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Polarization of Lambdas and Antilambdas Produced by 400 GeV Protons

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ABSTRACT

We have measured the polarization of 3×10^6 Λ° and 2.5×10^5 $\bar{\Lambda}^\circ$ hyperons produced by 400 GeV protons on a beryllium target. The hyperons were detected at a fixed angle of 7.2 mrad and in the momentum range from 50 to 300 GeV/c for Λ° and 50 to 200 GeV/c for $\bar{\Lambda}^\circ$. The Λ° polarization agrees with that measured at 24 and 300 GeV and is -0.24 ± 0.04 at p_T = 2.1 GeV/c. The $\bar{\Lambda}^\circ$ polarization is zero up to p_T = 1.2 GeV/c.

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The discovery[1] that $\Lambda°$ hyperons are polarized when produced by the interaction of 300 GeV unpolarized protons with an unpolarized target implies, contrary to early expectations, that spin effects are important in high energy particle production. Where measured, the polarization has the following properties:[1,2,3]

i) The polarization direction is perpendicular to the production plane as required by parity conservation.

ii) The magnitude increases monotonically with transverse momentum from 0 at $p_T = 0$ to over 20% at $p_T = 1.6$ GeV/c.

iii) The polarization does not depend strongly on the longitudinal momentum of the produced $\Lambda°$ for Feynman $x = 2p_L^{cm}/\sqrt{s}$ between $0.2 < x < 0.8$.

iv) No significant difference is observed in the polarization from beryllium, copper, and platinum targets.

v) The p_T dependence of the polarization for an incident proton energy of 300 GeV is consistent with that for 24 GeV.

A polarization measurement is a more delicate diagnostic of reaction dynamics than is a cross section. Polarization requires coherence between at least two amplitudes, and, therefore is sensitive to small spin-dependent terms. The existence of substantial polarization in an inclusive reaction suggests that only a few amplitudes contribute to the production process. One model which might satisfy this requirement of simplicity is the quark model. Within this model hadron interactions are described in terms of the elementary interactions of constituent quarks. This description is presumed to become more relevant as the transverse momentum involved in the reaction increases. The simplest version involving spin is the SU(6) quark model. It builds the Λ° hyperon of u, d, and s valence quarks, while the $\bar{\Lambda}^\circ$ is composed of $\bar{u}$, $\bar{d}$, and $\bar{s}$ quarks. In each case the nonstrange quarks form a singlet spin state so that the spin of the hyperon is the spin of a single quark, the strange quark. No other hadron has this property.

The present experiment extends the measurement of P_Λ, the polarization of Λ° hyperons produced by protons interacting in a beryllium target, to a projectile energy of 400 GeV and a transverse momentum of 2.1 GeV/c. In addition this is the first experiment to measure the polarization of $\bar{\Lambda}^\circ$ hyperons with sufficient accuracy to make a meaningful comparison between P_Λ and $P_{\bar{\Lambda}}$. The two polarization measurements give a comparison between quite different production mechanisms. For forward production, $x > 0.2$, the Λ°'s are presumably fragments of the incident proton whereas the $\bar{\Lambda}^\circ$'s seem to be the result of baryon pair production from the central region.[3,4] If the SU(6) quark model applies, and if $(s\bar{s})$ pairs are always produced polarized in hadronic collisions, the $\bar{\Lambda}^\circ$s might be polarized as well as the Λ°s.

The measurements were performed with the Fermilab neutral hyperon beam and spectrometer described previously.[1,3,4] The apparatus is shown in Figure 1. A 400 GeV proton beam was deflected in the vertical plane onto a 28.3 gm/cm^2 Be target, T, to give a production angle of 7.2 mrad between the incident proton beam and the collimator axis defining the neutral beam. The collimator axis (+z downstream), the vertical magnetic field in the collimator (+y upwards), and the horizontal ($\hat{x}$) formed the right-handed orthogonal coordinate system ($\hat{x},\hat{y},\hat{z}$) shown in Figure 1. The incident proton beam was in the $\hat{y}$-$\hat{z}$ plane and could be brought onto the target from below, +7.2 mrad, or from above, -7.2 mrad. The polarization vector was parallel to the unit vector, $-\hat{n} = -(\vec{k}_p \times \vec{k}_\Lambda)/|\vec{k}_p \times \vec{k}_\Lambda|$, so that positive and negative production angles gave equal but opposite polarizations in space. This allowed the elimination of biases in the measurement. Because of the small size of the collimator aperture, the deviation of the $\Lambda°$ direction from $\hat{z}$ was always less than 1/2 mrad.

