A STUDY OF INCLUSIVE Λ POLARIZATION FROM HYDROGEN AND OTHER TARGETS AT 28 GeV

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We report measurements of inclusive Λ polarization, produced by unpolarized protons incident at several momenta (20, 24, and 28.5 GeV/c) onto hydrogen, deuterium, and beryllium targets. A large polarization from hydrogen, $P = -0.34 \pm 0.06$ at $p_T = 1.2$ GeV/c, establishes the fact that inclusive Λ polarization arises from p–p collisions.

Three years ago, it was reported that 300 GeV/c unpolarized protons incident on an unpolarized target (beryllium) produce highly polarized Λ's [1]. This refuted the intuitive picture that particle production at high energy would involve a large number of final states, so no coherent interference of amplitudes would be possible, and thus, no polarization would be expected. Subsequently, Λ polarization with the same qualitative behavior has been seen for protons incident at 24 GeV/c (CERN PS) [2], 28 GeV/c (AGS) [3], 400 GeV/c (FNAL) [4] and for 1500 GeV/c [5] (ISR). In addition to Λ's, Ξ^0's are produced polarized [6], but $\bar{\Lambda}$'s [4] and protons [7] are not. These results suggest spin effects are a fundamental aspect of particle production at high energy [4,8]. Large spin effects have also been seen for the p–p elastic scattering parameter A_{nn} at 12 GeV/c incident momentum and $p_T = 2.2$ GeV/c [9].

There is a great diversity in the experiments quoted above which establish the phenomena of Λ polarization. In addition to various incident momentum protons, the targets used and kinematic regions covered were different. It is possible that the kinematic behavior and targets conspire to give similar effects for quite different mechanisms. This experiment was done at the Brookhaven AGS to investigate several of these differences. We measured Λ polarization with protons incident on hydrogen and deuterium targets at 28.5 GeV/c and on a beryllium target at incident momenta 20, 24 and 28.5 GeV/c.

The experiment has several goals: (1) to measure the polarization from a hydrogen target and verify that the polarization was not a nuclear effect; (2) to study the target-dependence of the polarization at one incident beam energy; (3) to use the same target as in higher energy experiments to measure the energy dependence of a polarization on a single target; and (4) to test the kinematic dependence of the polarization

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by varying the incident proton energy with Λ's produced at a fixed angle from one target.

A schematic of the upstream region of the experiment is shown in fig. 1a. A beam of 5×10^8 protons per second was incident on a production target. The cryogenic target flask for hydrogen and deuterium was 30 cm long in the proton beam direction, with a diameter of 6.4 cm. The beryllium target was a square metal bar 15 cm along the proton beam and 0.25 cm on each side. A Λ produced at 4° passed through the entire liquid target (a 5% interaction length for H_2, 10% for D_2) or exited through the side of the beryllium target after passing through an average of 2 cm of beryllium (a 7% interaction length). Thus, there was a relatively small probability that the Λ, once having left the nucleus, rescattered in the target, A 1.83 meter dipole magnet bending vertically, oriented at a horizontal angle of 4° to the proton beam, followed the target. The gap of the magnet was filled with a brass collimator with a 3.8 cm sqyare opening tapering to a 6.4 cm horizontal and a 5.4 cm vertical opening at the downstream face. The magnet served three purposes: the proton beam was dumped on its upstream face, the field swept charged particles produced in the target into the brass so that only neutrals within a 0.7 msr solid angle survived the collimator, and the field precessed the Λ spin in a vertical plane by 46°.

