Polarization study of inclusive Λ production in K^-p interactions*

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Data are presented on the inclusive reaction $K^-p \to \Lambda X$ at 7.3 GeV/c and compared with recent results at 3.93 and 14.3 GeV/c. The s dependence of the polarization can be qualitatively understood in the framework of triple-Regge phenomenology.

I. INTRODUCTION

In this paper a study is presented on the polarization of the Λ produced in the reaction

$$K^-p \to \Lambda + \text{anything} \tag{1}$$

at 7.3 GeV/c. The weak decay of the Λ, and the subsequent measurement of polarization, afford one the opportunity to investigate spin-dependent effects in an inclusive reaction. The data are compared with recent results on reaction (1) at 3.93 and 14.3 GeV/c.[1] Several interesting regularities are found. In particular, essentially energy-independent u-channel polarization is observed. This effect and the much stronger energy dependence of the t-channel polarization are qualitatively understood through the triple-Regge formalism.

In Sec. II the data sample is discussed; the experimental results on cross sections and polarization are presented in Sec. III. In Sec. IV we discuss polarization effects within the triple-Regge framework and make comparisons with the data in Sec. V. Section VI is reserved for a summary and conclusions.

II. DATA SAMPLE

Our data result from a 600 000-picture exposure of 7.3-GeV/c incident K^- mesons in the BNL 80-in. hydrogen-filled bubble chamber. All events were measured on the BNL HPD and processed through the BNL version of TVGP-SQUAW. A total of 22 000 events were obtained which fit at least one kinematic Λ^0-type hypothesis (including missing mass). All Λ^0-K^0 ambiguities (which amount to $<7\%$ of the total number of Λ^0 events) were decided in favor of the Λ^0 hypothesis. This procedure was justified in that the unfitted "π^+"π^- effective mass spectra, which resulted from the interchange of $p \to$ "π^+" in the $\Lambda \to p\pi^-$ decay, revealed only a very small (~120 events) signal for contamination from the decay $K^0 \to \pi^+\pi^-$. All distributions presented in this paper have been corrected for scanning and measuring inefficiencies on a topology-by-topology basis. Geometrical corrections for Λ^0's which decay either too close to the primary vertex (projected length less than 1 cm) or outside the fiducial volume have also been included. Finally, all cross sections contain corrections for the unobserved $\Lambda \to n\pi^0$ decay mode. The total corrected number of events was divided by the microbarn equivalent, as determined by the number of τ decays in the data sample, and resulted in a cross section of 3.08 ± 0.05 mb for reaction (1), where the error is statistical. The estimated uncertainty in the τ count and in the various inefficiency corrections results in an approximate 7% systematic uncertainty in this number and all cross sections quoted in this paper.[2]

III. EXPERIMENTAL RESULTS

Table I gives the distribution of the single-particle invariant cross section

$$f(x) = \int \frac{E^*_\Lambda}{P^*_{\text{inc}}} \frac{d\sigma}{dx\,dp_\perp^{\,2}}\, dp_\perp^{\,2} \tag{2}$$

as a function of the Feynman scaling variable $x = P^*_{\Lambda\parallel}/P^*_{\text{inc}}$. In Fig. 1 and in Table I the data are compared with recent results at 3.9 and 14.3 GeV/c. As expected,[3] no scaling behavior is observed in any region of x. However, the shape of the 7.3-GeV/c $f(x)$ distribution, while different from that at 3.9 GeV/c, is very similar to that at 14.3 GeV/c. In fact, as shown in Table I the ratio $R(x)$ of the values of $f(x)$ between 7.3 and 14.3 GeV/c is essentially constant at a value of ~1.6 for $-0.8 \leq x \leq 0.4$. This ratio (see Table I) for regions of x corresponding to the target and beam fragmentation exhibits a slightly smaller value, which implies a less steep energy dependence than in the central region.