Since the polarization was perpendicular to the collimator magnetic field, M_1, the neutral hyperon spin precessed through a large angle (about 150° at full field) between the target and the decay vertex in the vacuum downstream of the veto counter V. The precession angle was used to extract the $\Lambda°$ magnetic moment from this data and is presented elsewhere[5]. The polarization at the production target was calculated from the detected polarization, now in the $\hat{x}$-$\hat{z}$ plane, and the precession angle. Some data were also taken with the collimator field off to measure directly the polarization vector at production.

The charged products from the decays $\Lambda^\circ\to p\pi^-$ and $\bar{\Lambda}^\circ\to\bar{p}\pi^+$ were detected by six multiwire proportional chambers (Figure 1). Each chamber had two perpendicular signal planes. The spectrometer magnet, M_2, was used to measure the charged particle momenta. Its field was reversed periodically so that the decay products from equal momentum Λ°s and $\bar{\Lambda}^\circ$s populated the same regions of the downstream detectors.

The measured momenta allowed both the mass and momentum of the neutral parent particle to be calculated. The mass was computed under each of three hypotheses: $\Lambda^\circ\to p\pi^-$, $\bar{\Lambda}^\circ\to\bar{p}\pi^+$ and $K_S^\circ\to\pi^+\pi^-$. All events which were within three standard deviations of the Λ° mass were called Λ°s since the background from misidentified K_S° was less than 1%. Only events which fit the $\bar{\Lambda}^\circ$ hypothesis but not the K_S° hypothesis were retained as $\bar{\Lambda}^\circ$s to eliminate the K_S° background. This cut removed 20% of the $\bar{\Lambda}^\circ$ sample. The hyperon polarization, $\vec{P}$, was determined from the asymmetries in the distributions of the decay products of the parent particles. For the i^{th} event identified as a $\Lambda^\circ(\bar{\Lambda}^\circ)$, the direction of the proton (antiproton) in the $\Lambda^\circ(\bar{\Lambda}^\circ)$ center of mass, $\vec{k}_i$, was calculated. The distribution of protons (antiprotons) in the hyperon center of mass is of the form $[1+\alpha(\vec{P}\cdot\hat{u})(\vec{k}_i\cdot\hat{u})]$ for $\hat{u}$ being each of the three coordinate directions $(\hat{x},\hat{y},\hat{z})$. This expression was modified by the acceptance of the apparatus for hyperon decays, and in the $\bar{\Lambda}^\circ$ sample by the elimination of events which satified the K_S° mass hypothesis. Modified distributions were fit to the data to determine $\vec{P}\cdot\hat{u}$ for each of the fixed coordinate axes.[2,6] The measured polarization was in the $\hat{x}$-$\hat{z}$ plane. The Λ° parity violating components at production were always consistent with zero, $P_y = 0.0005 \pm 0.0017$, $P_z = -0.002 \pm 0.002$. It was assumed that the $\bar{\Lambda}^{\circ}$ magnetic moment, $\mu_{\bar{\Lambda}}$, and decay parameter $\alpha_{\bar{\Lambda}}$, were equal and opposite to those of the Λ°.

This analysis includes 3×10^6 $\Lambda^{\circ} \rightarrow p\pi^-$ and 2.5×10^5 $\bar{\Lambda}^{\circ} \rightarrow \bar{p}\pi^+$ decays where half of the hyperons were produced at + 7.2 mrad and half at - 7.2 mrad. Figure 2 shows the measured Λ° polarization versus laboratory momentum plotted separately for + 7.2 mrad and - 7.2 mrad. It is clear that the polarization reverses its direction in space. These data were combined by taking 1/2 their difference for each momentum bin. The results are given in the Table as a function of x and p_T. The values of p_T and x are correlated through the fixed production angle. In addition 5.3×10^5 Λ° and 6.5×10^3 $\bar{\Lambda}^{\circ}$ decays were obtained at a production angle of 0 mrad where parity conservation and rotational invariance allow no polarization. None was observed: $P_{\Lambda} = 0.006 \pm 0.004$ and $P_{\bar{\Lambda}} = -0.011 \pm 0.034$.

