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Polarization of Σ^+ hyperons produced by 800 GeV/c protons on Cu and Be

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We show that Σ^+ hyperons produced by 800 GeV/c protons on targets of Be and Cu have significant polarizations (15–20%). These polarizations persist at values of $p_t \approx 2$ GeV/c and a wide range of x_F. The polarizations from the Cu target are consistently less than from Be. The average ratio of the Σ^+ polarization from Cu to that from Be is 0.68 ± 0.08.

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I. INTRODUCTION

The hyperon programs at Fermilab have produced data [1–4] on hyperon polarization for a variety of hyperons produced at differing values of Feynman x (x_F) and transverse momentum (p_t). These measurements have provided valuable insights into the spin structure of baryon production in high-energy proton collisions and the dependence of baryon polarization on target material. However no theoretical model has been completely successful in explaining these results [5–13].

In this paper we report on the measurement of Σ^+ hyperon polarization at p_t up to 2 GeV/c produced by a 800 GeV/c proton beam on two different target materials (Be and Cu). With the completion of the 800 GeV Fermilab fixed target program in January 2000, these will remain the highest energy fixed target polarization measurements for the foreseeable future.

II. EXPERIMENT

This measurement which was part of Fermilab E781 (SELEX) [14–22] used the charged hyperon production channel installed in the Fermilab Proton Area. The channel was capable of producing hyperon beams with momentum up to 650 GeV/c and p_t up to 2 GeV/c for those particles following the curved track. Figure 1 shows that portion of the SELEX apparatus [23] relevant to this measurement.

The Fermilab Tevatron delivered a beam of 800 GeV/c protons to the proton area. Dipole and quadrupole magnets directed [12] and focused the protons onto a beryllium (Be) or copper (Cu) target with a thickness of one-interaction length [13] positioned at the entry of the hyperon magnet (Fig. 1). These dipole magnets [12] allowed us to change the proton beam position and angle in both the horizontal (x–z) and vertical (y–z) planes.

Embedded in the hyperon magnet is a tungsten-lined curved channel that selected charged particles coming from the production target. The 7.3 m long iron hyperon magnet [12] could operate at a magnetic field of up to 3.5 T corresponding to a channel momentum of about 650 GeV/c for those particles following the curved channel. The hyperon magnet also served as a shield for unwanted particles (both charged and neutral) and with the help of its magnetized iron return yoke deflected the more penetrating muons away from the detectors.

The comparison of the Be and Cu polarizations is the crux of this experiment and care was taken in the design of the targets and placement of the proton beam on these targets [12,13].

On exiting the hyperon channel, the secondary beam traverses a transition radiation detector that distinguished charged pions from heavier particles. Scintillation detectors were used to define the beam and provide the trigger. The maximum angular divergence of the hyperons defined by the trigger is such that all of them pass through all the planes of the beam spectrometer (Fig. 1). The beam spectrometer consists of the hyperon magnet and a silicon strip detector with a spatial resolution of 8 μm. The momentum of the hyperon was determined from its trajectory in the beam spectrometer. The momentum resolution ($\Delta p/p$) of the beam spectrometer is 0.6% and limited by the finite width (1 mm in the x-direction) of the production target.

The M2 spectrometer consists of an analyzing magnet (M2) with a station of large-aperture silicon strip detectors on each side (LASD2 and LASD3) of it. The M2 Spectrometer also includes 14 planes of large-aperture proportional wire chambers. The stations VDC A and B include vector drift chambers (VDC) with u-, y-, and x-planes and v-, y-, and x-planes (u and v are rotated 45° with respect to the x and y axis), respectively. The momentum resolution ($\Delta p/p$) of the M2 spectrometer is 1%; it is limited mainly by the multiple scattering of the protons.

III. DATA ANALYSIS

Six data sets were collected, one for each of the various combinations of the three different hyperon beam momenta and two targets, Cu and Be (Table I). For each of these six combinations, data were collected at two horizontal production angles; ± 4 mrad. The production angle is the angle between the momentum vectors of the proton in the primary beam and the outgoing Σ^+ particle.