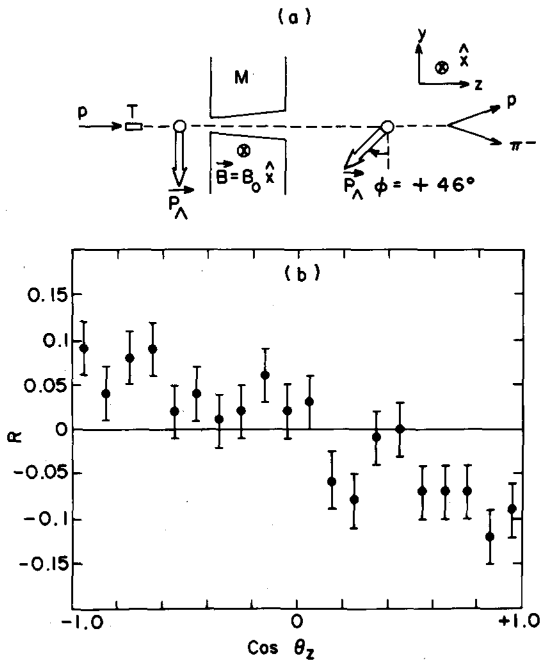

Fig. 1. (a) Shows a Λ with spin initially along $-\hat{y}$ precessed clockwise by the magnetic field $\boldsymbol{B} = B_0\hat{x}$ in M, giving an outgoing polarization at 46° from $-\hat{y}$. The z-component of polarization flips with the reversal of M polarity. (b) shows the ratio $R = (dN_+ - dN_-)/(dN_+ + dN_-) = \alpha P_z \cos\theta_z^*$.

After the precession magnet, there was a 70″ vacuum decay region followed by a charged particle spectrometer. The spectrometer, not shown, was unchanged from that used in a previous experiment described in ref. [3]. The event trigger required no charged particles entering the decay volume and at least one charged particle traversing the spectrometer. About 10% of the triggers gave reconstructed Λ's. The $\Lambda \to p-\pi^-$ events were required to have a small distance of closest approach at the vertex and the vee was required to point back to the production target. The $p-\pi^-$ effective mass had 6 MeV/c^2 FWHM consistent with resolution and showed 1.5% background, including background from misidentified $K_S^0 \to \pi^+\pi^-$ decays. The momentum of the Λ's ranged between 5 and 22 GeV/c with an average of 13.3 GeV/c, for the data with 28.5 GeV/c incident protons. There were a total of 80 000 Λ's for all targets and energies which were analyzed for polarization.

The Λ polarization was measured in two ways. The first method required no acceptance calculation. A polarization appears as an asymmetry of the proton emitted in the Λ rest frame:

$$dN(p)/d\Omega = (N_0/4\pi)(1 + \alpha_\Lambda \boldsymbol{P}_\Lambda \cdot \hat{\boldsymbol{p}}) , \quad (1)$$

where N_0 is a normalization parameter, α_Λ is the known analyzing power for Λ decay, $\boldsymbol{P}_\Lambda$ is the Λ polarization and $\hat{\boldsymbol{p}}$ is the direction of the proton for the event. Referring to fig. 1a, a Λ polarization initially in the vertical (or $\hat{y}$) direction, perpendicular to the production plane, precesses in the magnetic field of M to an angle $\pm\phi$ from $\hat{y}$ in the $y-z$ vertical plane. The precession angle ϕ depends on the field integral over the path of the Λ in M and on the Λ magnetic moment and is a constant independent of the Λ momentum to 2% over the range of the experiment, p_Λ = 5–28 GeV/c. For data taken with opposite M polarity, the z component of polarization reverses, but not the y component. This reversal allows the measurement of the z component of polarization without needing to know the acceptance of the apparatus. Eq. (1) can be written in terms of the z-polarization by expressing $\hat{\boldsymbol{p}}$ in polar coordinates about $\hat{z}$ and integrating over the azimuth in the $x-y$ plane:

$$\frac{dN(p)}{d\cos\theta_z^*} = \tfrac{1}{2}N_0(1+\alpha_\Lambda P_z\cos\theta_z^*)A(\cos\theta_z^*)\,, \quad (2)$$