The Λ° polarization data, together with the 300 GeV results[1], are shown in Figure 3a. The 300 GeV data combined several production angles and each point was summed over x. The average x for each point is given in the figure. The comparison between 300 GeV and 400 GeV data shows no obvious x dependence of the polarization.

This experiment has extended the Λ° polarization measurement to a transverse momentum of 2.1 GeV/c from the previous maximum of 1.6 GeV/c. The Λ° polarization is perpendicular to the production plane as required by parity and is negative falling monotonically with increasing p_T. There is some indication that the slope may be decreasing above p_T= 1.6 GeV/c. This polarization appears to be energy independent between 24 and 400 GeV.

The polarization of $\bar{\Lambda}°$'s is given in Figure 3b and the Table. The data show that $P_{\bar{\Lambda}}$ is consistent with zero up to p_T = 1.2 GeV/c. The χ^2/DF for this hypothesis is 0.6. The hypotheses that $P_{\bar{\Lambda}} = P_{\Lambda}$ for 0.37 GeV/c $\leq p_T \leq$ 1.16 GeV/c has a χ^2/DF = 24 indicating that the two are definitely different.

The above comparison makes it clear that polarization is not a universal property of all high energy baryon production. Lambdas, which in this experiment are leading particles, are polarized while the antilambdas, which are unrelated to the incident particle, are not. From the quark picture outlined previously, it might appear that the s quark of the $\Lambda°$ is produced polarized while the $\bar{s}$ quark of the antilambda is not. Figure 4 illustrates a mechanism, gluon bremsstrahlung, which could give rise to a $\Lambda°$ polarization without a $\bar{\Lambda}°$ polarization. In the interaction two of the proton quarks, u and d, are spectators in a singlet spin state. The other u quark is scattered by the target and radiates a gluon which produces an $s\bar{s}$ pair. It is the s from the pair which gives the $\Lambda°$ both its transverse momentum and its spin. The scattered u quark, the $\bar{s}$ and the fragments of the target form the unobserved products. If the gluon is polarized, so is the $s\bar{s}$ pair and this polarization is correlated with the transverse momentum direction of the

Λ°. To produce a $\bar{\Lambda}^\circ$, on the other hand, $\bar{u}$ and $\bar{d}$ quarks must also be produced. Regardless of how they are produced these quarks would contribute to the $\bar{\Lambda}^\circ$ transverse momentum but not its polarization. Thus the $\bar{\Lambda}^\circ$ polarization at a given p_T would be suppressed.

If a diagram such as Figure 4 is assumed for other baryon production processes, and if all $q\bar{q}$ pairs are produced with the same polarization, then SU(6) quark wavefunctions can be used to calculate various baryon polarizations in terms of P_Λ for $p \to \Lambda^\circ$. The results are: $P_p = 2/5\ P_\Lambda$ for $p \to p$, $P_n = 1/2\ P_\Lambda$ for $p \to n$, $P_{\Sigma^\circ} = -1/3\ P_\Lambda$ for $p \to \Sigma^\circ$ and $P_{\Sigma^+} = 1/3\ P_\Lambda$ for $p \to \Sigma^+$.[7] The proton polarization will probably be diluted since the inclusive cross section does not necessarily involve the production of a new proton valence quark. All these predictions are experimentally testable. It would be of great interest to study polarizations of other high energy baryons.

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References

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7. $P_p = \frac{2}{3}P_\Lambda$ and $P_n = \frac{17}{19}P_\Lambda$ from the SU(6) wavefunctions but these results must be modified by the $\frac{u}{s}$ and $\frac{d}{s}$ quark mass ratios. See G. Kane and Y.P. Yao, Nucl. Phys. B137, 313 (1978).