Hyperons, in contrast to protons and neutrons whose polarizations are difficult to measure at high energies, display their polarizations through their parity violating

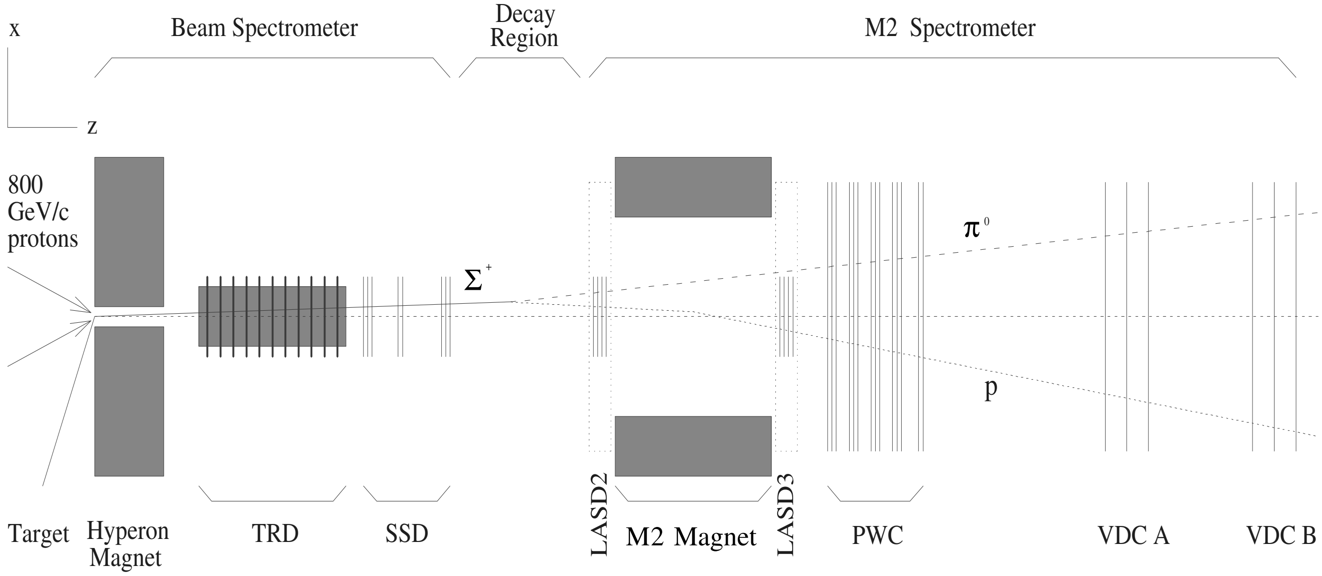

FIG. 1. Plan view (not to scale) shows the experimental apparatus and simulated events. Shown are the detectors, hyperon magnet and the M2 magnet. The major component of the magnets' fields are in the y-direction. Transition radiation detectors (TRD) were used to distinguish Σ^+ from lighter particles. Silicon strip detectors (SSD), proportional wire chambers (PWC), and vector drift chambers (VDC) were used to measure the spatial positions of the charged particles.

decays. The dominant (branching ratio $\approx 52\%$) decay mode, $\Sigma^+ \to p\pi^\circ$, of Σ^+ hyperons [24] has a large asymmetry parameter, $\alpha = -0.980 \pm 0.016$. Thus this decay mode is a sensitive analyzer of the Σ^+ polarization. We require the decay to occur within the 6.4 m long decay region that starts after the last plane of the silicon strip detector and continues to the LASD2 station (Fig. 1). All of their daughter protons produced in $\Sigma^+ \to p\pi^\circ$ decays occurring within the designated decay region pass through all the detectors of the M2 spectrometer. The apparatus has a uniform acceptance for these $\Sigma^+ \to p\pi^\circ$ decays.

The $\Sigma^+ \to p\pi^\circ$ decay was reconstructed from the momentum vectors of the Σ^+ hyperon and its daughter proton. As previously stated the momentum vector of the parent Σ^+ was determined from the beam spectrometer (Fig. 1). The track segment of the daughter proton downstream of the M2 magnet was obtained from LASD3 and the drift chambers. The upstream segment was obtained from LASD2. The momentum of the daughter proton was then determined by connecting the upstream and downstream segments with the help of the M2 magnetic field.

Joining the Σ^+ trajectory with the assumed proton trajectory results in an intersection point and a kink angle. Assuming that these belong to a $\Sigma^+ \to p\pi^\circ$ decay, energy and momentum conservation allows us to compute the invariant mass of the proton-pion pair, i.e., the reconstructed Σ^+ mass. The light gray histogram of Fig. 2 shows the effective mass of the Σ^+ for our combined event sample. The bin size in Fig. 2 is about one fourth of the mass resolution of the SELEX apparatus. The curve is a fit to the data of a Gaussian distribution plus a linear background. The peak coincides with the known [24] value (arrow) of the Σ^+ mass. More stringent criteria were then used to reduce the background signal. The dark gray histogram reflects the same data after the following event selection criteria were applied: a kink angle cut at $\theta > 0.2$ mrad, a cut on the kink angle component in the vertical plane (y-direction) of the M2 magnet at $\theta >$

TABLE I. Data Summary. Table one summarizes the data samples. See Sec. IV.