where P_z is the z component of Λ polarization, θ_z^* is the direction of the proton from the z axis and $A(\cos\theta_z^*)$ is the detection efficiency for the decay, integrated over azimuth. The polarization components P_x and P_y have dropped out of eq. (2) because $P_x = 0$ if the polarization conserves parity and integration over azimuth for the y component is zero because the apparatus was up–down symmetric. Runs with opposite polarity in M reverse P_z, but have the same detection efficiency A, so calculating the ratio

$$R(\cos\theta_z^*) = \frac{dN_+(\cos\theta_z^*) - dN_-(\cos\theta_z^*)}{dN_+(\cos\theta_z^*) + dN_-(\cos\theta_z^*)}$$

$$= \alpha_\Lambda P_z\cos\theta_z^*\,, \quad (3)$$

eleminates the acceptance A, where dN_+ and dN_- represent the number of events for positive and negative M polarity in a bin of $\cos\theta_z^*$. The dN_+ and dN_- distributions were normalized to the same number of events. Fig. 1b shows the ratio R versus $\cos\theta_z^*$ for all the hydrogen data. A least-squares fit to the ratio gives $\alpha_\Lambda P_z$. The χ^2 deviation for all fits to the different targets and different incident momenta was 134 for 114 degrees of freedom.

A second way to determine the polarization used a Monte Carlo technique [10] to calculate the detection efficiency for the measurement of P_y, the component which did not flip when the polarity of M was reversed. This technique gave $\chi^2 = 117$ for 114 degrees of freedom. The Monte Carlo technique was also used to calculate P_z. This result agreed with the ratio method of eq. (3).

Fig. 2 shows P_y, P_z and the precession angle ϕ for the hydrogen target data, as a function of Λ momentum. ϕ should be a constant for all the data. We measured $\phi = 40.9° \pm 4.1°$ compared with $\phi = 46.1° \pm 0.3°$ based on the known Λ magnetic moment [11] ‡1. The polarization in the results that follow

‡1 M was a standard AGS magnet and we have used a field integral value of 4.12 T m from measurements on a similar magnet to obtain the expected precession angle. A series shunt monitored the current and polarity during the experiment. Because the magnet iron was saturated, we have assumed the field was the same for opposite polarity runs.

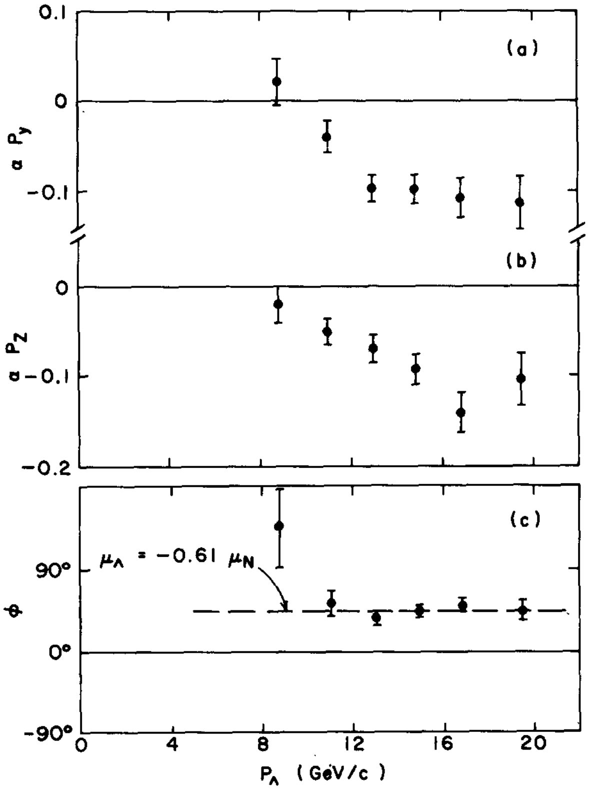

Fig. 2. This figure shows the polarization components P_y and P_z and the precession angle $\phi = \tan^{-1} P_z/P_y$ versus the Λ momentum for all the data. ϕ should be independent of the Λ momentum, even though the detection efficiency is a strong function of the Λ momentum. The dashed line shows the expected angle using the Λ magnetic moment $\mu_\Lambda = -0.61\mu_N$ [11] ‡1.