Figure 2 shows the polarization of the Λ^0, P_Λ, plotted as a function of $-t_{p\to\Lambda}$, the momentum

TABLE I. Values of $f(x)$ for different intervals of x.

x interval	$f(x)$ at 7.3 GeV/c (μb)	$f(x)$ at 7.3 GeV/c (μb)	$f(x)$ at 14.3 GeV/c (Ref. 1) (μb)	$R(x)=\dfrac{f(x)\vert_{7.3}}{f(x)\vert_{14.3}}$
−1.0 to −0.9 −0.9 to −0.8	764 ± 43 1479 ± 59	1121 ± 36	850 ± 35	1.32 ± 0.07
−0.8 to −0.7 −0.7 to −0.6	1760 ± 63 1812 ± 60	1785 ± 44	1120 ± 40	1.59 ± 0.07
−0.6 to −0.5 −0.5 to −0.4	1824 ± 58 1808 ± 56	1816 ± 40	1165 ± 42	1.56 ± 0.07
−0.4 to −0.3 −0.3 to −0.2	1783 ± 52 1689 ± 50	1735 ± 35	1055 ± 40	1.64 ± 0.07
−0.2 to −0.1 −0.1 to −0.0	1568 ± 47 1581 ± 45	1575 ± 33	970 ± 35	1.62 ± 0.07
0.0 to 0.1 0.1 to 0.2	1606 ± 46 1569 ± 46	1588 ± 33	980 ± 35	1.62 ± 0.07
0.2 to 0.3 0.3 to 0.4	1581 ± 48 1404 ± 46	1492 ± 33	940 ± 38	1.59 ± 0.07
0.4 to 0.5 0.5 to 0.6	1173 ± 43 912 ± 40	1043 ± 29	725 ± 35	1.44 ± 0.08
0.6 to 0.7 0.7 to 0.8	609 ± 34 334 ± 26	471 ± 21	332 ± 20	1.42 ± 0.11
0.8 to 0.9 0.9 to 1.0	227 ± 22 51 ± 10	139 ± 12	76 ± 10	1.83 ± 0.30

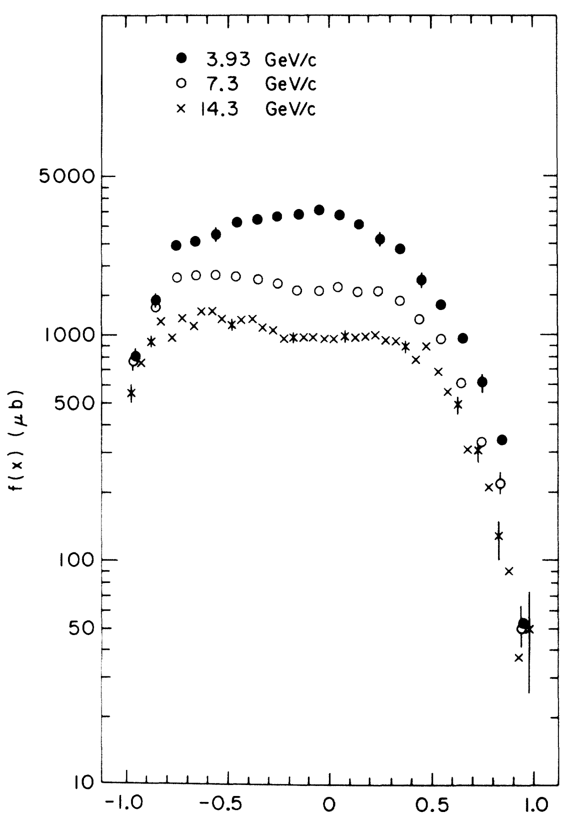

FIG. 1. Invariant cross section plotted as function of x for the data at 3.93 and 14.3 GeV/c of Borg *et al.* (Ref. 1) along with that of the present experiment.