	P_b (GeV/c)	P_t (GeV/c)	x_F	Events	P (%)
Cu	366 ± 24	1.41 ± 0.09	0.46 ± 0.03	2723	12.7 ± 3.3 ± 1.1
	478 ± 36	1.85 ± 0.14	0.60 ± 0.05	2905	18.0 ± 3.2 ± 1.1
	540 ± 39	2.09 ± 0.15	0.68 ± 0.05	4575	14.3 ± 2.9 ± 1.0
Be	364 ± 27	1.41 ± 0.10	0.46 ± 0.93	3542	18.8 ± 2.9 ± 1.0
	473 ± 39	1.83 ± 0.15	0.59 ± 0.05	3933	22.6 ± 2.8 ± 0.9
	539 ± 40	2.07 ± 0.15	0.67 ± 0.05	5128	19.6 ± 2.6 ± 0.9

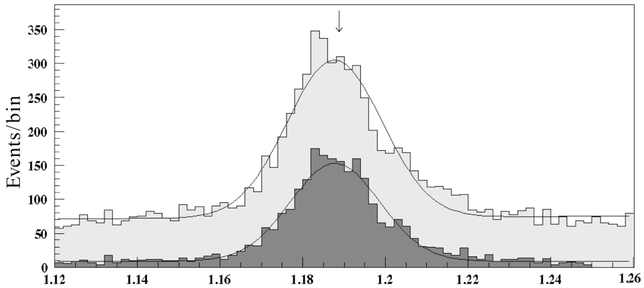

FIG. 2. Σ^+ effective mass GeV/c^2.

0.1 mrad, a kinematic requirement on the ratio of the daughter proton momentum to the Σ^+ momentum, ($0.64 < p_p/p_\Sigma < 0.88$) and a requirement that the decay vertex must occur in the decay region of the apparatus. For the subsequent polarization analysis, only events within ± 0.035 GeV/c^2 of the accepted Σ^+ mass [24] were included.

Parity conservation demands that the polarization of hyperons produced by proton-nucleon collisions be perpendicular to the production plane

$$\vec{\mathbf{P}} \propto \vec{\mathbf{p}}_{\mathrm{prim}} \otimes \vec{\mathbf{p}}_\Sigma.$$

In this experiment the production plane is horizontal which implies that the polarization is vertical. In our geometry a positive targeting angle (angle between the momentum of the incoming primary proton beam from the Tevatron and the momentum of the outgoing Σ^+) corresponds to downward polarization of the Σ^+. The polarization of the Σ^+ is determined from its decay, $\Sigma^+ \to p\pi^\circ$, by measuring the angular distribution of the decay protons. The angular distribution of the outgoing proton in the rest system of the parent Σ^+ is given by

$$\frac{1}{N}\frac{dN}{d\theta} = A(\theta, \phi)(1 + \alpha \mathrm{P} \cos\theta),$$

where θ is the angle between the direction of the polarization vector $\mathbf{P}$ and the momentum $\mathbf{p_p}$ of the daughter proton α is the asymmetry parameter for the decay [24] and $A(\theta, \phi)$ the acceptance of the detector. A bias canceling method is used to eliminate the acceptance factor $A(\theta, \phi)$. If the targeting angle is reversed the cross product reverses thereby reversing the direction of the polarization $\mathbf{P}$, which results in $\cos\theta \to \cos(\pi - \theta) \to -\cos\theta$. Thus, if data samples with positive and negative targeting angles are combined as follows we obtain a relation, free of the acceptance of the detector:

$$\frac{N^+(\theta) - N^-(\theta)}{N^+(\theta) + N^-(\theta)} = \alpha \mathrm{P} \cos\theta.$$

The slope of a histogram of the quantity on the left versus $\cos\theta$ yields αP. Since the magnetic field in all of the magnets is also vertical, there is no spin precession in the magnets. The Σ^+ polarization can thus be determined by using the known asymmetry of the $\Sigma^+ \to p\pi^\circ$ decay [24].

IV. RESULTS AND CONCLUSION

For each of the six data sets, the production polarization of the Σ^+ hyperons was determined by using the bias canceling method [4,25] described above (see Table I for details). The mean values of the hyperon beam momentum (p_b) and transverse momentum (p_t) are given. They have been computed by averaging the values corresponding to the events in each data set. Errors reported are simple standard deviations obtained from these events; x_F is the value of p_b divided by the 800 GeV/c momentum of the incident proton beam. For each measurement of the polarization (P) both the statistical and systematic uncertainty are presented. Some of the systematic effects in the polarization measurement were estimated by measuring false asymmetries, i.e., the asymmetries of the $\Sigma^+ \to p\pi^\circ$ decays where no polarizations were expected. In addition to this, the effects of changing specific cuts in the event selection criteria and also varying the bin sizes on the polarization values were studied. (Event selection criteria were explained above.) Systematic uncertainties were estimated by combining the results of these studies.