was obtained from using $\alpha_\Lambda = 0.647$ [12] and taking a weighted average of $P_\Lambda = P_z/\sin 46°$ and $P_\Lambda = P_y/\cos 46°$. The reference direction for the polarization was chosen as **beam** × $\hat{\mathbf{\Lambda}}$.

The target empty rates for Λ production were 13% that for the hydrogen target. The average polarization of the empty target data was $\bar{P} = -0.22 \pm 0.06$, compared with $\bar{P} = -0.21 \pm 0.03$ for hydrogen and $\bar{P} = -0.18 \pm 0.02$ for deuterium. Thus, it was not necessary to make a target-empty correction to the polarization. For the beryllium data, the target-out rate was 1% and, again, no target-out correction was made.

The Λ polarization data from hydrogen and deuterium targets are shown in fig. 3a. The large polarization from hydrogen establishes the fact that inclusive Λ polarization arises from p–p collisions. The

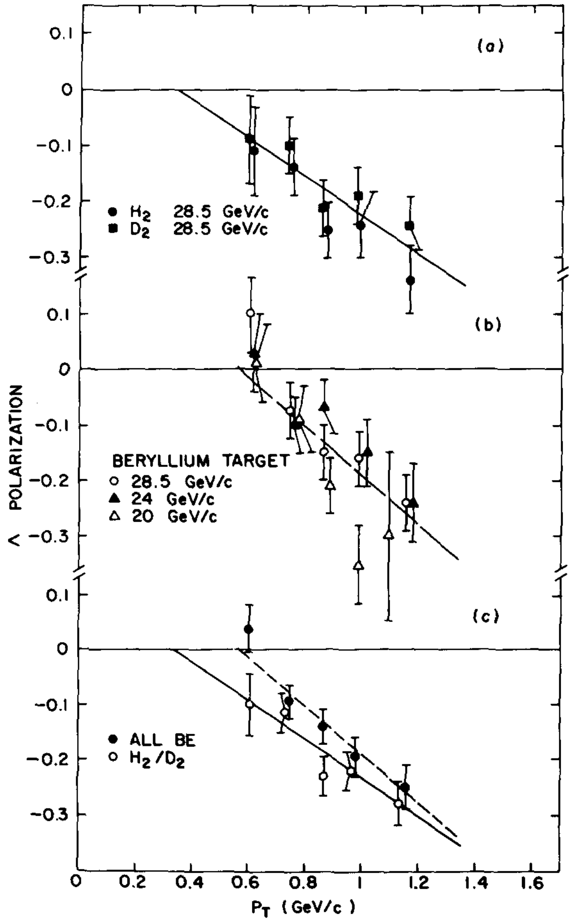

Fig. 3. The Λ polarization versus p_T for hydrogen and deuterium targets with protons incident at 28.5 GeV/c is shown in (a). (b) shows the results for a beryllium target for three incident momenta. (c) shows the H_2/D_2 combined data compared to the beryllium combined data. Straight line fits are shown for the combined data.

polarization data from both targets fit a straight line, shown in the figure,

$$P(H_2 + D_2) = (-0.35 \pm 0.02)\,(p_T - 0.34 \pm 0.05),$$

with the slope units in $(\text{GeV}/c)^{-1}$, with $\chi^2 = 5$ for 8 degrees of freedom. Thus, we find no difference in polarization between proton and neutron targets.