transfer between the target proton and the outgoing Λ. The polarization is obtained from

$$P_\Lambda = \frac{3}{\alpha}\langle\cos\theta\rangle\,,$$

where $\langle\cos\theta\rangle$ is the moment (weighted over events) of the cosine of the angle between the normal to the production plane defined by

$$\hat{n} = \frac{\hat{P}_{\text{target}}\times\hat{P}_\Lambda}{|\hat{P}_{\text{target}}\times\hat{P}_\Lambda|}$$

and the decay proton in the Λ^0 rest frame and

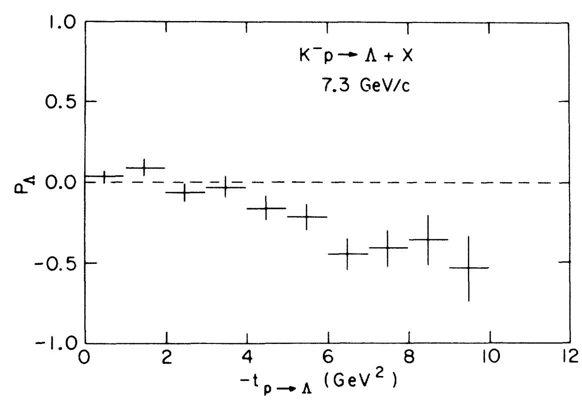

FIG. 2. Distribution of the Λ polarization as a function of the momentum transfer between the target proton and Λ.

$\alpha = 0.647$. As seen in Fig. 2 the polarization is small and positive at low $-t$, changes sign at $-t \approx 2.0$ GeV^2, and becomes large and negative in the large-$(-t)$ region. In Fig. 3 the polarization as a function of x is compared with that determined at 3.9 and 14.3 GeV/c. For $x < -0.5$ the polarization, significantly positive at 3.9 GeV/c, is observed to diminish in intensity with increasing energy; it is consistent with zero in the 7.3-GeV/c data. The region, $x > 0$, of forward Λ^0 production exhibits values of the polarization which are essentially independent of energy. This latter point is more convincingly demonstrated in Fig. 4, in which the polarization in the present data is compared, as a function of u, with that at 14.3 GeV/c. Except in the first u bin ($\sim 2\sigma$ disagreement) the polarization distributions are observed to be remarkably similar up to $u \approx 4.5$ GeV^2.

The polarization as a function of u for different slices of the X mass squared (M^2) is shown in Fig. 5 for the 7.3-GeV/c data. The negative polarization in each bin of u is observed to be built up from negative polarizations from each region of M^2.

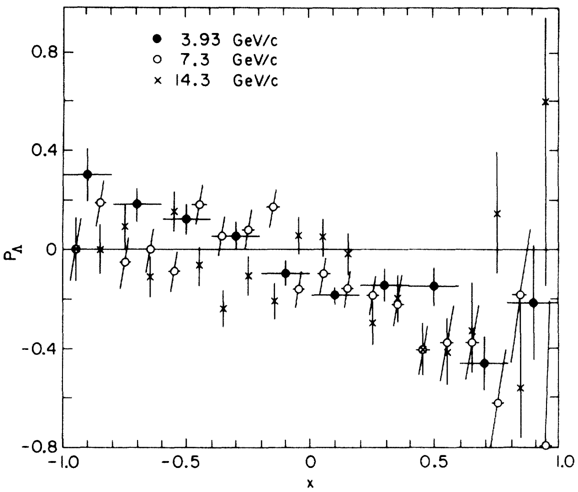

FIG. 3. Λ polarization as a function of x for the data at 3.93 and 14.3 GeV/c of Borg *et al.* (Ref. 1) along with that of the present experiment.

IV. POLARIZATION IN THE TRIPLE-REGGE FORMALISM

The generalized optical theorem of Mueller[4,5] relates the squares of the s-channel helicity amplitudes $F^X_{\lambda_\Lambda;\lambda_a\lambda_b}(s,t,M^2)$ for the inclusive process $a + b \to \Lambda + X$ to a discontinuity of the forward 3-to-3 amplitude $A_{ab\bar{\Lambda}\to ab\bar{\Lambda}}(s,t,M^2)$. In particular, defining the invariant cross section

$$\sigma(s,t,M^2) \equiv s\frac{d\sigma}{dt\,dM^2}(s,t,M^2) \tag{3a}$$

one has

$$\sigma(s,t,M^2) = \frac{1}{16\pi s(2s_a+1)(2s_b+1)} \times \sum_{\text{all } X}\sum_{\lambda_a,\lambda_b,\lambda_\Lambda} |F^X_{\lambda_\Lambda;\lambda_a\lambda_b}(s,t,M^2)|^2, \tag{3b}$$