Our polarization results are presented in Fig. 3 with the previous results [4] of Fermilab E761 [26]. Both Fermilab E761 and E781 used the same hyperon magnet, but E761 used a tungsten-lined channel with a smaller radius of curvature, which yielded a maximum momentum of

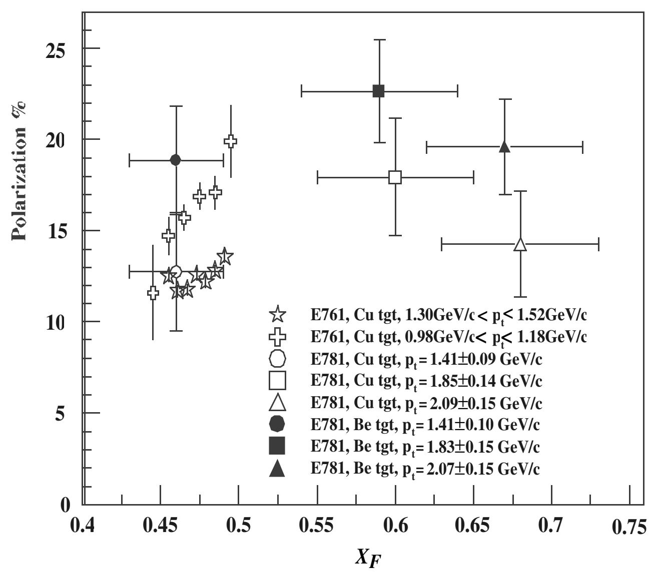

FIG. 3. A summary of the Σ^+ polarization data from E781 and E761. The polarization is plotted as a function of x_F. The corresponding p_t interval for each point is included in the legend.

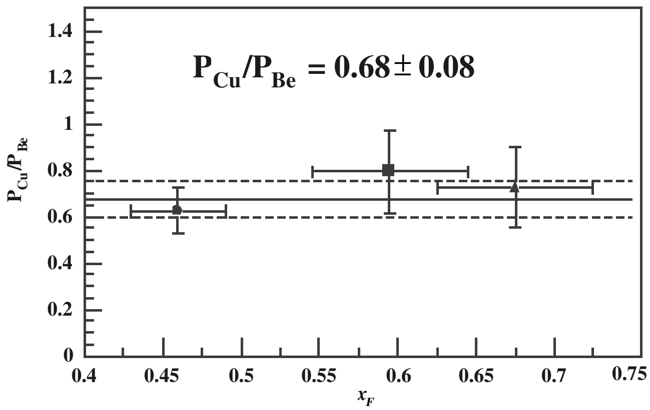

FIG. 4. Σ^+ polarization ratio vs x_F.

350 GeV/c for the particles following the tungsten-lined channel. However as can be seen from Fig. 3, our results corresponding to Cu target at the lowest x_F overlaps a set of points [4] from E761. We combine these data (both E761 and E781) in our subsequent analysis where we calculate the polarization ratios (Fig. 4) since the points cover similar ranges of p_t and x_F.

We have measured significant Σ^+ polarization ($\approx$ 15–20%) from both Cu and Be targets. The magnitudes of the polarization of Σ^+ produced in the heavier target (Cu) are found to be consistently smaller than the corresponding polarization on the lighter target (Be) (Fig. 3). The ratio of the Σ^+ polarization (P_{Cu}/P_{Be}) is shown in Fig. 4 (error bars show the statistical uncertainty only). In all cases it is less than 1 and if we calculate the weighted mean of the three points, we find $P_{Cu}/P_{Be} = 0.68 \pm 0.08$ (statistical uncertainty only).

The dependence of hyperon polarization on the production target material was measured [2,27] for $\Lambda°$ and Ξ^- hyperons produced by 400 GeV/c protons at ($0.6 < p_t < 1.9$) GeV/c. In that study the production polarization of $\Lambda°$ hyperons was measured for Be and Cu + Pb targets. The $\Lambda°$ polarization magnitude obtained from the combined Cu + Pb data was observed to be smaller from the Be data by about 2/3. We observe similar effects for Σ^+ hyperons produced by 800 GeV/c protons at ($1.41 < p_t < 2.08$) GeV/c.

There is no coherent theory which explains the rich panoply of hyperon polarization [5,28] data. This first measurement of Σ^+ polarization at large x_F and $p_t \approx$ 2 GeV/c again demonstrates that these effects are large. One hopes that this new dependence [11] on the target material (Cu and Be) may shed some light on the production mechanism.

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