TABLE

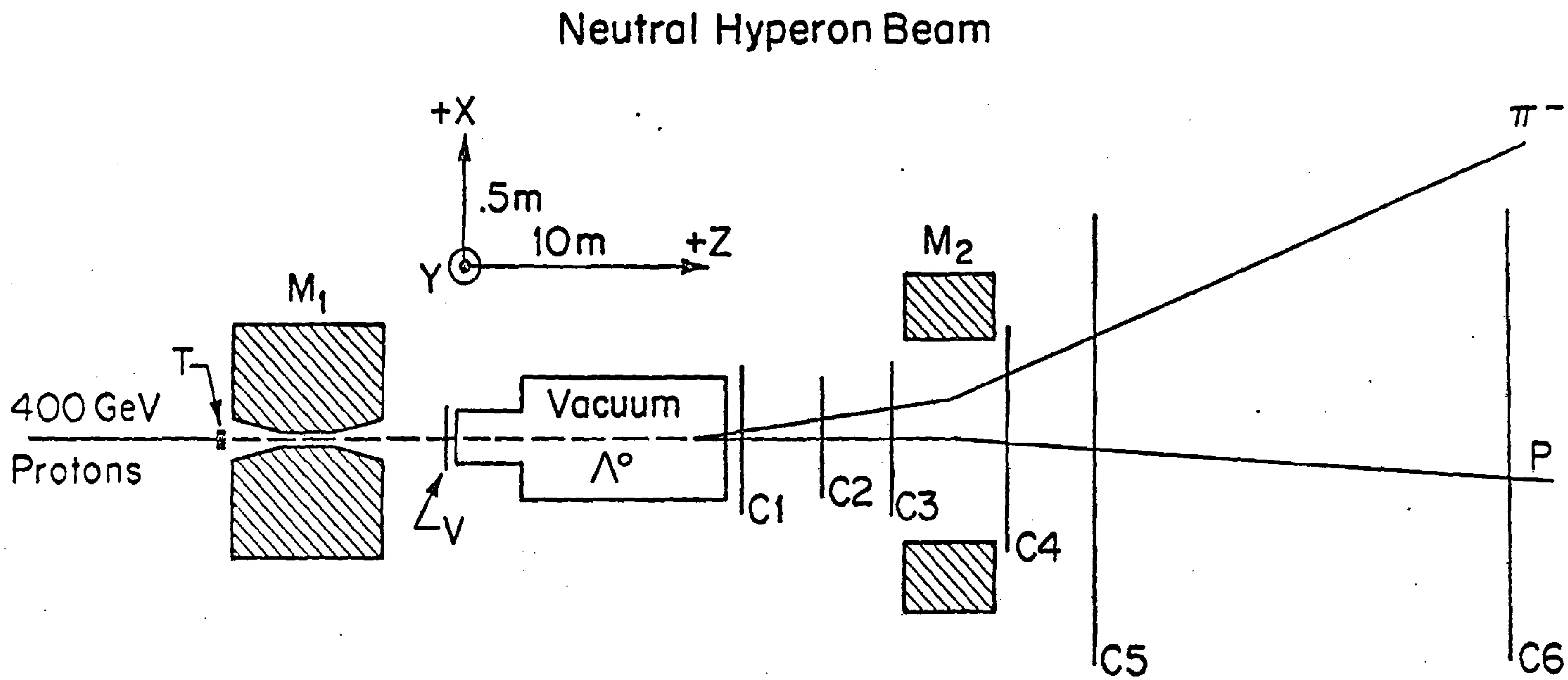
Λ° and $\bar{\Lambda}^\circ$ polarization for 7.2 mrad proton production as a function of hyperon transverse momentum, p_T in GeV/c, and Feynman x.