where s_a and s_b are the spins of particles a and b, respectively. By the use of the generalized optical theorem, (3b) becomes (see Fig. 6)

$$\sigma(s,t,M^2) = \frac{1}{16\pi s(2s_a+1)(2s_b+1)} \sum_{\lambda_a,\lambda_b,\lambda_{\bar{\Lambda}}} \text{Disc}_{M^2}\langle\lambda_a\lambda_b\lambda_{\bar{\Lambda}}|A(s,t,M^2)|\lambda_a\lambda_b\lambda_{\bar{\Lambda}}\rangle, \tag{3c}$$

which yields, in the triple-Regge region (large s/M^2, large M^2), the usual triple-Regge formula,

$$\sigma(s,t,M^2) = \frac{1}{s}\sum_{ijk} G_{ijk}(t)\left(\frac{s}{M^2}\right)^{\alpha_i(t)+\alpha_j(t)} (M^2)^{\alpha_k(0)}, \tag{4a}$$

where

$$G_{ijk}(t) = \frac{1}{16\pi(2s_a+1)(2s_b+1)} \sum_{\lambda_a,\lambda_b,\lambda_{\bar{\Lambda}}} \beta^i_{\lambda_{\bar{\Lambda}}\lambda_a}(t)\beta^j_{\lambda_{\bar{\Lambda}}\lambda_a}(t)\beta^k_{\lambda_b\lambda_b}(0)\, g_{ijk}(t)\xi_i(t)\xi_j^*(t)\text{Im}\,\xi_k(0). \tag{4b}$$

The term $g_{ijk}(t)$ denotes the triple-Regge coupling of the three Reggeons i, j, and k where Regge poles i and j with trajectories $\alpha_i(t)$ and $\alpha_j(t)$, respectively, are exchanged and the Regge pole k with intercept $\alpha_k(0)$ controls the Reggeon-particle total cross section (see Fig. 6). The residue function $\beta_{\lambda_{\bar{\Lambda}}\lambda_a}(t)$ $[\beta_{\lambda_b\lambda_b}(0)]$ is the Regge coupling to the $\bar{\Lambda}a$ $[bb]$ channel and $\xi(t)$ is the usual Regge signature factor.

The decay Λ polarization is given by[6]

$$P_\Lambda(s,t,M^2)\sigma(s,t,M^2)=\frac{1}{16\pi s(2s_a+1)(2s_b+1)}\sum_{\text{all }X}\sum_{\lambda_a,\lambda_b} 2\,\mathrm{Im}[F^X_{-1/2\,;\,\lambda_a\lambda_b}(s,t,M^2)F^{X*}_{+1/2;\,\lambda_a\lambda_b}(s,t,M^2)]\,, \qquad (5a)$$

which again by the use of the generalized optical theorem becomes[7]

$$P_\Lambda(s,t,M^2)\sigma(s,t,M^2)=\frac{1}{8\pi s(2s_a+1)(2s_b+1)}\sum_{\lambda_a,\lambda_b}\mathrm{Im}[\mathrm{Disc}_{M^2}\langle\lambda_a\lambda_b-\tfrac{1}{2}|A(s,t,M^2)|\lambda_a\lambda_b+\tfrac{1}{2}\rangle]\,. \qquad (5b)$$

This formula, in contrast to the unpolarized invariant cross section (3c), involves the forward 3-3 amplitude when initial and final Λ helicities are not the same. In the triple-Regge region (5b) becomes

$$P_\Lambda(s,t,M^2)\sigma(s,t,M^2)=\frac{1}{s}\sum_{ijk}\tilde{P}_{ijk}(t)\left(\frac{s}{M^2}\right)^{\alpha_i(t)+\alpha_j(t)}\times(M^2)^{\alpha_k(0)}\,, \qquad (6a)$$

where

$$\tilde{P}_{ijk}(t)=\frac{1}{8\pi(2s_a+1)(2s_b+1)}\times\sum_{\lambda_a\lambda_b}\beta^i_{+\lambda_a}(t)\beta^j_{-\lambda_a}(t)\mathrm{Im}[\xi_i(t)\xi_j^*(t)]\times g_{ijk}(t)\beta^k_{\lambda_b\lambda_b}(0)\mathrm{Im}\,\xi_k(0)\,. \qquad (6b)$$