The kinematic dependence of the polarization was investigated by varying the incident beam momentum while observing Λ's at a fixed production angle. At 28.5 GeV/c, the kinematic regions covered were $p_T = 0.5$–1.2 GeV/c or $x_F = 0.25$–0.6. For momenta of 20, 24, and 28.5 GeV/c, $x_F \approx p_\Lambda / p_{\text{beam}}$ varies by 30% for fixed p_Λ or p_T. The center-of mass energy changes by 16% over this range. Fig. 3b shows beryllium target data for the three incident momenta. The polarization from all three incident momenta are fit well by the straight line

$$P(\text{Be}) = (-0.44 \pm 0.02)\,(p_T - 0.57 \pm 0.04),$$

with $\chi^2 = 14$ for 13 degrees of freedom. We observe no kinematic dependence of the polarization other than the transverse momentum with a sensitivity of $\Delta P/P = 20\%$ for the range $\Delta x_F = 0.3$. An x_F dependence at about this level was observed at 400 GeV/c [13].

Fig. 3c shows the polarization data for hydrogen and deuterium combined and for the beryllium target data combined. The beryllium results are lower. Thus, the nuclear target may tend to wash out the effect through another scatter of the Λ in the struck nucleus [14]. Platinum target data [2] at 24 GeV/c show still

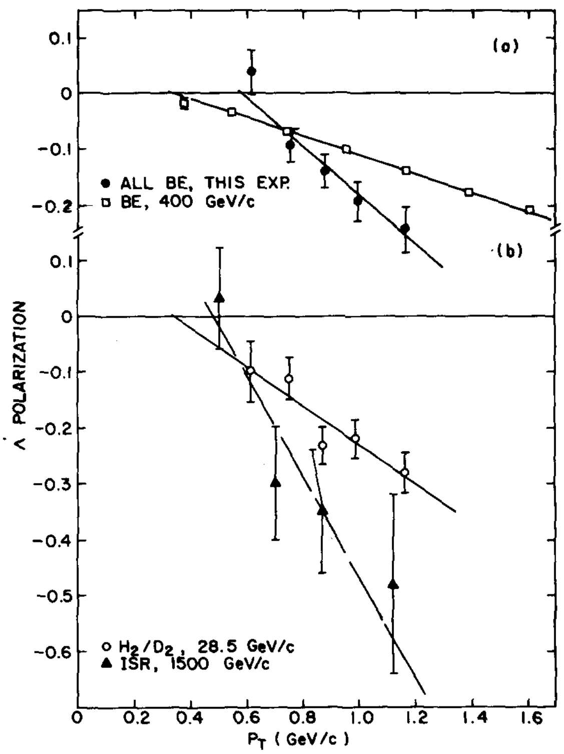

Fig. 4. The Λ polarization for this experiment is compared with higher energy data, for beryllium in (a) and for H_2/D_2 in (b).

lower polarization at fixed p_T than our beryllium results, indicating a trend that heavier targets give lower polarization. The iridium target data [3] at 28.5 GeV/c, however, have a shallower p_T-dependence than the others and are larger at small p_T than our H_2/D_2 results.

In fig. 4, we compare polarization results for different energies from the same target. Fig. 4a shows that polarization from a beryllium target at 400 GeV/c is lower than our data. Fig. 4b indicates that the polarization for incident protons with an equivalent lab momentum of 1500 GeV/c [5] is larger than at 28.5 GeV/c, for H_2/D_2 targets. It is seen that inclusive polarization is present and increases with transverse momentum over a large energy range. However, the energy dependence of the polarization is not yet clear.

For all of these experiments, no distinction could be made between Λ's produced directly and Λ's which come from $\Sigma \to \Lambda\gamma$ decay after a Σ^0 is produced. If the Σ^0's were polarized, their daughter Λ's would retain −1/3 of this polarization. The polarization of directly-produced Λ's may be considerably larger than the measured values for Λ/Σ^0, depending on the Λ/Σ^0 production ratio and the Σ^0 polarization. Thus, the comparison of polarization results from different targets and at different energies assumes that the Σ^0 contribution to the measured polarization is the mass for the different cases.

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