$\bar{p}_T$	$\bar{x}$	P_{Λ°	$P_{\bar{\Lambda}^\circ}$
0.37	0.11	−0.022±0.011	−0.02±0.02
0.54	0.18	−0.034±0.003	−0.00±0.01
0.74	0.25	−0.070±0.003	0.01±0.01
0.95	0.32	−0.104±0.003	0.01±0.02
1.16	0.39	−0.139±0.005	−0.02±0.04
1.38	0.48	−0.181±0.008	0.00±0.20
1.60	0.56	−0.209±0.014	
1.81	0.63	−0.223±0.026	
2.09	0.72	−0.237±0.044	

Figure Captions

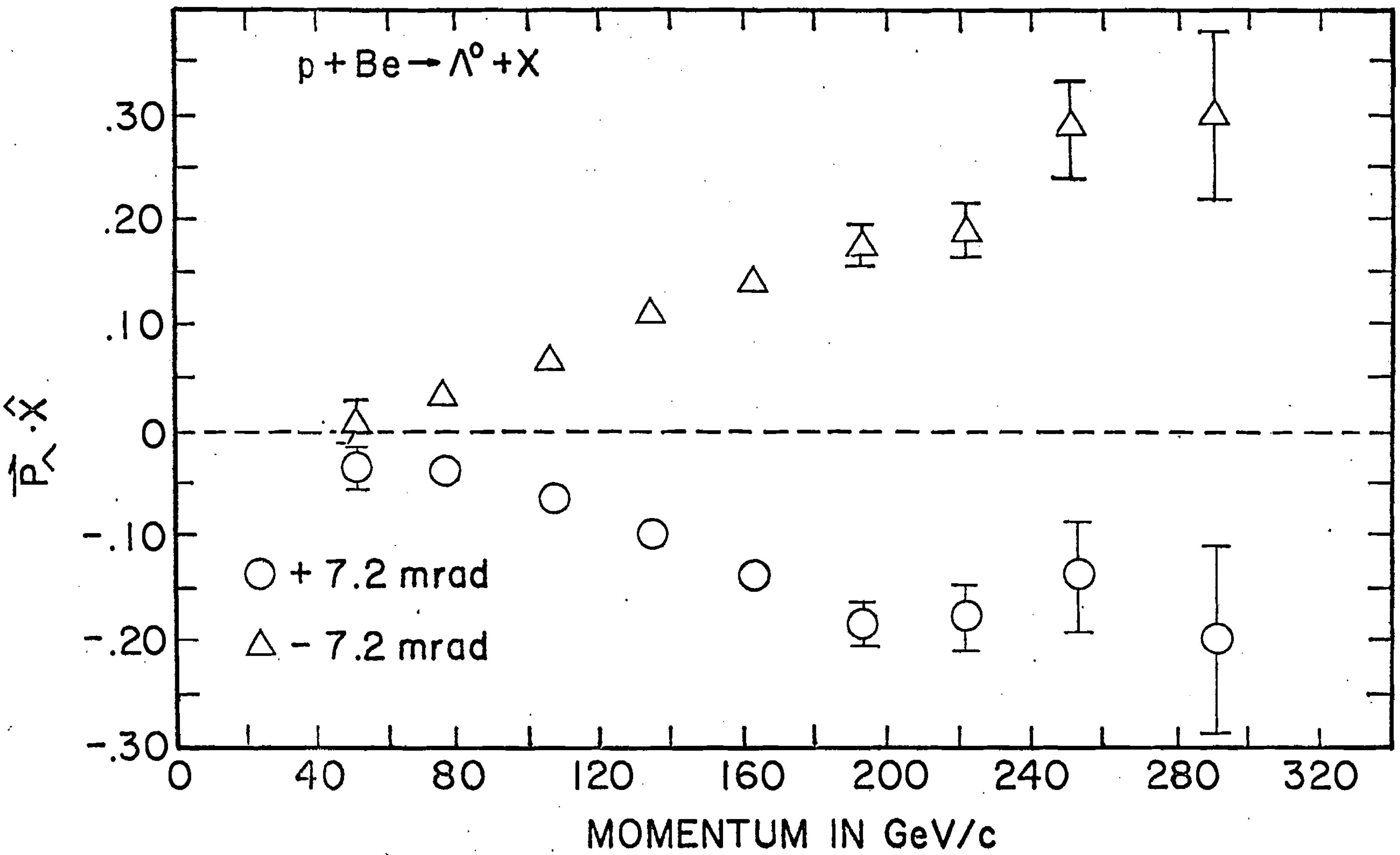
1. Plan view of the neutral hyperon beam and spectrometer. The production angle was in the y-z plane and is not shown in this view. The elements are described in the text. The electronic trigger required no signal from the veto counter, V, and one hit in each chamber, C_i, except C_5 in which two hits one on each side of the neutral beamline were required. A typical $\Lambda^\circ \rightarrow p\pi^-$ decay is shown.
2. Λ° polarization versus Λ° momentum for production angles of + 7.2 mrad and - 7.2 mrad. The direction of the polarization is positive in the direction of + $\hat{x}$.
3. (a) Λ° polarization from this experiment compared to that from 300 GeV incident protons from Reference 1 as a function of p_T. The number in parentheses is the average value of x for that point.