This formula is analogous to the polarization formula for two-body scattering (except P_Λ is also a function of M^2) and has the following properties:

(i) $P_\Lambda(s,t,M^2)=0$ if Regge pole i equals Regge pole j or if they have the same phase.

(ii) $P_\Lambda(s,t,M^2)$ arises from the interference between helicity-flip and -nonflip amplitudes.

(iii) Parity implies $P_\Lambda=0$ if i is a natural-parity Regge pole and j is an unnatural-parity Regge pole or vice versa.[8]

(iv) At fixed x, $P_\Lambda(s,t,x)\sigma(s,t,x)$ behaves like $s^{\alpha_k(0)-1}$. (If k is a Pomeron, then $P_\Lambda\sigma$ scales; if k is a normal meson Reggeon $[\alpha_k(0)=\frac{1}{2}]$, then $P_\Lambda\sigma\propto 1/\sqrt{s}$).[9]

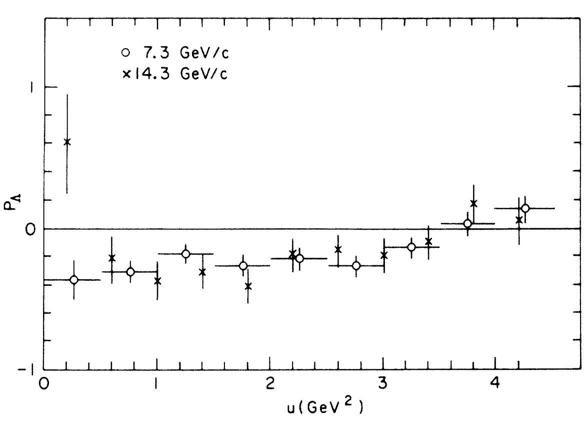

FIG. 4. Comparison between 7.3 and 14.3 GeV/c of the Λ polarization as a function of u, the momentum transfer between the incident K^- and the Λ.

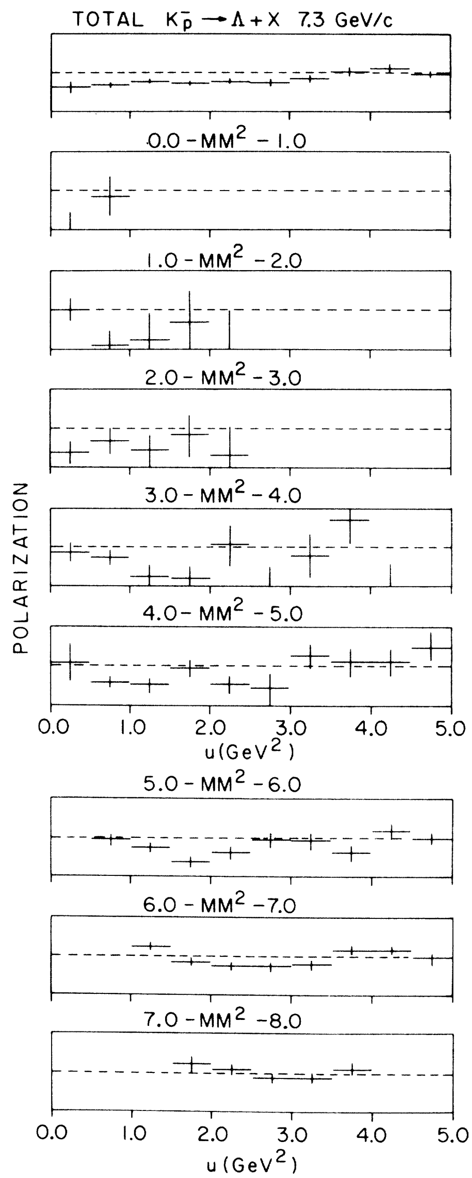

FIG. 5. Λ polarization as a function of u for different intervals of the mass squared of X.

