamonds are from the 1976 Bunce *et al.* in [1].

Table I. Figure 6 shows these results plotted with the results of Ref. [3]. The dashed lines in Fig. 6 indicating rapid changes in the polarization dependence on M_X are also depicted in the M_X distribution shown in Fig. 4. The striking feature of this data is the dependence of the polarization on M_X. Our result reproduces the observation of Ref. [3] that high $\Lambda^0 K^+$ mass is correlated to large negative Λ^0 polarization. In addition, our result shows that low $\Lambda^0 K^+$ mass is correlated to large *positive* Λ^0 polarization. This observation suggests that the polarization may be related to structure in the $\Lambda^0 K^+$ system. The data of Ref. [3] do not extend into the region of low M_X because of acceptance limitations, but agree with our result in the M_X range covered by both experiments.

When the data are analyzed in bins of $\Lambda^0 x_F$ and p_T (see Table II), the results are quite different from what has been observed by other experiments; both measurements of Λ^0 polarization in inclusive reactions [1] and measurements of Λ^0 polarization in exclusive reactions [6,7]. When the data are projected onto the p_T variable, Fig. 7, the low p_T data are quite different from previous measurements while the high p_T data show similar behavior.

No previous experiment has measured a statistically significant *positive* Λ polarization, and most results indicate that the magnitude of the observed negative polarization can be described with a simple monotonic function of x_F and p_T. The data presented here suggest that the origin of Λ polarization in reaction (2) is closely related to the production dynamics of this diffractive reaction.

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[1] G. Bunce *et al.,* Phys. Rev. Lett. **36,** 1113 (1976); V. Blobel *et al.,* Nucl. Phys. **B122**, 429 (1977); K. Heller *et al.,* Phys. Rev. Lett. **41**, 607 (1978); S. Erhan *et al.,* Phys. Lett. **82B**, 301 (1979); G. Bunce *et al.,* Phys. Lett. **86B**, 386 (1979); F. Lomanno *et al.,* Phys. Rev. Lett. **43**, 1905 (1979); K. Raychaudhuri *et al.,* Phys. Lett. **90B**, 319 (1980); F. Abe *et al.,* Phys. Rev. Lett. **50**, 1102 (1983); F. Abe *et al.,* J. Phys. Soc. Jpn. **52**, 4107 (1983); R. Rameika *et al.,* Phys. Rev. D **33**, 3172 (1986); C. Wilkinson *et al.,* Phys. Rev. Lett. **58**, 855 (1987); B. Lundberg *et al.,* Phys. Rev. D **40**, 3557 (1989); A. M. Smith *et al.,* Phys. Lett. B **185**, 209 (1987); J. Duryea *et al.,* Phys. Rev. Lett. **67**, 1193 (1991).

[2] K. J. M. Moriarty *et al.,* Lett. Nuovo Cimento **17**, 366 (1976); B. Andersson *et al.,* Phys. Lett. **85B**, 417 (1979); T. A. DeGrand *et al.,* Phys. Rev. D **24**, 2419 (1981); J. Szweed *et al.,* Phys. Lett. **105B**, 403 (1981); S. M. Troshin and N. E. Tyurin, Sov. J. Nucl. Phys. **38**, 639 (1983); W. G. D. Dharmaratna and G. R. Goldstein, Phys. Rev. D **41**, 1731 (1990); J. Soffer and N. A. Törnqvist, Phys. Rev. Lett. **68**, 907 (1992); R. Barni *et al.,* Phys. Lett. B **296**, 251 (1992); Y. Hama and T. Kodama, Phys. Rev. D **48**, 3116 (1993); W. G. D. Dharmaratna and G. R. Goldstein, Phys. Rev. D **53**, 1073 (1996); S. M. Troshin and N. E. Tyurin, Phys. Rev. D **55**, 1265 (1997); Liang Zuo-tang and C. Boros, Phys. Rev. Lett. **79**, 3608 (1997).

[3] T. Henkes *et al.,* Phys. Lett. B **283**, 155 (1992).

[4] J. Félix, Ph.D. thesis, Universidad de Guanajuato, México, 1994.

[5] S. Lee, Ph.D. thesis, University of Massachusetts, Amherst, 1994.

[6] J. Félix *et al.,* Phys. Rev. Lett. **76**, 22 (1996).

[7] J. Félix *et al.,* Phys. Rev. Lett. **82**, 5213 (1999).

[8] D. C. Christian *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **345**, 62 (1994).

[9] B. C. Knapp and W. Sippach, IEEE Trans. Nucl. Sci. **NS-27**, 578 (1980); E. P. Hartouni *et al., ibid.* **NS-36**, 1480 (1989); B. C. Knapp, Nucl. Instrum. Methods Phys. Res., Sect. A **289**, 561 (1990).

[10] Particle Data Group, M. Ameodo *et al.,* Phys. Rev. D **50**, 1 (1994).

[11] K. Heller *et al.,* Phys. Lett. **68B**, 480 (1977).