   (b) Λ° and $\bar{\Lambda}^\circ$ polarization from this experiment. The polarization is defined as positive along $\hat{n}=(\vec{k}_p \times \vec{k}_\Lambda)/|\vec{k}_p \times \vec{k}_\Lambda|$.
4. The gluon bremsstrahlung mechanism discussed in the text.



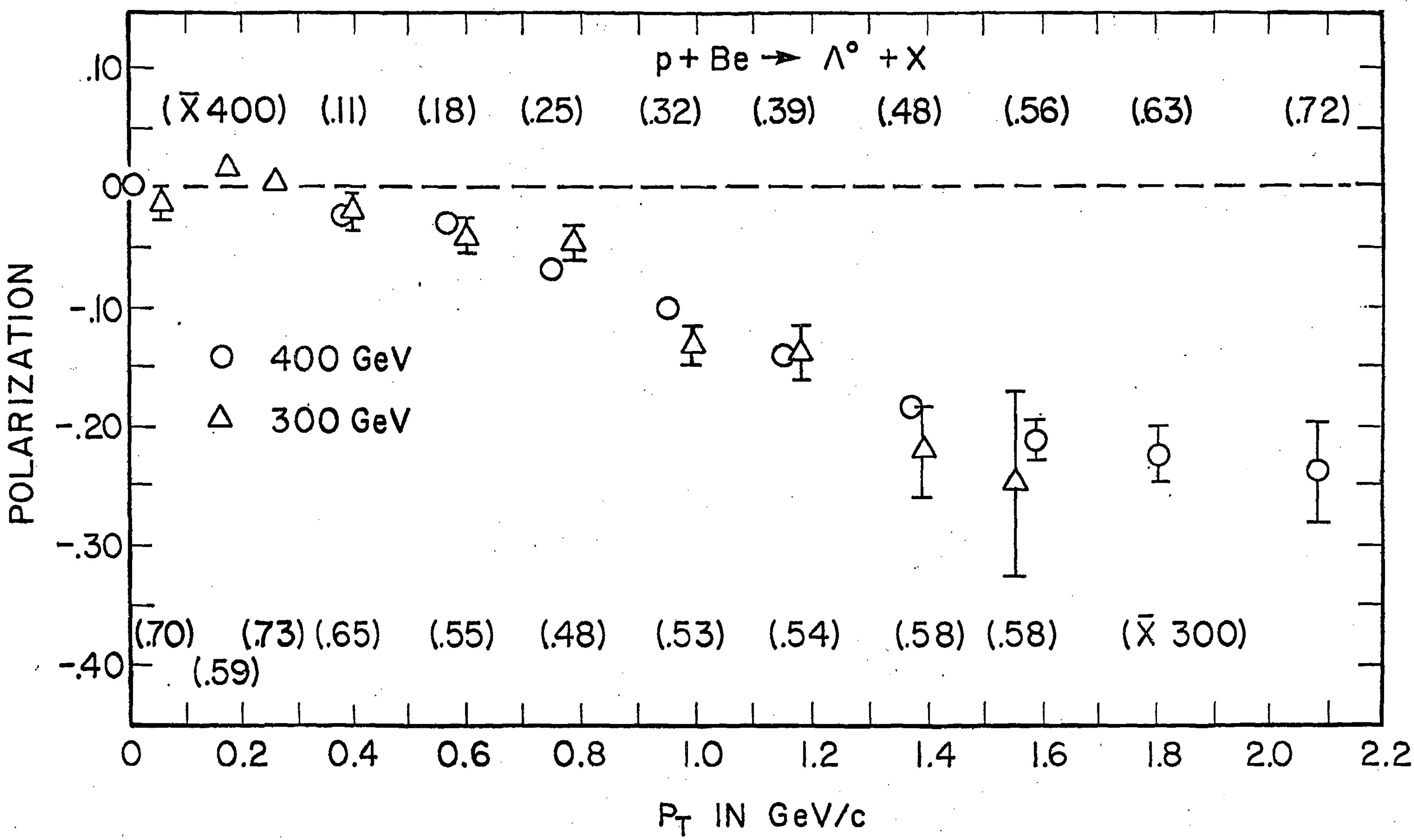
Neutral Hyperon Beam
+X
.5m
10m
+Z
Y
M1
M2
T
400 GeV
Protons
V
Vacuum
Λ°
C1
C2
C3
C4
C5
C6
π⁻
P