V. COMPARISON WITH THE DATA

We now attempt to understand the experimental results for $K^-p \to \Lambda X$ for x near ± 1 in terms of the triple-Regge formalism of Sec. IV.[10]

A. $K^-p \to \Lambda X$ (near $x = -1$)

For this case particle a is a proton and Eq. (6b) for the Λ polarization becomes[8]

$$\tilde{P}_{ijk}(t) + \tilde{P}_{jik}(t) = \frac{1}{16\pi}[\beta^i_{++}(t)\beta^j_{-+}(t) + \beta^i_{+-}(t)\beta^j_{--}(t) - \beta^j_{++}(t)\beta^i_{-+}(t) - \beta^j_{+-}(t)\beta^i_{--}(t)] \times \mathrm{Im}[\xi_i(t)\xi_j(t)^*]\,g_{ijk}(t)\beta^k(0)\,\mathrm{Im}\,\xi_k(0)\,. \tag{7}$$

The leading triple-Regge terms responsible for Λ polarization in $K^-p \to \Lambda X$ (small-t region) are thus of the form $K^{**}K^*R$,[11] where $R = f,\ \omega,\ \rho,\ A_2, f'$, or ϕ (see Fig. 7).[12] Note that terms of the form $K^{**}K^*P$ vanish by generalized C parity [i.e., $g_{K^{**}K^*P}(t) = 0$ assuming that the Pomeron P is an SU(3) singlet with $C = +1$]. This implies that $P_\Lambda\sigma$ has no scaling term[13] [see property (iv) above] and behaves at fixed x like

$$P_\Lambda(s, t, x)\sigma(s, t, x) = C(x, t)/\sqrt{s} + A(x, t)/s\,. \tag{8a}$$

The invariant cross section has both scaling and nonscaling terms so that at fixed x

$$\sigma(s, t, x) = c(x, t) + b(x, t)/\sqrt{s} + a(x, t)/s\,, \tag{8b}$$

which implies that $P_\Lambda(s, t, x) \equiv P_\Lambda\sigma/\sigma$ decreases as s increases.

Therefore, in agreement with our experimental observations, $P_\Lambda(s, t, x)$ (near $x = -1$) is expected to decrease with increasing s.

B. $K^-p \to \Lambda X$ (near $x = 1$)

The near-constant Λ polarization seen in $K^-p \to \Lambda X$ near $x = 1$ can be understood once it is realized that the RRP triple-Regge terms are small relative to RRR terms in the energy region under consideration (4–14 GeV/c). Thus both the polarized cross section $P_\Lambda\sigma(s, t, x)$ and the invariant cross section $\sigma(x, t, x)$ decrease at fixed x like $1/\sqrt{s}$ in this region, which results in $P_\Lambda(s, t, x)$ being approximately constant.[14] A $1/\sqrt{s}$ dependence of the unpolarized cross section is consistent with the experimentally observed energy dependence for large positive x (i.e., $R(x)$ for $x > 0.4$ is consistent with $[s(14.3\ \mathrm{GeV}/c)]^{1/2}/[s(7.3\ \mathrm{GeV}/c)]^{1/2} \simeq 1.4$ (see Table I)).

The small RRP term in $K^-p \to \Lambda X$ in this energy range for large positive x can be inferred from a small invariant cross section for the reaction $K^+p \to \bar{\Lambda}X$. This follows since the RRP term in $K^-p \to \Lambda X$ is equal to the corresponding term in $K^+p \to \bar{\Lambda}X$ by crossing (see Fig. 8). In addition, since the Reggeon-particle scattering amplitude for $N_ip \to N_jp$ is exotic its imaginary part vanishes for Reggeon exchange, and thus $K^+p \to \bar{\Lambda}X$ has no RRR term and its invariant cross section near $x = +1$ is given entirely by the RRP term. Data show[15] that the invariant cross section for $K^+p \to \bar{\Lambda}X$ is substantially smaller than $K^-p \to \Lambda X$ for $p_{\mathrm{lab}} \lesssim 14$ GeV/c, which then implies a small RRP

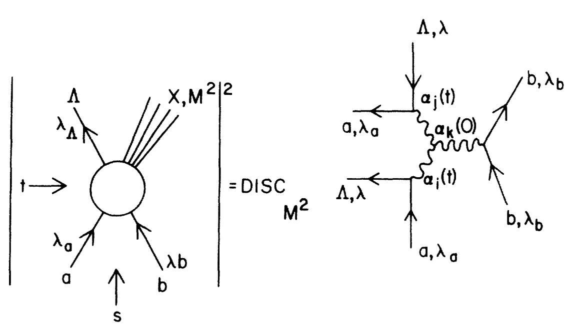

FIG. 6. Illustrates the generalized optical-theorem formula for the unpolarized invariant inclusive cross section for $a + b \to \Lambda + X$.

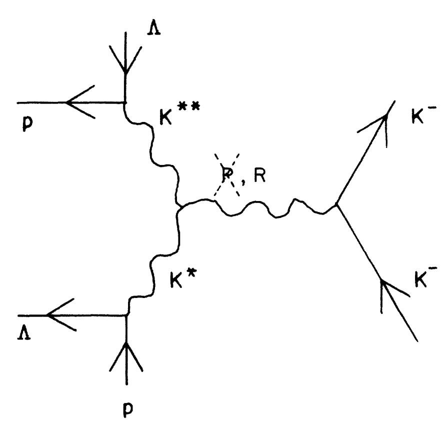

FIG. 7. Shows the leading triple-Regge term responsible for the Λ polarization in the inclusive reaction $K^-p \to \Lambda X$, where $R = f,\ \omega,\ \rho,\ A_2, f'$, or ϕ. The term $K^{**}K^*P$ vanishes by generalized C parity [assuming P is an SU(3) singlet with $C = +1$].

term and a large RRR term in the latter reaction and, hence, the prediction of a constant P_Λ.

The smallness of the RRP term can also be understood from the experimental knowledge that the "anything" in (1) is predominantly pions in the energy region under consideration [i.e., $K^-p \to \Lambda$ + pions dominates reaction (1)]. Duality implies that the Reggeon-particle ($\bar{N}p$) amplitude with pions intermediate in the direct channel (i.e., annihilation channel) is dual to Regge exchange in the crossed channel.[16] Thus the RRR term should dominate and the RRP is expected to be small in this region.[17]

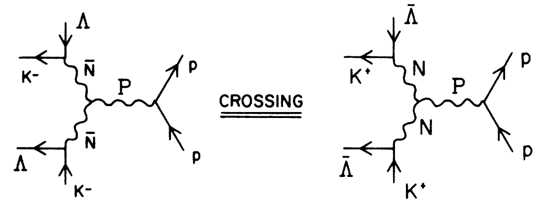

FIG. 8. Shows that the triple-Regge terms $\bar{N}_i\bar{N}_jP$ for the process $K^-p \to \Lambda X$ are related by crossing to the N_iN_jP terms for the process $K^+p \to \bar{\Lambda}X$. The latter reaction has an exotic Reggeon-particle scattering amplitude, which via duality implies no N_iN_jR triple-Regge term.

VI. CONCLUSION

In two-body exclusive processes, polarization and density-matrix data have been crucial in testing and refining our theoretical models. In inclusive processes, measurement of observables other than just the invariant cross section may well be of equal importance. We have seen that the Λ polarization data on the reaction $K^-p \to \Lambda X$ exhibit energy-dependent features which can be qualitatively understood in the framework of triple-Regge phenomenology. The large magnitude (≈ 40%) of the Λ polarization for the baryon-exchange process (x near 1.0) compared to the smaller Λ polarization for the meson-exchange process (x near −1.0) is not easily explained,[14] however. Further inclusive baryon-exchange polarization experiments should be done (especially at higher energies) to see if the large effects found in this experiment persist.