Figure 1



$p + Be \rightarrow \Lambda^0 + X$
.30
.20
.10
0
-.10
-.20
-.30
○ + 7.2 mrad
△ - 7.2 mrad
0
40
80
120
160
200
240
280
320
MOMENTUM IN GeV/c

Figure 2



p + Be → Λ° + X
(X̄ 400) (.11) (.18) (.25) (.32) (.39) (.48) (.56) (.63) (.72)
POLARIZATION
.10
0
-.10
-.20
-.30
-.40
○ 400 GeV
△ 300 GeV
(.70) (.59) (.73) (.65) (.55) (.48) (.53) (.54) (.58) (.58) (X̄ 300)
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
P_T IN GeV/c

Figure 3a

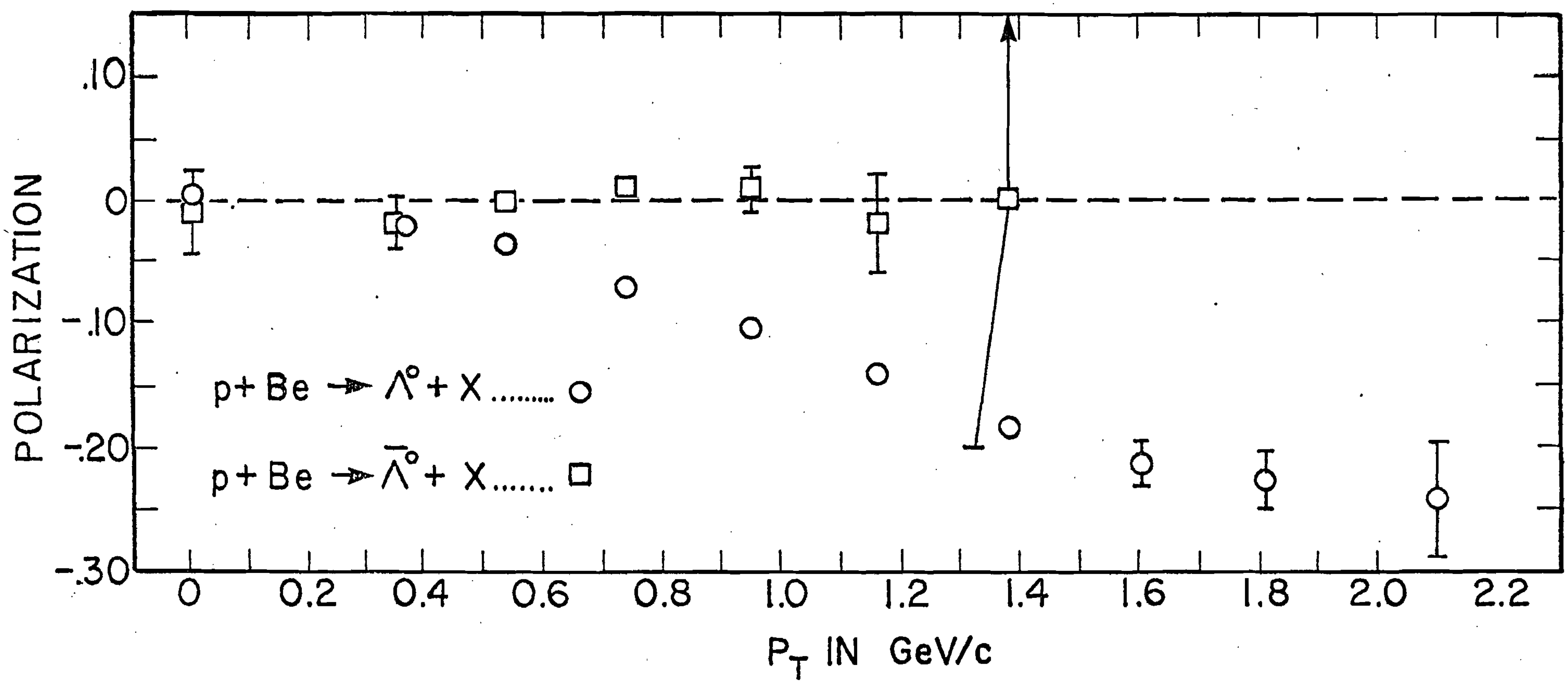

.10
0
-.10
-.20
-.30
POLARIZATION
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
P_T IN GeV/c
p+Be → Λ°+X .... ○
p+Be → $\bar{\Lambda}^{\circ}$+X .... □

Figure 3b

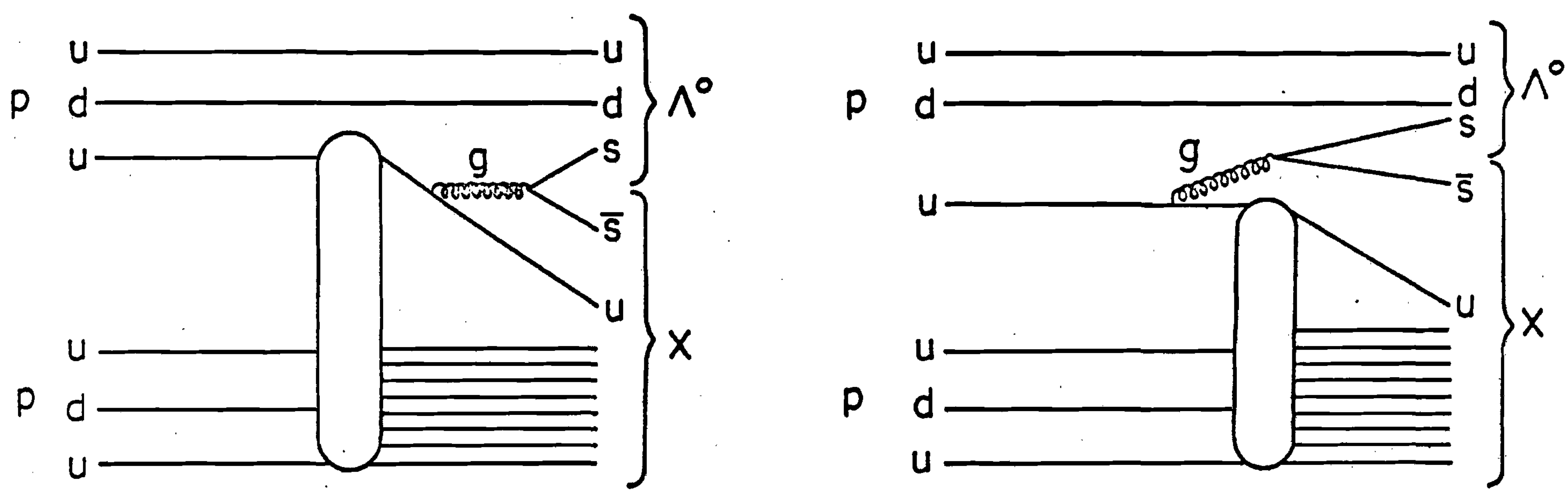


Figure 4