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[1]A. Borg, M. Bardadin-Otwinowska, R. Barloutaud, C. Louedec, L. Moscoso, F. Pierre, M. Spiro, B. Chaurand, B. Drevillon, G. Labrosse, R. Lestienne, A. Rouge, R. Salmeron, H. Videau, R. Miller, K. Paler, J. J. Phelan, T. P. Shah, and S. Tovey, Nuovo Cimento 22A, 559 (1974).

[2]Reaction (1) cannot be separated from the reaction $K^-p \to \Sigma^0(\to \Lambda^0\gamma) + X$, so that all distributions presented here must be considered to be from the reaction $K^-p \to \Lambda^0(\Sigma^0) + X$. We do not have an estimate of the Σ^0/Λ^0 production ratio at 7.3 GeV/c; however, at 14.3 GeV/c the ratio was determined to be 0.25± 0.08 (Ref. 1). The similarity of the $f(x)$ and $P_\Lambda(x)$ distributions (see below) between these two energies would argue against any strong energy dependence of this ratio.

[3]In terms of the triple-Regge formalism precocious (early) scaling could be expected if the state $ab\bar{c}$ (in the reaction $a + b \to c$ +anything) were exotic. For $K^-p \to \Lambda$ +anything, $a = K^-$, $b = p$, $\bar{c} = \bar{\Lambda}$ is nonexotic and reaction (1) is therefore not expected to scale at energies as low as studied in this paper.

[4]A. H. Mueller, Phys. Rev. D 2, 2963 (1970).

[5]A. H. Mueller, Phys. Rev. D 4, 150 (1971).

[6]This formula is identical to the Λ polarization formula for $a + b \to c + \Lambda$, where a, b, and c are definite particles.

[7]See, for example, R. J. N. Phillips, G. A. Ringland, and R. P. Worden, Phys. Lett. 40B, 239 (1972).

[8]Parity implies that for natural- (unnatural-) parity Regge exchange $\beta^N_{++}(t) = \beta^N_{--}(t)$, $\beta^N_{+-}(t) = -\beta^N_{-+}(t)$ [$\beta^u_{++}(t) = -\beta^u_{--}(t)$, $\beta^u_{+-}(t) = \beta^u_{-+}(t)$].

[9]This is easy to see using (6a) and the fact that $M^2 \simeq s(1-x)$.

[10]The triple-Regge formalism is only directly applicable for large $|x|$ and M^2 large. The latter constraint can be relaxed somewhat assuming semilocal M^2 duality, which implies that the triple-Regge formula will be valid on the average even at small M^2 [see for example, P. Hoyer, R. G. Roberts, and D. P. Roy, Nucl. Phys. B56, 173 (1973)].

[11]We always write the triple-Regge term $R_1R_2R_3$ to represent the coupling of three Reggeons $g_{ijk}(t)$ [Eq. (4b)], where $i = R_1$, $j = R_2$, and $k = R_3$.

[12]Apparently the f' and ϕ trajectories with intercept $\alpha(0) \simeq 0$ are dual to the annihilation channel $\bar{K}K \to$ pions $\to \bar{K}K$, while those of the Pomeron (normal Regge trajectories) are dual to nonannihilation background (resonance) intermediate states such as $\bar{K}K \to \bar{K}K$ +pions$\to \bar{K}K$. See T. Inami and H. I. Miettinen, Phys. Lett. 49B, 67 (1974).

[13]Terms of the form $K^{**}K^{**}P$ contribute to the invariant cross section (4b) but do not contribute to $P_\Lambda(s, t, M^2)$

[Eq. (6b)] because of property (i).

[14] This argument does not, of course, explain the size of $P_\Lambda(s, t, X)$, which is determined by the couplings and phases of the various nucleon trajectories exchanged [see Eq. (6b)].

[15] W. Barletta, M. Johnson, T. Ludlam, A. J. Slaughter, H. D. Taft, T. Ferbel, P. Slattery, S. Stone, and B. Werner, Nucl. Phys. B51, 499 (1973).

[16] See, for example, Peter D. Ting, Phys. Rev. 181, 1942 (1969).

[17] The RRP term is dual to direct-channel intermediate with baryons (antibaryons) present.